<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Elliptic curve constructor</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Construct elliptic curves as Jacobians</td>
<td>19</td>
</tr>
<tr>
<td>3</td>
<td>Points on elliptic curves</td>
<td>23</td>
</tr>
<tr>
<td>4</td>
<td>Elliptic curves over a general ring</td>
<td>57</td>
</tr>
<tr>
<td>5</td>
<td>Elliptic curves over a general field</td>
<td>87</td>
</tr>
<tr>
<td>6</td>
<td>Elliptic curves over finite fields</td>
<td>109</td>
</tr>
<tr>
<td>7</td>
<td>Formal groups of elliptic curves</td>
<td>129</td>
</tr>
<tr>
<td>8</td>
<td>Elliptic-curve morphisms</td>
<td>135</td>
</tr>
<tr>
<td>9</td>
<td>Isomorphisms between Weierstrass models of elliptic curves</td>
<td>143</td>
</tr>
<tr>
<td>10</td>
<td>Isogenies</td>
<td>147</td>
</tr>
<tr>
<td>11</td>
<td>$\sqrt{\text{el}u}$ Algorithm for Elliptic-Curve Isogenies</td>
<td>173</td>
</tr>
<tr>
<td>12</td>
<td>Composite morphisms of elliptic curves</td>
<td>181</td>
</tr>
<tr>
<td>13</td>
<td>Isogenies of small prime degree</td>
<td>189</td>
</tr>
<tr>
<td>14</td>
<td>Elliptic curves over number fields</td>
<td>217</td>
</tr>
<tr>
<td>14.1</td>
<td>Elliptic curves over the rational numbers</td>
<td>217</td>
</tr>
<tr>
<td>14.2</td>
<td>Tables of elliptic curves of given rank</td>
<td>310</td>
</tr>
<tr>
<td>14.3</td>
<td>Elliptic curves over number fields</td>
<td>311</td>
</tr>
<tr>
<td>14.4</td>
<td>Canonical heights for elliptic curves over number fields</td>
<td>364</td>
</tr>
<tr>
<td>14.5</td>
<td>Saturation of Mordell-Weil groups of elliptic curves over number fields</td>
<td>382</td>
</tr>
<tr>
<td>14.6</td>
<td>Torsion subgroups of elliptic curves over number fields (including $\mathbb{Q}$)</td>
<td>387</td>
</tr>
<tr>
<td>14.7</td>
<td>Galois representations attached to elliptic curves</td>
<td>391</td>
</tr>
<tr>
<td>14.8</td>
<td>Galois representations for elliptic curves over number fields</td>
<td>403</td>
</tr>
<tr>
<td>14.9</td>
<td>Isogeny class of elliptic curves over number fields</td>
<td>413</td>
</tr>
<tr>
<td>14.10</td>
<td>Tate-Shafarevich group</td>
<td>420</td>
</tr>
<tr>
<td>14.11</td>
<td>Complex multiplication for elliptic curves</td>
<td>431</td>
</tr>
<tr>
<td>14.12</td>
<td>Testing whether elliptic curves over number fields are $\mathbb{Q}$-curves</td>
<td>437</td>
</tr>
<tr>
<td>14.13</td>
<td>Local data for elliptic curves over number fields</td>
<td>441</td>
</tr>
<tr>
<td>14.14</td>
<td>Kodaira symbols</td>
<td>449</td>
</tr>
<tr>
<td>14.15</td>
<td>Tate’s parametrisation of $p$-adic curves with multiplicative reduction</td>
<td>450</td>
</tr>
</tbody>
</table>
### 14.16 Weierstrass $\wp$-function for elliptic curves .................................................. 455
### 14.17 Period lattices of elliptic curves and related functions ................................. 458
### 14.18 Regions in fundamental domains of period lattices ....................................... 477
### 14.19 Modular parametrization of elliptic curves over $\mathbb{Q}$ ................................. 482
### 14.20 Modular symbols attached to elliptic curves over $\mathbb{Q}$ ............................... 484
### 14.21 Modular symbols by numerical integration ...................................................... 489
### 14.22 $L$-series for elliptic curves ............................................................................ 495
### 14.23 Heegner points on elliptic curves over the rational numbers .......................... 504
### 14.24 $p$-adic $L$-functions of elliptic curves ........................................................... 561

### 15 To be sorted

15.1 Descent on elliptic curves over $\mathbb{Q}$ with a 2-isogeny ........................................ 577
15.2 Elliptic curves with prescribed good reduction ...................................................... 580
15.3 Elliptic curves over $p$-adic fields .......................................................................... 584
15.4 Denis Simon’s PARI scripts .................................................................................. 585
15.5 Elliptic curves with congruent mod-5 representation ........................................... 586
15.6 Morphism to bring a genus-one curve into Weierstrass form ............................... 586

### 16 Hyperelliptic curves

16.1 Hyperelliptic curve constructor ........................................................................... 591
16.2 Hyperelliptic curves over a general ring ............................................................... 593
16.3 Hyperelliptic curves over a finite field ................................................................... 601
16.4 Hyperelliptic curves over a $p$-adic field .............................................................. 616
16.5 Hyperelliptic curves over the rationals ................................................................. 633
16.6 Mestre’s algorithm .............................................................................................. 633
16.7 Computation of Frobenius matrix on Monsky-Washnitzer cohomology .................. 636
16.8 Frobenius on Monsky-Washnitzer cohomology of a hyperelliptic curve over a .... 666
16.9 Jacobian of a general hyperelliptic curve ............................................................. 668
16.10 Jacobian of a hyperelliptic curve of genus 2 ......................................................... 672
16.11 Rational point sets on a Jacobian .......................................................................... 673
16.12 Jacobian ‘morphism’ as a class in the Picard group ............................................. 674
16.13 Hyperelliptic curves of genus 2 over a general ring ............................................ 678
16.14 Compute invariants of quintics and sextics via ‘Ueberschiebung’ .......................... 680
16.15 Kummer surfaces over a general ring ................................................................. 685
16.16 Conductor and reduction types for genus 2 curves .............................................. 686

### 17 Indices and Tables

691

Bibliography 693

Python Module Index 695

Index 697
ELLIPTIC CURVE CONSTRUCTOR

AUTHORS:

- William Stein (2005): Initial version
- John Cremona (2008-01): EllipticCurve(j) fixed for all cases

class sage.schemes.elliptic_curves.constructor.EllipticCurveFactory
    Bases: sage.structure.factory.UniqueFactory

Construct an elliptic curve.

In Sage, an elliptic curve is always specified by (the coefficients of) a long Weierstrass equation

\[ y^2 + a_1 xy + a_3 y = x^3 + a_2 x^2 + a_4 x + a_6. \]

INPUT:

There are several ways to construct an elliptic curve:

- `EllipticCurve([a1,a2,a3,a4,a6])`: Elliptic curve with given \(a\)-invariants. The invariants are coerced into a common parent. If all are integers, they are coerced into the rational numbers.
- `EllipticCurve([a4,a6])`: Same as above, but \(a_1 = a_2 = a_3 = 0\).
- `EllipticCurve(label)`: Returns the elliptic curve over \(\mathbb{Q}\) from the Cremona database with the given label. The label is a string, such as "11a" or "37b2". The letters in the label must be lower case (Cremona's new labeling).
- `EllipticCurve(R, [a1,a2,a3,a4,a6])`: Create the elliptic curve over \(R\) with given \(a\)-invariants. Here \(R\) can be an arbitrary commutative ring, although most functionality is only implemented over fields.
- `EllipticCurve(j=j0)` or `EllipticCurve_from_j(j0)`: Return an elliptic curve with \(j\)-invariant \(j\).
- `EllipticCurve(polynomial)`: Read off the \(a\)-invariants from the polynomial coefficients, see `EllipticCurve_from_Weierstrass_polynomial()`.
- `EllipticCurve(cubic, point)`: The elliptic curve defined by a plane cubic (homogeneous polynomial in three variables), with a rational point.

Instead of giving the coefficients as a list of length 2 or 5, one can also give a tuple.

EXAMPLES:

We illustrate creating elliptic curves:

```
sage: EllipticCurve([0,0,1,-1,0])
Elliptic Curve defined by y^2 + y = x^3 - x over Rational Field
```

We create a curve from a Cremona label:
Elliptic curves, Release 9.7

```sage
sage: EllipticCurve('37b2')
Elliptic Curve defined by y^2 + y = x^3 + x^2 - 1873*x - 31833 over Rational Field
sage: EllipticCurve('5077a')
Elliptic Curve defined by y^2 + y = x^3 - 7*x + 6 over Rational Field
sage: EllipticCurve('389a')
Elliptic Curve defined by y^2 + y = x^3 + x^2 - 2*x over Rational Field

Old Cremona labels are allowed:

```sage
sage: EllipticCurve('2400FF')
Elliptic Curve defined by y^2 = x^3 + x^2 + 2*x + 8 over Rational Field

Unicode labels are allowed:

```sage
sage: EllipticCurve(u'389a')
Elliptic Curve defined by y^2 + y = x^3 + x^2 - 2*x over Rational Field

We create curves over a finite field as follows:

```sage
sage: F = Zmod(101)
sage: EllipticCurve(F, [2, 3])
Elliptic Curve defined by y^2 = x^3 + 2*x + 3 over Ring of integers modulo 101
sage: type(E)
<class 'sage.schemes.elliptic_curves.ell_finite_field.EllipticCurve_finite_field_with_category'>
sage: E.category()
Category of schemes over Ring of integers modulo 101

Elliptic curves over \( \mathbb{Z}/N\mathbb{Z} \) with \( N \) prime are of type “elliptic curve over a finite field”:

```sage
sage: F = Zmod(95)
sage: E = EllipticCurve(F, [2, 3])
Elliptic Curve defined by y^2 = x^3 + 2*x + 3 over Ring of integers modulo 95
sage: E.category()
Category of schemes over Ring of integers modulo 95

In contrast, elliptic curves over \( \mathbb{Z}/N\mathbb{Z} \) with \( N \) composite are of type “generic elliptic curve”:

```sage
sage: F = Zmod(95)
sage: E = EllipticCurve(F, [2, 3])
Elliptic Curve defined by y^2 = x^3 + 2*x + 3 over Ring of integers modulo 95
sage: E.category()
Category of schemes over Ring of integers modulo 95

The following is a curve over the complex numbers:

```sage
sage: E = EllipticCurve(CC, [0,0,1,-1,0])
sage: E
Elliptic Curve defined by y^2 + 1.00000000000000*x = x^3 + (-1.00000000000000)*x over Complex Field with 53 bits of precision
```
We can also create elliptic curves by giving the Weierstrass equation:

```
sage: R2.<x,y> = PolynomialRing(QQ,2)
sage: EllipticCurve(y^2 + y - ( x^3 + x - 9 ))
Elliptic Curve defined by y^2 + y = x^3 + x - 9 over Rational Field
sage: R.<x,y> = GF(5)[]
sage: EllipticCurve(x^3 + x^2 + 2 - y^2 - y*x)
Elliptic Curve defined by y^2 + x*y = x^3 + x^2 + 2 over Finite Field of size 5
```

We can also create elliptic curves by giving a smooth plane cubic with a rational point:

```
sage: R3.<x,y,z> = PolynomialRing(QQ,3)
sage: F = x^3+y^3+30*z^3
sage: P = [1,-1,0]
sage: EllipticCurve(F,P)
Elliptic Curve defined by y^2 - 270*y = x^3 - 24300 over Rational Field
```

We can explicitly specify the $j$-invariant:

```
sage: E = EllipticCurve(j=1728); E; E.j_invariant(); E.label()
Elliptic Curve defined by y^2 = x^3 - x over Rational Field
1728
'32a2'
sage: E = EllipticCurve(j=GF(5)(2)); E; E.j_invariant()
Elliptic Curve defined by y^2 = x^3 + x + 1 over Finite Field of size 5
2
```

See trac ticket #6657

```
sage: EllipticCurve(GF(144169),j=1728)
Elliptic Curve defined by y^2 = x^3 + x over Finite Field of size 144169
```

Elliptic curves over the same ring with the same Weierstrass coefficients are identical, even when they are constructed in different ways (see trac ticket #11474):

```
sage: EllipticCurve('11a3') is EllipticCurve(QQ, [0, -1, 1, 0, 0])
True
```

By default, when a rational value of $j$ is given, the constructed curve is a minimal twist (minimal conductor for curves with that $j$-invariant). This can be changed by setting the optional parameter `minimal_twist`, which is True by default, to False:

```
sage: EllipticCurve(j=100)
Elliptic Curve defined by y^2 = x^3 + x^2 + 3392*x + 307888 over Rational Field
sage: E =EllipticCurve(j=100); E
Elliptic Curve defined by y^2 = x^3 + x^2 + 3392*x + 307888 over Rational Field
sage: E.conductor()
33129800
```
Elliptic curves, Release 9.7

```
sage: E.j_invariant()
100
sage: E = EllipticCurve(j=100, minimal_twist=False); E
Elliptic Curve defined by y^2 = x^3 + 488400*x - 530076800 over Rational Field
sage: E.conductor()
298168200
sage: E.j_invariant()
100
```

Without this option, constructing the curve could take a long time since both \( j \) and \( j - 1728 \) have to be factored to compute the minimal twist (see trac ticket #13100):

```
sage: E = EllipticCurve_from_j(2^256+1, minimal_twist=False)
sage: E.j_invariant() == 2^256+1
True
```

`create_key_and_extra_args(x=None, y=None, j=None, minimal_twist=True, **kwds)`

Return a `UniqueFactory` key and possibly extra parameters.

**INPUT:**

See the documentation for `EllipticCurveFactory`.

**OUTPUT:**

A pair `(key, extra_args)`:

- `key` has the form \((R, (a_1, a_2, a_3, a_4, a_6))\), representing a ring and the Weierstrass coefficients of an elliptic curve over that ring;
- `extra_args` is a dictionary containing additional data to be inserted into the elliptic curve structure.

**EXAMPLES:**

```
sage: EllipticCurve.create_key_and_extra_args(j=8000)
((Rational Field, (0, 1, 0, -3, 1)), {})
```

When constructing a curve over \( \mathbb{Q} \) from a Cremona or LMFDB label, the invariants from the database are returned as `extra_args`:

```
sage: key, data = EllipticCurve.create_key_and_extra_args('389.a1')
sage: key
(Rational Field, (0, 1, 1, -2, 0))
sage: data['conductor']
389
sage: data['cremona_label']
'389a1'
```

User-specified keywords are also included in `extra_args`:

```
sage: data['torsion_order']
1
```
Furthermore, keywords takes precedence over data from the database, which can be used to specify an
alternative set of generators for the Mordell-Weil group:

```python
sage: key, data = EllipticCurve.create_key_and_extra_args('5077a1', gens=[[1, -1], [-2, 3], [4, -7]])
sage: data['gens']
[[1, -1], [-2, 3], [4, -7]]
sage: E = EllipticCurve.create_object(0, key, **data)
sage: E.gens()
[(-2 : 3 : 1), (1 : -1 : 1), (4 : -7 : 1)]
```

Note that elliptic curves are equal if and only they have the same base ring and Weierstrass equation; the
data in `extra_args` do not influence comparison of elliptic curves. A consequence of this is that passing
keyword arguments only works when constructing an elliptic curve the first time:

```python
sage: E = EllipticCurve('433a1', gens=[[-1, 1], [3, 4]])
sage: E.gens()
[(-1 : 1 : 1), (3 : 4 : 1)]
sage: E = EllipticCurve('433a1', gens=[[-1, 0], [0, 1]])
sage: E.gens()
[(-1 : 1 : 1), (3 : 4 : 1)]
```

**Warning:** Manually specifying extra data is almost never necessary and is not guaranteed to have any
effect, as the above example shows. Almost no checking is done, so specifying incorrect data may lead
to wrong results of computations instead of errors or warnings.

**create_object** *(version, key, **kwds)*
Create an object from a `UniqueFactory` key.

**EXAMPLES:**

```python
sage: E = EllipticCurve.create_object(0, (GF(3), (1, 2, 0, 1, 2)))
sage: type(E)
<class 'sage.schemes.elliptic_curves.ell_finite_field.EllipticCurve_finite_field'>
```

**Note:** Keyword arguments are currently only passed to the constructor for elliptic curves over \( \mathbb{Q} \); elliptic
curves over other fields do not support them.

**sage.schemes.elliptic_curves.constructor.EllipticCurve_from_Weierstrass_polynomial** *(f)*
Return the elliptic curve defined by a cubic in (long) Weierstrass form.

**INPUT:**

- \( f \) – a inhomogeneous cubic polynomial in long Weierstrass form.

**OUTPUT:**
The elliptic curve defined by it.

**EXAMPLES:**

```sage
tR.<x,y> = QQ[]
tf = y^2 + 1*x*y + 3*y - (x^3 + 2*x^2 + 4*x + 6)
tEllipticCurve(tf)

Elliptic Curve defined by y^2 + x*y + 3*y = x^3 + 2*x^2 + 4*x + 6 over Rational Field
```

```sage
tEllipticCurve(tf).a_invariants()
(1, 2, 3, 4, 6)
```

The polynomial ring may have extra variables as long as they do not occur in the polynomial itself:

```sage
tR.<x,y,z,w> = QQ[]
tEllipticCurve(-y^2 + x^3 + 1)
Elliptic Curve defined by y^2 = x^3 + 1 over Rational Field
tEllipticCurve(-x^2 + y^3 + 1)
Elliptic Curve defined by y^2 = x^3 + 1 over Rational Field
tEllipticCurve(-w^2 + z^3 + 1)
Elliptic Curve defined by y^2 = x^3 + 1 over Rational Field
```

`sage.schemes.elliptic_curves.constructor.EllipticCurve_from_c4c6(c4, c6)`

Return an elliptic curve with given $c_4$ and $c_6$ invariants.

**EXAMPLES:**

```sage
tE = EllipticCurve_from_c4c6(17, -2005)
tE

Elliptic Curve defined by y^2 = x^3 - 17/48*x + 2005/864 over Rational Field
tE.c_invariants()
(17, -2005)
```

`sage.schemes.elliptic_curves.constructor.EllipticCurve_from_cubic(F, P=None, morphism=True)`

Construct an elliptic curve from a ternary cubic with a rational point.

If you just want the Weierstrass form and are not interested in the morphism then it is easier to use the function `Jacobian()` instead. If there is a rational point on the given cubic, this function will construct the same elliptic curve but you do not have to supply the point $P$.

**INPUT:**

- $F$ – a homogeneous cubic in three variables with rational coefficients, as a polynomial ring element, defining a smooth plane cubic curve $C$.
- $P$ – a 3-tuple $(x, y, z)$ defining a projective point on $C$, or None. If None then a rational flex will be used as a base point if one exists, otherwise an error will be raised.
- `morphism` – boolean (default: True). If True returns a birational isomorphism from $C$ to a Weierstrass elliptic curve $E$, otherwise just returns $E$.

**OUTPUT:**

Either (when `morphism=False`) an elliptic curve $E$ in long Weierstrass form isomorphic to the plane cubic curve $C$ defined by the equation $F = 0$.

Or (when `morphism=True`), a birational isomorphism from $C$ to the elliptic curve $E$. If the given point is a flex, this is a linear isomorphism.
**Note:** The function \texttt{Jacobian()} may be used instead. It constructs the same elliptic curve (which is in all cases the Jacobian of \((F = 0)\)) and needs no base point to be provided, but also returns no isomorphism since in general there is none: the plane cubic is only isomorphic to its Jacobian when it has a rational point.

**Note:** When \texttt{morphism=True}, a birational isomorphism between the curve \(F = 0\) and the Weierstrass curve is returned. If the point happens to be a flex, then this is a linear isomorphism. The morphism does not necessarily take the given point \(P\) to the point at infinity on \(E\), since we always use a rational flex on \(C\) as base-point when one exists.

**EXAMPLES:**

First we find that the Fermat cubic is isomorphic to the curve with Cremona label 27a1:

```sage
R.<x,y,z> = QQ[]
sage: cubic = x^3+y^3+z^3
sage: P = [1,-1,0]
sage: E = EllipticCurve_from_cubic(cubic, P, morphism=False); E
Elliptic Curve defined by y^2 - 9*y = x^3 - 27 over Rational Field
sage: E.cremona_label()
'27a1'
sage: EllipticCurve_from_cubic(cubic, [0,1,-1], morphism=False).cremona_label()
'27a1'
sage: EllipticCurve_from_cubic(cubic, [1,0,-1], morphism=False).cremona_label()
'27a1'
```

Next we find the minimal model and conductor of the Jacobian of the Selmer curve:

```sage
R.<a,b,c> = QQ[]
sage: cubic = a^3+b^3+60*c^3
sage: P = [1,-1,0]
sage: E = EllipticCurve_from_cubic(cubic, P, morphism=False); E
Elliptic Curve defined by y^2 - 540*y = x^3 - 97200 over Rational Field
sage: E.minimal_model()
Elliptic Curve defined by y^2 = x^3 - 24300 over Rational Field
sage: E.conductor()
24300
```

We can also get the birational isomorphism to and from the Weierstrass form. We start with an example where \(P\) is a flex and the equivalence is a linear isomorphism:

```sage
f = EllipticCurve_from_cubic(cubic, P, morphism=True)
sage: f
Scheme morphism:
  From: Projective Plane Curve over Rational Field defined by a^3 + b^3 + 60*c^3
  To: Elliptic Curve defined by y^2 - 540*y = x^3 - 97200 over Rational Field
  Defn: Defined on coordinates by sending (a : b : c) to
        (-c : 3*a : 1/180*a + 1/180*b)
sage: finv = f.inverse(); finv
Scheme morphism:
  From: Elliptic Curve defined by y^2 - 540*y = x^3 - 97200 over Rational Field
(continues on next page)
```
To: Projective Plane Curve over Rational Field defined by $a^3 + b^3 + 60c^3$
Defn: Defined on coordinates by sending $(x : y : z)$ to
\[
\frac{1}{3}y : -\frac{1}{3}y + 180z : -x
\]

Scheme morphism:
From: Elliptic Curve defined by $y^2 + 2xy + 20y = x^3 - x^2 - 20x - 400/3$
over Rational Field
To: Closed subscheme of Projective Space of dimension 2 over Rational Field
\[
\text{defined by:}
\]
\[
a^3 + b^3 + 60c^3
\]
Defn: Defined on coordinates by sending $(x : y : z)$ to
\[
(x + y + 20z : -x - y : -x)
\]

We verify that $f$ maps the chosen point $P = (1, -1, 0)$ on the cubic to the origin of the elliptic curve:

\[
sage: f([1,-1,0])
(0 : 1 : 0)
\]
\[
sage: finv([0,1,0])
(-1 : 1 : 0)
\]

To verify the output, we plug in the polynomials to check that this indeed transforms the cubic into Weierstrass form:

\[
sage: cubic(finv.defining_polynomials()) * finv.post_rescaling()
-x^3 + y^2z - 540y^2z^2 + 97200z^3
\]
\[
sage: E.defining_polynomial()(f.defining_polynomials()) * f.post_rescaling()
a^3 + b^3 + 60c^3
\]

If the given point is not a flex and the cubic has no rational flexes, then the cubic can not be transformed to a Weierstrass equation by a linear transformation. The general birational transformation is still a birational isomorphism, but is quadratic:

\[
sage: R.<x,y,z> = QQ[]
sage: cubic = x^2*y + 4*x*y^2 + x^2*z + 8*x*y^2*z + 4*y^2*z + 9*x^2*z^2 + 9*y^2*z^2
sage: f = EllipticCurve_from_cubic(cubic, [1,-1,1], morphism=True); f
\]

Scheme morphism:
From: Projective Plane Curve over Rational Field defined by $x^2*y + 4*x*y^2 + x^2
-2*z + 8*x*y^2*z + 4*y^2*z + 9*x^2*z^2 + 9*y^2*z^2$
To: Elliptic Curve defined by $y^2 + 7560/19*x*y + 552960000000/2352637*y = x^3 -
3445200/133*x^2$ over Rational Field
Defn: Defined on coordinates by sending $(x : y : z)$ to
\[
(2527/17280*x^2 + 133/108000*x*y + 133/108000*x^2 + 133/2880*x^2 + 931/
-18000*y^2 - 3857/48000*z^2 : -6859/288*x^2 + 323/36*x*y + 359/1800*y^2 + 551/
-48*x^2 + 2813/300*y^2 + 24389/800*z^2 : -2352637/99532800000*x^2 - 2352637/
-12441600000000*x*y - 2352637/6220000000000*y^2 + 2352637/8294400000000*x^2 + 2352637/
-20736000000000*y^2 - 2352637/2764800000000*z^2)
\]

Note that the morphism returned cannot be evaluated directly at the given point $P=(1:-1:1)$ since the polynomials defining it all vanish there:

\[
sage: f([1,-1,1])
Traceback (most recent call last):
\]
Using the group law on the codomain elliptic curve, which has rank 1 and full 2-torsion, and the inverse morphism, we can find many points on the cubic. First we find the preimages of multiples of the generator:

```
sage: E = f.codomain()
sage: E.label()
'720e2'
sage: E.rank()
1
sage: R = E.gens()[0]; R
(-17280000/2527 : 9331200000/6859 : 1)
sage: finv = f.inverse()
sage: [finv(k*R) for k in range(1,10)]
[(-4 : 1 : 0),
 (-1 : 4 : 1),
 (-20 : -55/76 : 1),
 (319/399 : -11339/7539 : 1),
 (159919/14360 : -4078139/1327840 : 1),
 (-27809119/63578639 : 1856146436/3425378659 : 1),
 (-510646582340/56909753439 : 424000923715/30153806197284 : 1),
 (-56686114363679/4050436059492161 : -2433034816977728281/1072927821085593881 : 1),
 (650589598999815846721/72056273157352822480 : -34737618954606019931003881/
 194127383495944026752320 : 1)]
```

The elliptic curve also has torsion, which we can map back:

```
sage: E.torsion_points()
[(-144000000/17689 : 3533760000000/2352637 : 1),
 (-92160000/17689 : 2162073600000/2352637 : 1),
 (-5760000/17689 : -124070400000/2352637 : 1),
 (0 : 1 : 0)]
sage: [finv(Q) for Q in E.torsion_points() if Q]
[(9 : -9/4 : 1), (-9 : 0 : 1), (0 : 1 : 0)]
```

In this example, the given point \(P\) is not a flex but the cubic does have a rational flex, \((-4:0:1)\). We return a linear isomorphism which maps this flex to the point at infinity on the Weierstrass model:

```
sage: R.<a,b,c> = QQ[]
sage: cubic = a^3+7*b^3+64*c^3
sage: P = [2,2,-1]
sage: f = EllipticCurve_from_cubic(cubic, P, morphism=True)
sage: E = f.codomain(); E
Elliptic Curve defined by y^2 - 258048*y = x^3 - 22196256768 over Rational Field
sage: E.minimal_model()
Elliptic Curve defined by y^2 + y = x^3 - 331 over Rational Field
sage: f
Scheme morphism:
  From: Projective Plane Curve over Rational Field defined by a^3 + 7*b^3 + 64*c^3
  To:  Elliptic Curve defined by y^2 - 258048*y = x^3 - 22196256768 over Rational Field
```

Defn: Defined on coordinates by sending \((a : b : c)\) to 
\[
(b : -48*a : -1/5376*a - 1/1344*c)
\]
sage: finv = f.inverse(); finv  
Scheme morphism:  
From: Elliptic Curve defined by \(y^2 - 258048*y = x^3 - 22196256768\) over Rational Field  
To: Projective Plane Curve over Rational Field defined by \(a^3 + 7*b^3 + 64*c^3\)  
Defn: Defined on coordinates by sending \((x : y : z)\) to 
\[
(-1/48*y : x : 1/192*y - 1344*z)
\]
sage: cubic(finv.defining_polynomials()) * finv.post_rescaling()  
\[-x^3 + y^2*z - 258048*y*z^2 + 22196256768*z^3\]
sage: E.defining_polynomial()(f.defining_polynomials()) * f.post_rescaling()  
a^3 + 7*b^3 + 64*c^3

sage: f(P)  
\((5376 : -258048 : 1)\)
sage: f([-4,0,1])  
\((0 : 1 : 0)\)

It is possible to not provide a base point \(P\) provided that the cubic has a rational flex. In this case the flexes will be found and one will be used as a base point:

sage: R.<x,y,z> = QQ[]
sage: cubic = x^3+y^3+z^3  
sage: f = EllipticCurve_from_cubic(cubic, morphism=True)  
sage: f  
Scheme morphism:  
From: Projective Plane Curve over Rational Field defined by \(x^3 + y^3 + z^3\)  
To: Elliptic Curve defined by \(y^2 - 9*y = x^3 - 27\) over Rational Field  
Defn: Defined on coordinates by sending \((x : y : z)\) to  
\[
(y : -3*x : -1/3*x - 1/3*z)
\]

An error will be raised if no point is given and there are no rational flexes:

sage: R.<x,y,z> = QQ[]
sage: cubic = 3*x^3+4*y^3+5*z^3  
sage: EllipticCurve_from_cubic(cubic)  
Traceback (most recent call last):
...
ValueError: A point must be given when the cubic has no rational flexes

An example over a finite field, using a flex:

sage: K = GF(17)  
sage: R.<x,y,z> = K[]  
sage: cubic = 2*x^3+3*y^3+4*z^3  
sage: EllipticCurve_from_cubic(cubic,[0,3,1])  
Scheme morphism:  
From: Projective Plane Curve over Finite Field of size 17 defined by \(2*x^3 + 3*y^3 + 4*z^3\)  
To: Elliptic Curve defined by 
\[
\frac{3*x}{2} + \frac{4*y}{2} + z^3
\]
To: Elliptic Curve defined by $y^2 + 16y = x^3 + 11$ over Finite Field of size 17
Defn: Defined on coordinates by sending $(x : y : z)$ to $(-x : 4y : 4y + 5z)$

An example in characteristic 3:

```
sage: K = GF(3)
sage: R.<x,y,z> = K[]
sage: cubic = x^3+y^3+z^3+x*y*z
sage: EllipticCurve_from_cubic(cubic,[0,1,-1])
```
Scheme morphism:
From: Projective Plane Curve over Finite Field of size 3 defined by $x^3 + y^3 + z^3$.
To: Elliptic Curve defined by $y^2 + x*y = x^3 + 1$ over Finite Field of size 3.
Defn: Defined on coordinates by sending $(x : y : z)$ to $(y + z : -y : x)$

An example over a number field, using a non-flex and where there are no rational flexes:

```
sage: K.<a> = QuadraticField(-3)
sage: R.<x,y,z> = K[]
sage: cubic = 2*x^3+3*y^3+5*z^3
sage: EllipticCurve_from_cubic(cubic,[1,1,-1])
```
Scheme morphism:
From: Projective Plane Curve over Number Field in $a$ with defining polynomial $x^2 + 3$ defined by $2x^3 + 3y^3 + 5z^3$.
To: Elliptic Curve defined by $y^2 + (1627^6+13122^1-t^11+314928^3)*x*y + (2187^1+13122^1-t^11+314928^3)*x^2$ over Rational function field in $t$ over Rational Field.

An example over a function field, using a non-flex:

```
sage: K.<t> = FunctionField(QQ)
sage: R.<x,y,z> = K[]
sage: cubic = x^3+t*y^3+(1+t)*z^3
sage: EllipticCurve_from_cubic(cubic,[1,1,-1], morphism=False)
```
Elliptic Curve defined by $y^2 + ((162^t6+486^t4+810^t4+810^t3+810^t2+162^t2)/(t^ ^6+12^t5-3^t4+20^t3+3^t2+12^t1)) * y + ((314928^t14+490406^t13+23462136^t12--^12+78102144^t11+167561379^t10+243026001^t9+243026001^t8+167561379^t7--^7+78102144^t6+23462136^t5+490406^t4+314928^t3)/(t^14+40^t13+577^t12+3524^t1^ ^11+8075^t10+5288^t9-8661^t8-7688^t7-8661^t6+5288^t5+8075^t4+3524^t3--^ ^3+577^t2+40^t1)) * y + x^3 + ((2187^t12+13122^t11-17496^t10+207765^t9-^ ^9-516132^t8+673596^t7-516132^t6+207765^t5-17496^t4+13122^t3+2187^t2)/(t^ ^9+12^t8+1138^t7+1138^t6+708^t5+708^t4+708^t3+708^t2+708^t1)) * x^4 over Rational function field in $t$ over Rational Field.
sage.schemes.elliptic_curves.constructor.EllipticCurve_from_j(j, minimal_twist=True)
Return an elliptic curve with given \( j \)-invariant.

**INPUT:**
- \( j \) – an element of some field.
- minimal_twist (boolean, default True) – If True and \( j \) is in \( \mathbb{Q} \), the curve returned is a minimal twist, i.e. has minimal conductor; when there is more than one curve with minimal conductor, the curve returned is the one whose label comes first if the curves are in the CremonaDatabase, otherwise the one whose minimal \( a \)-invariants are first lexicographically. If \( j \) is not in \( \mathbb{Q} \) this parameter is ignored.

**OUTPUT:**
An elliptic curve with \( j \)-invariant \( j \).

**EXAMPLES:**

```sage
sage: E = EllipticCurve_from_j(0); E; E.j_invariant(); E.label()
Elliptic Curve defined by y^2 + y = x^3 over Rational Field
0
'27a3'
sage: E = EllipticCurve_from_j(1728); E; E.j_invariant(); E.label()
Elliptic Curve defined by y^2 = x^3 - x over Rational Field
1728
'32a2'
sage: E = EllipticCurve_from_j(1); E; E.j_invariant()
Elliptic Curve defined by y^2 + x*y = x^3 + 36*x + 3455 over Rational Field
1
```

The minimal_twist parameter (ignored except over \( \mathbb{Q} \) and True by default) controls whether or not a minimal twist is computed:

```sage
sage: E = EllipticCurve_from_j(100)
Elliptic Curve defined by y^2 = x^3 + x^2 + 3392*x + 307888 over Rational Field
sage: _.conductor()
33129800
sage: E = EllipticCurve_from_j(100, minimal_twist=False)
Elliptic Curve defined by y^2 = x^3 + 488400*x - 530076800 over Rational Field
sage: _.conductor()
298168200
```

Since computing the minimal twist requires factoring both \( j \) and \( j - 1728 \) the following example would take a long time without setting minimal_twist to False:

```sage
sage: E = EllipticCurve_from_j(2^256+1,minimal_twist=False)
sage: E.j_invariant() == 2^256+1
True
```

sage.schemes.elliptic_curves.constructor.EllipticCurves_with_good_reduction_outside_S(S=[], proof=None, verbose=False)

Return a sorted list of all elliptic curves defined over \( \mathbb{Q} \) with good reduction outside the set \( S \) of primes.

**INPUT:**
- \( S \) – a list of primes.
- proof (default: None) – If True, perform computations provably provably correct; if False, use only provable provably correct provable provable correct methods (only applicable to finite fields).
- verbose (default: False) – whether to print progress information.
• $S$ – list of primes (default: empty list)
• $\text{proof}$ – boolean (default $\text{True}$): the MW basis for auxiliary curves will be computed with this proof flag
• $\text{verbose}$ – boolean (default $\text{False}$): if $\text{True}$, some details of the computation will be output

**Note:** Proof flag: The algorithm used requires determining all $S$-integral points on several auxiliary curves, which in turn requires the computation of their generators. This is not always possible (even in theory) using current knowledge.

The value of this flag is passed to the function which computes generators of various auxiliary elliptic curves, in order to find their $S$-integral points. Set to $\text{False}$ if the default ($\text{True}$) causes warning messages, but note that you can then not rely on the set of curves returned being complete.

**EXAMPLES:**

```python
sage: EllipticCurves_with_good_reduction_outside_S([])
[]
sage: elist = EllipticCurves_with_good_reduction_outside_S([2])
sage: elist
[Elliptic Curve defined by $y^2 = x^3 + 4x$ over Rational Field,
Elliptic Curve defined by $y^2 = x^3 - x$ over Rational Field,
...]
Elliptic Curve defined by $y^2 = x^3 - x^2 - 13x + 21$ over Rational Field]
sage: len(elist)
24
sage: ','.join(e.label() for e in elist)
'32a1, 32a2, 32a3, 32a4, 64a1, 64a2, 64a3, 64a4, 128a1, 128a2, 128b1, 128b2, 128c1, ...
    128c2, 128d1, 128d2, 256a1, 256a2, 256b1, 256b2, 256c1, 256c2, 256d1, 256d2'
```

Without $\text{Proof=False}$, this example gives two warnings:

```python
sage: elist = EllipticCurves_with_good_reduction_outside_S([11], proof=False)  # long time (14s on sage.math, 2011)
sage: len(elist)  # long time
12
sage: ','.join(e.label() for e in elist)  # long time
'11a1, 11a2, 11a3, 121a1, 121a2, 121b1, 121b2, 121c1, 121c2, 121d1, 121d2, 121d3'
```

```python
sage: elist = EllipticCurves_with_good_reduction_outside_S([2,3])  # long time (26s, on sage.math, 2011)
sage: len(elist)  # long time
752
sage: conds = sorted(set([e.conductor() for e in elist]))  # long time
sage: max(conds)  # long time
62208
sage: [N.factor() for N in conds]  # long time
[[2^3 * 3, 3^3, 2^5, 2^2 * 3^2, 2^4 * 3, 2 * 3^3, 2^6], ...
(continues on next page)
Elliptic curves, Release 9.7

\[2^3 \cdot 3^2,\]
\[2^5 \cdot 3,\]
\[2^2 \cdot 3^3,\]
\[2^7,\]
\[2^4 \cdot 3^2,\]
\[2 \cdot 3^4,\]
\[2^6 \cdot 3,\]
\[2^3 \cdot 3^3,\]
\[3^5,\]
\[2^8,\]
\[2^5 \cdot 3^2,\]
\[2^2 \cdot 3^4,\]
\[2^7 \cdot 3,\]
\[2^4 \cdot 3^3,\]
\[2 \cdot 3^5,\]
\[2^6 \cdot 3^2,\]
\[2^3 \cdot 3^4,\]
\[2^8 \cdot 3,\]
\[2^5 \cdot 3^3,\]
\[2^2 \cdot 3^5,\]
\[2^7 \cdot 3^2,\]
\[2^4 \cdot 3^4,\]
\[2^6 \cdot 3^3,\]
\[2^3 \cdot 3^5,\]
\[2^8 \cdot 3^2,\]
\[2^5 \cdot 3^4,\]
\[2^7 \cdot 3^3,\]
\[2^4 \cdot 3^5,\]
\[2^6 \cdot 3^4,\]
\[2^8 \cdot 3^3,\]
\[2^5 \cdot 3^5,\]
\[2^7 \cdot 3^4,\]
\[2^6 \cdot 3^5,\]
\[2^8 \cdot 3^4,\]
\[2^7 \cdot 3^5,\]
\[2^8 \cdot 3^5\]

`sage.schemes.elliptic_curves.constructor.are_projectively_equivalent(P, Q, base_ring)`
Test whether P and Q are projectively equivalent.

INPUT:
- P, Q – list/tuple of projective coordinates.
- base_ring – the base ring.

OUTPUT:
Boolean.

EXAMPLES:
```
sage: from sage.schemes.elliptic_curves.constructor import are_projectively_equivalent
sage: are_projectively_equivalent([0,1,2,3], [0,1,2,2], base_ring=QQ)
```
False
sage: are_projectively_equivalent([0,1,2,3], [0,2,4,6], base_ring=QQ)
True

sage.schemes.elliptic_curves.constructor.chord_and_tangent\(F, P\)
Return the third point of intersection of a cubic with the tangent at one point.

**INPUT:**
- \(F\) – a homogeneous cubic in three variables with rational coefficients, as a polynomial ring element, defining a smooth plane cubic curve.
- \(P\) – a 3-tuple \((x, y, z)\) defining a projective point on the curve \(F = 0\).

**OUTPUT:**
A point \(Q\) such that \(F(Q) = 0\), namely the third point of intersection of the tangent at \(P\) with the curve \(F = 0\), so \(Q = P\) if and only if \(P\) is a flex.

**EXAMPLES:**

```
sage: R.<x,y,z> = QQ[]
sage: from sage.schemes.elliptic_curves.constructor import chord_and_tangent
sage: F = x^3+y^3+60*z^3
sage: chord_and_tangent(F, [1,-1,0])
(-1 : 1 : 0)
sage: F = x^3+7*y^3+64*z^3
sage: p0 = [2,2,-1]
sage: p1 = chord_and_tangent(F, p0); p1
(5 : -3 : 1)
sage: p2 = chord_and_tangent(F, p1); p2
(-1265/314 : 183/314 : 1)
```

sage.schemes.elliptic_curves.constructor.coefficients_from_Weierstrass_polynomial\(f\)
Return the coefficients \([a_1, a_2, a_3, a_4, a_6]\) of a cubic in Weierstrass form.

**EXAMPLES:**

```
sage: from sage.schemes.elliptic_curves.constructor import coefficients_from_Weierstrass_polynomial
sage: R.<w,z> = QQ[]
sage: coefficients_from_Weierstrass_polynomial(-w^2 + z^3 + 1)
[0, 0, 0, 0, 1]
```

sage.schemes.elliptic_curves.constructor.coefficients_from_j\(j\, \text{minimal_twist=True}\)
Return Weierstrass coefficients \([a_1, a_2, a_3, a_4, a_6]\) for an elliptic curve with given \(j\)-invariant.

**INPUT:**
See `EllipticCurve_from_j()`.

**EXAMPLES:**

```
sage: from sage.schemes.elliptic_curves.constructor import coefficients_from_j
sage: coefficients_from_j(0)
[0, 0, 0, 0, 0]
```

(continues on next page)
The minimal_twist parameter (ignored except over Q and True by default) controls whether or not a minimal twist is computed:

```
sage: coefficients_from_j(100)
[0, 1, 0, 3392, 307888]
sage: coefficients_from_j(100, minimal_twist=False)
[0, 0, 0, 488400, -530076800]
```

```
sage.schemes.elliptic_curves.constructor.projective_point(p)
```
Return equivalent point with denominators removed

INPUT:
- P, Q – list/tuple of projective coordinates.

OUTPUT:
List of projective coordinates.

EXAMPLES:

```
sage: from sage.schemes.elliptic_curves.constructor import projective_point
sage: projective_point([4/5, 6/5, 8/5])
[2, 3, 4]
sage: F = GF(11)
sage: projective_point([F(4), F(8), F(2)])
[4, 8, 2]
```

```
sage.schemes.elliptic_curves.constructor.tangent_at_smooth_point(C, P)
```
Return the tangent at the smooth point \( P \) of projective curve \( C \).

INPUT:
- \( C \) – a projective plane curve.
- \( P \) – a 3-tuple \((x, y, z)\) defining a projective point on \( C \).

OUTPUT:
The linear form defining the tangent at \( P \) to \( C \).

EXAMPLES:

```
sage: R.<x,y,z> = QQ[]
sage: from sage.schemes.elliptic_curves.constructor import tangent_at_smooth_point
sage: C = Curve(x^3+y^3+60*z^3)
sage: tangent_at_smooth_point(C, [1,-1,0])
x + y
sage: K.<t> = FunctionField(QQ)
sage: R.<x,y,z> = K[]
sage: C = Curve(x^3+2*y^3+3*z^3)
sage: from sage.schemes.elliptic_curves.constructor import tangent_at_smooth_point
```

(continues on next page)
sage: tangent_at_smooth_point(C,[1,1,-1])
3*x + 6*y + 9*z
CONSTRUCT ELLIPTIC CURVES AS JACOBIANS

An elliptic curve is a genus one curve with a designated point. The Jacobian of a genus-one curve can be defined as the set of line bundles on the curve, and is isomorphic to the original genus-one curve. It is also an elliptic curve with the trivial line bundle as designated point. The utility of this construction is that we can construct elliptic curves without having to specify which point we take as the origin.

EXAMPLES:

```
sage: R.<u,v,w> = QQ[]
sage: Jacobian(u^3+v^3+w^3)
Elliptic Curve defined by y^2 = x^3 - 27/4 over Rational Field
sage: Jacobian(u^4+v^4+w^2)
Elliptic Curve defined by y^2 = x^3 - 4*x over Rational Field
sage: C = Curve(u^3+v^3+w^3)
sage: Jacobian(C)
Elliptic Curve defined by y^2 = x^3 - 27/4 over Rational Field
sage: P2.<u,v,w> = ProjectiveSpace(2, QQ)
sage: C = P2.subscheme(u^3+v^3+w^3)
sage: Jacobian(C)
Elliptic Curve defined by y^2 = x^3 - 27/4 over Rational Field
```

One can also define Jacobians of varieties that are not genus-one curves. These are not implemented in this module, but we call the relevant functionality:

```
sage: R.<x> = PolynomialRing(QQ)
sage: f = x**5 + 1184*x**3 + 1846*x**2 + 956*x + 560
sage: C = HyperellipticCurve(f)
sage: Jacobian(C)
Jacobian of Hyperelliptic Curve over Rational Field defined by y^2 = x^5 + 1184*x^3 + 1846*x^2 + 956*x + 560
```

REFERENCES:

- Wikipedia article Jacobian_variety

sage.schemes.elliptic_curves.jacobian.Jacobian(X, **kwds)

Return the Jacobian.

INPUT:

- `X` – polynomial, algebraic variety, or anything else that has a Jacobian elliptic curve.
- `kwds` – optional keyword arguments.
The input $X$ can be one of the following:

- A polynomial, see `Jacobian_of_equation()` for details.
- A curve, see `Jacobian_of_curve()` for details.

**EXAMPLES:**

```python
sage: R.<u,v,w> = QQ[]
sage: Jacobian(u^3+v^3+w^3)
Elliptic Curve defined by y^2 = x^3 - 27/4 over Rational Field

sage: C = Curve(u^3+v^3+w^3)
Sage: Jacobian(C)
Elliptic Curve defined by y^2 = x^3 - 27/4 over Rational Field

sage: P2.<u,v,w> = ProjectiveSpace(2, QQ)
sage: C = P2.subscheme(u^3+v^3+w^3)
sage: Jacobian(C)
Elliptic Curve defined by y^2 = x^3 - 27/4 over Rational Field

sage: Jacobian(C, morphism=True)
Scheme morphism:
From: Closed subscheme of Projective Space of dimension 2 over Rational Field
˓→ Defined by:
    u^3 + v^3 + w^3
    1/2*u^6*v^3 - 1/2*u^3*v^6 - 1/2*u^6*w^3 + 1/2*v^6*w^3 + 1/2*u^3*w^6 - 1/2*v^3*w^6:
To:  Elliptic Curve defined by y^2 = x^3 - 27/4 over Rational Field
    Defined on coordinates by sending (u : v : w) to:
    (-u^4*v^4*w - u^4*v*w^4 - u*v^4*w^4 : 
     1/2*u^6*v^3 - 1/2*u^3*v^6 - 1/2*u^6*w^3 + 1/2*v^6*w^3 + 1/2*u^3*w^6 - 1/2*v^3*w^6 : u^3*v^3*w^3)
```

Construct the Jacobian of a genus-one curve given by a polynomial.

**INPUT:**

- `F` – a polynomial defining a plane curve of genus one. May be homogeneous or inhomogeneous.
• **variables** – list of two or three variables or `None` (default). The inhomogeneous or homogeneous coordinates. By default, all variables in the polynomial are used.

• **curve** – the genus-one curve defined by `polynomial` or `# None` (default). If specified, suitable morphism from the jacobian elliptic curve to the curve is returned.

**OUTPUT:**

An elliptic curve in short Weierstrass form isomorphic to the curve `polynomial=0`. If the optional argument `curve` is specified, a rational multicover from the Jacobian elliptic curve to the genus-one curve is returned.

**EXAMPLES:**

```
sage: R.<a,b,c> = QQ[]
sage: f = a^3+b^3+60*c^3
sage: Jacobian(f)
Elliptic Curve defined by y^2 = x^3 - 24300 over Rational Field
sage: Jacobian(f.subs(c=1))
Elliptic Curve defined by y^2 = x^3 - 24300 over Rational Field
```

If we specify the domain curve the birational covering is returned:

```
sage: h = Jacobian(f, curve=Curve(f)); h
Scheme morphism:
  From: Projective Plane Curve over Rational Field defined by a^3 + b^3 + 60*c^3
  To:  Elliptic Curve defined by y^2 = x^3 - 24300 over Rational Field
  Defn: Defined on coordinates by sending (a : b : c) to
    (-216000*a^4*b^4*c - 12960000*a^4*b*c^4 - 12960000*a*b^4*c^4 :
     108000*a^6*b^3 - 108000*a^3*b^6 - 6480000*a^6*c^3 + 6480000*b^6*c^3 +
     \cdots -38880000*a^3*c^6 - 388800000*b^3*c^6 :
     216000*a^3*b^3*c^3)
```

Plugging in the polynomials defining `h` allows us to verify that it is indeed a rational morphism to the elliptic curve:

```
sage: E = h.codomain()
sage: E.defining_polynomial()(h.defining_polynomials()).factor()
(251942400000000) * c^3 * b^3 * a^3 * (a^3 + b^3 + 60*c^3) *
(a^9*b^6 + a^6*b^9 - 120*a^9*b^3*c^3 + 900*a^6*b^6*c^3 - 120*a^3*b^9*c^3 +
3600*a^9*c^6 + 54000*a^6*b^3*c^6 + 54000*a^3*b^6*c^6 + 3600*b^9*c^6 +
216000*a^6*c^9 - 432000*a^3*b^3*c^9 + 216000*b^6*c^9)
```

By specifying the variables, we can also construct an elliptic curve over a polynomial ring:

```
sage: R.<u,v,t> = QQ[]
sage: Jacobian(u^3+v^3+t, variables=[u,v])
Elliptic Curve defined by y^2 = x^3 + (-27/4*t^2) over
Multivariate Polynomial Ring in u, v, t over Rational Field
```
CHAPTER THREE

POINTS ON ELLIPTIC CURVES

The base class `EllipticCurvePoint_field`, derived from `AdditiveGroupElement`, provides support for points on elliptic curves defined over general fields. The derived classes `EllipticCurvePoint_number_field` and `EllipticCurvePoint_finite_field` provide further support for points on curves defined over number fields (including the rational field $\mathbb{Q}$) and over finite fields.

The class `EllipticCurvePoint`, which is based on `SchemeMorphism_point_projective_ring`, currently has little extra functionality.

EXAMPLES:

An example over $\mathbb{Q}$:

```
sage: E = EllipticCurve('389a1')
sage: P = E(-1,1); P
(-1 : 1 : 1)
sage: Q = E(0,-1); Q
(0 : -1 : 1)
sage: P+Q
(4 : 8 : 1)
sage: P-Q
(1 : 0 : 1)
sage: 3*P-5*Q
(328/361 : -2800/6859 : 1)
```

An example over a number field:

```
sage: K.<i> = QuadraticField(-1)
sage: E = EllipticCurve(K,[1,0,0,0,-1])
sage: P = E(0,i); P
(0 : i : 1)
sage: P.order()
+Infinity
sage: 101*P-100*P == P
True
```

An example over a finite field:

```
sage: K.<a> = GF((101,3))
sage: E = EllipticCurve(K,[1,0,0,0,-1])
sage: P = E(40*a^2 + 69*a + 84 , 58*a^2 + 73*a + 45)
sage: P.order()
1032210
```

(continues on next page)
Arithmetic with a point over an extension of a finite field:

```
sage: k.<a> = GF((5,2))
sage: E = EllipticCurve(k,[1,0]); E
Elliptic Curve defined by y^2 = x^3 + x over Finite Field in a of size 5^2
sage: P = E([a,2*a+4])
sage: 5*P
(2*a + 3 : 2*a : 1)
sage: P^5
(2*a + 3 : 2*a : 1)
sage: P + P + P + P + P
(2*a + 3 : 2*a : 1)
sage: F = Zmod(3)
sage: E = EllipticCurve(F,[1,0]); E
```

Arithmetic over \(\mathbb{Z}/N\mathbb{Z}\) with composite \(N\) is supported. When an operation tries to invert a non-invertible element, a ZeroDivisionError is raised and a factorization of the modulus appears in the error message:

```
sage: N = 1715761513
sage: E = EllipticCurve(Integers(N),[3,-13])
sage: P = E(2,1)
sage: LCM([2..60])*P
Traceback (most recent call last):
  ... ZeroDivisionError: Inverse of 1520944668 does not exist (characteristic = 1715761513 = 26927*63719)
```

AUTHORS:
- William Stein (2005) – Initial version
- Robert Bradshaw et al.
- John Cremona (Feb 2008) – Point counting and group structure for non-prime fields, Frobenius endomorphism and order, elliptic logs
- John Cremona (Aug 2008) – Introduced EllipticCurvePoint_number_field class
- Tobias Nagel, Michael Mardaus, John Cremona (Dec 2008) – \(p\)-adic elliptic logarithm over \(\mathbb{Q}\)
- David Hansen (Jan 2009) – Added weil_pairing function to EllipticCurvePoint_finite_field class
- Mariah Lenox (March 2011) – Added tate_pairing and ate_pairing functions to EllipticCurvePoint_finite_field class

```python
class sage.schemes.elliptic_curves.ell_point.EllipticCurvePoint(X, v, check=True)
Bases: sage.schemes.projective.projective_point.SchemeMorphism_point_projective_ring
```
A point on an elliptic curve.

```python
class sage.schemes.elliptic_curves.ell_point.EllipticCurvePoint_field(curve, v, check=True)

Bases: sage.schemes.projective.projective_point.SchemeMorphism_point_abelian_variety_field

A point on an elliptic curve over a field. The point has coordinates in the base field.

EXAMPLES:

```sage`
E = EllipticCurve('37a')
sage: E([0,0])
(0 : 0 : 1)
sage: E(0,0)  # brackets are optional
(0 : 0 : 1)
sage: E([GF(5)(0), 0])  # entries are coerced
(0 : 0 : 1)
sage: E(0.000, 0)
(0 : 0 : 1)
sage: E(1,0,0)
Traceback (most recent call last):
  ...TypeError: Coordinates [1, 0, 0] do not define a point on
Elliptic Curve defined by y^2 + y = x^3 - x over Rational Field
```

```sage`
E = EllipticCurve([0,0,1,-1,0])
sage: S = E(QQ); S
Abelian group of points on Elliptic Curve defined by y^2 + y = x^3 - x over Rational Field
```sage`
K.<i>=NumberField(x^2+1)
sage: E=EllipticCurve(K,[0,1,0,-160,308])
sage: P=E(26,-120)
sage: Q=E(2+12*i,-36+48*i)
sage: P.order() == Q.order() == 4  # long time (3s)
True
sage: 2*P==2*Q
False
```

```sage`
K.<t>=FractionField(PolynomialRing(QQ,'t'))
sage: E=EllipticCurve([0,0,0,0,t^2])
sage: P=E(0,t)
sage: P,2*P,3*P
((0 : t : 1), (0 : -t : 1), (0 : 1 : 0))
```

additive_order()

Return the order of this point on the elliptic curve.

If the point is zero, returns 1, otherwise raise a Not Implemented Error.

For curves over number fields and finite fields, see below.

Note: `additive_order()` is a synonym for `order()`
EXAMPLES:

```
sage: K.<t>=FractionField(PolynomialRing(QQ,'t'))
sage: E=EllipticCurve([0,0,0,-t^2,0])
sage: P=E(t,0)
sage: P.order()
Traceback (most recent call last):
...  
NotImplementedError: Computation of order of a point not implemented over general fields.
sage: E(0).additive_order()
1
sage: E(0).order() == 1
True
```

ate_pairing($Q, n, k, t, q=None$)

Return ate pairing of $n$-torsion points $P = self$ and $Q$.

Also known as the $n$-th modified ate pairing. $P$ is $GF(q)$-rational, and $Q$ must be an element of $Ker(\pi - p)$, where $\pi$ is the $q$-Frobenius map (and hence $Q$ is $GF(q^k)$-rational).

**INPUT:**

- $P=self$ – a point of order $n$, in $ker(\pi - 1)$, where $\pi$ is the $q$-Frobenius map (e.g., $P$ is $q$-rational).
- $Q$ – a point of order $n$ in $ker(\pi - q)$
- $n$ – the order of $P$ and $Q$.
- $k$ – the embedding degree.
- $t$ – the trace of Frobenius of the curve over $GF(q)$.
- $q$ – (default: None) the size of base field (the “big” field is $GF(q^k)$). $q$ needs to be set only if its value cannot be deduced.

**OUTPUT:**

FiniteFieldElement in $GF(q^k)$ – the ate pairing of $P$ and $Q$.

**EXAMPLES:**

An example with embedding degree 6:

```
sage: p = 7549; A = 0; B = 1; n = 157; k = 6; t = 14
sage: F = GF(p); E = EllipticCurve(F, [A, B])
sage: R.<x> = F[]; K.<a> = GF((p,k), modulus=x^k+2)
sage: EK = E.base_extend(K)
sage: P = EK(3050, 5371); Q = EK(6908*a^4, 3231*a^3)
sage: P.ate_pairing(Q, n, k, t)
6708*a^5 + 4230*a^4 + 4350*a^3 + 2064*a^2 + 4022*a + 6733
sage: s = Integer(randrange(1, n))
sage: (s*P).ate_pairing(Q, n, k, t) == P.ate_pairing(s*Q, n, k, t)
True
sage: P.ate_pairing(s*Q, n, k, t) == P.ate_pairing(Q, n, k, t)^s
True
```

Another example with embedding degree 7 and positive trace:
Elliptic curves, Release 9.7

sage: p = 2213; A = 1; B = 49; n = 1093; k = 7; t = 28
sage: F = GF(p); E = EllipticCurve(F, [A, B])
sage: R.<x> = F[]; K.<a> = GF((p,k), modulus=x^k+2)
sage: EK = E.base_extend(K)
sage: P = EK(1583, 1734)
sage: Qx = 1729*a^6+1767*a^5+980*a^4+980*a^3+1592*a^2+1883*a+722
sage: Qy = 1299*a^6+1877*a^5+1030*a^4+1513*a^3+1457*a^2+309*a+1636
sage: Q = EK(Qx, Qy)
sage: P.ate_pairing(Q, n, k, t)
1665*a^6 + 1538*a^5 + 1979*a^4 + 239*a^3 + 2134*a^2 + 2151*a + 654
sage: s = Integer(randrange(1, n))
(s*P).ate_pairing(Q, n, k, t) == P.ate_pairing(s*Q, n, k, t)
True
sage: P.ate_pairing(s*Q, n, k, t) == P.ate_pairing(Q, n, k, t)^s
True

Another example with embedding degree 7 and negative trace:

sage: p = 2017; A = 1; B = 30; n = 29; k = 7; t = -70
sage: F = GF(p); E = EllipticCurve(F, [A, B])
sage: R.<x> = F[]; K.<a> = GF((p,k), modulus=x^k+2)
sage: EK = E.base_extend(K)
sage: P = EK(369, 716)
1794*a^6 + 1161*a^5 + 576*a^4 + 488*a^3 + 1950*a^2 + 1905*a + 1315
sage: s = Integer(randrange(1, n))
(s*P).ate_pairing(Q, n, k, t) == P.ate_pairing(s*Q, n, k, t)
True
sage: P.ate_pairing(s*Q, n, k, t) == P.ate_pairing(Q, n, k, t)^s
True

Using the same data, we show that the ate pairing is a power of the Tate pairing (see [HSV2006] end of section 3.1):

sage: c = (k*p^(k-1)).mod(n); T = t - 1
sage: N = gcd(T^k - 1, p^k - 1)
sage: s = Integer(N/n)
sage: L = Integer((T^k - 1)/N)
sage: M = (L*s*c.inverse_mod(n)).mod(n)
sage: P.ate_pairing(Q, n, k, t) == Q.tate_pairing(P, n, k)^M
True

An example where we have to pass the base field size (and we again have agreement with the Tate pairing). Note that though \( P \pi \) is not \( F \)-rational, (it is the homomorphic image of an \( F \)-rational point) it is nonetheless in \( \ker(\pi - 1) \), and so is a legitimate input:

sage: q = 2^5; F.<a>=GF(q)
sage: n = 41; k = 4; t = -8
sage: E=EllipticCurve(F,[0,0,1,1,1])
sage: P = E(a^4 + 1, a^3)

(continues on next page)
sage: F.<b> = GF(q^k)
sage: E = EllipticCurve(F, [0, 0, 1, 1, 1])
sage: phi = Hom(F, F)(F.gen().minpoly().roots(F)[0][0])
sage: Px = E(phi(P.xy()[0]), phi(P.xy()[1]))

sage: Qx = E(b^19 + b^18 + b^17 + b^16 + b^15 + b^14 + b^13 + b^12 + b^11 + b^9 + b^8 + b^5 + b^4 + b^3 + b)

sage: Qx = E(Qx[0]^q, Qx[1]^q) - Qx  # ensure Qx is in ker(pi - q)
sage: Px.ate_pairing(Qx, n, k, t)
Traceback (most recent call last):
  ... ValueError: Unexpected field degree: set keyword argument q equal to the size of the base field (big field is GF(q^4)).

sage: Px.ate_pairing(Qx, n, k, t, q)

b^19 + b^18 + b^17 + b^16 + b^15 + b^14 + b^13 + b^12 + b^11 + b^9 + b^8 + b^5 + b^4 + b^2 + b + 1

sage: s = Integer(randrange(1, n))
sage: (s*Px).ate_pairing(Qx, n, k, t, q) == Px.ate_pairing(s*Qx, n, k, t, q)
True

sage: Px.ate_pairing(s^Qx, n, k, t, q) == Px.ate_pairing(Qx, n, k, t, q)^s
True

sage: c = (k^q*(k-1)).mod(n); T = t - 1
sage: N = gcd(T^k - 1, q^k - 1)
sage: s = Integer(N/n)
sage: L = Integer((T^k - 1)/N)
sage: M = (L*s*c.inverse_mod(n)).mod(n)
sage: Px.ate_pairing(Qx, n, k, t, q) == Qx.tate_pairing(Px, n, k, q)^M
True

It is an error if $Q$ is not in the kernel of $\pi - p$, where $\pi$ is the Frobenius automorphism:

sage: p = 29; A = 1; B = 0; n = 5; k = 2; t = 10
sage: F = GF(p); R.<x> = F[]
sage: E = EllipticCurve(F, [A, B]);
sage: K.<a> = GF((p,k), modulus=x^k+2); EK = E.base_extend(K)
sage: P = EK(13, 8); Q = EK(13, 21)
sage: P.ate_pairing(Q, n, k, t)
Traceback (most recent call last):
  ... ValueError: Point (13 : 21 : 1) not in Ker(pi - q)

It is also an error if $P$ is not in the kernel of $\pi - 1$:

sage: p = 29; A = 1; B = 0; n = 5; k = 2; t = 10
sage: F = GF(p); R.<x> = F[]
sage: E = EllipticCurve(F, [A, B]);
sage: K.<a> = GF((p,k), modulus=x^k+2); EK = E.base_extend(K)
sage: P = EK(14, 10*a); Q = EK(13, 21)
sage: P.ate_pairing(Q, n, k, t)
Traceback (most recent call last):
  ... ValueError: This point (14 : 10*a : 1) is not in Ker(pi - 1)
Note: First defined in the paper of [HSV2006], the ate pairing can be computationally effective in those cases when the trace of the curve over the base field is significantly smaller than the expected value. This implementation is simply Miller’s algorithm followed by a naive exponentiation, and makes no claims towards efficiency.

AUTHORS:

- Mariah Lenox (2011-03-08)

curve()

Return the curve that this point is on.

EXAMPLES:

```
sage: E = EllipticCurve('389a')
sage: P = E([-1,1])
sage: P.curve()
Elliptic Curve defined by y^2 + y = x^3 + x^2 - 2*x over Rational Field
```

division_points(m, poly_only=False)

Return a list of all points \( Q \) such that \( mQ = P \) where \( P = \text{self} \).

Only points on the elliptic curve containing self and defined over the base field are included.

INPUT:

- \( m \) – a positive integer
- \( \text{poly\_only} \) – bool (default: False); if True return polynomial whose roots give all possible \( x \)-coordinates of \( m \)-th roots of self.

OUTPUT:

(list) – a (possibly empty) list of solutions \( Q \) to \( mQ = P \), where \( P = \text{self} \).

EXAMPLES:

We find the five 5-torsion points on an elliptic curve:

```
sage: E = EllipticCurve('11a'); E
Elliptic Curve defined by y^2 + y = x^3 - x^2 - 10*x - 20 over Rational Field
sage: P = E([0,0]); P
(0 : 1 : 0)
sage: P.division_points(5)
[(0 : 1 : 0), (5 : -6 : 1), (5 : 5 : 1), (16 : -61 : 1), (16 : 60 : 1)]
```

Note above that 0 is included since \([5]*0 = 0\).

We create a curve of rank 1 with no torsion and do a consistency check:

```
sage: E = EllipticCurve('11a').quadratic_twist(-7)
sage: Q = E([44,-270])
sage: (4*Q).division_points(4)
[(44 : -270 : 1)]
```

We create a curve over a non-prime finite field with group of order 18:
We find the 1-division points as a consistency check – there is just one, of course:

sage: P.division_points(1)
[[3 : 3*a + 4 : 1]]

The point $P$ has order coprime to 2 but divisible by 3, so:

sage: P.division_points(2)
[[2*a + 1 : 3*a + 4 : 1), (3*a + 1 : a : 1)]

We check that each of the 2-division points works as claimed:

sage: [2*Q for Q in P.division_points(2)]
[[3 : 3*a + 4 : 1], [3 : 3*a + 4 : 1]]

Some other checks:

sage: P.division_points(3)
[]
sage: P.division_points(4)
[[0 : 3*a + 2 : 1), (1 : 0 : 1)]
sage: P.division_points(5)
[[1 : 1 : 1]]

An example over a number field (see trac ticket #3383):

sage: E = EllipticCurve('19a1')
sage: K.<t> = NumberField(x^9-3*x^8-4*x^7+16*x^6-3*x^5-21*x^4+5*x^3+7*x^2-7*x+1)
sage: EK = E.base_extend(K)
sage: E(0).division_points(3)
[(0 : 1 : 0), (5 : -10 : 1), (5 : 9 : 1)]
sage: EK(0).division_points(3)
[(0 : 1 : 0), (5 : 9 : 1), (5 : -10 : 1), (-1383/484*t^8 + 970/121*t^7 + 3159/242*t^6 - 5211/121*t^5 + 37/484*t^4 + 654/11*t^3 - 909/484*t^2 - 4831/242*t + 6791/484 : 927/121*t^8 - 5209/242*t^7 + 799/242*t^6 - 1307/121*t^5 + 1165/484 : 1), (1383/484*t^8 + 970/121*t^7 + 3159/242*t^6 - 5211/121*t^5 + 37/484*t^4 + 654/11*t^3 - 909/484*t^2 - 4831/242*t + 6791/484 : 927/121*t^8 - 5209/242*t^7 + 799/242*t^6 - 1307/121*t^5 + 1165/484 : 1), (-1383/484*t^8 + 970/121*t^7 + 3159/242*t^6 - 5211/121*t^5 + 37/484*t^4 + 654/11*t^3 - 909/484*t^2 - 4831/242*t + 6791/484 : 927/121*t^8 - 5209/242*t^7 + 799/242*t^6 - 1307/121*t^5 + 1165/484 : 1)]

(continues on next page)
has_finite_order()
Return True if this point has finite additive order as an element of the group of points on this curve.
For fields other than number fields and finite fields, this is NotImplemented unless self.is_zero().

EXAMPLES:

```
sage: K.<t>=FractionField(PolynomialRing(QQ,'t'))
sage: E=EllipticCurve([0,0,0,-t^2,0])
sage: P = E(0)
sage: P.has_finite_order()
True
sage: P=E(t,0)
sage: P.has_finite_order()
Traceback (most recent call last):
... NotImplemntedError: Computation of order of a point not implemented over general fields.
sage: (2*P).is_zero()
True
```

has_infinite_order()
Return True if this point has infinite additive order as an element of the group of points on this curve.
For fields other than number fields and finite fields, this is NotImplemented unless self.is_zero().

EXAMPLES:

```
sage: K.<t>=FractionField(PolynomialRing(QQ,'t'))
sage: E=EllipticCurve([0,0,0,-t^2,0])
sage: P = E(0)
sage: P.has_infinite_order()
False
sage: P=E(t,0)
sage: P.has_infinite_order()
Traceback (most recent call last):
... NotImplemntedError: Computation of order of a point not implemented over general fields.
sage: (2*P).is_zero()
True
```

is_divisible_by(m)
Return True if there exists a point Q defined over the same field as self such that mQ == self.

INPUT:

• m – a positive integer.

OUTPUT:

(bool) – True if there is a solution, else False.
**Warning:** This function usually triggers the computation of the \( m \)-th division polynomial of the associated elliptic curve, which will be expensive if \( m \) is large, though it will be cached for subsequent calls with the same \( m \).

EXAMPLES:

```python
sage: E = EllipticCurve('389a')
sage: Q = 5*E(0,0); Q
(-2739/1444 : -77033/54872 : 1)
sage: Q.is_divisible_by(4)
False
sage: Q.is_divisible_by(5)
True
```

A finite field example:

```python
sage: E = EllipticCurve(GF(101),[23,34])
sage: E.cardinality().factor()
2 * 53
sage: Set([T.order() for T in E.points()])
{1, 106, 2, 53}
sage: len([T for T in E.points() if T.is_divisible_by(2)])
53
sage: len([T for T in E.points() if T.is_divisible_by(3)])
106
```

**is_finite_order()**

Return True if this point has finite additive order as an element of the group of points on this curve.

For fields other than number fields and finite fields, this is NotImplemented unless self.is_zero().

EXAMPLES:

```python
sage: K.<t>=FractionField(PolynomialRing(QQ,'t'))
sage: E=EllipticCurve([0,0,0,-t^2,0])
sage: P = E(0)
sage: P.has_finite_order()
True
sage: P=E(t,0)
sage: P.has_finite_order()
Traceback (most recent call last):
...
NotImplementedError: Computation of order of a point not implemented over general fields.
sage: (2*P).is_zero()
True
```

**order()**

Return the order of this point on the elliptic curve.

If the point is zero, returns 1, otherwise raise a NotImplementedError.

For curves over number fields and finite fields, see below.
Note: `additive_order()` is a synonym for `order()`

EXAMPLES:

```
sage: K.<t>=FractionField(PolynomialRing(QQ,'t'))
sage: E=EllipticCurve([0,0,0,-t^2,0])
sage: P=E(t,0)
sage: P.order()
Traceback (most recent call last):
  ... Not ImplementedError: Computation of order of a point not implemented over general fields.
sage: E(0).additive_order()
1
sage: E(0).order() == 1
True
```

`plot(**args)`

Plot this point on an elliptic curve.

**INPUT:**

- **args** – all arguments get passed directly onto the point plotting function.

**EXAMPLES:**

```
sage: E = EllipticCurve('389a')
sage: P = E([-1,1])
sage: P.plot(pointsize=30, rgbcolor=(1,0,0))
Graphics object consisting of 1 graphics primitive
```

`scheme()`

Return the scheme of this point, i.e., the curve it is on. This is synonymous with `curve()` which is perhaps more intuitive.

**EXAMPLES:**

```
sage: E=EllipticCurve(QQ,[1,1])
sage: P=E(0,1)
sage: P.scheme()
Elliptic Curve defined by y^2 = x^3 + x + 1 over Rational Field
sage: P.scheme() == P.curve()
True
sage: K.<a>=NumberField(x^2-3,'a')
sage: P=E.base_extend(K)(1,a)
sage: P.scheme()
Elliptic Curve defined by y^2 = x^3 + x + 1 over Number Field in a with defining polynomial x^2 - 3
```

`set_order(value)`

Set the value of self._order to value.

Use this when you know a priori the order of this point to avoid a potentially expensive order calculation.

**INPUT:**

- **value** – positive integer
OUTPUT:

None

EXAMPLES:

This example illustrates basic usage.

```
sage: E = EllipticCurve(GF(7), [0, 1]) # This curve has order 6
sage: G = E(5, 0)
sage: G.set_order(2)
sage: 2*G
(0 : 1 : 0)
```

We now give a more interesting case, the NIST-P521 curve. Its order is too big to calculate with Sage, and takes a long time using other packages, so it is very useful here.

```
sage: p = 2^521 - 1
sage: prev_proof_state = proof.arithmetic()
sage: proof.arithmetic(False) # turn off primality checking
sage: F = GF(p)
sage: A = p - 3
sage: B = 1093849038073734274511112390766805569936207598951683748994586394495953116150735016013708737573759623248592132296706313309438452531591012912142327488478985984
sage: q = 686479766013060971498190079908139321726943530014330540939446345918554318339765594245057746333591532759\n
sage: E = EllipticCurve([F(A), F(B)])
sage: G = E.random_point()
sage: G.set_order(q)
sage: G.order() * G # This takes practically no time.
(0 : 1 : 0)
sage: proof.arithmetic(prev_proof_state) # restore state
```

It is an error to pass a value equal to 0:

```
sage: E = EllipticCurve(GF(7), [0, 1]) # This curve has order 6
sage: G = E.random_point()
sage: G.set_order(0)
Traceback (most recent call last):
...
ValueError: Value 0 illegal for point order
sage: G.set_order(1000)
Traceback (most recent call last):
...
ValueError: Value 1000 illegal: outside max Hasse bound
```

It is also very likely an error to pass a value which is not the actual order of this point. How unlikely is determined by the factorization of the actual order, and the actual group structure:

```
sage: E = EllipticCurve(GF(7), [0, 1]) # This curve has order 6
sage: G = E(5, 0) # G has order 2
sage: G.set_order(11)
Traceback (most recent call last):
...
ValueError: Value 11 illegal: 11 * (5 : 0 : 1) is not the identity
```
However, set_order can be fooled, though it’s not likely in “real cases of interest”. For instance, the order can be set to a multiple the actual order:

```sage
E = EllipticCurve(GF(7), [0, 1])  # This curve has order 6
G = E(5, 0)  # G has order 2
G.set_order(8)
G.order()
```

```
8
```

AUTHORS:
- Mariah Lenox (2011-02-16)

`tate_pairing(Q, n, k, q=None)`

Return Tate pairing of \( n \)-torsion point \( P = \text{self} \) and point \( Q \).

The value returned is \( f_{n,P}(Q) \) where \( f_{n,P} \) is a function with divisor \( n[P] - n[O] \). This is also known as the “modified Tate pairing”. It is a well-defined bilinear map.

**INPUT:**
- \( P = \text{self} \) – Elliptic curve point having order \( n \)
- \( Q \) – Elliptic curve point on same curve as \( P \) (can be any order)
- \( n \) – a positive integer: order of \( P \)
- \( k \) – a positive integer: embedding degree
- \( q \) – a positive integer: size of base field (the “big” field is \( GF(q^k) \). \( q \) needs to be set only if its value cannot be deduced.)

**OUTPUT:**
An \( n \)’th root of unity in the base field \( \text{self.curve().base_field()} \)

**EXAMPLES:**

A simple example, pairing a point with itself, and pairing a point with another rational point:

```sage
p = 103; A = 1; B = 18; E = EllipticCurve(GF(p), [A, B])
P = E(33, 91); n = P.order(); n
```

```
19
```

```sage
k = GF(n)(p).multiplicative_order(); k
```

```
6
```

```sage
P.tate_pairing(P, n, k)
```

```
1
```

```sage
Q = E(87, 51)
P.tate_pairing(Q, n, k)
```

```
1
```

```sage
set_random_seed(35)
P.tate_pairing(P,n,k)
```

```
1
```

We now let \( Q \) be a point on the same curve as above, but defined over the pairing extension field, and we also demonstrate the bilinearity of the pairing:

```sage
K.<a> = GF((p,k))
EK = E.base_extend(K); P = EK(P)
Qx = 69*a^5 + 96*a^4 + 22*a^3 + 86*a^2 + 6*a + 35
```

(continues on next page)
Multiply by cofactor so Q has order n:

\[
\text{sage: } h = 551269674; Q = h^*Q \\
\text{sage: } P = \text{EK}(P); P.\text{tate\_pairing}(Q, n, k) \\
24*a^5 + 34*a^4 + 3*a^3 + 69*a^2 + 86*a + 45 \\
\text{sage: } s = \text{Integer}(\text{randrange}(1,n)) \\
\text{sage: } ans1 = (s^*P).\text{tate\_pairing}(Q, n, k) \\
\text{sage: } ans2 = P.\text{tate\_pairing}(s^*Q, n, k) \\
\text{sage: } ans3 = P.\text{tate\_pairing}(Q, n, k)^s \\
\text{sage: } ans1 == ans2 == ans3 \\
\text{True} \\
\text{sage: } (\text{ans1} != 1) \text{ and } (\text{ans1}^n == 1) \\
\text{True}
\]

Here is an example of using the Tate pairing to compute the Weil pairing (using the same data as above):

\[
\text{sage: } e = \text{Integer}((p^k-1)/n); e \\
62844857712 \\
\text{sage: } P.\text{weil\_pairing}(Q, n)^e \\
94*a^5 + 99*a^4 + 29*a^3 + 45*a^2 + 57*a + 34 \\
\text{sage: } P.\text{tate\_pairing}(Q, n, k) == P.\text{\_miller\_(Q, n)^e} \\
\text{True} \\
\text{sage: } Q.\text{tate\_pairing}(P, n, k) == Q.\text{\_miller\_(P, n)^e} \\
\text{True} \\
\text{sage: } P.\text{tate\_pairing}(Q, n, k)/Q.\text{tate\_pairing}(P, n, k) \\
94*a^5 + 99*a^4 + 29*a^3 + 45*a^2 + 57*a + 34
\]

An example where we have to pass the base field size (and we again have agreement with the Weil pairing):

\[
\text{sage: } F.\langle a\rangle = \text{GF}(2,5) \\
\text{sage: } E = \text{EllipticCurve}(F, [0,0,1,1,1]) \\
\text{sage: } P = E(a^4 + 1, a^3) \\
\text{sage: } Fx.\langle b\rangle = \text{GF}(2,4^5) \\
\text{sage: } Ex = \text{EllipticCurve}(Fx, [0,0,1,1,1]) \\
\text{sage: } \phi = \text{Hom}(F, Fx)(F.\text{gen().minpoly().roots(Fx)[0][0])} \\
\text{sage: } Px = Ex(\phi(P.x.y())[0], \phi(P.x.y())[1])) \\
\text{sage: } Qx = Ex(b^{19}+b^{18}+b^{16}+b^{12}+b^{10}+b^{8}+b^{5}+b^{3}+1, b^{18}+b^{13}+b^{10}+b^{8}+b^{5}+b^{4}+b^{3}+b) \\
\text{sage: } Px.\text{tate\_pairing}(Qx, n=41, k=4) \\
\text{Traceback (most recent call last):} \\
... \\
\text{ValueError: Unexpected field degree: set keyword argument q equal to the size} \\
\text{of the base field (big field is GF(q^4))}. \\
\text{sage: } \text{num} = \text{Px.\text{tate\_pairing}(Qx, n=41, k=4, q=32)}; \text{num} \\
b^{19} + b^{14} + b^{13} + b^{12} + b^{6} + b^{4} + b^{3} \\
\text{sage: } \text{den} = \text{Qx.\text{tate\_pairing}(Px, n=41, k=4, q=32)}; \text{den} \\
b^{19} + b^{17} + b^{16} + b^{15} + b^{14} + b^{10} + b^{6} + b^{2} + 1 \\
\text{sage: } e = \text{Integer}((32^4-1)/41); e \\
25575
\]
(continued from previous page)

sage: Px.weil_pairing(Qx, 41)^e == num/den
True

**Note:** This function uses Miller’s algorithm, followed by a naive exponentiation. It does not do anything fancy. In the case that there is an issue with $Q$ being on one of the lines generated in the $r * P$ calculation, $Q$ is offset by a random point $R$ and $P.tate_pairing(Q+R,n,k)/P.tate_pairing(R,n,k)$ is returned.

**AUTHORS:**

- Mariah Lenox (2011-03-07)

**weil_pairing**($Q$, $n$, **algorithm**=None)

Compute the Weil pairing of this point with another point $Q$ on the same curve.

**INPUT:**

- $Q$ – another point on the same curve as self.
- $n$ – an integer $n$ such that $nP = nQ = (0 : 1 : 0)$, where $P$ is self.
- **algorithm** (default: None) – choices are pari and sage. PARI is usually significantly faster, but it only works over finite fields. When None is given, a suitable algorithm is chosen automatically.

**OUTPUT:**

An $n$’th root of unity in the base field of the curve.

**EXAMPLES:**

```
sage: F.<a>=GF((2,5))
sage: E=EllipticCurve(F,[0,0,1,1,1])
sage: P = E(a^4 + 1, a^3)
sage: Fx.<b>=GF((2,4*5))
sage: Ex=EllipticCurve(Fx,[0,0,1,1,1])
sage: phi=Hom(F,Fx)(F.gen().minpoly().roots(Fx)[0][0])
sage: Px=Ex(phi(P.xy()[0]),phi(P.xy()[1]))
sage: O = Ex(0)
sage: Qx = Ex(b^19 + b^18 + b^16 + b^12 + b^10 + b^9 + b^8 + b^5 + b^3 + 1, b->18 + b^13 + b^10 + b^8 + b^5 + b^4 + b^3 + b)
sage: Px.weil_pairing(Qx,41) == b^19 + b^15 + b^9 + b^8 + b^6 + b^4 + b^3 + b^2, + 1
True
sage: Px.weil_pairing(17*Px,41) == Fx(1)
True
sage: Px.weil_pairing(O,41) == Fx(1)
True
```

An error is raised if either point is not $n$-torsion:

```
sage: Px.weil_pairing(O,40)
Traceback (most recent call last):
... ValueError: points must both be n-torsion
```

A larger example (see trac ticket #4964):
An example over a number field:

```python
sage: P, Q = EllipticCurve('11a1').change_ring(CyclotomicField(5)).torsion_subgroup().gens()
```

```python
sage: P, Q = (P.element(), Q.element())
```

```python
sage: (P.order(), Q.order())
(5, 5)
```

```python
sage: P.weil_pairing(Q, 5)
\zeta_5^2
```

```python
sage: Q.weil_pairing(P, 5)
\zeta_5^3
```

**ALGORITHM:**

- For `algorithm='pari'`: pari:ellweilpairing.
- For `algorithm='sage'`: Implemented using Proposition 8 in [Mil2004]. The value 1 is returned for linearly dependent input points. This condition is caught via a DivisionByZeroError, since the use of a discrete logarithm test for linear dependence is much too slow for large $n$.

**AUTHORS:**

- David Hansen (2009-01-25)
- Lorenz Panny (2022): `algorithm='pari'`

**xy()**

Return the $x$ and $y$ coordinates of this point, as a 2-tuple. If this is the point at infinity a ZeroDivisionError is raised.

**EXAMPLES:**

```python
sage: E = EllipticCurve('389a')
```

```python
sage: P = E([-1, 1])
```

```python
sage: P.xy()
(-1, 1)
```

```python
sage: Q = E(0); Q
(0 : 1 : 0)
```

```python
sage: Q.xy()
Traceback (most recent call last):
...
ZeroDivisionError: rational division by zero
```

**class** `sage.schemes.elliptic_curves.ell_point.EllipticCurvePoint_finite_field(curve, v, check=True)`

Bases: `sage.schemes.elliptic_curves.ell_point.EllipticCurvePoint_field`

Class for elliptic curve points over finite fields.

**additive_order()**

Return the order of this point on the elliptic curve.
ALGORITHM: Use PARI function \texttt{pari:ellorder}.

\textbf{Note:} \texttt{additive\_order()} is a synonym for \texttt{order()}

\textbf{EXAMPLES:}

\begin{verbatim}
\texttt{sage: k.<a> = GF((5,5))}
\texttt{sage: E = EllipticCurve(k,[2,4]); E}
Elliptic Curve defined by y^2 = x^3 + 2*x + 4 over Finite Field in a of size 5^5
\texttt{sage: P = E(3*a^4 + 3*a , 2*a + 1 )}
\texttt{sage: P.order()}
3227
\texttt{sage: Q = E(0,2)}
\texttt{sage: Q.order()}
7
\texttt{sage: Q.additive_order()}
7
\texttt{sage: p=next_prime(2^150)}
\texttt{sage: E=EllipticCurve(GF(p),[1,1])}
\texttt{sage: P=E(831623307675610677632782670796608848711856078, \}
\texttt{˓→4229578604287336670657329253358638217232964)}
\texttt{sage: P.order()}
1427247692705959881058262545272474300628281448
\texttt{sage: P.order() == E.cardinality()}
True
\end{verbatim}

The next example has \(j(E) = 0\):

\begin{verbatim}
\texttt{sage: p = 33554501}
\texttt{sage: F.<u> = GF((p,2))}
\texttt{sage: E = EllipticCurve(F,[0,1])}
\texttt{sage: E.j_invariant()}
0
\texttt{sage: P = E.random_point()}
\texttt{sage: P.order() # random}
16777251
\end{verbatim}

Similarly when \(j(E) = 1728\):

\begin{verbatim}
\texttt{sage: p = 33554473}
\texttt{sage: F.<u> = GF((p,2))}
\texttt{sage: E = EllipticCurve(F,[1,0])}
\texttt{sage: E.j_invariant()}
1728
\texttt{sage: P = E.random_point()}
\texttt{sage: P.order() # random}
46912611635760
\end{verbatim}

\texttt{discrete\_log(Q, ord=None)}

Return the discrete logarithm of \(Q\) to base \(P = \texttt{self}\), that is, an integer \(x\) such that \(xP = Q\).

A \texttt{ValueError} is raised if there is no solution.
ALGORITHM:

To compute the actual logarithm, pari:elllog is called.

However, elllog() does not guarantee termination if \( Q \) is not a multiple of \( P \), so we first need to check subgroup membership. This is done as follows:

- Let \( n \) denote the order of \( P \). First check that \( nQ \) equals the point at infinity (and hence the order of \( Q \) divides \( n \)).
- If the curve order \( \# E \) has been cached, check whether \( \gcd(n^2, \# E) = n \). If this holds, the curve has cyclic \( n \)-torsion, hence all points whose order divides \( n \) must be multiples of \( P \) and we are done.
- Otherwise (if this test is inconclusive), check that the Weil pairing of \( P \) and \( Q \) is trivial.

For anomalous curves with \( \# E = p \), the padic_elliptic_logarithm() function is called.

INPUT:

- \( Q \) (point) – another point on the same curve as \( self \).

OUTPUT:

(integer) – The discrete logarithm of \( Q \) with respect to \( P \), which is an integer \( x \) with \( 0 \leq x < \ord(P) \) such that \( xP = Q \), if one exists.

AUTHORS:

- John Cremona. Adapted to use generic functions 2008-04-05.
- Lorenz Panny (2022): switch to PARI.

EXAMPLES:

```sage
sage: F = GF((3,6), 'a')
sage: a = F.gen()
sage: E = EllipticCurve([0,1,1,a,a])
sage: E.cardinality()
762
sage: P = E.gens()[0]
sage: Q = 400*P
sage: P.discrete_log(Q)
400
```

**has_finite_order()**

Return True if this point has finite additive order as an element of the group of points on this curve.

Since the base field is finite, the answer will always be True.

EXAMPLES:

```sage
sage: E = EllipticCurve(GF(7), [1,3])
sage: P = E.points()[3]
sage: P.has_finite_order()
True
```

**order()**

Return the order of this point on the elliptic curve.

ALGORITHM: Use PARI function pari:ellorder.
Note: `additive_order()` is a synonym for `order()`

EXAMPLES:

```
sage: k.<a> = GF((5,5))
sage: E = EllipticCurve(k,[2,4]); E
Elliptic Curve defined by y^2 = x^3 + 2*x + 4 over Finite Field in a of size 5^5
sage: P = E(3*a^4 + 3*a , 2*a + 1 )
sage: P.order()
3227
sage: Q = E(0,2)
sage: Q.order()
7
sage: Q.additive_order()
7
```

```
sage: p=next_prime(2^150)
sage: E=EllipticCurve(GF(p),[1,1])
sage: P=E(831623307675610677632782670796608848711856078,42295786042873366706573292533588638217232964)
sage: P.order()
142724769270595988105826254272474300628281448
sage: P.order() == E.cardinality()
True
```

The next example has \( j(E) = 0 \):

```
sage: p = 33554501
sage: F.<u> = GF((p,2))
sage: E = EllipticCurve(F,[0,1])
sage: E.j_invariant()
0
sage: P = E.random_point()
sage: P.order() # random
16777251
```

Similarly when \( j(E) = 1728 \):

```
sage: p = 33554473
sage: F.<u> = GF((p,2))
sage: E = EllipticCurve(F,[1,0])
sage: E.j_invariant()
1728
sage: P = E.random_point()
sage: P.order() # random
46912611635760
```

**padic_elliptic_logarithm(Q, p)**

Return the discrete logarithm of \( Q \) to base \( P = \text{self} \), that is, an integer \( x \) such that \( xP = Q \) only for anomalous curves.

**ALGORITHM:**

Discrete logarithm computed as in [Sma1999] with a loop to avoid the canonical lift.
INPUT:

- $Q$ (point) – another point on the same curve as self.
- $p$ (integer) – a prime equals the order of the curve.

OUTPUT:

(integer) – The discrete logarithm of $Q$ with respect to $P$, which is an integer $x$ with $0 \leq x < \text{ord}(P)$ such that $xP = Q$.

AUTHORS:

- Sylvain Pelissier (2022) based on Samuel Neves code.

EXAMPLES:

```sage
p = 235322474717419
sage: b = 8856682
sage: E = EllipticCurve(GF(p), [0, b])
sage: P = E(200673830421813, 57025307876612)
sage: Q = E(40345734829479, 211738132651297)
sage: x = P.padic_elliptic_logarithm(Q, p)
sage: x * P == Q
True
```

```python
class sage.schemes.elliptic_curves.ell_point.EllipticCurvePoint_number_field(curve, v, check=True):
    # Bases: sage.schemes.elliptic_curves.ell_point.EllipticCurvePoint_field
    A point on an elliptic curve over a number field.
    Most of the functionality is derived from the parent class EllipticCurvePoint_field. In addition we have
    support for orders, heights, reduction modulo primes, and elliptic logarithms.

    EXAMPLES:

    sage: E = EllipticCurve('37a')
    sage: E([0,0])
    (0 : 0 : 1)
    sage: E(0,0) # brackets are optional
    (0 : 0 : 1)
    sage: E([GF(5)(0), 0]) # entries are coerced
    (0 : 0 : 1)
    sage: E(0.000, 0)
    (0 : 0 : 1)
    sage: E(1,0,0)
    Traceback (most recent call last):
      ...TypeError: Coordinates [1, 0, 0] do not define a point on Elliptic Curve defined by y^2 + y = x^3 - x over Rational Field

    sage: E = EllipticCurve([0,0,1,-1,0])
    sage: S = E(QQ); S
    Abelian group of points on Elliptic Curve defined by y^2 + y = x^3 - x over Rational Field
```

42 Chapter 3. Points on elliptic curves
**additive_order()**

Return the order of this point on the elliptic curve.

If the point has infinite order, returns +Infinity. For curves defined over \( \mathbb{Q} \), we call PARI; over other number fields we implement the function here.

**Note:** `additive_order()` is a synonym for `order()`

**EXAMPLES:**

```sage
sage: E = EllipticCurve([0,0,1,-1,0])
sage: P = E([0,0]); P
(0 : 0 : 1)
sage: P.order()
+Infinity
```

```sage
sage: E = EllipticCurve([0,1])
sage: P = E([-1,0])
sage: P.order()
2
sage: P.additive_order()
2
```

**archimedean_local_height**

\( (v=None, prec=None, weighted=False) \)

Compute the local height of self at the archimedean place \( v \).

**INPUT:**

- `self` – a point on an elliptic curve over a number field \( K \).
- \( v \) – a real or complex embedding of \( K \), or None (default). If \( v \) is a real or complex embedding, return the local height of self at \( v \). If \( v \) is None, return the total archimedean contribution to the global height.
- `prec` – integer, or None (default). The precision of the computation. If None, the precision is deduced from \( v \).
- `weighted` – boolean. If False (default), the height is normalised to be invariant under extension of \( K \). If True, return this normalised height multiplied by the local degree if \( v \) is a single place, or by the degree of \( K \) if \( v \) is None.

**OUTPUT:**

A real number. The normalisation is twice that in Silverman’s paper [Sil1988]. Note that this local height depends on the model of the curve.

**ALGORITHM:**

See [Sil1988], Section 4.

**EXAMPLES:**

Examples 1, 2, and 3 from [Sil1988]:

```sage
sage: K.<a> = QuadraticField(-2)
sage: E = EllipticCurve(K, [0,-1,0,0]); E
Elliptic Curve defined by y^2 + y = x^3 + (-1)*x^2 over Number Field in a with defining polynomial x^2 + 2 with a = 1.4142135623730957*I
sage: P = E.lift_x(2+a); P
```

(continues on next page)
(a + 2 : 2*a + 1 : 1)
sage: P.archimedean_local_height(K.places(prec=170)[0]) / 2
0.4575477328752327673621121074142365436576029814695

sage: K.<i> = NumberField(x^2+1)
sage: E = EllipticCurve(K, [0,0,4,6*i,0]); E
Elliptic Curve defined by y^2 + 4*y = x^3 + 6*i*x over Number Field in i with defining polynomial x^2 + 1
sage: P = E((0,0))
sage: P.archimedean_local_height(K.places()[0]) / 2
0.510184995162373

sage: Q = E.lift_x(-9/4); Q
(-9/4 : -27/8*i : 1)
sage: Q.archimedean_local_height(K.places()[0]) / 2
0.654445619529600

An example over the rational numbers:
sage: E = EllipticCurve([0, 0, 0, -36, 0])
sage: P = E([-3, 9])
sage: P.archimedean_local_height()
1.98723816350773

Local heights of torsion points can be non-zero (unlike the global height):

sage: K.<i> = QuadraticField(-1)
sage: E = EllipticCurve([0, 0, 0, K(1), 0])
sage: P = E(i, 0)
sage: P.archimedean_local_height()
0.346573590279973

elliptic_logarithm(embdedding=None, precision=100, algorithm='pari')
Return the elliptic logarithm of this elliptic curve point.

An embedding of the base field into R or C (with arbitrary precision) may be given; otherwise the first real embedding is used (with the specified precision) if any, else the first complex embedding.

INPUT:
- embedding: an embedding of the base field into R or C
- precision: a positive integer (default 100) setting the number of bits of precision for the computation
- algorithm: either 'pari' (default for real embeddings) to use PARI’s pari:ellpointtoz, or 'sage' for a native implementation. Ignored for complex embeddings.

ALGORITHM:

AUTHORS:
- Michael Mardaus (2008-07),
- Tobias Nagel (2008-07) – original version from [Coh1993].
- John Cremona (2010-03) – implementation for complex embeddings.

**EXAMPLES:**

```python
sage: E = EllipticCurve('389a')
sage: E.discriminant() > 0
True
sage: P = E([-1,1])
sage: P.is_on_identity_component()
False
sage: P.elliptic_logarithm(precision=96)
0.4793482501902193161295330101 + 0.985868850775824102211203849...*I
sage: Q = E([3,5])
sage: Q.is_on_identity_component()
True
sage: Q.elliptic_logarithm(precision=96)
1.931128271542559442488585220
```

An example with negative discriminant, and a torsion point:

```python
sage: E = EllipticCurve('11a1')
sage: E.discriminant() < 0
True
sage: P = E([16,-61])
sage: P.elliptic_logarithm(precision=70)
0.25384186085591068434
sage: E.period_lattice().real_period(prec=70) / P.elliptic_logarithm(precision=70)
5.0000000000000000000
```

A larger example. The default algorithm uses PARI and makes sure the result has the requested precision:

```python
sage: E = EllipticCurve([1, 0, 1, -85357462, 303528987048]) #18074g1
sage: P = E([4458713781401/835903744, -64466909836503771/24167649046528, 1])
sage: P.elliptic_logarithm()  # 100 bits
0.2765620401410706146076203097
```

The native algorithm 'sage' used to have trouble with precision in this example, but no longer:

```python
sage: P.elliptic_logarithm(algorithm='sage')  # 100 bits
0.2765620401410706146076203097
```

This shows that the bug reported at trac ticket #4901 has been fixed:

```python
sage: E = EllipticCurve("4390c2")
sage: P = E([683762969925/44944,-565388972095220019/9528128])
sage: P.elliptic_logarithm()
0.00025638725886520225353198932529
sage: P.elliptic_logarithm(precision=64)
0.00025638725886520225254
sage: P.elliptic_logarithm(precision=65)
0.0002563872588652022535
sage: P.elliptic_logarithm(precision=128)
0.00025638725886520225353198932528666427412
sage: P.elliptic_logarithm(precision=129)
```

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Examples over number fields:

```
sage: K.<a> = NumberField(x^3-2)
sage: embs = K.embeddings(CC)
sage: E = EllipticCurve([0,1,0,a,a])
sage: Ls = [E.period_lattice(e) for e in embs]
sage: [L.real_flag for L in Ls]
[0, 0, -1]
sage: P = E(-1,0)  # order 2
sage: [L.elliptic_logarithm(P) for L in Ls]
[-1.73964256006716 - 1.07861534489191*I, -0.363756518406398 - 1.50699412135253*I, 1.90726488608927]
sage: E = EllipticCurve([-a^2 - a - 1, a^2 + a])
sage: Ls = [E.period_lattice(e) for e in embs]
sage: pts = [E(2*a^2 - a - 1, 2*a^2 + a), E(-2/3*a^2 - 1/3 - 2/3*a^2 - 1/3 + 4/3*a^2 + 10/3*a - 12)]
sage: [[L.elliptic_logarithm(P) for P in pts] for L in Ls]
[[0.250819591818930 - 0.411963479992219*I, -0.290994550611374 - 1.37239400324105*I, 0.390154532655013 + 0.529423541805758*I, 0.931968675085317 - 0.431006981443071*I, 1.14758249506109 + 0.853389664016075*I, 2.5982362472518 + 0.853389664016075*I, 1.75372176444709, 0.303693634723001]],
```

```
sage: K.<i> = QuadraticField(-1)
sage: E = EllipticCurve([0,0,0,9*i-10,21-i])
sage: emb = K.embeddings(CC)[1]
sage: L = E.period_lattice(emb)
sage: P = E(2-i,4+2*i)
sage: L.elliptic_logarithm(P,prec=100)
0.7044837553778220846099649302 - 0.79246725643650979858266018068*I
```

\texttt{has_finite_order()}

Return True if this point has finite order on the elliptic curve.

\textbf{EXAMPLES:}

```
sage: E = EllipticCurve([0,0,0,9*i-10,21-i])
sage: P = E([0,0]); P
(0 : 0 : 1)
sage: P.has_finite_order()
False
```

\textbf{Chapter 3. Points on elliptic curves}

46
sage: E = EllipticCurve([0,1])
sage: P = E([-1,0])
sage: P.has_finite_order()
True

has_good_reduction(P=None)
Returns True iff this point has good reduction modulo a prime.

INPUT:

• P – a prime of the base_field of the point’s curve, or None (default)

OUTPUT:

(bool) If a prime $P$ of the base field is specified, returns True iff the point has good reduction at $P$; otherwise, return true if the point has good reduction at all primes in the support of the discriminant of this model.

EXAMPLES:

sage: E = EllipticCurve('990e1')
sage: P = E.gen(0); P
(15 : 51 : 1)
sage: [E.has_good_reduction(p) for p in [2,3,5,7]]
[False, False, False, True]
sage: [P.has_good_reduction(p) for p in [2,3,5,7]]
[True, False, True, True]
sage: [E.tamagawa_exponent(p) for p in [2,3,5,7]]
[2, 2, 1, 1]
sage: [(2*P).has_good_reduction(p) for p in [2,3,5,7]]
[True, True, True, True]
sage: P.has_good_reduction()
False
sage: (2*P).has_good_reduction()
True
sage: (3*P).has_good_reduction()
False

sage: K.<i> = NumberField(x^2+1)
sage: E = EllipticCurve(K,[0,1,0,-160,308])
sage: P = E(26,-120)
sage: E.discriminant().support()  # Fractional ideal (i + 1),
[Fractional ideal (-i - 2),
 Fractional ideal (2*i + 1),
 Fractional ideal (3)]
sage: [E.tamagawa_exponent(p) for p in E.discriminant().support()]
[1, 4, 4, 4]
sage: P.has_good_reduction()
False
sage: (2*P).has_good_reduction()
False
sage: (4*P).has_good_reduction()
True

has_infinite_order()
Return True iff this point has infinite order on the elliptic curve.
EXAMPLES:

```python
sage: E = EllipticCurve([0,0,1,-1,0])
sage: P = E([0,0]); P
(0 : 0 : 1)
sage: P.has_infinite_order()
True
```

```python
sage: E = EllipticCurve([0,1])
sage: P = E([-1,0])
sage: P.has_infinite_order()
False
```

**height** *(precision=None, normalised=True, algorithm='pari')*

Return the Néron-Tate canonical height of the point.

**INPUT:**

- **self** – a point on an elliptic curve over a number field \(K\).
- **precision** – positive integer, or None (default). The precision in bits of the result. If None, the default real precision is used.
- **normalised** – boolean. If True (default), the height is normalised to be invariant under extension of \(K\). If False, return this normalised height multiplied by the degree of \(K\).
- **algorithm** – string: either ‘pari’ (default) or ‘sage’. If ‘pari’ and the base field is \(\mathbb{Q}\), use the PARI library function; otherwise use the Sage implementation.

**OUTPUT:**

The rational number 0, or a non-negative real number.

There are two normalisations used in the literature, one of which is double the other. We use the larger of the two, which is the one appropriate for the BSD conjecture. This is consistent with [Cre1997] and double that of [Sil2009].

See Wikipedia article Néron-Tate height.

**Note:** The correct height to use for the regulator in the BSD formula is the non-normalised height.

EXAMPLES:

```python
sage: E = EllipticCurve('11a'); E
Elliptic Curve defined by y^2 + y = x^3 - x^2 - 10*x - 20 over Rational Field
sage: P = E([5,5]); P
(5 : 5 : 1)
sage: P.height()
0
sage: Q = 5*P
sage: Q.height()
0
```

```python
sage: E = EllipticCurve('37a'); E
Elliptic Curve defined by y^2 + y = x^3 - x over Rational Field
sage: P = E([0,0])
```

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**Elliptic curves, Release 9.7**

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```python
sage: P.height()
0.0511114082399688
sage: P.order()
+Infinity
sage: E.regulator()
0.0511114082399688...

sage: def naive_height(P):
    ....:     return log(RR(max(abs(P[0].numerator()), abs(P[0].denominator()))))

sage: for n in [1..10]:
    ....:     print(naive_height(2^n*P)/4^n)
0.000000000000000
0.0433216987849966
0.0502949347635656
0.0511006335618645
0.0511007834799612
0.0511013666152466
0.0511034199907743
0.0511106492906471
0.0511114081541082
0.0511114081541180

sage: E = EllipticCurve('4602a1'); E
Elliptic Curve defined by y^2 + x*y = x^3 + x^2 - 37746035*x - 89296920339
→ over Rational Field
sage: x = 77985922458974949246858229195945103471590
sage: y = 19575260230015313702261379022151675961965157108920263594545223
sage: d = 2254020761884782243
sage: E([x / d^2, y / d^3]).height()
86.7406561381275

sage: E = EllipticCurve([17, -60, -120, 0, 0]); E
Elliptic Curve defined by y^2 + 17*x*y - 120*y = x^3 - 60*x^2 over Rational
→ Field
sage: E([30, -90]).height()
0

sage: E = EllipticCurve('389a1'); E
Elliptic Curve defined by y^2 + x^3 + x^2 - 2*x over Rational Field
sage: [P,Q] = [E(-1,1),E(0,-1)]
sage: P.height(precision=100)
0.68666708330558572355210295
sage: (3*Q).height(precision=100)/Q.height(precision=100)
9.0000000000000000000000000000
sage: _.parent()
Real Field with 100 bits of precision

Canonical heights over number fields are implemented as well:

```python
sage: R.<x> = QQ[]
sage: K.<a> = NumberField(x^3-2)
sage: E = EllipticCurve([a, 4]); E
```

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Elliptic Curve defined by $y^2 = x^3 + a\cdot x + 4$ over Number Field in $a$ with defining polynomial $x^3 - 2$

```
sage: P = E((0,2))
sage: P.height()
 0.810463096585925
sage: P.height(precision=100)
 0.81046309658592536863991810577
sage: P.height(precision=200)
 0.81046309658592536863991810576865158896130286417155832378086
sage: (2*P).height() / P.height()
 4.00000000000000
sage: (100*P).height() / P.height()
 10000.00000000000000
```

Setting normalised=False multiplies the height by the degree of $K$:

```
sage: E = EllipticCurve('37a')
sage: P = E([0,0])
sage: P.height()
 0.0511114082399688
sage: P.height(normalised=False)
 0.0511114082399688
sage: K.<z> = CyclotomicField(5)
sage: EK = E.change_ring(K)
sage: PK = EK([0,0])
sage: PK.height()
 0.0511114082399688
sage: PK.height(normalised=False)
 0.204445632959875
```

Some consistency checks:

```
sage: E = EllipticCurve('5077a1')
sage: P = E([-2,3,1])
sage: P.height()
 1.36857250535393
sage: EK = E.change_ring(QuadraticField(-3,'a'))
sage: PK = EK([-2,3,1])
sage: PK.height()
 1.36857250535393
sage: K.<i> = NumberField(x^2+1)
sage: E = EllipticCurve(K, [0,0,4,6*i,0])
sage: Q = E.lift_x(-9/4); Q
  (-9/4 : -27/8*i : 1)
sage: Q.height()
 2.69518560017909
sage: (15*Q).height() / Q.height()
 225.000000000000
sage: E = EllipticCurve('37a')
```

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An example to show that the bug at trac ticket #5252 is fixed:

```
sage: E = EllipticCurve([-1, -1, 1, -2063758701246626370773726978, 32838647793306133075103747085833809114881])
sage: P = E([-30987785091199, 258909576181697016447])
sage: P.height()
25.8603170675462
sage: P.height(precision=100)
25.86031706754619074386840741
sage: P.height(precision=250)
25.860317067546190743868407407351103230988738903441616215577171041783572513
sage: P.height(precision=500)
25.
```

An example to show that the bug at trac ticket #8319 is fixed (correct height when the curve is not minimal):

```
sage: E = EllipticCurve([-55804723294461149528055058045939498080000,-157397373853681103282973689903536954578770049722330636800000000])
sage: xP = 20488514773287954648757684013172906430828938547904673627174585676211859152978311600/2362550190705794813226221718898368120485907657753178415430361
sage: E = EllipticCurve(v)
sage: P = E.lift_x(xP)
sage: P.height()
157.43259851675
sage: Q = 2*P
sage: Q.height() # long time (4s)
629.730394067016
sage: Q.height()-4*P.height() # long time
0.000000000000000
```

An example to show that the bug at trac ticket #12509 is fixed (precision issues):

```
sage: x = polygen(QQ)
```

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This shows that the bug reported at trac ticket #13951 has been fixed:

```
sage: E = EllipticCurve([0,17])
sage: P1 = E(2,5)
sage: P1.height()
1.06248137652528
sage: F = E.change_ring(QuadraticField(-3, 'a'))
sage: P2 = F([2,5])
sage: P2.height()
1.06248137652528
```

**is_on_identity_component**(embedding=None)

Returns True iff this point is on the identity component of its curve with respect to a given (real or complex) embedding.

**INPUT:**

- `self` – a point on a curve over any ordered field (e.g. Q)
- `embedding` – an embedding from the base field of the point's curve into R or C; if None (the default) it uses the first embedding of the base field into R if any, else the first embedding into C.

**OUTPUT:**

(boo) – True iff the point is on the identity component of the curve. (If the point is zero then the result is True.)

**EXAMPLES:**

For $K = \mathbb{Q}$ there is no need to specify an embedding:

```
sage: E = EllipticCurve('5077a1')
sage: [E.lift_x(x).is_on_identity_component() for x in srange(-3, 5)]
[False, False, False, False, False, True, True, True]
```

An example over a field with two real embeddings:

```
sage: L.<a> = QuadraticField(2)
sage: E = EllipticCurve(L,[0,1,0,a,a])
sage: P = E(-1,0)
sage: [P.is_on_identity_component(e) for e in L.embeddings(RR)]
[False, True]
```

We can check this as follows:
sage: [e(E.discriminant())>0 for e in L.embeddings(RR)]
[True, False]
sage: e = L.embeddings(RR)[0]
sage: E1 = EllipticCurve(RR,[e(ai) for ai in E.ainvs()])
sage: e1,e2,e3 = E1.two_division_polynomial().roots(RR,multiplicities=False)
sage: e1 < e2 < e3 and e(P[0]) < e3
True

non_archimedean_local_height\(v=None, \text{prec}=None, \text{weighted}=False, \text{is\_minimal}=None\)
Compute the local height of self at the non-archimedean place \(v\).

INPUT:

- self – a point on an elliptic curve over a number field \(K\).
- \(v\) – a non-archimedean place of \(K\), or None (default). If \(v\) is a non-archimedean place, return the local height of self at \(v\). If \(v\) is None, return the total non-archimedean contribution to the global height.
- \text{prec} – integer, or None (default). The precision of the computation. If None, the height is returned symbolically.
- \text{weighted} – boolean. If False (default), the height is normalised to be invariant under extension of \(K\). If True, return this normalised height multiplied by the local degree if \(v\) is a single place, or by the degree of \(K\) if \(v\) is None.

OUTPUT:

A real number. The normalisation is twice that in Silverman’s paper [Sil1988]. Note that this local height depends on the model of the curve.

ALGORITHM:

See [Sil1988], Section 5.

EXAMPLES:

Examples 2 and 3 from [Sil1988]:

sage: K.<i> = NumberField(x^2+1)
sage: E = EllipticCurve(K, [0,0,4,6*i,0]); E
Elliptic Curve defined by y^2 + 4*y = x^3 + 6*i*x over Number Field in i with defining polynomial x^2 + 1
sage: P = E((0,0))
sage: P.non_archimedean_local_height(K.ideal(i+1))
-1/2*log(2)
sage: P.non_archimedean_local_height(K.ideal(3))
0
sage: P.non_archimedean_local_height(K.ideal(1-2*i))
0
sage: Q = E.lift_x(-9/4); Q
(-9/4 : -27/8*i : 1)
sage: Q.non_archimedean_local_height(K.ideal(1+i))
2*log(2)
sage: Q.non_archimedean_local_height(K.ideal(3))
0
sage: Q.non_archimedean_local_height(K.ideal(1-2*i))
0

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An example over the rational numbers:

```
sage: E = EllipticCurve([0, 0, 0, -36, 0])
sage: P = E([-3, 9])
sage: P.non_archimedean_local_height()
-log(3)
```

Local heights of torsion points can be non-zero (unlike the global height):

```
sage: K.<i> = QuadraticField(-1)
sage: E = EllipticCurve([0, 0, 0, K(1), 0])
sage: P = E(i, 0)
sage: P.non_archimedean_local_height()
-1/2*log(2)
```

**order()**

Return the order of this point on the elliptic curve.

If the point has infinite order, returns +Infinity. For curves defined over \( \mathbb{Q} \), we call PARI; over other number fields we implement the function here.

**Note:** `additive_order()` is a synonym for `order()`

**EXAMPLS:**

```
sage: E = EllipticCurve([0,0,1,-1,0])
sage: P = E([0,0]); P
(0 : 0 : 1)
sage: P.order()
+Infinity
```

```
sage: E = EllipticCurve([0,1])
sage: P = E([-1,0])
sage: P.order()
2
sage: P.additive_order()
2
```

**padic_elliptic_logarithm\( (p, \text{absprec}=20)\)**

Computes the \( p \)-adic elliptic logarithm of this point.

**INPUT:**

- \( p \) - integer: a prime
- `\text{absprec}` - integer (default: 20): the initial \( p \)-adic absolute precision of the computation

**OUTPUT:**

The \( p \)-adic elliptic logarithm of self, with precision `absprec`.

**AUTHORS:**

- Tobias Nagel
Elliptic curves, Release 9.7

- Michael Mardaus
- John Cremona

ALGORITHM:

For points in the formal group (i.e. not integral at $p$) we take the $\log$() function from the formal groups module and evaluate it at $-x/y$. Otherwise we first multiply the point to get into the formal group, and divide the result afterwards.

Todo: See comments at trac ticket #4805. Currently the absolute precision of the result may be less than the given value of absprec, and error-handling is imperfect.

EXAMPLES:

```
sage: E = EllipticCurve([0,1,1,-2,0])
sage: E(0).padic_elliptic_logarithm(3)
0
sage: P = E(0,0)
sage: P.padic_elliptic_logarithm(3)
2 + 2*3 + 3^3 + 2*3^5 + 3^8 + 3^9 + 3^11 + 3^15 + 2*3^17 + 3^18 + 0(3^19)
sage: P.padic_elliptic_logarithm(3).lift()
660257522
sage: P = E(-11/9,28/27)
sage: [(2*P).padic_elliptic_logarithm(p)/P.padic_elliptic_logarithm(p) for p in prime_range(20)]
# long time (3s)
[2 + O(2^19), 2 + O(3^20), 2 + O(5^19), 2 + O(7^19), 2 + O(11^19), 2 + O(13^19),
 2 + O(17^19), 2 + O(19^19)]
sage: [(3*P).padic_elliptic_logarithm(p)/P.padic_elliptic_logarithm(p) for p in prime_range(12)]
# long time (2s)
[1 + 2 + O(2^19), 3 + O(3^20) + O(3^21), 3 + O(5^19), 3 + O(7^19), 3 + O(11^19)]
sage: [(5*P).padic_elliptic_logarithm(p)/P.padic_elliptic_logarithm(p) for p in prime_range(12)]
# long time (2s)
[1 + 2^2 + O(2^19), 2 + 3 + O(3^20), 5 + O(5^19), 5 + O(7^19), 5 + O(11^19)]
```

An example which arose during reviewing trac ticket #4741:

```
sage: E = EllipticCurve('794a1')
sage: P = E(-1,2)
sage: P.padic_elliptic_logarithm(2)  # default precision=20
2^4 + 2^5 + 2^6 + 2^8 + 2^9 + 2^13 + 2^14 + 2^15 + O(2^16)
sage: P.padic_elliptic_logarithm(2, absprec=30)
2^4 + 2^5 + 2^6 + 2^8 + 2^9 + 2^13 + 2^14 + 2^15 + 2^22 + 2^23 + 2^24 + O(2^26)
sage: P.padic_elliptic_logarithm(2, absprec=40)
2^4 + 2^5 + 2^6 + 2^8 + 2^9 + 2^13 + 2^14 + 2^15 + 2^22 + 2^23 + 2^24 + 2^28 +
 2^29 + 2^31 + 2^34 + O(2^35)
```

`reduction(p)`

This finds the reduction of a point $P$ on the elliptic curve modulo the prime $p$.

INPUT:

- self – A point on an elliptic curve.
- p – a prime number

OUTPUT:
The point reduced to be a point on the elliptic curve modulo $p$.

**EXAMPLES:**

```sage
sage: E = EllipticCurve([1,2,3,4,0])
sage: P = E(0,0)
(0 : 0 : 1)
sage: Q = E(98,931)
(3 : 1 : 1)
sage: P.reduction(5).curve() == E.reduction(5)
True
```

```sage
sage: F.<a> = NumberField(x^2+5)
sage: E = EllipticCurve(F,[1,2,3,4,0])
sage: Q = E(98,931)
(3 : 1 : 1)
sage: Q.reduction(a)
(10 : 7 : 1)
```

```sage
sage: F.<a> = NumberField(x^3+x^2+1)
sage: E = EllipticCurve(F,[a,2])
sage: P = E(a,1)
(abar : 1 : 1)
sage: P.reduction(F.ideal(5))
(abar : 1 : 1)
sage: P.reduction(F.ideal(a^2-4*a-2))
(abar : 1 : 1)
```
Sage defines an elliptic curve over a ring $R$ as a *Weierstrass Model* with five coefficients $[a_1, a_2, a_3, a_4, a_6]$ in $R$ given by

$$y^2 + a_1 xy + a_3 y = x^3 + a_2 x^2 + a_4 x + a_6.$$ 

Note that the (usual) scheme-theoretic definition of an elliptic curve over $R$ would require the discriminant to be a unit in $R$; Sage only imposes that the discriminant is non-zero. Also note that in Magma, “Weierstrass Model” refers to a model with $a_1 = a_2 = a_3 = 0$, which is called *Short Weierstrass Model* in Sage; these do not always exist in characteristics 2 and 3.

**EXAMPLES:**

We construct an elliptic curve over an elaborate base ring:

```sage
sage: p, a, b = 97, 1, 3
sage: R.<u> = GF(p)[]
sage: S.<v> = R[]
sage: T = S.fraction_field()
E = EllipticCurve(T, [a, b]); E
Elliptic Curve defined by y^2 = x^3 + x + 3 over Fraction Field of Univariate Polynomial Ring in v over Univariate Polynomial Ring in u over Finite Field of size 97
sage: latex(E)
y^2 = x^3 + x + 3
```

**AUTHORS:**

- William Stein (2005): Initial version
- Robert Bradshaw et al....
- John Cremona (2008-01): isomorphisms, automorphisms and twists in all characteristics
- Lorenz Panny (2022-04-14): added `.montgomery_model()`

**class** `sage.schemes.elliptic_curves.ell_generic.EllipticCurve_generic(K, ainvs)`

Bases: `sage.misc.fast_methods.WithEqualityById, sage.schemes.curves.projective_curve.ProjectivePlaneCurve`

Elliptic curve over a generic base ring.

**EXAMPLES:**
sage: E = EllipticCurve([1,2,3/4,7,19]); E
Elliptic Curve defined by y^2 + x*y + 3/4*y = x^3 + 2*x^2 + 7*x + 19 over Rational Field
sage: loads(E.dumps()) == E
True
sage: E = EllipticCurve([1,3])
sage: P = E([-1,1,1])
sage: -5*P
(179051/80089 : -91814227/22665187 : 1)

\textbf{a1()}  
Return the $a_1$ invariant of this elliptic curve.

\textbf{EXAMPLES:}

sage: E = EllipticCurve([1,2,3,4,6])
sage: E.a1()
1

\textbf{a2()}  
Return the $a_2$ invariant of this elliptic curve.

\textbf{EXAMPLES:}

sage: E = EllipticCurve([1,2,3,4,6])
sage: E.a2()
2

\textbf{a3()}  
Return the $a_3$ invariant of this elliptic curve.

\textbf{EXAMPLES:}

sage: E = EllipticCurve([1,2,3,4,6])
sage: E.a3()
3

\textbf{a4()}  
Return the $a_4$ invariant of this elliptic curve.

\textbf{EXAMPLES:}

sage: E = EllipticCurve([1,2,3,4,6])
sage: E.a4()
4

\textbf{a6()}  
Return the $a_6$ invariant of this elliptic curve.

\textbf{EXAMPLES:}

sage: E = EllipticCurve([1,2,3,4,6])
sage: E.a6()
6

\textbf{a_invariants()}  
The $a$-invariants of this elliptic curve, as a tuple.
OUTPUT:
(tuple) - a 5-tuple of the $a$-invariants of this elliptic curve.

EXAMPLES:

```
sage: E = EllipticCurve([1,2,3,4,5])
sage: E.a_invariants()
(1, 2, 3, 4, 5)

sage: E = EllipticCurve([0,1]); E
Elliptic Curve defined by y^2 = x^3 + 1 over Rational Field
sage: E.a_invariants()
(0, 0, 0, 0, 1)

sage: E = EllipticCurve([GF(7)(3),5])
sage: E.a_invariants()
(0, 0, 0, 3, 5)
```

ainvs()

The $a$-invariants of this elliptic curve, as a tuple.

OUTPUT:
(tuple) - a 5-tuple of the $a$-invariants of this elliptic curve.

EXAMPLES:

```
sage: E = EllipticCurve([1,2,3,4,5])
sage: E.a_invariants()
(1, 2, 3, 4, 5)

sage: E = EllipticCurve([0,1]); E
Elliptic Curve defined by y^2 = x^3 + 1 over Rational Field
sage: E.a_invariants()
(0, 0, 0, 0, 1)

sage: E = EllipticCurve([GF(7)(3),5])
sage: E.a_invariants()
(0, 0, 0, 3, 5)
```

automorphisms(field=None)

Return the set of isomorphisms from self to itself (as a list).

INPUT:

- field (default None) – a field into which the coefficients of the curve may be coerced (by default, uses the base field of the curve).

OUTPUT:

(list) A list of WeierstrassIsomorphism objects consisting of all the isomorphisms from the curve self to itself defined over field.

EXAMPLES:

```
sage: E = EllipticCurve_from_j(QQ(0)) # a curve with j=0 over QQ
sage: E.automorphisms();
[Elliptic-curve endomorphism of Elliptic Curve defined by y^2 + y = x^3 over Rational Field
  (continues on next page)```
Elliptic curves, Release 9.7

Via: \((u,r,s,t) = (-1, 0, 0, -1)\), Elliptic-curve endomorphism of Elliptic Curve defined by \(y^2 + y = x^3\) over Rational Field
Via: \((u,r,s,t) = (1, 0, 0, 0)\)

We can also find automorphisms defined over extension fields:

sage: K.<a> = NumberField(x^2+3) # adjoin roots of unity
sage: E.automorphisms(K)

sage: [ len(EllipticCurve_from_j(GF(q,'a')(0)).automorphisms()) for q in [2,4,3,9,5,25,7,49] ]
[2, 24, 2, 12, 2, 6, 6, 6]

\(b_2()\)
Return the \(b_2\) invariant of this elliptic curve.

EXAMPLES:

sage: E = EllipticCurve([1,2,3,4,5])
sage: E.b2()
9

\(b_4()\)
Return the \(b_4\) invariant of this elliptic curve.

EXAMPLES:

sage: E = EllipticCurve([1,2,3,4,5])
sage: E.b4()
11

\(b_6()\)
Return the \(b_6\) invariant of this elliptic curve.

EXAMPLES:

sage: E = EllipticCurve([1,2,3,4,5])
sage: E.b6()
29

\(b_8()\)
Return the \(b_8\) invariant of this elliptic curve.

EXAMPLES:

sage: E = EllipticCurve([1,2,3,4,5])
sage: E.b8()
35
**b_invariants()**

Return the $b$-invariants of this elliptic curve, as a tuple.

**OUTPUT:**

(tuple) - a 4-tuple of the $b$-invariants of this elliptic curve.

This method is cached.

**EXAMPLES:**

```sage
sage: E = EllipticCurve([0, -1, 1, -10, -20])
sage: E.b_invariants()
(-4, -20, -79, -21)
```

```sage
sage: E = EllipticCurve([-4,0])
sage: E.b_invariants()
(0, -8, 0, -16)
```

```sage
sage: E = EllipticCurve([1,2,3,4,5])
sage: E.b_invariants()
(9, 11, 29, 35)
sage: E.b2()
9
sage: E.b4()
11
sage: E.b6()
29
sage: E.b8()
35
```

**ALGORITHM:**

These are simple functions of the $a$-invariants.

**AUTHORS:**

• William Stein (2005-04-25)

**base_extend(R)**

Return the base extension of self to $R$.

**INPUT:**

• $R$ – either a ring into which the $a$-invariants of self may be converted, or a morphism which may be applied to them.

**OUTPUT:**

An elliptic curve over the new ring whose $a$-invariants are the images of the $a$-invariants of self.

**EXAMPLES:**

```sage
sage: E = EllipticCurve(GF(5),[1,1]); E
Elliptic Curve defined by y^2 = x^3 + x + 1 over Finite Field of size 5
sage: E1 = E.base_extend(GF(125,'a')); E1
Elliptic Curve defined by y^2 = x^3 + x + 1 over Finite Field in a of size 5^3
```

**base_ring()**

Return the base ring of the elliptic curve.
EXAMPLES:

```
sage: E = EllipticCurve(GF(49, 'a'), [3,5])
sage: E.base_ring()
Finite Field in a of size 7^2
```

```
sage: E = EllipticCurve([1,1])
sage: E.base_ring()
Rational Field
```

```
sage: E = EllipticCurve(ZZ, [3,5])
sage: E.base_ring()
Integer Ring
```

c4()  
Return the $c_4$ invariant of this elliptic curve.  

EXAMPLES:

```
sage: E = EllipticCurve([0, -1, 1, -10, -20])
sage: E.c4()
496
```

c6()  
Return the $c_6$ invariant of this elliptic curve.  

EXAMPLES:

```
sage: E = EllipticCurve([0, -1, 1, -10, -20])
sage: E.c6()
20008
```

c_invariants()  
Return the $c$-invariants of this elliptic curve, as a tuple.  

This method is cached.  

OUTPUT:  
(tuple) - a 2-tuple of the $c$-invariants of the elliptic curve.  

EXAMPLES:

```
sage: E = EllipticCurve([0, -1, 1, -10, -20])
sage: E.c_invariants()
(496, 20008)
sage: E = EllipticCurve([-4,0])
sage: E.c_invariants()
(192, 0)
```

ALGORITHM:  
These are simple functions of the $a$-invariants.

AUTHORS:  
**change_ring**(*R*)

Return the base change of self to *R*.

This has the same effect as **self.base_extend(R)**.

**EXAMPLES:**

```
sage: F2 = GF(5^2,'a'); a = F2.gen()
sage: F4 = GF(5^4,'b'); b = F4.gen()
sage: h = F2.hom([a.charpoly().roots(ring=F4,multiplicities=False)[0]],F4)
sage: E = EllipticCurve(F2,[1,a]); E
Elliptic Curve defined by y^2 = x^3 + x + a over Finite Field in a of size 5^2
sage: E.change_ring(h)
Elliptic Curve defined by y^2 = x^3 + x + (4*b^3+4*b^2+4*b+3) over Finite Field in b of size 5^4
```

**change_weierstrass_model**(*urst*)

Return a new Weierstrass model of self under the standard transformation \((u, r, s, t) \mapsto (x', y') = (u^2 x + r, u^3 y + su^2 x + t)\).

**EXAMPLES:**

```
sage: E = EllipticCurve('15a')
sage: F1 = E.change_weierstrass_model([1/2,0,0,0]); F1
Elliptic Curve defined by y^2 + 2*x*y + 8*y = x^3 + 4*x^2 - 160*x - 640 over Rational Field
sage: F2 = E.change_weierstrass_model([7,2,1/3,5]); F2
Elliptic Curve defined by y^2 + 5/21*x*y + 13/343*y = x^3 + 59/441*x^2 - 10/7203*x - 58/117649 over Rational Field
sage: F1.is_isomorphic(F2)
True
```

**discriminant**()

Return the discriminant of this elliptic curve.

This method is cached.

**EXAMPLES:**

```
sage: E = EllipticCurve([0,0,1,-1,0])
sage: E.discriminant()
37
sage: E = EllipticCurve([0, -1, 1, -10, -20])
sage: E.discriminant()
-161051
sage: E = EllipticCurve([GF(7)(2),1])
sage: E.discriminant()
1
```

**division_polynomial**(*m*, *x=None*, *two_torsion_multiplicity=2*, *force_evaluate=None*)

Return the \(m\)th division polynomial of this elliptic curve evaluated at \(x\).

The division polynomial is cached if \(x\) is None.

**INPUT:**
• \( m \) – positive integer.

• \( x \) – optional ring element to use as the \( x \) variable. If \( x \) is None (omitted), then a new polynomial ring will be constructed over the base ring of the elliptic curve, and its generator will be used as \( x \). Note that \( x \) does not need to be a generator of a polynomial ring; any ring element works. This permits fast calculation of the torsion polynomial evaluated on any element of a ring.

• two_torsion_multiplicity – 0, 1, or 2
  
  If 0: For even \( m \) when \( x \) is None, a univariate polynomial over the base ring of the curve is returned, which omits factors whose roots are the \( x \)-coordinates of the 2-torsion points. When \( x \) is not None, the evaluation of such a polynomial at \( x \) is returned.

  If 2: For even \( m \) when \( x \) is None, a univariate polynomial over the base ring of the curve is returned, which includes a factor of degree 3 whose roots are the \( x \)-coordinates of the 2-torsion points. Similarly, when \( x \) is not None, the evaluation of such a polynomial at \( x \) is returned.

  If 1: For even \( m \) when \( x \) is None, a bivariate polynomial over the base ring of the curve is returned, which includes a factor \( 2y + a_1x + a_3 \) having simple zeros at the 2-torsion points. When \( x \) is not None, it should be a tuple of length 2, and the evaluation of such a polynomial at \( x \) is returned.

• force_evaluate (optional) – 0, 1, or 2
  
  By default, this method makes use of previously cached generic division polynomials to compute the value of the polynomial at a given element \( x \) whenever it appears beneficial to do so. Explicitly setting this flag overrides the default behavior.

  Note that the complexity of evaluating a generic division polynomial scales much worse than that of computing the value at a point directly (using the recursive formulas), hence setting this flag can be detrimental to performance.

  If 0: Do not use cached generic division polynomials.

  If 1: If the generic division polynomial for this \( m \) has been cached before, evaluate it at \( x \) to compute the result.

  If 2: Compute the value at \( x \) by evaluating the generic division polynomial. If the generic \( m \)-division polynomial has not yet been cached, compute and cache it first.

EXAMPLES:

```
sage: E = EllipticCurve([0,0,1,-1,0])
sage: E.division_polynomial(1)
1
sage: E.division_polynomial(2, two_torsion_multiplicity=0)
1
sage: E.division_polynomial(2, two_torsion_multiplicity=1)
2*y + 1
sage: E.division_polynomial(2, two_torsion_multiplicity=2)
4*x^3 - 4*x + 1
sage: E.division_polynomial(2)
4*x^3 - 4*x + 1
sage: [E.division_polynomial(3, two_torsion_multiplicity=i) for i in range(3)]
[3*x^4 - 6*x^2 + 3*x - 1, 3*x^4 - 6*x^2 + 3*x - 1, 3*x^4 - 6*x^2 + 3*x - 1]
sage: [type(E.division_polynomial(3, two_torsion_multiplicity=i)) for i in range(3)]
[<... 'sage.rings.polynomial.polynomial_rational_flint.Polynomial_rational_flint', ...],
[<... 'sage.rings.polynomial.multipolynomial_libsingular.MPolynomial_libsingular', ...],
[<... 'sage.rings.polynomial.multipolynomial_libsingular.MPolynomial_libsingular', ...]]
```
sage: E = EllipticCurve([0, -1, 1, -10, -20])
sage: R.<z>=PolynomialRing(QQ)
sage: E.division_polynomial(4,z,0)
2*z^6 - 4*z^5 - 100*z^4 - 790*z^3 - 210*z^2 - 1496*z - 5821
sage: E.division_polynomial(4,z)
8*z^9 - 24*z^8 - 464*z^7 - 2758*z^6 + 6636*z^5 + 34356*z^4 + 53510*z^3 +
˓→99714*z^2 + 351024*z + 459859

This does not work, since when two_torsion_multiplicity is 1, we compute a bivariate polynomial, and must evaluate at a tuple of length 2:

sage: E.division_polynomial(4,z,1)
Traceback (most recent call last):
... ValueError: x should be a tuple of length 2 (or None) when two_torsion_
˓→multiplicity is 1
sage: R.<z,w>=PolynomialRing(QQ,2)
sage: E.division_polynomial(4,(z,w),1).factor()
(2*w + 1) * (2*z^6 - 4*z^5 - 100*z^4 - 790*z^3 - 210*z^2 - 1496*z - 5821)

We can also evaluate this bivariate polynomial at a point:

sage: P = E(5,5)
sage: E.division_polynomial(4,P,two_torsion_multiplicity=1)
-1771561

`division_polynomial_0(n, x=None)`
Return the \( n^{\text{th}} \) torsion (division) polynomial, without the 2-torsion factor if \( n \) is even, as a polynomial in \( x \).

These are the polynomials \( g_n \) defined in [MT1991], but with the sign flipped for even \( n \), so that the leading coefficient is always positive.

**Note:** This function is intended for internal use; users should use `division_polynomial()`.

**See also:**
- `division_polynomial()`
- `_multiple_x_numerator()`
- `_multiple_x_denominator()`

**INPUT:**

- \( n \) – positive integer, or the special values \(-1\) and \(-2\) which mean \( B_0 = (2y + a_1x + a_3)^2 \) and \( B_0^2 \) respectively (in the notation of [MT1991]); or a list of integers.
- \( x \) – a ring element to use as the “\( x \)” variable or \( \text{None} \) (default: \( \text{None} \)). If \( \text{None} \), then a new polynomial ring will be constructed over the base ring of the elliptic curve, and its generator will be used as \( x \).
Note that \( x \) does not need to be a generator of a polynomial ring; any ring element is ok. This permits fast calculation of the torsion polynomial \( \text{evaluated} \) on any element of a ring.

**ALGORITHM:**

Recursion described in [MT1991]. The recursive formulae are evaluated \( O(\log^2 n) \) times.

**AUTHORS:**

- David Harvey (2006-09-24): initial version
- John Cremona (2008-08-26): unified division polynomial code

**EXAMPLES:**

```python
sage: E = EllipticCurve("37a")
sage: E.division_polynomial_0(1)
1
sage: E.division_polynomial_0(2)
1
sage: E.division_polynomial_0(3)
3*x^4 - 6*x^2 + 3*x - 1
sage: E.division_polynomial_0(4)
2*x^6 - 10*x^4 + 10*x^3 - 10*x^2 + 2*x + 1
sage: E.division_polynomial_0(5)
5*x^12 - 62*x^10 + 95*x^9 - 105*x^8 - 60*x^7 + 285*x^6 - 174*x^5 - 5*x^4 - 5*x^3 + 3 + 35*x^2 - 15*x + 2
sage: E.division_polynomial_0(6)
3*x^16 - 72*x^14 + 168*x^13 - 364*x^12 + 1120*x^10 - 1144*x^9 + 300*x^8 - 540*x^7 + 7 + 1120*x^6 - 588*x^5 - 133*x^4 + 252*x^3 - 114*x^2 + 22*x - 1
sage: E.division_polynomial_0(7)
7*x^24 - 308*x^22 + 986*x^21 - 2954*x^20 + 288*x^19 + 17171*x^18 - 23142*x^17 +
    511*x^16 - 5012*x^15 + 43804*x^14 - 7140*x^13 - 96950*x^12 + 111356*x^11 -
    19516*x^10 - 49707*x^9 + 40054*x^8 - 124*x^7 - 18382*x^6 + 13342*x^5 - 4816*x^4 +
    1099*x^3 - 210*x^2 + 35*x - 3
sage: E.division_polynomial_0(8)
4*x^30 - 292*x^28 + 1252*x^27 - 5436*x^26 + 2340*x^25 + 39834*x^24 - 79560*x^23 -
    51432*x^22 - 142896*x^21 + 451596*x^20 - 212040*x^19 - 1005316*x^18 +
    1726416*x^17 - 671160*x^16 - 954924*x^15 + 1119552*x^14 + 313308*x^13 -
    1582818*x^12 + 1189908*x^11 - 160152*x^10 + 399176*x^9 - 386142*x^8 -
    220128*x^7 + 99558*x^6 - 33528*x^5 + 6042*x^4 + 310*x^3 - 406*x^2 + 78*x - 5
sage: E.division_polynomial_0(18) % E.division_polynomial_0(6) == 0
True
```

An example to illustrate the relationship with torsion points:

```python
sage: F = GF(11)
sage: E = EllipticCurve(F, [0, 2]); E
Elliptic Curve defined by y^2 = x^3 + 2 over Finite Field of size 11
sage: f = E.division_polynomial_0(5); f
5*x^12 + x^9 + 8*x^6 + 4*x^3 + 7
sage: f.factor()
(5) * (x^2 + 5) * (x^2 + 2*x + 5) * (x^2 + 5*x + 7) * (x^2 + 7*x + 7) * (x^2 + 9*x + 5) * (x^2 + 10*x + 7)
```
This indicates that the $x$-coordinates of all the 5-torsion points of $E$ are in $\mathbb{F}_{11^2}$, and therefore the $y$-coordinates are in $\mathbb{F}_{11^4}$:

```
sage: K = GF(11^4, 'a')
sage: X = E.change_ring(K)
sage: f = X.division_polynomial_0(5)
sage: x_coords = f.roots(multiplicities=False); x_coords
[10*a^3 + 4*a^2 + 5*a + 6,
  9*a^3 + 8*a^2 + 10*a + 8,
  8*a^3 + a^2 + 4*a + 10,
  8*a^3 + a^2 + 4*a + 8,
  8*a^3 + a^2 + 4*a + 4,
  6*a^3 + 9*a^2 + 3*a + 4,
  5*a^3 + 2*a^2 + 8*a + 7,
  3*a^3 + 10*a^2 + 7*a + 8,
  3*a^3 + 10*a^2 + 7*a + 3,
  3*a^3 + 10*a^2 + 7*a + 1,
  2*a^3 + 3*a^2 + a + 7,
  a^3 + 7*a^2 + 6*a]
```

Now we check that these are exactly the $x$-coordinates of the 5-torsion points of $E$:

```
sage: for x in x_coords:
....:   assert X.lift_x(x).order() == 5
```

The roots of the polynomial are the $x$-coordinates of the points $P$ such that $mP = 0$ but $2P \neq 0$:

```
sage: E = EllipticCurve('14a1')
sage: T = E.torsion_subgroup()
sage: [n*T.0 for n in range(6)]
[(0 : 1 : 0),
 (9 : 23 : 1),
 (2 : 2 : 1),
 (1 : -1 : 1),
 (2 : -5 : 1),
 (9 : -33 : 1)]
sage: pol = E.division_polynomial_0(6)
sage: xlist = pol.roots(multiplicities=False); xlist
[9, 2, -1/3, -5]
sage: [E.lift_x(x, all=True) for x in xlist]
[[[9 : 23 : 1], (9 : -33 : 1)], [(2 : 2 : 1), (2 : -5 : 1)], [], []]
```

**Note:** The point of order 2 and the identity do not appear. The points with $x = -1/3$ and $x = -5$ are not rational.

`formal()`

Return the formal group associated to this elliptic curve.

This method is cached.

**EXAMPLES:**
Sage: E = EllipticCurve("37a")
Sage: E.formal_group()
Formal Group associated to the Elliptic Curve defined by y^2 + y = x^3 - x over Rational Field

formal_group()
Return the formal group associated to this elliptic curve.
This method is cached.

EXAMPLES:
Sage: E = EllipticCurve("37a")
Sage: E.formal_group()
Formal Group associated to the Elliptic Curve defined by y^2 + y = x^3 - x over Rational Field

gen()  
Function returning the i'th generator of this elliptic curve.

Note: Relies on gens() being implemented.

EXAMPLES:
Sage: R.<a1,a2,a3,a4,a6>=QQ[]
Sage: E = EllipticCurve([a1,a2,a3,a4,a6])
Sage: E.gen(0)
Traceback (most recent call last):
...  
NotImplementedError: not implemented.

gens()  
Placeholder function to return generators of an elliptic curve.

Note: This functionality is implemented in certain derived classes, such as EllipticCurve_rational_field.

EXAMPLES:
Sage: R.<a1,a2,a3,a4,a6>=QQ[]
Sage: E = EllipticCurve([a1,a2,a3,a4,a6])
Sage: E.gens()
Traceback (most recent call last):
...  
NotImplementedError: not implemented.

Sage: E = EllipticCurve(QQ,[1,1])
Sage: E.gens()
[(0 : 1 : 1)]

hyperelliptic_polynomials()
Return a pair of polynomials \( g(x), h(x) \) such that this elliptic curve can be defined by the standard hyperelliptic equation

\[
y^2 + h(x)y = g(x).
\]
EXAMPLES:

```
sage: R.<a1,a2,a3,a4,a6>=QQ[]
sage: E = EllipticCurve([a1,a2,a3,a4,a6])
sage: E.hyperelliptic_polynomials()
(x^3 + a2*x^2 + a4*x + a6, a1*x + a3)
```

`is_isomorphic(other, field=None)`
Return whether or not self is isomorphic to other.

**INPUT:**

- `other` – another elliptic curve.
- `field` (default None) – a field into which the coefficients of the curves may be coerced (by default, uses the base field of the curves).

**OUTPUT:**

(bool) True if there is an isomorphism from curve `self` to curve `other` defined over `field`.

EXAMPLES:

```
sage: E = EllipticCurve('389a')
sage: F = E.change_weierstrass_model([2,3,4,5]); F
Elliptic Curve defined by y^2 + 4*x*y + 11/8*y = x^3 - 3/2*x^2 - 13/16*x over Rational Field
sage: E.is_isomorphic(F)
True
sage: E.is_isomorphic(F.change_ring(CC))
False
```

`is_on_curve(x, y)`
Return True if \((x, y)\) is an affine point on this curve.

**INPUT:**

- `x, y` – elements of the base ring of the curve.

**EXAMPLES:**

```
sage: E = EllipticCurve(QQ,[1,1])
sage: E.is_on_curve(0,1)
True
sage: E.is_on_curve(1,1)
False
```

`is_x_coord(x)`
Return True if \(x\) is the \(x\)-coordinate of a point on this curve.

**Note:** See also `lift_x()` to find the point(s) with a given \(x\)-coordinate. This function may be useful in cases where testing an element of the base field for being a square is faster than finding its square root.

**EXAMPLES:**

```
sage: E = EllipticCurve('37a'); E
Elliptic Curve defined by y^2 + y = x^3 - x over Rational Field
```
sage: E.is_x_coord(1)
True
sage: E.is_x_coord(2)
True

There are no rational points with x-coordinate 3:

sage: E.is_x_coord(3)
False

However, there are such points in $E(R)$:

sage: E.change_ring(RR).is_x_coord(3)
True

And of course it always works in $E(C)$:

sage: E.change_ring(RR).is_x_coord(-3)
False
sage: E.change_ring(CC).is_x_coord(-3)
True

AUTHORS:
• John Cremona (2008-08-07): adapted from $lift_x()$

isomorphism_to(other)
Given another weierstrass model other of self, return an isomorphism from self to other.

INPUT:
• other – an elliptic curve isomorphic to self.

OUTPUT:
(Weierstrassmorphism) An isomorphism from self to other.

Note: If the curves in question are not isomorphic, a ValueError is raised.

EXAMPLES:

sage: E = EllipticCurve('37a')
sage: F = E.short_weierstrass_model()
sage: w = E.isomorphism_to(F); w
Elliptic-curve morphism:
From: Elliptic Curve defined by y^2 + y = x^3 - x over Rational Field
To:   Elliptic Curve defined by y^2 = x^3 - 16*x + 16 over Rational Field
Via:  (u,r,s,t) = (1/2, 0, 0, -1/2)
sage: P = E(0,-1,1)
sage: w(P)
(0 : -4 : 1)
sage: w(5*P)
(1 : 1 : 1)
sage: 5*w(P)
(1 : 1 : 1)
Elliptic curves, Release 9.7

We can also handle injections to different base rings:

```python
sage: K.<a> = NumberField(x^3-7)
sage: E.isomorphism_to(E.change_ring(K))
Elliptic-curve morphism:
  From: Elliptic Curve defined by y^2 + y = x^3 - x over Rational Field
  To:   Elliptic Curve defined by y^2 + y = x^3 + (-1)*x over Number Field in a
        with defining polynomial x^3 - 7
  Via:   (u,r,s,t) = (1, 0, 0, 0)
```

isomorphisms(other, field=None)

Return the set of isomorphisms from self to other (as a list).

INPUT:

- `other` – another elliptic curve.
- `field` (default None) – a field into which the coefficients of the curves may be coerced (by default, uses the base field of the curves).

OUTPUT:

(list) A list of WeierstrassIsomorphism objects consisting of all the isomorphisms from the curve self to the curve other defined over field.

EXAMPLES:

```python
sage: E = EllipticCurve_from_j(QQ(0)) # a curve with j=0 over QQ
sage: F = EllipticCurve('27a3') # should be the same one
sage: E.isomorphisms(F);
[Elliptic-curve endomorphism of Elliptic Curve defined by y^2 + y = x^3 over Rational Field
  Via: (u,r,s,t) = (-1, 0, 0, -1),
Elliptic-curve endomorphism of Elliptic Curve defined by y^2 + y = x^3 over Rational Field
  Via: (u,r,s,t) = (1, 0, 0, 0)]
```

We can also find isomorphisms defined over extension fields:

```python
sage: E = EllipticCurve(GF(7),[0,0,0,1,1])
sage: F = EllipticCurve(GF(7),[0,0,0,1,-1])
sage: E.isomorphisms(F)
[]
sage: E.isomorphisms(F,GF(49,'a'))
[Elliptic-curve morphism:
  From: Elliptic Curve defined by y^2 = x^3 + x + 1 over Finite Field in a of size 7^2
  To:   Elliptic Curve defined by y^2 = x^3 + x + 6 over Finite Field in a of size 7^2
  Via:   (u,r,s,t) = (a + 3, 0, 0, 0), Elliptic-curve morphism:
  From: Elliptic Curve defined by y^2 = x^3 + x + 1 over Finite Field in a of size 7^2
  To:   Elliptic Curve defined by y^2 = x^3 + x + 6 over Finite Field in a of size 7^2
```

(continues on next page)
j_invariant()
Return the \( j \)-invariant of this elliptic curve.
This method is cached.

EXAMPLES:

```
sage: E = EllipticCurve([0,0,1,-1,0])
sage: E.j_invariant()
110592/37
sage: E = EllipticCurve([0, -1, 1, -10, -20])
sage: E.j_invariant()
-122023936/161051
sage: E = EllipticCurve([-4,0])
sage: E.j_invariant()
1728
sage: E = EllipticCurve([GF(7)(2),1])
sage: E.j_invariant()
1
```

lift_x(x, all=False, extend=False)
Return one or all points with given \( x \)-coordinate.

INPUT:

- \( x \) – an element of the base ring of the curve, or of an extension.
- all (bool, default False) – if True, return a (possibly empty) list of all points; if False, return just one point, or raise a ValueError if there are none.
- extend (bool, default False) –
  - if False, extend the base if necessary and possible to include \( x \), and only return point(s) defined over this ring, or raise an error when there are none with this \( x \)-coordinate;
  - If True, the base ring will be extended if necessary to contain the \( y \)-coordinates of the point(s) with this \( x \)-coordinate, in addition to a possible base change to include \( x \).

OUTPUT:
A point or list of up to 2 points on this curve, or a base-change of this curve to a larger ring.

See also:
is_x_coord()

EXAMPLES:

```
sage: E = EllipticCurve('37a'); E
Elliptic Curve defined by y^2 + y = x^3 - x over Rational Field
sage: E.lift_x(1)
(1 : 0 : 1)
```
Elliptic curves, Release 9.7

There are no rational points with $x$-coordinate 3:

```python
sage: E.lift_x(3)
Traceback (most recent call last):
  ...  
ValueError: No point with x-coordinate 3 on Elliptic Curve defined by y^2 + y = \to x^3 - x over Rational Field
```

We can use the `extend` parameter to make the necessary quadratic extension. Note that in such cases the returned point is a point on a new curve object, the result of changing the base ring to the parent of $x$:

```python
sage: P = E.lift_x(3, extend=True); P
(3 : y : 1)
sage: P.curve()
Elliptic Curve defined by y^2 + y = x^3 + (-1)*x over Number Field in y with defining polynomial y^2 + y - 24
```

Or we can extend scalars. There are two such points in $E(\mathbb{R})$:

```python
sage: E.change_ring(RR).lift_x(3, all=True)
[(3.00000000000000 : 4.42442890089805 : 1.00000000000000),
 (3.00000000000000 : -5.42442890089805 : 1.00000000000000)]
```

And of course it always works in $E(\mathbb{C})$:

```python
sage: E.change_ring(CC).lift_x(.5, all=True)
[]
sage: E.change_ring(CC).lift_x(.5)
(0.500000000000000 : -0.500000000000000 + 0.353553390593274*I : 1.
  ...00000000000000)
```

In this example we start with a curve defined over $\mathbb{Q}$ which has no rational points with $x = 0$, but using `extend = True` we can construct such a point over a quadratic field:

```python
sage: E = EllipticCurve([0,0,0,0,2]); E
Elliptic Curve defined by y^2 = x^3 + 2 over Rational Field
sage: P = E.lift_x(0, extend=True); P
(0 : y : 1)
sage: P.curve()
Elliptic Curve defined by y^2 = x^3 + 2 over Number Field in y with defining polynomial y^2 - 2
```

We can perform these operations over finite fields too:

```python
sage: E = EllipticCurve('37a').change_ring(GF(17)); E
Elliptic Curve defined by y^2 + y = x^3 + 16*x over Finite Field of size 17
sage: E.lift_x(7)
(7 : 11 : 1)
```
sage: E.lift_x(3)
Traceback (most recent call last):
...
ValueError: No point with x-coordinate 3 on Elliptic Curve defined by y^2 + y = x^3 + 16*x over Finite Field of size 17

Note that there is only one lift with x-coordinate 10 in \( E(\mathbb{F}_{17}) \):

sage: E.lift_x(10, all=True)
[(10 : 8 : 1)]

We can lift over more exotic rings too. If the supplied x value is in an extension of the base, note that the point returned is on the base-extended curve:

sage: E = EllipticCurve('37a')
sage: P = E.lift_x(pAdicField(17, 5)(6)); P
(6 + O(17^5) : 2 + 16*17 + 16*17^2 + 16*17^3 + 16*17^4 + O(17^5) : 1 + O(17^5))
sage: P.curve()
Elliptic Curve defined by y^2 + (1+O(17^5))*y = x^3 + (16+16*17+16*17^2+16*17^3+16*17^4+O(17^5))*x over 17-adic Field with capped relative precision 5
sage: K.<t> = PowerSeriesRing(QQ, 't', 5)
sage: P = E.lift_x(1+t); P
(1 + t : 2*t - t^2 + 5*t^3 - 21*t^4 + O(t^5) : 1)
sage: K.<a> = GF(16)
sage: P = E.change_ring(K).lift_x(a^3); P
(a^3 : a^3 + a : 1)
sage: P.curve()
Elliptic Curve defined by y^2 + y = x^3 + x over Finite Field in a of size 2^4

We can extend the base field to include the associated y value(s):

sage: E = EllipticCurve([0,0,0,0,2]); E
Elliptic Curve defined by y^2 = x^3 + 2 over Rational Field
sage: x = polygen(QQ)
sage: P = E.lift_x(x, extend=True); P
(x : y : 1)

This point is a generic point on E:

sage: P.curve()
Elliptic Curve defined by y^2 = x^3 + 2 over Univariate Quotient Polynomial Ring in y over Fraction Field of Univariate Polynomial Ring in x over Rational Field with modulus y^2 - x^3 - 2
sage: -P
(x : -y : 1)
sage: 2*P
((1/4*x^4 - 4*x)/(x^3 + 2) : ((1/8*x^5 + 5*x^3 - 4)/(x^6 + 4*x^3 + 4))*y : 1)

Check that trac ticket #30297 is fixed:

sage: K = Qp(5)
sage: E = EllipticCurve([K(0), K(1)])

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AUTHORS:

• Robert Bradshaw (2007-04-24)
• John Cremona (2017-11-10)

**montgomery_model**(twisted=False, morphism=False)

Return a (twisted or untwisted) Montgomery model for this elliptic curve, if possible.

A Montgomery curve is a smooth projective curve of the form

\[ BY^2 = X^3 + AX^2 + X. \]

The Montgomery curve is called *untwisted* if \( B = 1 \).

**INPUT:**

- twisted – boolean (default: False); allow \( B \neq 1 \)
- morphism – boolean (default: False); also return an isomorphism from this curve to the computed Montgomery model

**OUTPUT:**

If `twisted` is `False` (the default), an `EllipticCurve_generic` object encapsulating an untwisted Montgomery curve. Otherwise, a `ProjectivePlaneCurve` object encapsulating a (potentially twisted) Montgomery curve.

If `morphism` is `True`, this method returns a tuple consisting of such a curve together with an isomorphism of suitable type (either `WeierstrassIsomorphism` or `WeierstrassTransformationWithInverse`) from this curve to the Montgomery model.

**EXAMPLES:**

```python
sage: E = EllipticCurve(QQbar, '11a1')
sage: E.montgomery_model()
Elliptic Curve defined by y^2 = x^3 + (-1.953522420987248?)*x^2 + x over Algebraic Field

sage: E = EllipticCurve(GF(431^2), [7,7])
sage: E.montgomery_model()
Elliptic Curve defined by y^2 = x^3 + (51*z2+190)*x^2 + x over Finite Field in z2 of size 431^2
```

An isomorphism between the Montgomery and Weierstrass form can be obtained using the `morphism` parameter:

```python
sage: E.montgomery_model(morphism=True)
(Elliptic Curve defined by y^2 = x^3 + (51*z2+190)*x^2 + x over Finite Field in z2 of size 431^2,
Elliptic-curve morphism:
    From: Elliptic Curve defined by y^2 = x^3 + 7*x + 7 over Finite Field in z2 of size 431^2
    To:   Elliptic Curve defined by y^2 = x^3 + (51*z2+190)*x^2 + x over Finite Field in z2 of size 431^2
    Via:  (u,r,s,t) = (64*z2 + 407, 159, 0, 0))
```
Not all elliptic curves have a Montgomery model over their field of definition:

```
sage: E = EllipticCurve(GF(257), [1,1])
sage: E.montgomery_model()
Traceback (most recent call last):
...  
ValueError: Elliptic Curve defined by y^2 = x^3 + x + 1 over Finite Field of size 257 has no Montgomery model
```

```
sage: E = EllipticCurve(GF(257), [10,10])
sage: E.montgomery_model()
Traceback (most recent call last):
...  
ValueError: Elliptic Curve defined by y^2 = x^3 + 10*x + 10 over Finite Field of size 257 has no untwisted Montgomery model
```

However, as hinted by the error message, the latter curve does admit a twisted Montgomery model, which can be computed by passing `twisted=True`:

```
sage: E.montgomery_model(twisted=True)
Projective Plane Curve over Finite Field of size 257 defined by -x^3 + 8*x^2*z - 127*y^2*z - x*z^2
```

Since Sage internally represents elliptic curves as (long) Weierstrass curves, which do not feature the Montgomery $B$ coefficient, the returned curve in this case is merely a `ProjectivePlaneCurve` rather than the usual `EllipticCurve_generic`.

Arithmetic on curves of this type is not implemented natively, but can easily be emulated by mapping back and forth to the corresponding Weierstrass curve:

```
sage: C, f = E.montgomery_model(twisted=True, morphism=True)
sage: f
    Scheme morphism:
    From: Elliptic Curve defined by y^2 = x^3 + 10*x + 10 over Finite Field of size 257
    To: Projective Plane Curve over Finite Field of size 257 defined by -x^3 + 8*x^2*z - 127*y^2*z - x*z^2
    Defn: Defined on coordinates by sending (x : y : z) to (x + 116*z : -y : -85*z)
sage: g = f.inverse(); g
    Scheme morphism:
    From: Projective Plane Curve over Finite Field of size 257 defined by -x^3 + 8*x^2*z - 127*y^2*z - x*z^2
    To: Elliptic Curve defined by y^2 = x^3 + 10*x + 10 over Finite Field of size 257
    Defn: Defined on coordinates by sending (x : y : z) to (-85*x - 116*z : 85*y : z)
sage: P = C(70, 8)
sage: Q = C(17, 17)
sage: P + Q  # this doesn't work...
Traceback (most recent call last):...
TypeError: unsupported operand parent(s) for +: ...
sage: f(g(P) + g(Q))  # ...but this does
```
(continues on next page)
Using the fact that the Weil pairing satisfies $e(\psi(P), \psi(Q)) = e(P, Q)^{\deg \psi}$, even pairings can be emulated in this way (note that isomorphisms have degree 1):

```sage
sage: F.<z2> = GF(257^2)
sage: C_ = C.change_ring(F)
sage: g_ = g.change_ring(F)
sage: g_(P).order()
12
sage: T = C_(-7 * z2 - 57, 31 * z2 - 52, 1)
sage: g_(T).order()
12
sage: g_(P).weil_pairing(g_(T), 12)
15*z2 + 204
```

Another alternative is to simply extend the base field enough for the curve to have an untwisted Montgomery model:

```sage
sage: C_ = E.change_ring(F).montgomery_model(); C_
Elliptic Curve defined by y^2 = x^3 + 249*x^2 + x over Finite Field in z2 of size 257^2
sage: h = C.defining_polynomial().change_ring(F); h
-x^3 + 8*x^2*z - 127*y^2*z - x*z^2
sage: C_.is_isomorphic(EllipticCurve_from_cubic(h).codomain())
True
```

See also:

The inverse conversion — computing a Weierstrass model for a given Montgomery curve — can be performed using `EllipticCurve_from_cubic()`.

ALGORITHM: [CS2018], §2.4

REFERENCES:

• Original publication: [Mont1987], §10.3.1
• More recent survey article: [CS2018]

`multiplication_by_m(m, x_only=False)`

Return the multiplication-by-$m$ map from `self` to `self`

The result is a pair of rational functions in two variables $x$, $y$ (or a rational function in one variable $x$ if `x_only` is `True`).

INPUT:

• $m$ – a nonzero integer
• $x$ _only_ – boolean (default: `False`) if `True`, return only the $x$-coordinate of the map (as a rational function in one variable).

OUTPUT:

• a pair $(f(x), g(x, y))$, where $f$ and $g$ are rational functions with the degree of $y$ in $g(x, y)$ exactly 1,
• or just $f(x)$ if `x_only` is `True`
Note:
• The result is not cached.
• \( m \) is allowed to be negative (but not 0).

EXAMPLES:

```sage
E = EllipticCurve([-1,3])
```

We verify that multiplication by 1 is just the identity:

```sage
E.multiplication_by_m(1)
(x, y)
```

Multiplication by 2 is more complicated:

```sage
f = E.multiplication_by_m(2)
f
((x^4 + 2*x^2 - 24*x + 1)/(4*x^3 - 4*x + 12), (8*x^6*y - 40*x^4*y + 480*x^3*y - 40*x^2*y + 96*x*y - 568*y)/(64*x^6 - 128*x^4 + 384*x^3 + 64*x^2 - 384*x + 576))
```

Grab only the x-coordinate (less work):

```sage
mx = E.multiplication_by_m(2, x_only=True)
mx
(1/4*x^4 + 1/2*x^2 - 6*x + 1/4)/(x^3 - x + 3)
```

We check that it works on a point:

```sage
P = E([2,3])
eval = lambda f,P: [fi(P[0],P[1]) for fi in f]
assert E(eval(f,P)) == 2*P
```

We do the same but with multiplication by 3:

```sage
f = E.multiplication_by_m(3)
assert E(eval(f,P)) == 3*P
```

And the same with multiplication by 4:

```sage
f = E.multiplication_by_m(4)
assert E(eval(f,P)) == 4*P
```

And the same with multiplication by -1,-2,-3,-4:

```sage
for m in [-1,-2,-3,-4]:
    f = E.multiplication_by_m(m)
    assert E(eval(f,P)) == m*P
```

`multiplication_by_m_isogeny(m)`

Return the `EllipticCurveIsogeny` object associated to the multiplication-by-\( m \) map on this elliptic curve.
The resulting isogeny will have the associated rational maps (i.e. those returned by \texttt{self.multiplication_by_m()})) already computed.

NOTE: This function is currently \textit{much} slower than the result of \texttt{self.multiplication_by_m()}, because constructing an isogeny precomputes a significant amount of information. See trac ticket #7368 and trac ticket #8014 for the status of improving this situation.

INPUT:
• \(m\) – a nonzero integer

OUTPUT:
• An \texttt{EllipticCurveIsogeny} object associated to the multiplication-by-\(m\) map on this elliptic curve.

EXAMPLES:

\begin{verbatim}
 sage: E = EllipticCurve('11a1')
 sage: E.multiplication_by_m_isogeny(7)
\end{verbatim}

Isogeny of degree 49 from Elliptic Curve defined by \(y^2 + y = x^3 - x^2 - 10x - 20\) over Rational Field to Elliptic Curve defined by \(y^2 + y = x^3 - x^2 - 10x - 20\) over Rational Field

\begin{verbatim}
 pari_curve()
\end{verbatim}

Return the PARI curve corresponding to this elliptic curve.

The result is cached.

EXAMPLES:

\begin{verbatim}
 sage: E = EllipticCurve([RR(0), RR(0), RR(1), RR(-1), RR(0)])
 sage: e = E.pari_curve()
\end{verbatim}

\begin{verbatim}
 Over a finite field:
 sage: EllipticCurve(GF(41),[2,5]).pari_curve() [Mod(0, 41), Mod(0, 41), Mod(0, 41), Mod(2, 41), Mod(5, 41), Mod(0, 41), Mod(4, 41), Mod(20, 41), Mod(37, 41), Mod(27, 41), Mod(26, 41), Mod(4, 41), Mod(11, 41), Vecsmall([3]), [41, [9, 31, [6, 0, 0, 0]]], [0, 0, 0, 0]]
\end{verbatim}

Over a \(p\)-adic field:

\begin{verbatim}
 sage: Qp = pAdicField(5, prec=3)
 sage: E = EllipticCurve(Qp,[3, 4])
\end{verbatim}

\begin{verbatim}
 Over a number field:
\end{verbatim}
sage: K.<a> = QuadraticField(2)
sage: E = EllipticCurve([1,a])
sage: E.pari_curve()
[Mod(0, y^2 - 2), Mod(0, y^2 - 2), Mod(0, y^2 - 2), Mod(1, y^2 - 2),
 Mod(y, y^2 - 2), Mod(0, y^2 - 2), Mod(2, y^2 - 2), Mod(4*y, y^2 - 2),
 Mod(-1, y^2 - 2), Mod(-48, y^2 - 2), Mod(-864*y, y^2 - 2),
 Mod(-928, y^2 - 2), Mod(3456/29, y^2 - 2), Vecsmall([5]),
 [[y^2 - 2, [2, 0], 8, 1, [1, -1.41421356237310; 1, 1.41421356237310],
  [16, -23; 16, 23], [2, 0; 0, 4], [4, 0; 0, 2], [2, 0; 0, 1],
  [2, [0, 2; 1, 0]], [2]], [-1.41421356237310, 1.41421356237310],
  [1, y], [1, 0; 0, 1], [1, 0, 0, 2; 0, 1, 1, 0]], [0, 0, 0, 0]]

PARI no longer requires that the $j$-invariant has negative $p$-adic valuation:

sage: E = EllipticCurve(Qp,[1, 1])
sage: E.j_invariant()
2 + 4*5^2 + O(5^3)  # the j-invariant is a p-adic integer
sage: E.pari_curve()
[0, 0, 0, 1, 0, 2, 4, -1, -48, -864, -496, 6912/31, Vecsmall([2]), [0(5^3)],
 --([0, 0])

plot(xmin=None, xmax=None, components='both', **args)
Draw a graph of this elliptic curve.

The plot method is only implemented when there is a natural coercion from the base ring of self to RR. In this case, self is plotted as if it was defined over RR.

INPUT:

• xmin, xmax – (optional) points will be computed at least within this range, but possibly farther.

• components – a string, one of the following:
  – both – (default), scale so that both bounded and unbounded components appear
  – bounded – scale the plot to show the bounded component. Raises an error if there is only one real component.
  – unbounded – scale the plot to show the unbounded component, including the two flex points.

• plot_points – passed to sage.plot.generate_plot_points()

• adaptive_tolerance – passed to sage.plot.generate_plot_points()

• adaptive_recursion – passed to sage.plot.generate_plot_points()

• randomize – passed to sage.plot.generate_plot_points()

• **args – all other options are passed to sage.plot.line.Line

EXAMPLES:

sage: E = EllipticCurve([0,-1])
sage: plot(E, rgbcolor=hue(0.7))
Graphics object consisting of 1 graphics primitive
sage: E = EllipticCurve('37a')
sage: plot(E)
Graphics object consisting of 2 graphics primitives
Elliptic curves, Release 9.7

(continued from previous page)

```python
sage: plot(E, xmin=25, xmax=26)
Graphics object consisting of 2 graphics primitives
```

With trac ticket #12766 we added the components keyword:

```python
sage: E.real_components()
2
sage: E.plot(components='bounded')
Graphics object consisting of 1 graphics primitive
sage: E.plot(components='unbounded')
Graphics object consisting of 1 graphics primitive
```

If there is only one component then specifying components='bounded' raises a ValueError:

```python
sage: E = EllipticCurve('9990be2')

Traceback (most recent call last):
  ... ValueError: no bounded component for this curve
```

An elliptic curve defined over the Complex Field can not be plotted:

```python
sage: E = EllipticCurve(CC, [0,0,1,-1,0])

Traceback (most recent call last):
  ... Not Implemented: plotting of curves over Complex Field with 53 bits of →
precision is not implemented yet
```

**rst_transform** \((r, s, t)\)

Return the transform of the curve by \((r, s, t)\) (with \(u = 1\)).

**INPUT:**

- \(r, s, t\) – three elements of the base ring.

**OUTPUT:**

The elliptic curve obtained from self by the standard Weierstrass transformation \((u, r, s, t)\) with \(u = 1\).

**Note:** This is just a special case of `change_weierstrass_model()`, with \(u = 1\).

**EXAMPLES:**

```python
sage: R.<r,s,t>=QQ[]
sage: E = EllipticCurve([1,2,3,4,5])
sage: E.rst_transform(r,s,t)
Elliptic Curve defined by y^2 + ((2*s+1)*x+y + (r+2*t+3)*y = x^3 + (-s^2+3*r-
→s+2)*x^2 + (3*r^2-r*s-2*s*t+4*r-3*s-t+4)*x + (r^3+2*r^2-r*t-t^2+4*r-3*t+5)␣
→over Multivariate Polynomial Ring in r, s, t over Rational Field
```

**scale_curve** \((u)\)

Return the transform of the curve by scale factor \(u\).

**INPUT:**
• \( u \) – an invertible element of the base ring.

**OUTPUT:**

The elliptic curve obtained from self by the standard Weierstrass transformation \((u, r, s, t)\) with \( r = s = t = 0 \).

**Note:** This is just a special case of \texttt{change_weierstrass_model()}, with \( r = s = t = 0 \).

**EXAMPLES:**

```python
sage: K = Frac(PolynomialRing(QQ, 'u'))
sage: u = K.gen()
sage: E = EllipticCurve([1,2,3,4,5])
sage: E.scale_curve(u)
Elliptic Curve defined by y^2 + u*x*y + 3*u^3*y = x^3 + 2*u^2*x^2 + 4*u^4*x + ...
˓→ 5*u^6 over Fraction Field of Univariate Polynomial Ring in u over Rational Field

short_weierstrass_model\( (\text{complete\_cube=True})\)

Return a short Weierstrass model for self.

**INPUT:**

• \texttt{complete\_cube} – boolean (default: True); for meaning, see below.

**OUTPUT:**

An elliptic curve.

If \texttt{complete\_cube=True}: Return a model of the form \( y^2 = x^3 + a \cdot x + b \) for this curve. The characteristic must not be 2; in characteristic 3, it is only possible if \( b_2 = 0 \).

If \texttt{complete\_cube=False}: Return a model of the form \( y^2 = x^3 + a \cdot x^2 + b \cdot x + c \) for this curve. The characteristic must not be 2.

**EXAMPLES:**

```python
sage: E = EllipticCurve([1,2,3,4,5])
sage: E
Elliptic Curve defined by y^2 + x*y + 3*y = x^3 + 2*x^2 + 4*x + 5 over Rational Field
sage: F = E.short_weierstrass_model()
sage: F
Elliptic Curve defined by y^2 = x^3 + 4941*x + 185166 over Rational Field
sage: E.is_isomorphic(F)
True
sage: F = E.short_weierstrass_model(complete_cube=False)
sage: F
Elliptic Curve defined by y^2 = x^3 + x + 2 over Finite Field of size 3
```

This used to be different see trac ticket \#3973:
More tests in characteristic 3:

```python
sage: E = EllipticCurve(GF(3),[0,2,1,2,1])
```
```
Traceback (most recent call last):
  ... ValueError: short_weierstrass_model(): no short model for Elliptic Curve
defined by y^2 + y = x^3 + 2*x^2 + 2*x + 1 over Finite Field of size 3
(characteristic is 3)
```
```
sage: E.short_weierstrass_model(complete_cube=False)
```
```
Elliptic Curve defined by y^2 = x^3 + 2*x^2 + 2*x + 2 over Finite Field of size 3
```
```
sage: E.short_weierstrass_model(complete_cube=False).is_isomorphic(E)
True
```
```
torsion_polynomial(m, x=None, two_torsion_multiplicity=2, force_evaluate=None)
```

Return the \( m^{th} \) division polynomial of this elliptic curve evaluated at \( x \). The division polynomial is cached if \( x \) is None.

**INPUT:**

- \( m \) – positive integer.
- \( x \) – optional ring element to use as the \( x \) variable. If \( x \) is None (omitted), then a new polynomial ring will be constructed over the base ring of the elliptic curve, and its generator will be used as \( x \). Note that \( x \) does not need to be a generator of a polynomial ring; any ring element works. This permits fast calculation of the torsion polynomial evaluated on any element of a ring.
- `two_torsion_multiplicity` – 0, 1, or 2
  - If 0: For even \( m \) when \( x \) is None, a univariate polynomial over the base ring of the curve is returned, which omits factors whose roots are the \( x \)-coordinates of the 2-torsion points. When \( x \) is not None, the evaluation of such a polynomial at \( x \) is returned.
  - If 2: For even \( m \) when \( x \) is None, a univariate polynomial over the base ring of the curve is returned, which includes a factor of degree 3 whose roots are the \( x \)-coordinates of the 2-torsion points. Similarly, when \( x \) is not None, the evaluation of such a polynomial at \( x \) is returned.
  - If 1: For even \( m \) when \( x \) is None, a bivariate polynomial over the base ring of the curve is returned, which includes a factor \( 2y + a_1 x + a_3 \) having simple zeros at the 2-torsion points. When \( x \) is not None, it should be a tuple of length 2, and the evaluation of such a polynomial at \( x \) is returned.
- `force_evaluate` (optional) – 0, 1, or 2
  - By default, this method makes use of previously cached generic division polynomials to compute the value of the polynomial at a given element \( x \) whenever it appears beneficial to do so. Explicitly setting this flag overrides the default behavior.
  - Note that the complexity of evaluating a generic division polynomial scales much worse than that of computing the value at a point directly (using the recursive formulas), hence setting this flag can be detrimental to performance.
  - If 0: Do not use cached generic division polynomials.
  - If 1: If the generic division polynomial for this \( m \) has been cached before, evaluate it at \( x \) to compute the result.
If 2: Compute the value at $x$ by evaluating the generic division polynomial. If the generic $m$-division polynomial has not yet been cached, compute and cache it first.

**EXAMPLES:**

```python
sage: E = EllipticCurve([0,0,1,-1,0])
sage: E.division_polynomial(1)
1
sage: E.division_polynomial(2, two_torsion_multiplicity=0)
1
sage: E.division_polynomial(2, two_torsion_multiplicity=1)
2*y + 1
sage: E.division_polynomial(2, two_torsion_multiplicity=2)
4*x^3 - 4*x + 1
sage: E.division_polynomial(2)
4*x^3 - 4*x + 1
sage: [E.division_polynomial(3, two_torsion_multiplicity=i) for i in range(3)]
[3*x^4 - 6*x^2 + 3*x - 1, 3*x^4 - 6*x^2 + 3*x - 1, 3*x^4 - 6*x^2 + 3*x - 1]
sage: [type(E.division_polynomial(3, two_torsion_multiplicity=i)) for i in range(3)]
[<... 'sage.rings.polynomial.polynomial_rational_flint.Polynomial_rational_flint',
  '<... 'sage.rings.polynomial.multi_polynomial_libsingular.MPolynomial_libsingular'>,
  '<... 'sage.rings.polynomial.polynomial_rational_flint.Polynomial_rational_flint'>]
```

```python
sage: E = EllipticCurve([0, -1, 1, -10, -20])
sage: R.<z>=PolynomialRing(QQ)
sage: E.division_polynomial(4,z,0)
2*z^6 - 4*z^5 - 100*z^4 - 790*z^3 - 210*z^2 - 1496*z - 5821
sage: E.division_polynomial(4,z)
8*z^9 - 24*z^8 - 464*z^7 - 2758*z^6 + 6636*z^5 + 34356*z^4 + 53510*z^3 +
  99714*z^2 + 351024*z + 459859
```

This does not work, since when two_torsion_multiplicity is 1, we compute a bivariate polynomial, and must evaluate at a tuple of length 2:

```python
sage: E.division_polynomial(4,z,1)
Traceback (most recent call last):
... ValueError: x should be a tuple of length 2 (or None) when two_torsion_multiplicity is 1
```

```python
sage: R.<z,w>=PolynomialRing(QQ,2)
sage: E.division_polynomial(4,(z,w),1).factor()
(2*w + 1) * (2*z^6 - 4*z^5 - 100*z^4 - 790*z^3 - 210*z^2 - 1496*z - 5821)
```

We can also evaluate this bivariate polynomial at a point:

```python
sage: P = E(5,5)
sage: E.division_polynomial(4,P,two_torsion_multiplicity=1)
-1771561
```

**two_division_polynomial** ($x=None$)

Return the 2-division polynomial of this elliptic curve evaluated at $x$. 

---

84 Chapter 4. Elliptic curves over a general ring
INPUT:

• \texttt{x} – optional ring element to use as the \texttt{x} variable. If \texttt{x} is \texttt{None}, then a new polynomial ring will be constructed over the base ring of the elliptic curve, and its generator will be used as \texttt{x}. Note that \texttt{x} does not need to be a generator of a polynomial ring; any ring element is acceptable. This permits fast calculation of the torsion polynomial \textit{evaluated} on any element of a ring.

EXAMPLES:

```python
sage: E = EllipticCurve('5077a1')
sage: E.two_division_polynomial()
4*x^3 - 28*x + 25
sage: E = EllipticCurve(GF(3^2,'a'),[1,1,1,1,1])
sage: E.two_division_polynomial()
x^3 + 2*x^2 + 2
sage: E.two_division_polynomial().roots()
[(2, 1), (2*a, 1), (a + 2, 1)]
```

\texttt{sage.schemes.elliptic_curves.ell_generic.is_EllipticCurve}(\texttt{x})

Utility function to test if \texttt{x} is an instance of an Elliptic Curve class.

EXAMPLES:

```python
sage: from sage.schemes.elliptic_curves.ell_generic import is_EllipticCurve
sage: E = EllipticCurve([1,2,3/4,7,19])
sage: is_EllipticCurve(E)
True
sage: is_EllipticCurve(0)
False
```
This module defines the class `EllipticCurve_field`, based on `EllipticCurve_generic`, for elliptic curves over general fields.

```python
class sage.schemes.elliptic_curves.ell_field.EllipticCurve_field(K, ainvs)
curves.projective_curve.ProjectivePlaneCurve_field

base_field()
    Return the base ring of the elliptic curve.

EXAMPLES:

```
sage: E = EllipticCurve(GF(49, 'a'), [3,5])
sage: E.base_ring()
Finite Field in a of size 7^2
```

```
sage: E = EllipticCurve([1,1])
sage: E.base_ring()
Rational Field
```

```
sage: E = EllipticCurve(ZZ, [3,5])
sage: E.base_ring()
Integer Ring
```

descend_to(K, f=None)
    Given an elliptic curve self defined over a field \( L \) and a subfield \( K \) of \( L \), return all elliptic curves over \( K \) which are isomorphic over \( L \) to self.

INPUT:

- \( K \) – a field which embeds into the base field \( L \) of self.
- \( f \) (optional) – an embedding of \( K \) into \( L \). Ignored if \( K \) is \( \mathbb{Q} \).

OUTPUT:

A list (possibly empty) of elliptic curves defined over \( K \) which are isomorphic to self over \( L \), up to isomorphism over \( K \).

Note: Currently only implemented over number fields. To extend to other fields of characteristic not 2 or 3, what is needed is a method giving the preimages in \( K^*/(K^*)^m \) of an element of the base field, for \( m = 2, 4, 6 \).

EXAMPLES:
Elliptic curves, Release 9.7

```
sage: E = EllipticCurve([1,2,3,4,5])
sage: E.descend_to(ZZ)
Traceback (most recent call last):
  ...TypeError: Input must be a field.
```

```
sage: F.<b> = QuadraticField(23)
sage: G.<a> = F.extension(x^3+5)
sage: E = EllipticCurve(j=1728*b).change_ring(G)
sage: EF = E.descend_to(F); EF
[Elliptic Curve defined by y^2 = x^3 + (27*b-621)*x + (-1296*b+2484) over
 →Number Field in b with defining polynomial x^2 - 23 with b = 4.
 →795831523312720?]
sage: all(Ei.change_ring(G).is_isomorphic(E) for Ei in EF)
True
```

```
sage: L.<a> = NumberField(x^4 - 7)
sage: K.<b> = NumberField(x^2 - 7, embedding=a^2)
sage: E = EllipticCurve([a^6,0])
sage: EK = E.descend_to(K); EK
[Elliptic Curve defined by y^2 = x^3 + b*x over Number Field in b with defining polynomial x^2 - 7 with b = a^2,
 Elliptic Curve defined by y^2 = x^3 + 7*b*x over Number Field in b with defining polynomial x^2 - 7 with b = a^2]
sage: all(Ei.change_ring(L).is_isomorphic(E) for Ei in EK)
True
```

```
sage: K.<a> = QuadraticField(17)
sage: E = EllipticCurve(j = 2*a)
sage: E.E.descend_to(QQ)
[]
```

`division_field(l, names='t', map=False, **kwds)`

Given an elliptic curve over a number field or finite field \( F \) and a prime number \( \ell \), construct the \( \ell \)-division field \( F(E[\ell]) \).

The \( \ell \)-division field is the smallest extension of \( F \) over which all \( \ell \)-torsion points of \( E \) are defined.

**INPUT:**
- \( \ell \) – a prime number (an element of \( \mathbb{Z} \))
- names – (default: 't') a variable name for the division field
- map – (default: False) also return an embedding of the base_field() into the resulting field
- kwds – additional keyword arguments passed to splitting_field()

**OUTPUT:**
- If map is False, the division field \( K \) as an absolute number field or a finite field. If map is True, a tuple \((K, \phi)\) where \( \phi \) is an embedding of the base field in the division field \( K \).

**Warning:** This can take a very long time when the degree of the division field is large (e.g. when \( \ell \) is large or when the Galois representation is surjective). The simplify flag also has a big influence
on the running time over number fields: sometimes simplify=False is faster, sometimes the default simplify=True is faster.

EXAMPLES:
The 2-division field is the same as the splitting field of the 2-division polynomial (therefore, it has degree 1, 2, 3 or 6):

```
sage: E = EllipticCurve('15a1')
sage: K.<b> = E.division_field(2); K
Number Field in b with defining polynomial x
```
```
sage: E = EllipticCurve('14a1')
sage: K.<b> = E.division_field(2); K
Number Field in b with defining polynomial x^2 + 5*x + 92
```
```
sage: E = EllipticCurve('196b1')
sage: K.<b> = E.division_field(2); K
Number Field in b with defining polynomial x^3 + x^2 - 114*x - 127
```
```
sage: E = EllipticCurve('19a1')
sage: K.<b> = E.division_field(2); K
Number Field in b with defining polynomial x^6 + 10*x^5 + 24*x^4 - 212*x^3 + 1364*x^2 + 24072*x + 104292
```

For odd primes \( \ell \), the division field is either the splitting field of the \( \ell \)-division polynomial, or a quadratic extension of it.

```
sage: E = EllipticCurve('50a1')
sage: F.<a> = E.division_polynomial(3).splitting_field(simplify_all=True); F
Number Field in a with defining polynomial x^6 - 3*x^5 + 4*x^4 - 3*x^3 - 2*x^2 + 3*x + 3
```
```
sage: K.<b> = E.division_field(3, simplify_all=True); K
Number Field in b with defining polynomial x^12 - 3*x^11 + 8*x^10 - 15*x^9 + 30*x^8 - 63*x^7 + 109*x^6 - 144*x^5 + 150*x^4 - 120*x^3 + 68*x^2 - 24*x + 4
```

If we take any quadratic twist, the splitting field of the 3-division polynomial remains the same, but the 3-division field becomes a quadratic extension:

```
sage: E = E.quadratic_twist(5) # 50b3
sage: F.<a> = E.division_polynomial(3).splitting_field(simplify_all=True); F
Number Field in a with defining polynomial x^6 - 3*x^5 + 4*x^4 - 3*x^3 - 2*x^2 + 3*x + 3
```
```
sage: K.<b> = E.division_field(3, simplify_all=True); K
Number Field in b with defining polynomial x^12 - 3*x^11 + 8*x^10 - 15*x^9 + 30*x^8 - 63*x^7 + 109*x^6 - 144*x^5 + 150*x^4 - 120*x^3 + 68*x^2 - 24*x + 4
```

Try another quadratic twist, this time over a subfield of \( F \):

```
sage: G.<c>,_,_ = F.subfields(3)[0]
sage: E = E.base_extend(G).quadratic_twist(c); E
Elliptic Curve defined by y^2 = x^3 + 5*a0*x^2 + (-200*a0^2)*x + (-42000*a0^2+2+42000*a0+126000) over Number Field in a0 with defining polynomial x^3 - 3*x^2 + 3*x + 9
```
```
sage: K.<b> = E.division_field(3, simplify_all=True); K
Number Field in b with defining polynomial x^12 - 10*x^10 + 55*x^8 - 60*x^6 + 75*x^4 + 1350*x^2 + 2025
```
Some higher-degree examples:

```
sage: E = EllipticCurve('11a1')
sage: K.<b> = E.division_field(2); K
Number Field in b with defining polynomial x^6 + 2*x^5 - 48*x^4 - 436*x^3 + 1668*x^2 + 28792*x + 73844
sage: K.<b> = E.division_field(3); K  # long time (3s on sage.math, 2014)
Number Field in b with defining polynomial x^48 ...
sage: K.<b> = E.division_field(5); K
Number Field in b with defining polynomial x^4 - x^3 + x^2 - x + 1
sage: E.division_field(5, 'b', simplify=False)
Number Field in b with defining polynomial x^4 + x^3 + 11*x^2 + 41*x + 101
sage: E.base_extend(K).torsion_subgroup()  # long time (2s on sage.math, 2014)
Torsion Subgroup isomorphic to Z/5 + Z/5 associated to the Elliptic Curve defined by y^2 + y = x^3 + (-1)*x^2 + (-10)*x + (-20) over Number Field in b with defining polynomial x^4 - x^3 + x^2 - x + 1
```

Over a number field:

```
sage: R.<x> = PolynomialRing(QQ)
sage: K.<i> = NumberField(x^2 + 1)
sage: E = EllipticCurve([0,0,0,0,i])
sage: L.<b> = E.division_field(2); L
Number Field in b with defining polynomial x^4 - x^2 + 1
sage: L.<b>, phi = E.division_field(3, map=True);
Ring morphism:
From: Number Field in i with defining polynomial x^2 + 1
To:   Number Field in b with defining polynomial x^4 - x^2 + 1
Defn: i |--> -b^3
sage: L.<b>, phi = E.division_field(3, map=True)
sage: L
Number Field in b with defining polynomial x^24 - 6*x^22 - 12*x^21 - 21*x^20 + 216*x^19 + 48*x^18 + 804*x^17 + 1194*x^16 - 13488*x^15 + 21222*x^14 + 44196*x^13 - 47977*x^12 - 10288*x^11 + 173424*x^10 - 172308*x^9 + 302046*x^8 + 252864*x^7 - 931182*x^6 + 180300*x^5 + 879567*x^4 - 415896*x^3 + 1941012*x^2 + 650220*x + 443089
sage: phi
Ring morphism:
From: Number Field in i with defining polynomial x^2 + 1
To:   Number Field in b with defining polynomial x^24 ...
Defn: i |--> -215621657062634529/183360797284413355040732*b^23 ...
```
Over a finite field:

```python
sage: E = EllipticCurve(GF(431^2), [1,0])
sage: E.division_field(5, map=True)
(Finite Field in t of size 431^4,
 Ring morphism:
   From: Finite Field in z2 of size 431^2
   To:  Finite Field in t of size 431^4
   Defn: z2 |--> 52*t^3 + 222*t^2 + 78*t + 105)
```

```python
sage: E = EllipticCurve(GF(433^2), [1,0])
sage: K.<v> = E.division_field(7); K
Finite Field in v of size 433^16
```

AUTHORS:
- Jeroen Demeyer (2014-01-06): trac ticket #11905, use splitting_field method, moved from gal_reps.py, make it work over number fields.
- Lorenz Panny (2022): extend to finite fields

**genus**

Return 1 for elliptic curves.

EXAMPLES:

```python
sage: E = EllipticCurve(GF(3), [0, -1, 0, -346, 2652])
sage: E.genus()
1
```

```python
sage: R = FractionField(QQ['z'])
sage: E = EllipticCurve(R, [0, -1, 0, -346, 2652])
sage: E.genus()
1
```

**hasse_invariant**

Return the Hasse invariant of this elliptic curve.

OUTPUT:

The Hasse invariant of this elliptic curve, as an element of the base field. This is only defined over fields of positive characteristic, and is an element of the field which is zero if and only if the curve is supersingular. Over a field of characteristic zero, where the Hasse invariant is undefined, a `ValueError` is returned.

EXAMPLES:

```python
sage: E = EllipticCurve([Mod(1,2),Mod(1,2),0,0,Mod(1,2)])
sage: E.hasse_invariant()
1
```

```python
sage: E = EllipticCurve([0,0,Mod(1,3),Mod(1,3),Mod(1,3)])
sage: E.hasse_invariant()
0
```

```python
sage: E = EllipticCurve([0,0,Mod(1,5),0,Mod(2,5)])
sage: E.hasse_invariant()
0
```

```python
sage: E = EllipticCurve([0,0,Mod(1,5),Mod(1,5),Mod(2,5)])
```

Elliptic curves, Release 9.7

Some examples over larger fields:

```python
sage: E.hasse_invariant()
2

sage: EllipticCurve(GF(101),[0,0,0,0,1]).hasse_invariant()
0
sage: EllipticCurve(GF(101),[0,0,0,1,1]).hasse_invariant()
98
sage: EllipticCurve(GF(103),[0,0,0,0,1]).hasse_invariant()
20
sage: EllipticCurve(GF(103),[0,0,0,1,1]).hasse_invariant()
17
sage: F.<a> = GF(107^2)

sage: EllipticCurve(F,[0,0,0,a,1]).hasse_invariant()
62*a + 75
sage: EllipticCurve(F,[0,0,0,0,a]).hasse_invariant()
0
```

Over fields of characteristic zero, the Hasse invariant is undefined:

```python
sage: E = EllipticCurve([0,0,0,0,1])
sage: E.hasse_invariant()
Traceback (most recent call last):
  ...
ValueError: Hasse invariant only defined in positive characteristic
```

is_isogenous(other, field=None)

Return whether or not self is isogenous to other.

INPUT:

- `other` – another elliptic curve.

- `field` (default None) – Currently not implemented. A field containing the base fields of the two elliptic curves onto which the two curves may be extended to test if they are isogenous over this field. By default is_isogenous will not try to find this field unless one of the curves can be be extended into the base field of the other, in which case it will test over the larger base field.

OUTPUT:

(bool) True if there is an isogeny from curve self to curve other defined over field.

METHOD:

Over general fields this is only implemented in trivial cases.

EXAMPLES:

```python
sage: E1 = EllipticCurve(CC, [1,18]); E1
Elliptic Curve defined by y^2 = x^3 + 1.00000000000000*x + 18.0000000000000_...
˓
over Complex Field with 53 bits of precision
sage: E2 = EllipticCurve(CC, [2,7]); E2
Elliptic Curve defined by y^2 = x^3 + 2.00000000000000*x + 7.00000000000000...
˓
over Complex Field with 53 bits of precision
sage: E1.is_isogenous(E2)
```
Traceback (most recent call last):
...
NotImplementedError: Only implemented for isomorphic curves over general fields.

```
sage: E1 = EllipticCurve(Frac(PolynomialRing(ZZ,'t')), [2,19]); E1
Elliptic Curve defined by y^2 = x^3 + 2*x + 19 over Fraction Field of
\text{Univariate Polynomial Ring in } t \text{ over Integer Ring}
```

```
sage: E2 = EllipticCurve(CC, [23,4]); E2
Elliptic Curve defined by y^2 = x^3 + 23.00000000000000*x + 4.00000000000000
\text{over Complex Field with 53 bits of precision}
```

```
sage: E1.is_isogenous(E2)
Traceback (most recent call last):
...
NotImplementedError: Only implemented for isomorphic curves over general fields.
```

**is_quadratic_twist**(other)

Determine whether this curve is a quadratic twist of another.

**INPUT:**

- `other` – an elliptic curves with the same base field as self.

**OUTPUT:**

Either 0, if the curves are not quadratic twists, or $D$ if `other` is `self.quadratic_twist(D)` (up to isomorphism). If `self` and `other` are isomorphic, returns 1.

If the curves are defined over $\mathbb{Q}$, the output $D$ is a squarefree integer.

**Note:** Not fully implemented in characteristic 2, or in characteristic 3 when both $j$-invariants are 0.

**EXAMPLES:**

```
sage: E = EllipticCurve('11a1')
sage: Et = E.quadratic_twist(-24)
sage: E.is_quadratic_twist(Et)
-6
```

```
sage: E1=EllipticCurve([0,0,1,0,0])
sage: E1.j_invariant()
0
```

```
sage: E2=EllipticCurve([0,0,0,2])
sage: E1.is_quadratic_twist(E2)
2
```

```
sage: E1.is_quadratic_twist(E1)
1
```

```
sage: type(E1.is_quadratic_twist(E1)) == type(E1.is_quadratic_twist(E2))
#trac 6574
True
```

```
sage: E1=EllipticCurve([0,0,0,1,0])
sage: E1.j_invariant()
1728
```
A characteristic 3 example:

```
sage: F = GF(3^5,'a')
sage: E1 = EllipticCurve_from_j(F(1))
sage: E2 = E1.quadratic_twist(-1)
sage: D = E1.is_quadratic_twist(E2); D!=0
    True
sage: E1.quadratic_twist(D).is_isomorphic(E2)
    True
```

**is_quartic_twist**(*other*)

Determine whether this curve is a quartic twist of another.

**INPUT:**

- *other* – an elliptic curves with the same base field as self.

**OUTPUT:**

Either 0, if the curves are not quartic twists, or *D* if others is self.quartic_twist(*D*) (up to isomorphism). If self and other are isomorphic, returns 1.
Note: Not fully implemented in characteristics 2 or 3.

EXAMPLES:

```sage
e = EllipticCurve_from_j(GF(13)(1728))
e1 = e.quartic_twist(2)
d = e.is_quartic_twist(e1); d!=0
True
e.quartic_twist(d).is_isomorphic(e1)
True
```

```sage
e = EllipticCurve_from_j(1728)
e1 = e.quartic_twist(12345)
d = e.is_quartic_twist(e1); d
15999120
e1 = (d/12345).is_perfect_power(4)
True
```

**is_sextic_twist**(other)

Determine whether this curve is a sextic twist of another.

**INPUT:**

- **other** – an elliptic curves with the same base field as self.

**OUTPUT:**

Either 0, if the curves are not sextic twists, or $D$ if other is self.sextic_twist($D$) (up to isomorphism). If self and other are isomorphic, returns 1.

**Note:** Not fully implemented in characteristics 2 or 3.

**EXAMPLES:**

```sage
e = EllipticCurve_from_j(GF(13)(0))
e1 = e.sextic_twist(2)
d = e.is_sextic_twist(e1); d!=0
True
e.sextic_twist(d).is_isomorphic(e1)
True
```

```sage
e = EllipticCurve_from_j(0)
e1 = e.sextic_twist(12345)
d = e.is_sextic_twist(e1); d
575968320
e1 = (d/12345).is_perfect_power(6)
True
```

**isogenies_prime_degree**(l=None, max_l=31)

Return a list of all separable isogenies of given prime degree(s) with domain equal to self, which are defined over the base field of self.

**INPUT:**
• a prime or a list of primes.
• max_l – (default: 31) a bound on the primes to be tested. This is only used if \( l \) is None.

OUTPUT:

(list) All separable \( l \)-isogenies for the given \( l \) with domain self.

ALGORITHM:

Calls the generic function \texttt{isogenies_prime_degree()}. This is generic code, valid for all fields. It requires that certain operations have been implemented over the base field, such as root-finding for univariate polynomials.

EXAMPLES:

Examples over finite fields:

```python
sage: E = EllipticCurve(GF(next_prime(1000000)), [7,8])
sage: E.isogenies_prime_degree(2)
[Isogeny of degree 2 from Elliptic Curve defined by y^2 = x^3 + 7*x + 8 over \( \mathbb{F}_{1000003} \) to Elliptic Curve defined by y^2 = x^3 + 970389*x + 794257 over \( \mathbb{F}_{1000003} \),
Isogeny of degree 2 from Elliptic Curve defined by y^2 = x^3 + 7*x + 8 over \( \mathbb{F}_{1000003} \) to Elliptic Curve defined by y^2 = x^3 + 29783*x + 206196 over \( \mathbb{F}_{1000003} \),
Isogeny of degree 2 from Elliptic Curve defined by y^2 = x^3 + 7*x + 8 over \( \mathbb{F}_{1000003} \) to Elliptic Curve defined by y^2 = x^3 + 999960*x + 78 over \( \mathbb{F}_{1000003} \)]
sage: E.isogenies_prime_degree(3)
[]
sage: E.isogenies_prime_degree(5)
[]
sage: E.isogenies_prime_degree(7)
[]
sage: E.isogenies_prime_degree(11)
[]
sage: E.isogenies_prime_degree(13)
[Isogeny of degree 13 from Elliptic Curve defined by y^2 = x^3 + 7*x + 8 over \( \mathbb{F}_{1000003} \) to Elliptic Curve defined by y^2 = x^3 + 878063*x + 845666 over \( \mathbb{F}_{1000003} \),
Isogeny of degree 13 from Elliptic Curve defined by y^2 = x^3 + 7*x + 8 over \( \mathbb{F}_{1000003} \) to Elliptic Curve defined by y^2 = x^3 + 375648*x + 342776 over \( \mathbb{F}_{1000003} \)]
sage: E.isogenies_prime_degree(max_l=13)
[Isogeny of degree 2 from Elliptic Curve defined by y^2 = x^3 + 7*x + 8 over \( \mathbb{F}_{1000003} \) to Elliptic Curve defined by y^2 = x^3 + 970389*x + 794257 over \( \mathbb{F}_{1000003} \),
Isogeny of degree 2 from Elliptic Curve defined by y^2 = x^3 + 7*x + 8 over \( \mathbb{F}_{1000003} \) to Elliptic Curve defined by y^2 = x^3 + 29783*x + 206196 over \( \mathbb{F}_{1000003} \),
Isogeny of degree 2 from Elliptic Curve defined by y^2 = x^3 + 7*x + 8 over \( \mathbb{F}_{1000003} \) to Elliptic Curve defined by y^2 = x^3 + 999960*x + 78 over \( \mathbb{F}_{1000003} \),
Isogeny of degree 13 from Elliptic Curve defined by y^2 = x^3 + 7*x + 8 over \( \mathbb{F}_{1000003} \) to Elliptic Curve defined by y^2 = x^3 + 878063*x + 845666 over \( \mathbb{F}_{1000003} \),
Isogeny of degree 13 from Elliptic Curve defined by y^2 = x^3 + 7*x + 8 over \( \mathbb{F}_{1000003} \) to Elliptic Curve defined by y^2 = x^3 + 375648*x + 342776 over \( \mathbb{F}_{1000003} \) ]
```
(continues on next page)
Isogeny of degree 13 from Elliptic Curve defined by $y^2 = x^3 + 7x + 8$ over Finite Field of size 1000003 to Elliptic Curve defined by $y^2 = x^3 + 375648x + 342776$ over Finite Field of size 1000003.

Isogeny of degree 13 from Elliptic Curve defined by $y^2 = x^3 + 7x + 8$ over Finite Field of size 1000003 to Elliptic Curve defined by $y^2 = x^3 + 878063x + 845666$ over Finite Field of size 1000003.

Isogeny of degree 13 from Elliptic Curve defined by $y^2 = x^3 + 7x + 8$ over Finite Field of size 1000003 to Elliptic Curve defined by $y^2 = x^3 + 375648x + 342776$ over Finite Field of size 1000003.

Isogeny of degree 17 from Elliptic Curve defined by $y^2 = x^3 + 7x + 8$ over Finite Field of size 1000003 to Elliptic Curve defined by $y^2 = x^3 + 347438x + 594729$ over Finite Field of size 1000003.

Isogeny of degree 17 from Elliptic Curve defined by $y^2 = x^3 + 7x + 8$ over Finite Field of size 1000003 to Elliptic Curve defined by $y^2 = x^3 + 674846x + 7392$ over Finite Field of size 1000003.

Isogeny of degree 23 from Elliptic Curve defined by $y^2 = x^3 + 7x + 8$ over Finite Field of size 1000003 to Elliptic Curve defined by $y^2 = x^3 + 390065x + 605596$ over Finite Field of size 1000003.

The base field matters, over a field extension we find more isogenies:

```python
sage: E = EllipticCurve(GF(13), [2,8])
sage: E.isogenies_prime_degree(max_l=3)
[Isogeny of degree 2 from Elliptic Curve defined by $y^2 = x^3 + 2x + 8$ over Finite Field of size 13 to Elliptic Curve defined by $y^2 = x^3 + 7x + 4$ over Finite Field of size 13,
  Field of size 17 to Elliptic Curve defined by $y^2 = x^3 + 9x$ over Finite Field of size 13,
  Field of size 17,
  Isogeny of degree 2 from Elliptic Curve defined by $y^2 = x^3 + 2x + 8$ over Finite Field of size 13,
  Field of size 17 to Elliptic Curve defined by $y^2 = x^3 + 5x + 9$ over Finite Field of size 13,
  Field of size 17,
  Isogeny of degree 2 from Elliptic Curve defined by $y^2 = x^3 + 2x + 8$ over Finite Field of size 13,
  Field of size 17 to Elliptic Curve defined by $y^2 = x^3 + 5x + 8$ over Finite Field of size 17,
  Field of size 17]
```

(continues on next page)
sage: E = EllipticCurve(GF(13^6), [2,8])

sage: E.isogenies_prime_degree(max_l=3)

[Isogeny of degree 2 from Elliptic Curve defined by y^2 = x^3 + 2*x + 8 over Finite Field in z6 of size 13^6 to Elliptic Curve defined by y^2 = x^3 + 7*x over Finite Field in z6 of size 13^6,
Isogeny of degree 2 from Elliptic Curve defined by y^2 = x^3 + 2*x + 8 over Finite Field in z6 of size 13^6 to Elliptic Curve defined by y^2 = x^3 + 2*z6^5+6*z6^4+4*z6^3+5*z6+9)*x + (10*z6^5+4*z6^4+6*z6^3+z6+10) over Finite Field in z6 of size 13^6,
Isogeny of degree 2 from Elliptic Curve defined by y^2 = x^3 + 2*x + 8 over Finite Field in z6 of size 13^6 to Elliptic Curve defined by y^2 = x^3 + 2*z6^5+6*z6^4+4*z6^3+5*z6+9)*x + (10*z6^5+4*z6^4+6*z6^3+z6+10) over Finite Field in z6 of size 13^6,
Isogeny of degree 2 from Elliptic Curve defined by y^2 = x^3 + 2*x + 8 over Finite Field in z6 of size 13^6 to Elliptic Curve defined by y^2 = x^3 + 2*z6^5+6*z6^4+4*z6^3+5*z6+9)*x + (10*z6^5+4*z6^4+6*z6^3+z6+10) over Finite Field in z6 of size 13^6,
Isogeny of degree 2 from Elliptic Curve defined by y^2 = x^3 + 2*x + 8 over Finite Field in z6 of size 13^6 to Elliptic Curve defined by y^2 = x^3 + 2*z6^5+6*z6^4+4*z6^3+5*z6+9)*x + (10*z6^5+4*z6^4+6*z6^3+z6+10) over Finite Field in z6 of size 13^6,
Isogeny of degree 2 from Elliptic Curve defined by y^2 = x^3 + 2*x + 8 over Finite Field in z6 of size 13^6 to Elliptic Curve defined by y^2 = x^3 + 2*z6^5+6*z6^4+4*z6^3+5*z6+9)*x + (10*z6^5+4*z6^4+6*z6^3+z6+10) over Finite Field in z6 of size 13^6,
Isogeny of degree 2 from Elliptic Curve defined by y^2 = x^3 + 2*x + 8 over Finite Field in z6 of size 13^6 to Elliptic Curve defined by y^2 = x^3 + 2*z6^5+6*z6^4+4*z6^3+5*z6+9)*x + (10*z6^5+4*z6^4+6*z6^3+z6+10) over Finite Field in z6 of size 13^6,
Isogeny of degree 2 from Elliptic Curve defined by y^2 = x^3 + 2*x + 8 over Finite Field in z6 of size 13^6 to Elliptic Curve defined by y^2 = x^3 + 2*z6^5+6*z6^4+4*z6^3+5*z6+9)*x + (10*z6^5+4*z6^4+6*z6^3+z6+10) over Finite Field in z6 of size 13^6]

If the degree equals the characteristic, we find only separable isogenies:

sage: E = EllipticCurve(GF(13), [2,8])

sage: E.isogenies_prime_degree(13)

[Isogeny of degree 13 from Elliptic Curve defined by y^2 = x^3 + 2*x + 8 over Finite Field of size 13 to Elliptic Curve defined by y^2 = x^3 + 6*x + 5 over Finite Field of size 13]

sage: E = EllipticCurve(GF(5), [1,1])

sage: E.isogenies_prime_degree(5)

[Isogeny of degree 5 from Elliptic Curve defined by y^2 = x^3 + x + 1 over Finite Field of size 5 to Elliptic Curve defined by y^2 = x^3 + x + 4 over Finite Field of size 5]

sage: k.<a> = GF(3^4)

sage: E = EllipticCurve(k, [0,1,0,0,a])

sage: E.isogenies_prime_degree(3)

[Isogeny of degree 3 from Elliptic Curve defined by y^2 = x^3 + x^2 + a over Finite Field in a of size 3^4 to Elliptic Curve defined by y^2 = x^3 + x^2 + over Finite Field in a of size 3^4]

In the supersingular case, there are no separable isogenies of degree equal to the characteristic:

sage: E = EllipticCurve(GF(5), [0,1])

sage: E.isogenies_prime_degree(5)

[]
Examples over a rational function field:

```
sage: R.<t> = GF(5)[]
sage: K = R.fraction_field()
sage: E = EllipticCurve(K, [1, t^5])
sage: E.isogenies_prime_degree(5)
[Isogeny of degree 5 from Elliptic Curve defined by y^2 = x^3 + x + t^5 over \(\text{Fraction Field of Univariate Polynomial Ring in t over Finite Field of size 5}\) to Elliptic Curve defined by y^2 = x^3 + x + 4*t over Fraction Field of Univariate Polynomial Ring in t over Finite Field of size 5]
```

Examples over number fields (other than QQ):

```
sage: QQroot2.<e> = NumberField(x^2-2)
sage: E = EllipticCurve(QQroot2, j=8000)
sage: E.isogenies_prime_degree()

[Isogeny of degree 2 from Elliptic Curve defined by y^2 = x^3 + (-150528000)*x + (-629407744000) over Number Field in e with defining polynomial x^2 - 2 to Elliptic Curve defined by y^2 = x^3 + (-36750)*x + 2401000 over Number Field in e with defining polynomial x^2 - 2, Isogeny of degree 2 from Elliptic Curve defined by y^2 = x^3 + (-150528000)*x + (-629407744000) over Number Field in e with defining polynomial x^2 - 2 to Elliptic Curve defined by y^2 = x^3 + (220500*e-257250)*x + (54022500*e-88837000) over Number Field in e with defining polynomial x^2 - 2, Isogeny of degree 2 from Elliptic Curve defined by y^2 = x^3 + (-150528000)*x + (-629407744000) over Number Field in e with defining polynomial x^2 - 2 to Elliptic Curve defined by y^2 = x^3 + (-220500*e-257250)*x + (-54022500*e-88837000) over Number Field in e with defining polynomial x^2 - 2]\n```

These are not implemented yet:

```
sage: E = EllipticCurve(QQbar, [1,18]); E
Elliptic Curve defined by y^2 = x^3 + x + 18 over Algebraic Field
sage: E.isogenies_prime_degree()
Traceback (most recent call last):
```

(continues on next page)
isogeny\( (\text{kernel}, \text{codomain}=\text{None}, \text{degree}=\text{None}, \text{model}=\text{None}, \text{check}=\text{True}, \text{algorithm}=\text{None}) \)

Return an elliptic-curve isogeny from this elliptic curve.

The isogeny can be specified in two ways, by passing either a polynomial or a set of torsion points. The methods used are:

- Vélu’s Formulas: Vélu’s original formulas for computing isogenies. This algorithm is selected by giving as the \( \text{kernel} \) parameter a single point, or a list of points, generating a finite subgroup.

- Kohel’s Formulas: Kohel’s original formulas for computing isogenies. This algorithm is selected by giving as the \( \text{kernel} \) parameter a monic polynomial (or a coefficient list in little endian) which will define the kernel of the isogeny. Kohel’s algorithm is currently only implemented for cyclic isogenies, with the exception of \([2]\).

- √élu Algorithm (see \texttt{hom_velusqrt}): A variant of Vélu’s formulas with essentially square-root instead of linear complexity (in the degree). Currently only available over finite fields. The input must be a single kernel point of odd order \( \geq 5 \). This algorithm is selected using \texttt{algorithm=“velusqrt”}.

- Factored Isogenies (experimental — see \texttt{hom_composite}): Given a list of points which generate a composite-order subgroup, decomposes the isogeny into prime-degree steps. This can be used to construct isogenies of extremely large, smooth degree. This algorithm is selected using \texttt{algorithm=“factored”}.

INPUT:

- \( \text{kernel} \) – a kernel: either a point on this curve, a list of points on this curve, a monic kernel polynomial, or \texttt{None}. If initializing from a codomain, this must be \texttt{None}.

- \( \text{codomain} \) – an elliptic curve (default: \texttt{None}).
  - If \( \text{kernel} \) is \texttt{None}, then \( \text{degree} \) must be given as well and the given \( \text{codomain} \) must be the codomain of a cyclic, separable, normalized isogeny of the given degree.
  - If \( \text{kernel} \) is not \texttt{None}, then this must be isomorphic to the codomain of the separable isogeny defined by \( \text{kernel} \); in this case, the isogeny is post-composed with an isomorphism so that the codomain equals the given curve.

- \( \text{degree} \) – an integer (default: \texttt{None}).
  - If \( \text{kernel} \) is \texttt{None}, then this is the degree of the isogeny from this curve to \( \text{codomain} \).
  - If \( \text{kernel} \) is not \texttt{None}, then this is used to determine whether or not to skip a \texttt{gcd} of the given kernel polynomial with the two-torsion polynomial of this curve.

- \( \text{model} \) – a string (default: \texttt{None}). Supported values (cf. \texttt{compute_model()}):
  - "minimal": If \texttt{self} is a curve over the rationals or over a number field, then the codomain is a global minimal model where this exists.
- "short_weierstrass": The codomain is a short Weierstrass curve, assuming one exists.
- "montgomery": The codomain is an (untwisted) Montgomery curve, assuming one exists over this field.

- **check** (default: True) – check whether the input is valid. Setting this to False can lead to significant speedups.

- **algorithm** – string (optional). By default (when algorithm is omitted), the “traditional” implementation `EllipticCurveIsogeny` is used. The other choices are:
  - "velusqrt": Use `EllipticCurveHom_velusqrt`.
  - "factored": Use `EllipticCurveHom_composite` to decompose the isogeny into prime-degree steps.

   The degree parameter is not supported when an algorithm is specified.

**OUTPUT:**

An isogeny between elliptic curves. This is a morphism of curves. (In all cases, the returned object will be an instance of `EllipticCurveHom`.)

**EXAMPLES:**

```sage
sage: F = GF(2^5, 'alpha'); alpha = F.gen()
sage: E = EllipticCurve(F, [1,0,1,1,1])
sage: R.<x> = F[]
sage: phi = E.isogeny(x+1)
sage: phi.rational_maps()
((x^2 + x + 1)/(x + 1), (x^2*y + x)/(x^2 + 1))
```

```sage
sage: E = EllipticCurve('11a1')
sage: P = E.torsion_points()[1]
sage: E.isogeny(P)
Isogeny of degree 5 from Elliptic Curve defined by y^2 + y = x^3 - x^2 - 10*x - 20 over Rational Field to Elliptic Curve defined by y^2 + y = x^3 - x^2 - 7820*x - 263580 over Rational Field
```

```sage
sage: E = EllipticCurve(GF(19),[1,1])
sage: P = E(15,3); Q = E(2,12);
sage: (P.order(), Q.order())
(7, 3)
sage: phi = E.isogeny([P,Q]); phi
Isogeny of degree 21 from Elliptic Curve defined by y^2 + y = x^3 + x + 1 over Finite Field of size 19 to Elliptic Curve defined by y^2 = x^3 + x + 1 over Finite Field of size 19
sage: phi(E.random_point()) # all points defined over GF(19) are in the kernel (0 : 1 : 0)
```

```sage
sage: E = EllipticCurve(GF(2^32-5), [170246996, 2036646110])
sage: P = E.lift_x(2)
sage: E.isogeny(P, algorithm="factored") # experimental
doctest:warning
...
Composite morphism of degree 1073721825 = 3^4*5^2*11*19*43*59:
(continues on next page)
```
From: Elliptic Curve defined by $y^2 = x^3 + 170246996x + 2036646110$ over Finite Field of size 4294967291
To: Elliptic Curve defined by $y^2 = x^3 + 272790262x + 1903695400$ over Finite Field of size 4294967291

Not all polynomials define a finite subgroup (trac ticket #6384):

```python
sage: E = EllipticCurve(GF(31),[1,0,0,1,2])
sage: phi = E.isogeny([14,27,4,1])
Traceback (most recent call last):
  ...  
ValueError: the polynomial $x^3 + 4x^2 + 27x + 14$ does not define a finite subgroup of Elliptic Curve defined by $y^2 + x*y = x^3 + x + 2$ over Finite Field of size 31
```

See also:

- `EllipticCurveHom`
- `EllipticCurveIsogeny`
- `EllipticCurveHom_composite`

**isogeny_codomain**(*kernel, degree=None*)

Return the codomain of the isogeny from `self` with given kernel.

**INPUT:**

- `kernel` – Either a list of points in the kernel of the isogeny, or a kernel polynomial (specified as either a univariate polynomial or a coefficient list.)

**OUTPUT:**

An elliptic curve, the codomain of the separable normalized isogeny defined by this kernel.

**EXAMPLES:**

```python
sage: E = EllipticCurve('17a1')
sage: R.<x> = QQ[]
sage: E2 = E.isogeny_codomain(x - 11/4); E2
Elliptic Curve defined by $y^2 + x*y + y = x^3 - x^2 - 1461/16*x - 19681/64$ over Rational Field
```

**isogeny_ell_graph**(*l, directed=True, label_by_j=False*)

Return a graph representing the 1-degree K-isogenies between K-isomorphism classes of elliptic curves for $K = self.base_field()$.

**INPUT:**

- `l` – prime degree of isogenies
- `directed` – boolean (default: True); whether to return a directed or undirected graph. In the undirected case, the in-degrees and out-degrees of the vertices must be balanced and therefore the number of out-edges from the vertices corresponding to j-invariants 0 and 1728 (if they are part of the graph) are reduced to match the number of in-edges.
- `label_by_j` – boolean (default: False); whether to label graph vertices by the j-invariant corresponding to the isomorphism class of curves. If the j-invariant is not unique in the isogeny class, append * to it to indicate a twist. Otherwise, if False label vertices by the equation of a representative curve.
OUTPUT:

A Graph or Digraph

EXAMPLES:

Ordinary curve over finite extension field of degree 2:

```
sage: E = EllipticCurve(GF(59^2, "i", x^2 + 1), j=5)
sage: G = E.isogeny_ell_graph(5, directed=False, label_by_j=True)
sage: G
Graph on 20 vertices
sage: G.vertices(sort=True)
["1",
 '12',
...
 'i + 55']
sage: G.edges(sort=True)
[('1', '28*i + 11', None),
 ('1', '31*i + 11', None),
...
 ('8', 'i + 1', None)]
```

Supersingular curve over prime field:

```
sage: E = EllipticCurve(GF(419), j=1728)
sage: G3 = E.isogeny_ell_graph(3, directed=False, label_by_j=True)
sage: G3
Graph on 27 vertices
sage: G3.vertices(sort=True)
['0*,
 '13*,
...
 '98*']
sage: G3.edges(sort=True)
[('0*', '0*', None),
 ('0*', '13', None),
...
 ('48*', '98*', None)]
sage: G5 = E.isogeny_ell_graph(5, directed=False, label_by_j=True)
sage: G5
Graph on 9 vertices
sage: G5.vertices(sort=True)
['13',
 '13*',
 '407',
 '407*',
 '52',
 '62',
 '62*',
 '98',
 '98*']
sage: G5.edges(sort=True)
[('13', '52', None),
 ('13', '98', None),
...
 ('62*', '98*', None)]
```

Supersingular curve over finite extension field of degree 2:

```
sage: K = GF(431^2, "i", x^2 + 1)
sage: E = EllipticCurve(K, j=0)
sage: E.is_supersingular()
```

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True
sage: G = E.isogeny_ell_graph(2, directed=True, label_by_j=True)
sage: G
Looped multi-digraph on 37 vertices
sage: G.vertices(sort=True)
['0', '102', ...
'87*i + 190']
sage: G.edges(sort=True)
[(0, 0, None), (0, 0, None), ...
(81*i + 65, 87*i + 190, None)]

sage: H = E.isogeny_ell_graph(2, directed=False, label_by_j=True)
sage: H
Looped multi-graph on 37 vertices
sage: H.vertices(sort=True)
['0', '102', ...
'87*i + 190']
sage: H.edges(sort=True)
[(0, 0, None), (102, 125, None), ...
(81*i + 65, 87*i + 190, None)]

Curve over a quadratic number field:

sage: K.<e> = NumberField(x^2 - 2)
sage: E = EllipticCurve(K, [1,0,1,4, -6])
sage: G2 = E.isogeny_ell_graph(2, directed=False)
sage: G2.vertices(sort=True)
['y^2 + x*y + y = x^3 + (-130*e-356)*x + (-2000*e-2038)',
'y^2 + x*y + y = x^3 + (-36)*x + (-70)',
'y^2 + x*y + y = x^3 + (130*e-356)*x + (2000*e-2038)',
'y^2 + x*y + y = x^3 + 4*x + (-6)']
sage: G2.edges(sort=True)
[(y^2 + x*y + y = x^3 + (-130*e-356)*x + (-2000*e-2038), 0, None),
(y^2 + x*y + y = x^3 + (-36)*x + (-70), None),
(y^2 + x*y + y = x^3 + (130*e-356)*x + (2000*e-2038), None),
(y^2 + x*y + y = x^3 + 4*x + (-6), None)]

sage: G3 = E.isogeny_ell_graph(3, directed=False)
sage: G3.vertices(sort=True)
['y^2 + x*y + y = x^3 + (171)*x + (-874)',
'y^2 + x*y + y = x^3 + 4*x + (-6)']
sage: G3.edges(sort=True)
[(y^2 + x*y + y = x^3 + (171)*x + (-874), 0, None),
(y^2 + x*y + y = x^3 + 4*x + (-6), None)]
quadratic_twist($D=\text{None}$)
Return the quadratic twist of this curve by $D$.

INPUT:

- $D$ (default None) the twisting parameter (see below).

In characteristics other than 2, $D$ must be nonzero, and the twist is isomorphic to self after adjoining $\sqrt{D}$ to the base.

In characteristic 2, $D$ is arbitrary, and the twist is isomorphic to self after adjoining a root of $x^2 + x + D$ to the base.

In characteristic 2 when $j = 0$, this is not implemented.

If the base field $F$ is finite, $D$ need not be specified, and the curve returned is the unique curve (up to isomorphism) defined over $F$ isomorphic to the original curve over the quadratic extension of $F$ but not over $F$ itself. Over infinite fields, an error is raised if $D$ is not given.

EXAMPLES:

```
sage: E = EllipticCurve([GF(1103)(1), 0, 0, 107, 340]); E
Elliptic Curve defined by $y^2 + x*y = x^3 + 107*x + 340$ over Finite Field of size 1103
sage: F=E.quadratic_twist(-1); F
Elliptic Curve defined by $y^2 = x^3 + 1102*x^2 + 609*x + 300$ over Finite Field of size 1103
sage: E.is_isomorphic(F)
False
sage: E.is_isomorphic(F,GF(1103^2,'a'))
True
```

A characteristic 2 example:

```
sage: E=EllipticCurve(GF(2),[1,0,1,1,1])
sage: E1=E.quadratic_twist(1)
sage: E.is_isomorphic(E1)
False
sage: E.is_isomorphic(E1,GF(4,'a'))
True
```

Over finite fields, the twisting parameter may be omitted:

```
sage: k.<a> = GF(2^10)
sage: E = EllipticCurve(k,[a^2,a,1,a+1,1])
sage: Et = E.quadratic_twist()
sage: Et # random (only determined up to isomorphism)
Elliptic Curve defined by $y^2 + x*y = x^3 + (a^7+a^4+a^3+a^2+a+1)*x^2 + (a^8+a^6+6+a^4+1)$ over Finite Field in a of size 2^10
sage: E.is_isomorphic(Et)
False
sage: E.j_invariant()==Et.j_invariant()
```

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Elliptic curves, Release 9.7

True

sage: p=next_prime(10^10)
sage: k = GF(p)
sage: E = EllipticCurve(k,[1,2,3,4,5])
sage: Et = E.quadratic_twist()

sage: Et
# random (only determined up to isomorphism)
Elliptic Curve defined by y^2 = x^3 + 7860088097*x^2 + 9495240877*x + →3048660957 over Finite Field of size 10000000019

sage: E.is_isomorphic(Et)
False
sage: k2 = GF(p^2, 'a')
sage: E.change_ring(k2).is_isomorphic(Et.change_ring(k2))
True

quartic_twist(D)
Return the quartic twist of this curve by $D$.

INPUT:

• $D$ (must be nonzero) – the twisting parameter.

Note: The characteristic must not be 2 or 3, and the $j$-invariant must be 1728.

EXAMPLES:

sage: E=EllipticCurve_from_j(GF(13)(1728)); E
Elliptic Curve defined by $y^2 = x^3 + x$ over Finite Field of size 13

sage: E1=E.quartic_twist(2); E1
Elliptic Curve defined by $y^2 = x^3 + 5*x$ over Finite Field of size 13

sage: E.is_isomorphic(E1)
False
sage: E.is_isomorphic(E1,GF(13^2, 'a'))
False
sage: E.is_isomorphic(E1,GF(13^4, 'a'))
True

sextic_twist(D)
Return the quartic twist of this curve by $D$.

INPUT:

• $D$ (must be nonzero) – the twisting parameter.

Note: The characteristic must not be 2 or 3, and the $j$-invariant must be 0.

EXAMPLES:

sage: E=EllipticCurve_from_j(GF(13)(0)); E
Elliptic Curve defined by $y^2 = x^3 + 1$ over Finite Field of size 13

sage: E1=E.sextic_twist(2); E1
Elliptic Curve defined by $y^2 = x^3 + 11$ over Finite Field of size 13

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sage: E.is_isomorphic(E1)
False
sage: E.is_isomorphic(E1,GF(13^2,'a'))
False
sage: E.is_isomorphic(E1,GF(13^4,'a'))
False
sage: E.is_isomorphic(E1,GF(13^6,'a'))
True

**two_torsion_rank()**

Return the dimension of the 2-torsion subgroup of $E(K)$.

This will be 0, 1 or 2.

**EXAMPLES:**

```python
sage: E=EllipticCurve('11a1')
sage: E.two_torsion_rank()
0
sage: K.<alpha>=QQ.extension(E.division_polynomial(2).monic())
sage: E.base_extend(K).two_torsion_rank()
1
sage: E_reduction(53).two_torsion_rank()
2
sage: E = EllipticCurve('14a1')
sage: E.two_torsion_rank()
1
sage: K.<alpha>=QQ.extension(E.division_polynomial(2).monic().factor()[1][0])
sage: E.base_extend(K).two_torsion_rank()
2
sage: EllipticCurve('15a1').two_torsion_rank()
2
```

**weierstrass_p**(prec=20, algorithm=None)

Compute the Weierstrass $\wp$-function of this elliptic curve.

**ALGORITHM:** `$sage.schemes.elliptic_curves.ell_wp.weierstrass_p()`

**INPUT:**

- prec – precision
- algorithm – string or None (default: None): a choice of algorithm among "pari", "fast", "quadratic"; or None to let this function determine the best algorithm to use.

**OUTPUT:**

a Laurent series in one variable $z$ with coefficients in the base field $k$ of $E$.

**EXAMPLES:**

```python
sage: E = EllipticCurve('11a1')
sage: E.weierstrass_p(prec=10)
z^-2 + 31/15*z^2 + 2501/756*z^4 + 961/675*z^6 + 77531/41580*z^8 + O(z^10)
```
sage: E.weierstrass_p(prec=8)
z^-2 + 31/15*z^2 + 2501/756*z^4 + 961/675*z^6 + O(z^8)
sage: E shorthand = E.short_weierstrass_model()
sage: E shorthand .weierstrass_p(prec=8)
z^-2 + 13392/5*z^2 + 1080432/7*z^4 + 59781888/25*z^6 + O(z^8)
sage: E .weierstrass_p(prec=20, algorithm='fast')
z^-2 + 31/15*z^2 + 2501/756*z^4 + 961/675*z^6 + 77531/41580*z^8 + 1202285717/928746000*z^10 + 2403461/2806650*z^12 + 3539374016033/7723451736000*z^16 + 128954060235000000*z^18 + O(z^20)
sage: E .weierstrass_p(prec=20, algorithm='pari')
z^-2 + 31/15*z^2 + 2501/756*z^4 + 961/675*z^6 + 77531/41580*z^8 + 1202285717/928746000*z^10 + 2403461/2806650*z^12 + 3539374016033/7723451736000*z^16 + 128954060235000000*z^18 + O(z^20)
sage: E .weierstrass_p(prec=20, algorithm='quadratic')
z^-2 + 31/15*z^2 + 2501/756*z^4 + 961/675*z^6 + 77531/41580*z^8 + 1202285717/928746000*z^10 + 2403461/2806650*z^12 + 3539374016033/7723451736000*z^16 + 128954060235000000*z^18 + O(z^20)

sage.schemes.elliptic_curves.ell_field.compute_model(E, name)

Return a model of an elliptic curve E of the type specified in the name parameter.

Used as a helper function in EllipticCurveIsogeny.

INPUT:

• E (elliptic curve)
• name (string) – current options:
  • "minimal": Return a global minimal model of E if it exists, and a semi-global minimal model otherwise. For this choice, E must be defined over a number field. See global_minimal_model().
  • "short_weierstrass": Return a short Weierstrass model of E assuming one exists. See short_weierstrass_model().
  • "montgomery": Return an (untwisted) Montgomery model of E assuming one exists over this field. See montgomery_model().

OUTPUT:

An elliptic curve of the specified type isomorphic to E.

EXAMPLES:

sage: from sage.schemes.elliptic_curves.ell_field import compute_model
sage: E = EllipticCurve([[12/7, 405/49, 0, -81/8, 135/64]])
sage: compute_model(E, 'minimal')
Elliptic Curve defined by y^2 = x^3 - x^2 - 7*x + 10 over Rational Field
sage: compute_model(E, 'short_weierstrass')
Elliptic Curve defined by y^2 = x^3 - 48114*x + 4035015 over Rational Field
sage: compute_model(E, 'montgomery')
Elliptic Curve defined by y^2 = x^3 + 5*x^2 + x over Rational Field
ELLIPTIC CURVES OVER FINITE FIELDS

AUTHORS:

- William Stein (2005): Initial version
- Robert Bradshaw et al....
- John Cremona (2008-02): Point counting and group structure for non-prime fields, Frobenius endomorphism and order, elliptic logs
- Mariah Lenox (2011-03): Added set_order method

class sage.schemes.elliptic_curves.ell_finite_field.EllipticCurve_finite_field(K, ainvs)
Bases: sage.schemes.elliptic_curves.ell_field.EllipticCurve_field, sage.schemes.hyperelliptic_curves.hyperelliptic_finite_field.HyperellipticCurve_finite_field

Elliptic curve over a finite field.

EXAMPLES:

```
sage: EllipticCurve(GF(101),[2,3])
Elliptic Curve defined by y^2 = x^3 + 2*x + 3 over Finite Field of size 101
sage: F = GF(101^2, 'a')
sage: EllipticCurve([F(2),F(3)])
Elliptic Curve defined by y^2 = x^3 + 2*x + 3 over Finite Field in a of size 101^2
```

Elliptic curves over $\mathbb{Z}/N\mathbb{Z}$ with $N$ prime are of type “elliptic curve over a finite field”:

```
sage: F = Zmod(101)
sage: EllipticCurve(F, [2, 3])
Elliptic Curve defined by y^2 = x^3 + 2*x + 3 over Ring of integers modulo 101
sage: E = EllipticCurve([F(2), F(3)])
sage: type(E)
<class 'sage.schemes.elliptic_curves.ell_finite_field.EllipticCurve_finite_field_˓
→with_category'>
sage: E.category()
Category of schemes over Ring of integers modulo 101
```

Elliptic curves over $\mathbb{Z}/N\mathbb{Z}$ with $N$ composite are of type “generic elliptic curve”:

```
sage: F = Zmod(95)
sage: EllipticCurve(F, [2, 3])
Elliptic Curve defined by y^2 = x^3 + 2*x + 3 over Ring of integers modulo 95
sage: E = EllipticCurve([F(2), F(3)])
```

(continues on next page)
abelfel_group()

Return the abelian group structure of the group of points on this elliptic curve.

See also:

If you do not need the complete abelian group structure but only generators of the group, use \texttt{gens()} which can be much faster in some cases.

This method relies on \texttt{gens()}, which uses random points on the curve and hence the generators are likely to differ from one run to another. However, the group is cached, so the generators will not change in any one run of Sage.

OUTPUT:

- an \texttt{AdditiveAbelianGroupWrapper} object encapsulating the abelian group of rational points on this elliptic curve

ALGORITHM:

We first call \texttt{gens()} to obtain a generating set \((P, Q)\). Letting \(P\) denote the point of larger order \(n_1\), we extend \(P\) to a basis \((P, Q')\) by computing a scalar \(x\) such that \(Q' = Q - [x]P\) has order \(n_2 = #E/n_1\). Finding \(x\) involves a (typically easy) discrete-logarithm computation.

The complexity of the algorithm is the cost of factoring the group order, plus \(\Theta(\sqrt{\ell})\) for each prime \(\ell\) such that the rational \(\ell\)-torsion of \texttt{self} is isomorphic to \(\mathbb{Z}/\ell^r \times \mathbb{Z}/\ell^s\) with \(r > s > 0\), times a polynomial in the logarithm of the base-field size.

AUTHORS:

- John Cremona: original implementation
- Lorenz Panny (2021): current implementation

EXAMPLES:

\begin{verbatim}
sage: E = EllipticCurve(GF(11),[2,5])
sage: E.abelian_group()
Additive abelian group isomorphic to Z/10 embedded in Abelian group of points on Elliptic Curve defined by y^2 = x^3 + 2*x + 5 over Finite Field of size 11

sage: E = EllipticCurve(GF(41),[2,5])
sage: E.abelian_group()
Additive abelian group isomorphic to Z/22 + Z/2 ...

sage: F.<a> = GF(3^6,'a')
sage: E = EllipticCurve([a^4 + a^3 + 2*a^2 + 2*a, 2*a^5 + 2*a^3 + 2*a^2 + 1])
sage: E.abelian_group()
Additive abelian group isomorphic to Z/26 + Z/26 ...
\end{verbatim}
The group can be trivial:

```python
sage: E = EllipticCurve(GF(2),[0,0,1,1,1])
sage: E.abelian_group()
Trivial group embedded in Abelian group of points on Elliptic Curve defined by
˓→y^2 + y = x^3 + x + 1 over Finite Field of size 2
```

Of course, there are plenty of points if we extend the field:

```python
sage: E.cardinality(extension_degree=100)
1267650600228231653296516890625
```

This tests the patch for trac ticket #3111, using 10 primes randomly selected:

```python
sage: E = EllipticCurve('389a4')
sage: for p in [5927, 2297, 1571, 1709, 3851, 127, 3253, 5783, 3499, 4817]:
    ....: G = E.change_ring(GF(p)).abelian_group()
```

This tests that the bug reported in trac ticket #3926 has been fixed:

```python
sage: K.<i> = QuadraticField(-1)
sage: OK = K.ring_of_integers()
sage: P=K.factor(10007)[0][0]
sage: OKmodP = OK.residue_field(P)
sage: E = EllipticCurve([0,0,0,i,i+3])
sage: Emod = E.change_ring(OKmodP); Emod
Elliptic Curve defined by y^2 = x^3 + ibar*x + (ibar+3) over Residue field in...
禳ibar of Fractional ideal (10007)
sage: Emod.abelian_group()  #random generators
(Multiplicative Abelian group isomorphic to C50067594 x C2, ((3152*ibar + 7679 : 7330*ibar + 7913 : 1), (8466*ibar + 1770 : 0 : 1)))
```

cardinality(algorithm=None, extension_degree=1)
Return the number of points on this elliptic curve.

INPUT:

- algorithm -- (optional) string:
  - 'pari' -- use the PARI C-library function ellcard.
  - 'bsgs' -- use the baby-step giant-step method as implemented in Sage, with the Cremona-Sutherland version of Mestre’s trick.
  - 'exhaustive' -- naive point counting.
  - 'subfield' -- reduce to a smaller field, provided that the j-invariant lies in a subfield.
  - 'all' -- compute cardinality with both 'pari' and 'bsgs'; return result if they agree or raise a AssertionError if they do not
• extension_degree – an integer \( d \) (default: 1): if the base field is \( \mathbb{F}_q \), return the cardinality of \( \text{self} \) over the extension \( \mathbb{F}_{q^d} \) of degree \( d \).

**OUTPUT:**
The order of the group of rational points of \( \text{self} \) over its base field, or over an extension field of degree \( d \) as above. The result is cached.

**EXAMPLES:**

```python
sage: EllipticCurve(GF(4,'a'), [1,2,3,4,5]).cardinality()
8
sage: k.<a> = GF(3^3)
sage: l = [a^2 + 1, 2*a^2 + 2*a + 1, a^2 + a + 1, 2, 2*a]
sage: EllipticCurve(k,l).cardinality()
29

sage: l = [1, 1, 0, 2, 0]
sage: EllipticCurve(k,l).cardinality()
38
```

An even bigger extension (which we check against Magma):

```python
sage: EllipticCurve(GF(3^100,'a'), [1,2,3,4,5]).cardinality()
51537752073201133103645963969645888996929981504
sage: magma.eval("Order(EllipticCurve([GF(3^100)|1,2,3,4,5]))") # optional - magma
'm51537752073201133103645963969645888996929981504'
```

```python
sage: EllipticCurve(GF(10007), [1,2,3,4,5]).cardinality()
10076
sage: EllipticCurve(GF(10007), [1,2,3,4,5]).cardinality(algorithm='pari')
10076
sage: EllipticCurve(GF(next_prime(10**20)), [1,2,3,4,5]).cardinality()
100000000011093199520
```

The cardinality is cached:

```python
sage: E = EllipticCurve(GF(3^100,'a'), [1,2,3,4,5])
sage: E.cardinality() is E.cardinality()
True
```

The following is very fast since the curve is actually defined over the prime field:

```python
sage: k.<a> = GF(11^100)
sage: E1 = EllipticCurve(k, [3,3])
sage: N1 = E1.cardinality(algorithm="subfield"); N1
13786123398222701841183371720896367762643312000384671846835266941791510341065565176497846502745362304472492176
sage: E1.cardinality_pari() == N1
True
sage: E2 = E1.quadratic_twist()
sage: N2 = E2.cardinality(algorithm="subfield"); N2
13786123398222701841183371720896367762643312000384656816094284101308193849980588062304472492176
sage: E2.cardinality_pari() == N2
True
```

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We can count points over curves defined as a reduction:

```sage
x = polygen(QQ)
sage: K.<w> = NumberField(x^2 + x + 1)
sage: EK = EllipticCurve(K, [0, 0, w, 2, 1])
sage: E = EK.base_extend(K.residue_field(2))
sage: E
Elliptic Curve defined by y^2 + wbar*y = x^3 + 1 over Residue field in wbar of
   Fractional ideal (2)
sage: E.cardinality()
7
sage: E = EK.base_extend(K.residue_field(w - 1))
sage: E.abelian_group()
Trivial group embedded in Abelian group of points on Elliptic Curve defined by
   y^2 + y = x^3 + 2*x + 1 over Residue field of Fractional ideal (w - 1)
sage: R.<x> = GF(17)[x]
sage: pol = R.irreducible_element(5)
sage: k.<a> = R.residue_field(pol)
sage: E = EllipticCurve(R, [1, x]).base_extend(k)
sage: E
Elliptic Curve defined by y^2 = x^3 + x + a over Residue field in a of
   Principal ideal (x^5 + x + 14) of Univariate Polynomial Ring in x over Finite
   Field of size 17
sage: E.cardinality()
1421004
```

`cardinality_bsgs(\texttt{verbose=False})`

Return the cardinality of self over the base field.

**ALGORITHM:** A variant of “Mestre’s trick” extended to all finite fields by Cremona and Sutherland, 2008.

**Note:**

1. The Mestre-Schoof-Cremona-Sutherland algorithm may fail for a small finite number of curves over \( \mathbb{F}_q \) for \( q \) at most 49, so for \( q < 50 \) we use an exhaustive count.

2. Quadratic twists are not implemented in characteristic 2 when \( j = 0 (= 1728) \); but this case is treated separately.

**EXAMPLES:**

```sage
p = next_prime(10^3)
sage: E = EllipticCurve(GF(p), [3, 4])
sage: E.cardinality_bsgs()
1020
sage: E = EllipticCurve(GF(3^4, 'a'), [1, 1])
sage: E.cardinality_bsgs()
64
sage: F.<a> = GF(101^3, 'a')
```

(continues on next page)
sage: E=EllipticCurve([2*a^2 + 48*a + 27, 89*a^2 + 76*a + 24])
sage: E.cardinality_bsgs()
1031352

cardinality_exhaustive()
Return the cardinality of self over the base field. Simply adds up the number of points with each x-coordinate: only used for small field sizes!

EXAMPLES:

```
sage: p = next_prime(10^3)
sage: E = EllipticCurve(GF(p),[3,4])
sage: E.cardinality_exhaustive()
1020
sage: E = EllipticCurve(GF(3^4,'a'),[1,1])
sage: E.cardinality_exhaustive()
64
```

cardinality_pari()
Return the cardinality of self using PARI.

This uses pari:ellcard.

EXAMPLES:

```
sage: p = next_prime(10^3)
sage: E = EllipticCurve(GF(p),[3,4])
sage: E.cardinality_pari()
1020
sage: K = GF(next_prime(10^6))
sage: E = EllipticCurve(K,[1,0,0,1,1])
sage: E.cardinality_pari()
999945
```

Since trac ticket #16931, this now works over finite fields which are not prime fields:

```
sage: k.<a> = GF(7^3)
sage: E = EllipticCurve_from_j(a)
sage: E.cardinality_pari()
318
sage: K.<a> = GF(3^20)
sage: E = EllipticCurve(K,[1,0,0,1,a])
sage: E.cardinality_pari()
3486794310
```

count_points(n=1)
Return the cardinality of this elliptic curve over the base field or extensions.

INPUT:

- n (int) – a positive integer

OUTPUT:

If n = 1, returns the cardinality of the curve over its base field.
If \( n > 1 \), returns a list \([c_1, c_2, ..., c_n]\) where \( c_d \) is the cardinality of the curve over the extension of degree \( d \) of its base field.

**EXAMPLES:**

```
sage: p = 101
sage: F = GF(p)
sage: E = EllipticCurve(F, [2,3])
sage: E.count_points(1)
96
sage: E.count_points(5)
[96, 10368, 1031904, 104053248, 10509895776]
sage: F.<a> = GF(p^2)
sage: E = EllipticCurve(F, [a,a])
sage: E.cardinality()
10295
sage: E.count_points()
10295
sage: E.count_points(1)
10295
sage: E.count_points(5)
[10295, 104072155, 1061518108880, 10828567126268595, 110462212555439192375]
```

**frobenius()**

Return the frobenius of self as an element of a quadratic order.

**Note:** This computes the curve cardinality, which may be time-consuming.

Frobenius is only determined up to conjugacy.

**EXAMPLES:**

```
sage: E = EllipticCurve(GF(11),[3,3])
sage: E.frobenius()
phi
sage: E.frobenius().minpoly()
x^2 - 4*x + 11
```

For some supersingular curves, Frobenius is in \( \mathbb{Z} \):

```
sage: E = EllipticCurve(GF(25,'a'),[0,0,0,0,1])
sage: E.frobenius()
-5
```

**frobenius_order()**

Return the quadratic order \( \mathbb{Z}[\phi] \) where \( \phi \) is the Frobenius endomorphism of the elliptic curve.

**Note:** This computes the curve cardinality, which may be time-consuming.

**EXAMPLES:**
Elliptic curves, Release 9.7

```
sage: E = EllipticCurve(GF(11),[3,3])
sage: E.frobenius_order()
Order in Number Field in phi with defining polynomial x^2 - 4*x + 11
```

For some supersingular curves, Frobenius is in \(\mathbb{Z}\) and the Frobenius order is \(\mathbb{Z}\):

```
sage: E = EllipticCurve(GF(25,'a'),[0,0,0,0,1])
sage: R = E.frobenius_order()
sage: R
Order in Number Field in phi with defining polynomial x + 5
sage: R.degree()
1
```

```
\textbf{frobenius\_polynomial()}
\textmd{Return the characteristic polynomial of Frobenius.}

The Frobenius endomorphism of the elliptic curve has quadratic characteristic polynomial. In most cases
this is irreducible and defines an imaginary quadratic order; for some supersingular curves, Frobenius is an
integer \(a\) and the polynomial is \((x - a)^2\).

\textbf{Note}: This computes the curve cardinality, which may be time-consuming.
```

\textbf{EXAMPLES:}

```
sage: E = EllipticCurve(GF(11),[3,3])
sage: E.frobenius_polynomial()
x^2 - 4*x + 11
```

For some supersingular curves, Frobenius is in \(\mathbb{Z}\) and the polynomial is a square:

```
sage: E = EllipticCurve(GF(25,'a'),[0,0,0,0,1])
sage: E.frobenius_polynomial().factor()
(x + 5)^2
```

gens()
\textmd{Return points which generate the abelian group of points on this elliptic curve.}

The algorithm involves factoring the group order of \texttt{self}, but is otherwise (randomized) polynomial-time.
(The points returned by this function are not guaranteed to be the same each time, although they should remain fixed within a single run of Sage unless \texttt{abelian\_group()} is called.)

\textbf{OUTPUT}: a tuple of points on the curve.
- if the group is trivial: an empty tuple.
- if the group is cyclic: a tuple with 1 point, a generator.
- if the group is not cyclic: a tuple with 2 points, where the order of the first point equals the exponent
  of the group.

\textbf{Warning}: In the case of 2 generators \(P\) and \(Q\), it is not guaranteed that the group is the cartesian
product of the 2 cyclic groups \(<P>\) and \(<Q>\). In other words, the order of \(Q\) is not as small as possible. If you really need a basis (rather than just a generating set) of the group, use \texttt{abelian\_group()}. 

116 Chapter 6. Elliptic curves over finite fields
EXAMPLES:

```python
sage: E = EllipticCurve(GF(11),[2,5])
sage: P = E.gens()[0]; P # random
(0 : 7 : 1)
sage: E.cardinality(), P.order()
(10, 10)
sage: E = EllipticCurve(GF(41),[2,5])
sage: E.gens() # random
((20 : 38 : 1), (25 : 31 : 1))
sage: E.cardinality()
44
```

If the abelian group has been computed, return those generators instead:

```python
sage: E.abelian_group()
Additive abelian group isomorphic to Z/22 + Z/2 embedded in Abelian group of points on Elliptic Curve defined by y^2 = x^3 + 2*x + 5 over Finite Field of size 41
sage: ab_gens = E.abelian_group().gens()
sage: ab_gens == E.gens()
True
sage: E.gens()[0].order()
22
sage: E.gens()[1].order()
2
```

Examples with 1 and 0 generators:

```python
sage: F.<a> = GF(3^6)
sage: E = EllipticCurve([a, a+1])
sage: pts = E.gens()
sage: len(pts)
1
sage: pts[0].order() == E.cardinality()
True
sage: E = EllipticCurve(GF(2), [0,0,1,1,1])
sage: E.gens()
()
```

This works over larger finite fields where `abelian_group()` may be too expensive:

```python
sage: k.<a> = GF(5^60)
sage: E = EllipticCurve([a, a])
sage: len(E.gens())
2
sage: E.cardinality()
867361737988403547206134229616487867594472
sage: a = E.gens()[0].order(); a # random
433680868994201773603067114808243933797236
sage: b = E.gens()[1].order(); b # random
30977204928157269543076222486303138128374
sage: lcm(a,b)
433680868994201773603067114808243933797236
```
**is_isogenous**(*other*, *field=None*, *proof=True*)

Return whether or not self is isogenous to other.

**INPUT:**

- **other** – another elliptic curve.
- **field** (default None) – a field containing the base fields of the two elliptic curves into which the two curves may be extended to test if they are isogenous over this field. By default is_isogenous will not try to find this field unless one of the curves can be extended into the base field of the other, in which case it will test over the larger base field.
- **proof** (default True) – this parameter is here only to be consistent with versions for other types of elliptic curves.

**OUTPUT:**

(bool) True if there is an isogeny from curve self to curve other defined over field.

**EXAMPLES:**

```python
sage: E1 = EllipticCurve(GF(11^2,'a'),[2,7]); E1
Elliptic Curve defined by y^2 = x^3 + 2*x + 7 over Finite Field in a of size 11^2
sage: E1.is_isogenous(5)
Traceback (most recent call last):
  ... ValueError: Second argument is not an Elliptic Curve.

sage: E1.is_isogenous(E1)
True
sage: E2 = EllipticCurve(GF(7^3,'b'),[3,1]); E2
Elliptic Curve defined by y^2 = x^3 + 3*x + 1 over Finite Field in b of size 7^3
sage: E1.is_isogenous(E2)
Traceback (most recent call last):
  ... ValueError: The base fields must have the same characteristic.

sage: E3 = EllipticCurve(GF(11^2,'c'),[4,3]); E3
Elliptic Curve defined by y^2 = x^3 + 4*x + 3 over Finite Field in c of size 11^2
sage: E1.is_isogenous(E3)
False
sage: E4 = EllipticCurve(GF(11^6,'d'),[6,5]); E4
Elliptic Curve defined by y^2 = x^3 + 6*x + 5 over Finite Field in d of size 11^6
sage: E1.is_isogenous(E4)
True
sage: E5 = EllipticCurve(GF(11^7,'e'),[4,2]); E5
Elliptic Curve defined by y^2 = x^3 + 4*x + 2 over Finite Field in e of size 11^7
sage: E1.is_isogenous(E5)
Traceback (most recent call last):
  ... ValueError: Curves have different base fields: use the field parameter.
```
When the field is given:

```sage
E1 = EllipticCurve(GF(13^2,'a'),[2,7]); E1
Elliptic Curve defined by y^2 = x^3 + 2*x + 7 over Finite Field in a of size 13^2
sage: E1.is_isogenous(5,GF(13^6,'f'))
Traceback (most recent call last): ... ValueError: Second argument is not an Elliptic Curve.
sage: E6 = EllipticCurve(GF(11^3,'g'),[9,3]); E6
Elliptic Curve defined by y^2 = x^3 + 9*x + 3 over Finite Field in g of size 11^3
sage: E1.is_isogenous(E6,QQ)
Traceback (most recent call last): ... ValueError: The base fields must have the same characteristic.
sage: E7 = EllipticCurve(GF(13^5,'h'),[2,9]); E7
Elliptic Curve defined by y^2 = x^3 + 2*x + 9 over Finite Field in h of size 13^5
sage: E1.is_isogenous(E7,GF(13^4,'i'))
Traceback (most recent call last): ... ValueError: Field must be an extension of the base fields of both curves
sage: E1.is_isogenous(E7,GF(13^10,'j'))
False
sage: E1.is_isogenous(E7,GF(13^30,'j'))
False
```

**is_ordinary**(proof=True)

Return True if this elliptic curve is ordinary, else False.

**INPUT:**

- **proof** (boolean, default True) – If True, returns a proved result. If False, then a return value of True is certain but a return value of False may be based on a probabilistic test. See the documentation of the function `is_j_supersingular()` for more details.

**EXAMPLES:**

```sage
sage: F = GF(101)
sage: EllipticCurve(j=F(0)).is_ordinary()
False
sage: EllipticCurve(j=F(1728)).is_ordinary()
True
sage: EllipticCurve(j=F(66)).is_ordinary()
False
sage: EllipticCurve(j=F(99)).is_ordinary()
True
```

**is_supersingular**(proof=True)

Return True if this elliptic curve is supersingular, else False.

**INPUT:**

- **proof** (boolean, default True) – If True, returns a proved result. If False, then a return value of False is certain but a return value of True may be based on a probabilistic test. See the documentation of the function `is_j_supersingular()` for more details.

**EXAMPLES:**

```sage
sage: F = GF(101)
sage: EllipticCurve(j=F(0)).is_supersingular()
True
sage: EllipticCurve(j=F(1728)).is_supersingular()
False
sage: EllipticCurve(j=F(66)).is_supersingular()
True
sage: EllipticCurve(j=F(99)).is_supersingular()
False
```

**order**(algorithm=None, extension_degree=1)

Return the number of points on this elliptic curve.

**INPUT:**
• algorithm – (optional) string:
  – 'pari' – use the PARI C-library function ellcard.
  – 'bsgs' – use the baby-step giant-step method as implemented in Sage, with the Cremona-Sutherland version of Mestre’s trick.
  – 'exhaustive' – naive point counting.
  – 'subfield' – reduce to a smaller field, provided that the j-invariant lies in a subfield.
  – 'all' – compute cardinality with both 'pari' and 'bsgs'; return result if they agree or raise a AssertionError if they do not

• extension_degree – an integer \(d\) (default: 1): if the base field is \(\mathbb{F}_q\), return the cardinality of \(\text{self}\) over the extension \(\mathbb{F}_{q^d}\) of degree \(d\).

OUTPUT:
The order of the group of rational points of \(\text{self}\) over its base field, or over an extension field of degree \(d\) as above. The result is cached.

EXAMPLES:

```python
sage: EllipticCurve(GF(4, 'a'), [1,2,3,4,5]).cardinality()
8
sage: k.<a> = GF(3^3)
sage: l = [a^2 + 1, 2*a^2 + 2*a + 1, a^2 + a + 1, 2, 2*a]
sage: EllipticCurve(k,l).cardinality()
29

sage: l = [1, 1, 0, 2, 0]
sage: EllipticCurve(k, l).cardinality()
38
```

An even bigger extension (which we check against Magma):

```python
sage: EllipticCurve(GF(3^100, 'a'), [1,2,3,4,5]).cardinality()
515377520732011331036459693969645888996929981504
sage: magma.eval("Order(EllipticCurve([GF(3^100)|1,2,3,4,5]))")  # optional ~
'm515377520732011331036459693969645888996929981504'
```

```python
sage: EllipticCurve(GF(10007), [1,2,3,4,5]).cardinality()
10076
sage: EllipticCurve(GF(10007), [1,2,3,4,5]).cardinality(algorithm='pari')
10076
sage: EllipticCurve(GF(next_prime(10**20)), [1,2,3,4,5]).cardinality()
100000000000011093199520
```

The cardinality is cached:

```python
sage: E = EllipticCurve(GF(3^100, 'a'), [1,2,3,4,5])
sage: E.cardinality() is E.cardinality()
True
```

The following is very fast since the curve is actually defined over the prime field:
We can count points over curves defined as a reduction:

```
sage: x = polygen(QQ)
sage: K.<w> = NumberField(x^2 + x + 1)
sage: EK = EllipticCurve(K, [0, 0, w, 2, 1])
sage: E = EK.base_extend(K.residue_field(2))
sage: E
Elliptic Curve defined by y^2 + wbar*y = x^3 + 1 over Residue field in wbar of Fractional ideal (2)
sage: E.cardinality()
7
```

```
sage: E = EK.base_extend(K.residue_field(w - 1))
sage: E.abelian_group()
Trivial group embedded in Abelian group of points on Elliptic Curve defined by y^2 + y = x^3 + 2*x + 1 over Residue field of Fractional ideal (w - 1)
```

```
sage: R.<x> = GF(17)[]
sage: pol = R.irreducible_element(5)
sage: k.<a> = R.residue_field(pol)
sage: E = EllipticCurve(R, [1, x]).base_extend(k)
sage: E
Elliptic Curve defined by y^2 = x^3 + x + a over Residue field in a of Principal ideal (x^5 + x + 14) of Univariate Polynomial Ring in x over Finite Field of size 17
sage: E.cardinality()
1421004
```

```
plot(*args, **kwds)

Draw a graph of this elliptic curve over a prime finite field.

INPUT:

• *args, **kwds – all other options are passed to the circle graphing primitive.

EXAMPLES:

```
sage: E = EllipticCurve(FiniteField(17), [0,1])
sage: P = plot(E, rgbcolor=(0,0,1))
```

```
points()

All the points on this elliptic curve. The list of points is cached so subsequent calls are free.
```
Elliptic curves, Release 9.7

EXAMPLES:

```
sage: p = 5
sage: F = GF(p)
sage: E = EllipticCurve(F, [1, 3])
sage: a_sub_p = E.change_ring(QQ).ap(p); a_sub_p
2

sage: len(E.points())
4
sage: p + 1 - a_sub_p
4
sage: E.points()
[(0 : 1 : 0), (1 : 0 : 1), (4 : 1 : 1), (4 : 4 : 1)]

sage: K = GF((p, 2), 'a')
sage: E = E.change_ring(K)
sage: len(E.points())
32
sage: (p + 1)**2 - a_sub_p**2
32
sage: W = E.points(); W
[(0 : 1 : 0), (0 : 2*a + 4 : 1), (0 : 3*a + 1 : 1), (1 : 0 : 1), (2 : 2*a + 4 : 1), (2 : 3*a + 1 : 1), (3 : 2*a + 4 : 1), (3 : 3*a + 1 : 1), (4 : 1 : 1), (4 : 4 : 1), (a : 1 : 1), (a : 4 : 1), (a + 2 : a + 1 : 1), (a + 2 : 4*a + 4 : 1), (a + 3 : a : 1), (a + 3 : 4*a : 1), (a + 4 : 0 : 1), (2*a : 2*a : 1), (2*a : 3*a : 1), (2*a + 4 : a + 1 : 1), (2*a + 4 : 4*a + 4 : 1), (3*a + 1 : a + 3 : 1), (3*a + 1 : 4*a + 2 : 1), (3*a + 2 : 2*a + 3 : 1), (3*a + 2 : 3*a + 2 : 1), (4*a : 0 : 1), (4*a + 1 : 1 : 1), (4*a + 1 : 4 : 1), (4*a + 3 : a + 3 : 1), (4*a + 3 : 4*a + 2 : 1), (4*a + 4 : a + 4 : 1), (4*a + 4 : 4*a + 1 : 1)]
```

Note that the returned list is an immutable sorted Sequence:

```
sage: W[0] = 9
Traceback (most recent call last):
...
ValueError: object is immutable; please change a copy instead.
```

random_element()

Return a random point on this elliptic curve, uniformly chosen among all rational points.

ALGORITHM:

Choose the point at infinity with probability \(1/(2q + 1)\). Otherwise, take a random element from the field as x-coordinate and compute the possible y-coordinates. Return the i'th possible y-coordinate, where i is randomly chosen to be 0 or 1. If the i’th y-coordinate does not exist (either there is no point with the given x-coordinate or we hit a 2-torsion point with i == 1), try again.

This gives a uniform distribution because you can imagine \(2q + 1\) buckets, one for the point at infinity and 2 for each element of the field (representing the x-coordinates). This gives a 1-to-1 map of elliptic curve points into buckets. At every iteration, we simply choose a random bucket until we find a bucket containing a point.

AUTHORS:

- Jeroen Demeyer (2014-09-09): choose points uniformly random, see trac ticket #16951.
EXAMPLES:

```python
sage: k = GF(next_prime(7^5))
sage: E = EllipticCurve(k,[2,4])
sage: P = E.random_element(); P  # random
(16740 : 12486 : 1)
sage: type(P)
<class 'sage.schemes.elliptic_curves.ell_point.EllipticCurvePoint_finite_field'>
sage: P in E
True
```

```python
sage: k.<a> = GF(7^5)
sage: E = EllipticCurve(k,[2,4])
sage: P = E.random_element(); P  # random
(5*a^4 + 3*a^3 + 2*a^2 + a + 4 : 2*a^4 + 3*a^3 + 4*a^2 + a + 5 : 1)
sage: type(P)
<class 'sage.schemes.elliptic_curves.ell_point.EllipticCurvePoint_finite_field'>
sage: P in E
True
```

```python
sage: k.<a> = GF(2^5)
sage: E = EllipticCurve(k,[a^2,a,1,a+1,1])
sage: P = E.random_element(); P  # random
(a^4 + a : a^4 + a^3 + a^2 : 1)
sage: type(P)
<class 'sage.schemes.elliptic_curves.ell_point.EllipticCurvePoint_finite_field'>
sage: P in E
True
```

Ensure that the entire point set is reachable:

```python
sage: E = EllipticCurve(GF(11), [2,1])
sage: S = set()
sage: while len(S) < E.cardinality():
    ....:     S.add(E.random_element())
```

`random_point()`

Return a random point on this elliptic curve, uniformly chosen among all rational points.

ALGORITHM:

Choose the point at infinity with probability $1/(2^q + 1)$. Otherwise, take a random element from the field as x-coordinate and compute the possible y-coordinates. Return the i’th possible y-coordinate, where i is randomly chosen to be 0 or 1. If the i’th y-coordinate does not exist (either there is no point with the given x-coordinate or we hit a 2-torsion point with i == 1), try again.

This gives a uniform distribution because you can imagine $2^q + 1$ buckets, one for the point at infinity and 2 for each element of the field (representing the x-coordinates). This gives a 1-to-1 map of elliptic curve points into buckets. At every iteration, we simply choose a random bucket until we find a bucket containing a point.

AUTHORS:

• Jeroen Demeyer (2014-09-09): choose points uniformly random, see trac ticket #16951.

EXAMPLES:
sage: k = GF(next_prime(7^5))
sage: E = EllipticCurve(k,[2,4])
sage: P = E.random_element(); P  # random
(16740 : 12486 : 1)
sage: type(P)
<class 'sage.schemes.elliptic_curves.ell_point.EllipticCurvePoint_finite_field'>
sage: P in E
True

sage: k.<a> = GF(7^5)
sage: E = EllipticCurve(k,[2,4])
sage: P = E.random_element(); P  # random
(5*a^4 + 3*a^3 + 2*a^2 + a + 4 : 2*a^4 + 3*a^3 + 4*a^2 + a + 5 : 1)
sage: type(P)
<class 'sage.schemes.elliptic_curves.ell_point.EllipticCurvePoint_finite_field'>
sage: P in E
True

sage: k.<a> = GF(2^5)
sage: E = EllipticCurve(k,[a^2,a,1,a+1,1])
sage: P = E.random_element();P  # random
(a^4 + a : a^4 + a^3 + a^2 + 1)
sage: type(P)
<class 'sage.schemes.elliptic_curves.ell_point.EllipticCurvePoint_finite_field'>
sage: P in E
True

Ensure that the entire point set is reachable:

sage: E = EllipticCurve(GF(11), [2,1])
sage: S = set()
sage: while len(S) < E.cardinality():
....:     S.add(E.random_element())

rational_points()
All the points on this elliptic curve. The list of points is cached so subsequent calls are free.

EXAMPLES:

sage: p = 5
sage: F = GF(p)
sage: E = EllipticCurve(F, [1, 3])
sage: a_sub_p = E.change_ring(QQ).ap(p); a_sub_p
2

sage: len(E.points())
4
sage: p + 1 - a_sub_p
4
sage: E.points()
[(0 : 1 : 0), (1 : 0 : 1), (4 : 1 : 1), (4 : 4 : 1)]
Elliptic curves, Release 9.7

sage: K = GF((p, 2), 'a')
sage: E = E.change_ring(K)
sage: len(E.points())
32
sage: (p + 1)**2 - a_sub_p**2
32
sage: w = E.points(); w
[(0 : 1 : 0), (0 : 2*a + 4 : 1), (0 : 3*a + 1 : 1), (1 : 0 : 1), (2 : 2*a + 4 : 1),
 (2 : 3*a + 1 : 1), (3 : 2*a + 4 : 1), (3 : 3*a + 1 : 1), (4 : 1 : 1), (4 : 2 : 4*a + 4 : 1),
 (4 : 3 : a : 1), (a : 1 : 1), (a : 4 : 1), (a + 2 : a + 1 : 1), (a + 2 : 4*a + 4 : 1),
 (a + 3 : a : 1), (a + 3 : 4*a : 1), (a + 4 : 0 : 1), (2*a : 2*a : 1),
 (2*a : 3*a : 1), (2*a + 4 : a + 1 : 1), (2*a + 4 : 4*a + 4 : 1), (3*a + 1 : a : 1),
 (3*a + 1 : 4*a + 2 : 1), (3*a + 2 : 2*a + 3 : 1), (3*a + 2 : 3*a + 1 : 1),
 (3*a + 3 : 4*a + 2 : 1), (4*a : 2*a : 1), (4*a : 3*a + 1 : 1), (4*a + 1 : 4 : 1), (4*a + 3 : a + 3 : 1),
 (4*a + 3 : 4*a + 1 : 1)]

Note that the returned list is an immutable sorted Sequence:

sage: w[0] = 9
Traceback (most recent call last):
  ... ValueError: object is immutable; please change a copy instead.

set_order(value, num_checks=8)
Set the value of self._order to value.

Use this when you know a priori the order of the curve to avoid a potentially expensive order calculation.

INPUT:

• value – integer in the Hasse-Weil range for this curve.

• num_checks (integer, default: 8) – number of times to check whether value*(a random point on this
curve) is equal to the identity.

OUTPUT:

None

EXAMPLES:

This example illustrates basic usage.

sage: E = EllipticCurve(GF(7), [0, 1])  # This curve has order 6
sage: E.set_order(6)
sage: E.order()
6
sage: E.order() * E.random_point()
(0 : 1 : 0)

We now give a more interesting case, the NIST-P521 curve. Its order is too big to calculate with Sage, and
takes a long time using other packages, so it is very useful here.

sage: p = 2^521 - 1
sage: prev_proof_state = proof.arithmetic()
sage: proof.arithmetic(False)  # turn off primality checking
sage: F = GF(p)

(continues on next page)
sage: A = p - 3
sage: B = \ldots
\ldots 109384903807373427451112390766805569936207598951683748994586394495953116150735016013708737572
sage: q = \ldots
\ldots 686479766013060971498190079908139321726943530014330540939446345918554318339765519424505774633
sage: E = EllipticCurve([F(A), F(B)])
sage: E.set_order(q)
sage: G = E.random_point()
sage: G.order() * G  # This takes practically no time.
(0 : 1 : 0)
sage: proof.arithmetic(prev_proof_state)  # restore state

It is an error to pass a value which is not an integer in the Hasse-Weil range:

sage: E = EllipticCurve(GF(7), [0, 1])  # This curve has order 6
sage: E.set_order("hi")
Traceback (most recent call last):
...
TypeError: unable to convert 'hi' to an integer
sage: E.set_order(0)
Traceback (most recent call last):
...
ValueError: Value 0 illegal (not an integer in the Hasse range)

sage: E.set_order(1000)
Traceback (most recent call last):
...
ValueError: Value 1000 illegal (not an integer in the Hasse range)

It is also very likely an error to pass a value which is not the actual order of this curve. How unlikely is
determined by num_checks, the factorization of the actual order, and the actual group structure:

sage: E = EllipticCurve(GF(7), [0, 1])  # This curve has order 6
sage: E.set_order(11)
Traceback (most recent call last):
...
ValueError: Value 11 illegal (multiple of random point not the identity)

However, set_order can be fooled, though it's not likely in “real cases of interest”. For instance, the order
can be set to a multiple of the actual order:

sage: E = EllipticCurve(GF(7), [0, 1])  # This curve has order 6
sage: E.set_order(12)  # 12 just fits in the Hasse range
sage: E.order()
12

Or, the order can be set incorrectly along with num_checks set too small:

sage: E = EllipticCurve(GF(7), [0, 1])  # This curve has order 6
sage: E.set_order(4, num_checks=0)
sage: E.order()
4

The value of num_checks must be an integer. Negative values are interpreted as zero, which means don’t
do any checking:
Elliptic curves, Release 9.7

```python
sage: E = EllipticCurve(GF(7), [0, 1]) # This curve has order 6
sage: E.set_order(4, num_checks=-12)
sage: E.order()
4
```

AUTHORS:
- Mariah Lenox (2011-02-16)

**trace_of_frobenius()**
Return the trace of Frobenius acting on this elliptic curve.

**Note:** This computes the curve cardinality, which may be time-consuming.

**EXAMPLES:**

```python
sage: E = EllipticCurve(GF(101),[2,3])
sage: E.trace_of_frobenius()
6
sage: E = EllipticCurve(GF(11^5,'a'),[2,5])
sage: E.trace_of_frobenius()
802
```

The following shows that the issue from trac ticket #2849 is fixed:

```python
sage: E = EllipticCurve(GF(3^5,'a'),[-1,-1])
sage: E.trace_of_frobenius()
-27
```

`sage.schemes.elliptic_curves.ell_finite_field.fill_ss_j_dict()`
Fill the global cache of supersingular \( j \)-polynomials.

This function does nothing except the first time it is called, when it fills `supersingular_j_polynomials` with precomputed values for \( p < 300 \). Setting the values this way avoids start-up costs.

`sage.schemes.elliptic_curves.ell_finite_field.is_j_supersingular(j, proof=True)`
Return True if \( j \) is a supersingular \( j \)-invariant.

**INPUT:**
- \( j \) (finite field element) – an element of a finite field
- `proof` (boolean, default True) – If True, returns a proved result. If False, then a return value of False is certain but a return value of True may be based on a probabilistic test. See the ALGORITHM section below for more details.

**OUTPUT:**
(boolean) True if \( j \) is supersingular, else False.

**ALGORITHM:**
For small characteristics \( p \) we check whether the \( j \)-invariant is in a precomputed list of supersingular values. Otherwise we next check the \( j \)-invariant. If \( j = 0 \), the curve is supersingular if and only if \( p = 2 \) or \( p \equiv 3 \pmod{4} \); if \( j = 1728 \), the curve is supersingular if and only if \( p = 3 \) or \( p \equiv 2 \pmod{3} \). Next, if the base field is the prime field \( GF(p) \), we check that \((p + 1)P = 0\) for several random points \( P \), returning False if any fail: supersingular curves over \( GF(p) \) have cardinality \( p + 1 \). If Proof is false we now return True. Otherwise we compute the cardinality and return True if and only if it is divisible by \( p \).
EXAMPLES:

```python
sage: from sage.schemes.elliptic_curves.ell Finite_field import is_j_supersingular, supersingular_j_polynomials
sage: [(p, [j for j in GF(p) if is_j_supersingular(j)]) for p in prime_range(30)]
[(2, [0]), (3, [0]), (5, [0]), (7, [6]), (11, [0, 1]), (13, [5]), (17, [0, 8]), (19, [7, 18]), (23, [0, 3, 19]), (29, [0, 2, 25])]
```

```python
sage: [j for j in GF(109) if is_j_supersingular(j)]
[17, 41, 43]
```

```python
sage: PolynomialRing(GF(109), 'j')(supersingular_j_polynomials[109]).roots()
[(43, 1), (41, 1), (17, 1)]
```

```python
sage: [p for p in prime_range(100) if is_j_supersingular(GF(p)(0))]
[2, 3, 5, 11, 17, 23, 29, 41, 47, 53, 59, 71, 83, 89]
```

```python
sage: [p for p in prime_range(100) if is_j_supersingular(GF(p)(1728))]
```

```python
sage: [p for p in prime_range(100) if is_j_supersingular(GF(p)(123456))]
[2, 3, 59, 89]
```

```
sage.schemes.elliptic_curves.ell Finite_field.supersingular_j_polynomial(p, use_cache=True)
```

Return a polynomial whose roots are the supersingular \( j \)-invariants in characteristic \( p \), other than 0, 1728.

INPUT:

- \( p \) (integer) – a prime number.
- \( use\_cache \) (boolean, default True) – use cached coefficients if they exist

ALGORITHM:

First compute \( H(X) \) whose roots are the Legendre \( \lambda \)-invariants of supersingular curves (Silverman V.4.1(b)) in characteristic \( p \). Then, using a resultant computation with the polynomial relating \( \lambda \) and \( j \) (Silverman III.1.7(b)), we recover the polynomial (in variable \( j \)) whose roots are the \( j \)-invariants. Factors of \( j \) and \( j – 1728 \) are removed if present.

**Note:** The only point of the use_cache parameter is to allow checking the precomputed coefficients.

EXAMPLES:

```python
sage: from sage.schemes.elliptic_curves.ell Finite_field import supersingular_j_polynomial
sage: f = supersingular_j_polynomial(67); f
j^5 + 538j^4 + 48j^3 + 478j^2 + 368j + 8
```

```python
sage: f.factor()
(j + 1) * (j^2 + 88j + 45) * (j^2 + 448j + 24)
```

```python
sage: [supersingular_j_polynomial(p) for p in prime_range(30)]
[1, 1, 1, 1, 1, j + 8, j + 9, j + 12, j + 4, j^2 + 28j + 21]
```
CHAPTER
SEVEN

FORMAL GROUPS OF ELLIPTIC CURVES

AUTHORS:

• William Stein: original implementations
• David Harvey: improved asymptotics of some methods
• Nick Alexander: separation from ell_generic.py, bugfixes and docstrings

class sage.schemes.elliptic_curves.formal_group.EllipticCurveFormalGroup(E)

    Bases: sage.structure.sage_object.SageObject

    The formal group associated to an elliptic curve.

    curve()

        Return the elliptic curve this formal group is associated to.

        EXAMPLES:

        sage: E = EllipticCurve("37a")
        sage: F = E.formal_group()
        sage: F.curve()
        Elliptic Curve defined by y^2 + y = x^3 - x over Rational Field

    differential(prec=20)

        Return the power series \( f(t) = 1 + \cdots \) such that \( f(t)dt \) is the usual invariant differential \( dx/(2y+a_1x+a_3) \).

        INPUT:

        • \( \text{prec} \): nonnegative integer (default: 20), answer will be returned \( O(t^{\text{prec}}) \)

        OUTPUT: a power series with given precision

        Return the formal series

        \[
        f(t) = 1 + a_1 t + (a_1^2 + a_2)t^2 + \cdots
        \]

        to precision \( O(t^{\text{prec}}) \) of page 113 of [Sil2009].

        The result is cached, and a cached version is returned if possible.

        Warning: The resulting series will have precision \( \text{prec} \), but its parent PowerSeriesRing will have default precision 20 (or whatever the default default is).

        EXAMPLES:
AUTHORS:

• David Harvey (2006-09-10): factored out of log

\textbf{group\_law}(\texttt{prec=10})

Return the formal group law.

INPUT:

• \texttt{prec} – integer (default: 10)

OUTPUT: a power series with given precision in $R[\left['t1', 't2'\right]]$, where the curve is defined over $R$.

Return the formal power series

$$F(t_1, t_2) = t_1 + t_2 - a_1 t_1 t_2 - \cdots$$

to precision $O(t_1, t_2)^{\text{prec}}$ of page 115 of [Sil2009].

The result is cached, and a cached version is returned if possible.

AUTHORS:

• Nick Alexander: minor fixes, docstring

• Francis Clarke (2012-08): modified to use two-variable power series ring

EXAMPLES:

\begin{verbatim}
sage: e = EllipticCurve([1, 2])
sage: e.formal_group().group_law(6)
t1 + t2 - 2*t1^4*t2 - 4*t1^3*t2^2 - 4*t1^2*t2^3 - 2*t1*t2^4 + O(t1, t2)^6

sage: e = EllipticCurve('14a1')
sage: ehat = e.formal()
sage: ehat.group_law(3)
t1 + t2 - t1*t2 + O(t1, t2)^3

sage: ehat.group_law(5)
t1 + t2 - t1*t2 - 2*t1^3*t2 - 3*t1^2*t2^2 - 2*t1*t2^3 + O(t1, t2)^5

sage: e = EllipticCurve(GF(7), [3, 4])
sage: ehat = e.formal()
sage: ehat.group_law(3)
t1 + t2 + O(t1, t2)^3

sage: F = ehat.group_law(7); F
t1 + t2 + t1^4*t2 + 2*t1^3*t2^2 + 2*t1^2*t2^3 + t1*t2^4 + O(t1, t2)^7
\end{verbatim}

\textbf{inverse}(\texttt{prec=20})

Return the formal group inverse law $i(t)$, which satisfies $F(t, i(t)) = 0$.

INPUT:

• \texttt{prec} – integer (default: 20)

OUTPUT: a power series with given precision
Return the formal power series
\[ i(t) = -t + a_1 t^2 + \cdots \]
to precision \( O(t^{\text{prec}}) \) of page 114 of [Sil2009].
The result is cached, and a cached version is returned if possible.

**Warning:** The resulting power series will have precision \( \text{prec} \), but its parent \texttt{PowerSeriesRing} will have default precision 20 (or whatever the default default is).

**EXAMPLES:**

```sage
sage: P.<a1, a2, a3, a4, a6> = ZZ[]
sage: E = EllipticCurve(list(P.gens()))
sage: i = E.formal_group().inverse(6); i
-t - a1*t^2 - a1^2*t^3 + (-a1^3 - a3)*t^4 + (-a1^4 - 3*a1*a3)*t^5 + O(t^6)
sage: F = E.formal_group().group_law(6)
sage: F(i.parent().gen(), i)
O(t^6)
```

\[ \log(\text{prec}=20) \]
Return the power series \( f(t) = t + \cdots \) which is an isomorphism to the additive formal group.

Generally this only makes sense in characteristic zero, although the terms before \( t^p \) may work in characteristic \( p \).

**INPUT:**

- \( \text{prec} \) – nonnegative integer (default: 20)

**OUTPUT:** a power series with given precision

**EXAMPLES:**

```sage
sage: EllipticCurve([-1, 1/4]).formal_group().log(15)
t - 2/5*t^5 + 3/28*t^7 + 2/3*t^9 - 5/11*t^11 - 305/208*t^13 + O(t^15)
```

**AUTHORS:**

- David Harvey (2006-09-10): rewrote to use differential

\[ \text{mult}_n(n, \text{prec}=10) \]
Return the formal ‘multiplication by \( n \)’ endomorphism \([n]\).

**INPUT:**

- \( \text{prec} \) – integer (default: 10)

**OUTPUT:** a power series with given precision

Return the formal power series
\[ [n](t) = nt + \cdots \]
to precision \( O(t^{\text{prec}}) \) of Proposition 2.3 of [Sil2009].

**Warning:** The resulting power series will have precision \( \text{prec} \), but its parent \texttt{PowerSeriesRing} will have default precision 20 (or whatever the default default is).
AUTHORS:

- Nick Alexander: minor fixes, docstring
- David Harvey (2007-03): faster algorithm for char 0 field case
- Tom Boothby (2009-06): slight improvement to double-and-add
- Francis Clarke (2012-08): adjustments and simplifications using group_law code as modified to yield a two-variable power series.

EXAMPLES:

```
sage: e = EllipticCurve([1, 2, 3, 4, 6])
sage: e.formal_group().mult_by_n(0, 5)
O(t^5)
sage: e.formal_group().mult_by_n(1, 5)
t + O(t^5)
```

We verify an identity of low degree:

```
sage: none = e.formal_group().mult_by_n(-1, 5)
sage: two = e.formal_group().mult_by_n(2, 5)
sage: ntwo = e.formal_group().mult_by_n(-2, 5)
sage: ntwo - none(two)
O(t^5)
sage: ntwo - two(none)
O(t^5)
```

It’s quite fast:

```
sage: E = EllipticCurve("37a"); F = E.formal_group()
sage: F.mult_by_n(100, 20)
100*t - 49999950*t^4 + 399999960*t^5 + 14285614285800*t^7 - 2999989200000150*t^8 + 1333332533333400*t^9 - 3571378571674999800*t^10 + 148258362624965454000*t^11 - 146666057066712847999500*t^12 + 5336978000000004213190385000*t^13 - 519472799950932256570002000*t^14 + 93851927683683567279320028000*t^15 - 667378721156381236636370325175*t^16 + 328129060335050875009191524993000*t^17 - 4567028886973478472872833214986000*t^18 + 5302464956134111125466184947310391600*t^19 + O(t^20)
```

```
sigma(prec=10)

Return the Weierstrass sigma function as a formal power series solution to the differential equation

\[ \frac{d^2 \log \sigma}{dz^2} = -\varphi(z) \]

with initial conditions \( \sigma(O) = 0 \) and \( \sigma'(O) = 1 \), expressed in the variable \( t = \log_{\mathcal{E}}(z) \) of the formal group.

INPUT:

- \( \text{prec} \) – integer (default: 10)

OUTPUT: a power series with given precision
Other solutions can be obtained by multiplication with a function of the form \(\exp(cz^2)\). If the curve has good ordinary reduction at a prime \(p\) then there is a canonical choice of \(c\) that produces the canonical \(p\)-adic sigma function. To obtain that, please use \(E.padic\_sigma(p)\) instead. See \(padic\_sigma()\)

**EXAMPLES:**

```python
sage: E = EllipticCurve('14a')
sage: F = E.formal_group()
sage: F.sigma(5)
t + 1/2*t^2 + 1/3*t^3 + 3/4*t^4 + O(t^5)
```

\(w(\text{prec}=20)\)

Return the formal group power series \(w\).  

**INPUT:**

- \(\text{prec} \) \(-\) integer (default: 20)

**OUTPUT:** a power series with given precision

Return the formal power series

\[
w(t) = t^3 + a_1 t^4 + (a_2 + a_1^2) t^5 + \cdots
\]

to precision \(O(t^{\text{prec}})\) of Proposition IV.1.1 of [Sil2009]. This is the formal expansion of \(w = -1/y\) about the formal parameter \(t = -x/y\) at \(\infty\).

The result is cached, and a cached version is returned if possible.

**Warning:** The resulting power series will have precision \(\text{prec}\), but its parent PowerSeriesRing will have default precision 20 (or whatever the default default is).

**ALGORITHM:** Uses Newton’s method to solve the elliptic curve equation at the origin. Complexity is roughly \(O(M(n))\) where \(n\) is the precision and \(M(n)\) is the time required to multiply polynomials of length \(n\) over the coefficient ring of \(E\).

**AUTHORS:**

- David Harvey (2006-09-09): modified to use Newton’s method instead of a recurrence formula.

**EXAMPLES:**

```python
sage: e = EllipticCurve([0, 0, 1, -1, 0])
sage: e.formal_group().w(10)
t^3 + t^6 - t^7 + 2*t^9 + O(t^10)
```

Check that caching works:

```python
sage: e = EllipticCurve([3, 2, -4, -2, 5])
sage: e.formal_group().w(7)
t^3 + 3*t^4 + 11*t^5 + 35*t^6 + O(t^7)
sage: e.formal_group().w(35)
t^3 + 3*t^4 + 11*t^5 + 35*t^6 + 101*t^7 + 237*t^8 + 312*t^9 - 949*t^{10} - \cdots
```

(continues on next page)
\( \mathbf{x}(\text{prec}=20) \)

Return the formal series \( x(t) = t/w(t) \) in terms of the local parameter \( t = -x/y \) at infinity.

**INPUT:**
- \( \text{prec} \) – integer (default: 20)

**OUTPUT:** a Laurent series with given precision

Return the formal series

\[
x(t) = t^{-2} - a_1 t^{-1} - a_2 - a_3 t - \cdots
\]

to precision \( O(t^{\text{prec}}) \) of page 113 of [Sil2009].

**Warning:** The resulting series will have precision \( \text{prec} \), but its parent PowerSeriesRing will have default precision 20 (or whatever the default default is).

**EXAMPLES:**

```python
sage: EllipticCurve([0, 0, 1, -1, 0]).formal_group().x(10)
t^\cdot 2 - t + t^2 + 2^*t^5 - t^6 - 2^*t^7 + 6^*t^8 - 6^*t^9 + O(t^10)
```

\( \mathbf{y}(\text{prec}=20) \)

Return the formal series \( y(t) = -1/w(t) \) in terms of the local parameter \( t = -x/y \) at infinity.

**INPUT:**
- \( \text{prec} \) – integer (default: 20)

**OUTPUT:** a Laurent series with given precision

Return the formal series

\[
y(t) = -t^{-3} + a_1 t^{-2} + a_2 t + a_3 + \cdots
\]

to precision \( O(t^{\text{prec}}) \) of page 113 of [Sil2009].

The result is cached, and a cached version is returned if possible.

**Warning:** The resulting series will have precision \( \text{prec} \), but its parent PowerSeriesRing will have default precision 20 (or whatever the default default is).

**EXAMPLES:**

```python
sage: EllipticCurve([0, 0, 1, -1, 0]).formal_group().y(10)
-t^\cdot 3 + 1 - t + t^3 - 2^*t^4 + t^5 + 2^*t^6 - 6^*t^7 + 6^*t^8 + 3^*t^9 + O(t^10)
```

Maps between them
This class serves as a common parent for various specializations of morphisms between elliptic curves, with the aim of providing a common interface regardless of implementation details.

Current implementations of elliptic-curve morphisms (child classes):

- \texttt{EllipticCurveIsogeny}
- \texttt{WeierstrassIsomorphism}
- \texttt{EllipticCurveHom\_composite}
- \texttt{EllipticCurveHom\_velusqrt}

AUTHORS:

- See authors of \texttt{EllipticCurveIsogeny}. Some of the code in this class was lifted from there.
- Lorenz Panny (2021): Refactor isogenies and isomorphisms into the common \texttt{EllipticCurveHom} interface.

class \texttt{sage.schemes.elliptic_curves.hom.EllipticCurveHom}

Bases: \texttt{sage.categories.morphism.Morphism}

Base class for elliptic-curve morphisms.

def degree() returns the degree of this elliptic-curve morphism.

EXAMPLES:

\begin{verbatim}
sage: E = EllipticCurve(QQ, [0,0,0,1,0])
sage: phi = EllipticCurveIsogeny(E, E((0,0)))
sage: phi.degree() 2
sage: phi = EllipticCurveIsogeny(E, [0,1,0,1])
sage: phi.degree() 4
sage: E = EllipticCurve(GF(31), [1,0,0,1,2])
sage: phi = EllipticCurveIsogeny(E, [17, 1])
sage: phi.degree() 3
\end{verbatim}

Degrees are multiplicative, so the degree of a composite isogeny is the product of the degrees of the individual factors:
Elliptic curves, Release 9.7

```python
sage: from sage.schemes.elliptic_curves.hom_composite import EllipticCurveHom_composite
sage: E = EllipticCurve(GF(419), [1, 0])
sage: P = E.gens()
sage: phi = EllipticCurveHom_composite(E, P+P)
sage: phi.degree()
210
sage: phi.degree() == prod(f.degree() for f in phi.factors())
True
```

Isomorphisms always have degree 1 by definition:

```python
sage: E1 = EllipticCurve([1, 2, 3, 4, 5])
sage: E2 = EllipticCurve_from_j(E1.j_invariant())
sage: E1.isomorphism_to(E2).degree()
1
```

dual()

Return the dual of this elliptic-curve morphism.

Implemented by child classes. For examples, see:

- `EllipticCurveIsogeny.dual()`
- `sage.schemes.elliptic_curves.weierstrass_morphism.WeierstrassIsomorphism.dual()`
- `sage.schemes.elliptic_curves.hom_composite.EllipticCurveHom_composite.dual()`

formal(prec=20)

Return the formal isogeny associated to this elliptic-curve morphism as a power series in the variable $t = -x/y$ on the domain curve.

INPUT:

- prec – (default: 20), the precision with which the computations in the formal group are carried out.

EXAMPLES:

```python
sage: E = EllipticCurve(GF(13), [1, 7])
sage: phi = E.isogeny(E(10, 4))
sage: phi.formal()
t + 12*t^13 + 2*t^17 + 8*t^19 + 2*t^21 + O(t^23)
sage: E = EllipticCurve([0, 1])
sage: phi = E.isogeny(E(2, 3))
sage: phi.formal(prec=10)
t + 54*t^5 + 255*t^7 + 2430*t^9 + 19278*t^11 + O(t^13)
sage: E = EllipticCurve('11a2')
sage: R.<x> = QQ[]
sage: phi = E.isogeny(x^2 + 101*x + 12751/5)
sage: phi.formal(prec=7)
t - 2724/5*t^5 + 209046/5*t^7 - 4767/5*t^8 + 29200946/5*t^9 + O(t^10)
```
**is_injective()**
Determine whether or not this morphism has trivial kernel.

**EXAMPLES:**
```
sage: E = EllipticCurve('11a1')
sage: R.<x> = QQ[]
sage: f = x^2 + x - 29/5
sage: phi = EllipticCurveIsogeny(E, f)
sage: phi.is_injective()
False
sage: phi = EllipticCurveIsogeny(E, R(1))
sage: phi.is_injective()
True
```

**is_normalized()**
Determine whether this morphism is a normalized isogeny.

**Note:** An isogeny \( \varphi: E_1 \to E_2 \) between two given Weierstrass equations is said to be *normalized* if the \( \varphi^*(\omega_2) = \omega_1 \), where \( \omega_1 \) and \( \omega_2 \) are the invariant differentials on \( E_1 \) and \( E_2 \) corresponding to the given equation.

**EXAMPLES:**
```
sage: from sage.schemes.elliptic_curves.weierstrass_morphism import WeierstrassIsomorphism
sage: E = EllipticCurve(GF(7), [0,0,0,1,0])
sage: R.<x> = GF(7)[]
sage: phi = EllipticCurveIsogeny(E, x)
sage: phi.is_normalized()
True
sage: isom = WeierstrassIsomorphism(phi.codomain(), (3, 0, 0, 0))
sage: phi = isom * phi
sage: phi.is_normalized()
False
sage: isom = WeierstrassIsomorphism(phi.codomain(), (5, 0, 0, 0))
sage: phi = isom * phi
sage: phi.is_normalized()
True
sage: isom = WeierstrassIsomorphism(phi.codomain(), (1, 1, 1, 1))
sage: phi = isom * phi
sage: phi.is_normalized()
True
```
Elliptic curves, Release 9.7

```python
sage: F = GF(2^5, 'alpha'); alpha = F.gen()
sage: E = EllipticCurve(F, [1,0,1,1,1])
sage: R.<x> = F[]
sage: phi = EllipticCurveIsogeny(E, x+1)
sage: isom = WeierstrassIsomorphism(phi.codomain(), (alpha, 0, 0, 0))
sage: phi.is_normalized()
True
sage: phi = isom * phi
sage: phi.is_normalized()
False
sage: isom = WeierstrassIsomorphism(phi.codomain(), (1/alpha, 0, 0, 0))
```

```python
sage: phi = isom * phi
sage: phi.is_normalized()
True
sage: isom = WeierstrassIsomorphism(phi.codomain(), (1, 1, 1, 1))
```

```python
sage: E = EllipticCurve('11a1')
sage: R.<x> = QQ[]
sage: f = x^3 - x^2 - 10*x - 79/4
sage: phi = EllipticCurveIsogeny(E, f)
```

```python
sage: isom = WeierstrassIsomorphism(phi.codomain(), (2, 0, 0, 0))
```

```python
sage: phi.is_normalized()
True
sage: phi = isom * phi
sage: phi.is_normalized()
False
sage: isom = WeierstrassIsomorphism(phi.codomain(), (1/2, 0, 0, 0))
```

```python
sage: phi = isom * phi
sage: phi.is_normalized()
True
```

ALGORITHM: We check if `scaling_factor()` returns 1.

`is_separable()`

Determine whether or not this morphism is separable.

**Note:** This method currently always returns True as Sage does not yet implement inseparable isogenies. This will probably change in the future.

**EXAMPLES:**

```python
sage: E = EllipticCurve(GF(17), [0,0,0,3,0])
sage: phi = EllipticCurveIsogeny(E, E((0,0)))
sage: phi.is_separable()
True
```
sage: E = EllipticCurve('11a1')
sage: phi = EllipticCurveIsogeny(E, E.torsion_points())
sage: phi.is_separable()
True

is_surjective()  
Determine whether or not this morphism is surjective.

**Note:** This method currently always returns True, since a non-constant map of algebraic curves must be surjective, and Sage does not yet implement the constant zero map. This will probably change in the future.

**EXAMPLES:**

sage: E = EllipticCurve('11a1')
sage: R.<x> = QQ[]
sage: f = x^2 + x - 29/5
sage: phi = EllipticCurveIsogeny(E, f)
sage: phi.is_surjective()
True

sage: E = EllipticCurve(GF(7), [0,0,0,1,0])
sage: phi = EllipticCurveIsogeny(E, E((0,0)))
Sage: phi.is_surjective()
True

sage: F = GF(2^5, 'omega')
sage: E = EllipticCurve(j=F(0))
sage: R.<x> = F[]
sage: phi = EllipticCurveIsogeny(E, x)
sage: phi.is_surjective()
True

is_zero()  
Check whether this elliptic-curve morphism is the zero map.

**Note:** This function currently always returns True as Sage does not yet implement the constant zero morphism. This will probably change in the future.

**EXAMPLES:**

sage: E = EllipticCurve(j=GF(7)(0))
sage: phi = EllipticCurveIsogeny(E, [E(0,1), E(0,-1)])
sage: phi.is_zero()
False

kernel_polynomial()  
Return the kernel polynomial of this elliptic-curve morphism.

Implemented by child classes. For examples, see:

- `EllipticCurveIsogeny.kernel_polynomial()`
rational_maps()

Return the pair of explicit rational maps defining this elliptic-curve morphism as fractions of bivariate polynomials in $x$ and $y$.

Implemented by child classes. For examples, see:

- `EllipticCurveIsogeny.rational_maps()
- `sage.schemes.elliptic_curves.weierstrass_morphism.WeierstrassIsomorphism.rational_maps()
- `sage.schemes.elliptic_curves.hom_composite.EllipticCurveHom_composite.rational_maps()

scaling_factor()

Return the Weierstrass scaling factor associated to this elliptic-curve morphism.

The scaling factor is the constant $u$ (in the base field) such that $\varphi^*\omega_2 = u\omega_1$, where $\varphi : E_1 \rightarrow E_2$ is this morphism and $\omega_i$ are the standard Weierstrass differentials on $E_i$ defined by $dx/(2y + a_1x + a_3)$.

Implemented by child classes. For examples, see:

- `EllipticCurveIsogeny.scaling_factor()
- `sage.schemes.elliptic_curves.weierstrass_morphism.WeierstrassIsomorphism.scaling_factor()
- `sage.schemes.elliptic_curves.hom_composite.EllipticCurveHom_composite.scaling_factor()

x_rational_map()

Return the $x$-coordinate rational map of this elliptic-curve morphism as a univariate rational expression in $x$.

Implemented by child classes. For examples, see:

- `EllipticCurveIsogeny.x_rational_map()
- `sage.schemes.elliptic_curves.weierstrass_morphism.WeierstrassIsomorphism.x_rational_map()
- `sage.schemes.elliptic_curves.hom_composite.EllipticCurveHom_composite.x_rational_map()

sage.schemes.elliptic_curves.hom.compare_via_evaluation(left, right)

Test if two elliptic-curve morphisms are equal by evaluating them at enough points.

INPUT:

- `left, right – EllipticCurveHom objects

ALGORITHM:

We use the fact that two isogenies of equal degree $d$ must be the same if and only if they behave identically on more than $4d$ points. (It suffices to check this on a few points that generate a large enough subgroup.)

If the domain curve does not have sufficiently many rational points, the base field is extended first: Taking an extension of degree $O(\log(d))$ suffices.

EXAMPLES:
sage: E = EllipticCurve(GF(83), [1,0])
sage: phi = E.isogeny(12*E.0, model='montgomery'); phi
Isogeny of degree 7 from Elliptic Curve defined by y^2 = x^3 + x over Finite Field of size 83 to Elliptic Curve defined by y^2 = x^3 + 70*x^2 + x over Finite Field of size 83
sage: psi = phi.dual(); psi
Isogeny of degree 7 from Elliptic Curve defined by y^2 = x^3 + 70*x^2 + x over Finite Field of size 83 to Elliptic Curve defined by y^2 = x^3 + x over Finite Field of size 83
sage: from sage.schemes.elliptic_curves.hom_composite import EllipticCurveHom_composite
sage: mu = EllipticCurveHom_composite.from_factors([phi, psi])
sage: from sage.schemes.elliptic_curves.hom import compare_via_evaluation
sage: compare_via_evaluation(mu, E.multiplication_by_m_isogeny(7))
True

See also:

- sage.schemes.elliptic_curves.hom_composite.EllipticCurveHom_composite._richcmp_()
ISOMORPHISMS BETWEEN WEIERSTRASS MODELS OF ELLIPTIC CURVES

AUTHORS:

- Robert Bradshaw (2007): initial version
- John Cremona (Jan 2008): isomorphisms, automorphisms and twists in all characteristics
- Lorenz Panny (2021): `EllipticCurveHom` interface

```python
class sage.schemes.elliptic_curves.weierstrass_morphism.WeierstrassIsomorphism(E=None, urst=None, F=None):
    weierstrass_morphism.baseWI

    Class representing a Weierstrass isomorphism between two elliptic curves.

    dual()
    Return the dual isogeny of this isomorphism.
    For isomorphisms, the dual is just the inverse.

    EXAMPLES:

    sage: from sage.schemes.elliptic_curves.weierstrass_morphism import WeierstrassIsomorphism
    sage: E = EllipticCurve(QuadraticField(-3), [0,1])
    sage: w = WeierstrassIsomorphism(E, (CyclotomicField(3).gen(),0,0,0))
    sage: (w.dual() * w).rational_maps()
    (x, y)

    sage: E1 = EllipticCurve([11,22,33,44,55])
    sage: E2 = E1.short_weierstrass_model()
    sage: iso = E1.isomorphism_to(E2)
    sage: iso.dual() == ~iso
    True

    kernel_polynomial()
    Return the kernel polynomial of this isomorphism.
    Isomorphisms have trivial kernel by definition, hence this method always returns 1.

    EXAMPLES:
```
sage: E1 = EllipticCurve([11,22,33,44,55])
sage: E2 = EllipticCurve_from_j(E1.j_invariant())
sage: iso = E1.isomorphism_to(E2)
sage: iso.kernel_polynomial()
1
sage: psi = E1.isogeny(iso.kernel_polynomial(), codomain=E2); psi
Isogeny of degree 1 from Elliptic Curve defined by y^2 + 11*x*y + 33*y = x^3 + 22*x^2 + 44*x + 55 over Rational Field to Elliptic Curve defined by y^2 + x*y = x^3 + x^2 - 684*x + 6681 over Rational Field
sage: psi in {iso, -iso}
True

rational_maps()
Return the pair of rational maps defining this isomorphism.

EXAMPLES:

sage: E1 = EllipticCurve([11,22,33,44,55])
sage: E2 = EllipticCurve_from_j(E1.j_invariant())
sage: iso = E1.isomorphism_to(E2); iso
Elliptic-curve morphism:
  From: Elliptic Curve defined by y^2 + 11*x*y + 33*y = x^3 + 22*x^2 + 44*x + 55 over Rational Field
  To:  Elliptic Curve defined by y^2 + x*y = x^3 + x^2 - 684*x + 6681 over Rational Field
  Via: (u,r,s,t) = (1, -17, -5, 77)
sage: iso.rational_maps()
(x + 17, 5*x + y + 8)
sage: f = E2.defining_polynomial()(*iso.rational_maps(), 1)
sage: I = E1.defining_ideal()
sage: x,y,z = I.ring().gens()
sage: f
in
I + Ideal(z-1)
True

sage: E = EllipticCurve(GF(65537), [1,1,1,1,1])
sage: w = E.isomorphism_to(E.short_weierstrass_model())
sage: f,g = w.rational_maps()
sage: P = E.random_point()
sage: w(P).xy() == (f(P.xy()), g(P.xy()))
True

scaling_factor()
Return the Weierstrass scaling factor associated to this Weierstrass isomorphism.

The scaling factor is the constant $u$ (in the base field) such that $\varphi^* \omega_1 = u \omega_1$, where $\varphi : E_1 \rightarrow E_2$ is this isomorphism and $\omega_i$ are the standard Weierstrass differentials on $E_i$ defined by $dx/(2y + a_1 x + a_3)$.

EXAMPLES:

sage: E = EllipticCurve(QQbar, [0,1])
sage: all(f.scaling_factor() == f.formal()[1] for f in E.automorphisms())
True

ALGORITHM: The scaling factor equals the $u$ component of the tuple $(u, r, s, t)$ defining the isomorphism.
**x_rational_map()**

Return the \(x\)-coordinate rational map of this isomorphism.

**EXAMPLES:**

```python
sage: E1 = EllipticCurve([11,22,33,44,55])
sage: E2 = EllipticCurve_from_j(E1.j_invariant())
sage: iso = E1.isomorphism_to(E2); iso
Elliptic-curve morphism:
  From: Elliptic Curve defined by y^2 + 11*x*y + 33*y = x^3 + 22*x^2 + 44*x +
˓→55 over Rational Field
  To: Elliptic Curve defined by y^2 + x*y = x^3 + x^2 - 684*x + 6681 over˓→Rational Field
    Via: (u,r,s,t) = (1, -17, -5, 77)
sage: iso.x_rational_map()
x + 17
sage: iso.x_rational_map() == iso.rational_maps()[0]
True
```

**class** `sage.schemes.elliptic_curves.weierstrass_morphism.baseWI(u=1, r=0, s=0, t=0)`

Bases: `object`

This class implements the basic arithmetic of isomorphisms between Weierstrass models of elliptic curves.

These are specified by lists of the form \([u, r, s, t]\) (with \(u \neq 0\)) which specifies a transformation \((x, y) \mapsto (x', y')\) where

\[(x, y) = (u^2 x' + r, u^3 y' + su^2 x' + t).\]

**INPUT:**

- \(u, r, s, t\) (default \((1, 0, 0, 0)\)) – standard parameters of an isomorphism between Weierstrass models.

**EXAMPLES:**

```python
sage: from sage.schemes.elliptic_curves.weierstrass_morphism import *
sage: baseWI()
(1, 0, 0, 0)
sage: baseWI(2,3,4,5)
(2, 3, 4, 5)
sage: R.<u,r,s,t> = QQ[]
sage: baseWI(u,r,s,t)
(u, r, s, t)
```

**is_identity()**

Return True if this is the identity isomorphism.

**EXAMPLES:**

```python
sage: from sage.schemes.elliptic_curves.weierstrass_morphism import *
sage: w = baseWI(); w.is_identity()
True
sage: w = baseWI(2,3,4,5); w.is_identity()
False
```

**tuple()**

Return the parameters \(u, r, s, t\) as a tuple.

**EXAMPLES:**
sage: from sage.schemes.elliptic_curves.weierstrass_morphism import *
sage: w = baseWI(2,3,4,5)
sage: w.tuple()
(2, 3, 4, 5)

sage.schemes.elliptic_curves.weierstrass_morphism.isomorphisms(E, F, JustOne=False)
Return one or all isomorphisms between two elliptic curves.

INPUT:
• E, F (EllipticCurve) – Two elliptic curves.
• JustOne (bool) If True, returns one isomorphism, or None if the curves are not isomorphic. If False, returns a (possibly empty) list of isomorphisms.

OUTPUT:
Either None, or a 4-tuple \((u, r, s, t)\) representing an isomorphism, or a list of these.

Note: This function is not intended for users, who should use the interface provided by ell_generic.

EXAMPLES:
sage: from sage.schemes.elliptic_curves.weierstrass_morphism import *
sage: isomorphisms(EllipticCurve_from_j(0),EllipticCurve('27a3'))
[(-1, 0, 0, -1), (1, 0, 0, 0)]
sage: isomorphisms(EllipticCurve_from_j(0),EllipticCurve('27a3'),JustOne=True)
(1, 0, 0, 0)
sage: isomorphisms(EllipticCurve_from_j(0),EllipticCurve('27a1'))
[]
sage: isomorphisms(EllipticCurve_from_j(0),EllipticCurve('27a1'),JustOne=True)
An isogeny $\varphi : E_1 \to E_2$ between two elliptic curves $E_1$ and $E_2$ is a morphism of curves that sends the origin of $E_1$ to the origin of $E_2$. Such a morphism is automatically a morphism of group schemes and the kernel is a finite subgroup scheme of $E_1$. Such a subscheme can either be given by a list of generators, which have to be torsion points, or by a polynomial in the coordinate $x$ of the Weierstrass equation of $E_1$.

The usual way to create and work with isogenies is illustrated with the following example:

```
sage: k = GF(11)
sage: E = EllipticCurve(k, [1, 1])
sage: Q = E(6, 5)
sage: phi = E.isogeny(Q)
sage: phi
Isogeny of degree 7 from Elliptic Curve defined by y^2 = x^3 + x + 1 over Finite Field of size 11 to Elliptic Curve defined by y^2 = x^3 + 7*x + 8 over Finite Field of size 11
sage: P = E(4, 5)
sage: phi(P)
(10 : 0 : 1)
sage: phi.codomain()
Elliptic Curve defined by y^2 = x^3 + 7*x + 8 over Finite Field of size 11
sage: phi.rational_maps()
((x^7 + 4*x^6 - 3*x^5 - 2*x^4 - 3*x^3 + 3*x^2 + x - 2)/(x^6 + 4*x^5 - 4*x^4 - 5*x^3 + 5*x^2), (x^9*y - 5*x^8*y - x^7*y + x^5*y - x^4*y - 5*x^3*y - 5*x^2*y - 2*x*y - 5*y)/(x^9 - 5*x^8 + 4*x^6 - 3*x^4 + 2*x^3))
```

The methods directly accessible from an elliptic curve $E$ over a field are `isogeny()` and `isogeny_codomain()`.

The most useful methods that apply to isogenies are:

- `.domain()`
- `.codomain()`
- `.degree()`
- `.dual()`
- `.rational_maps()`
- `.kernel_polynomial()`

**Warning:** This class only implements separable isogenies. When using Kohel’s algorithm, only cyclic isogenies can be computed (except for $[2]$).
Elliptic curves, Release 9.7

Working with other kinds of isogenies may be possible using other child classes of \texttt{EllipticCurveHom}. Some algorithms may need the isogeny to be normalized.

AUTHORS:

- Daniel Shumow (<shumow@gmail.com>): 2009-04-19: initial version
- Chris Wuthrich: 7/09: add check of input, not the full list is needed. 10/09: eliminating some bugs.
- John Cremona 2014-08-08: tidying of code and docstrings, systematic use of univariate vs. bivariate polynomials and rational functions.
- Lorenz Panny (2022-04): major cleanup of code and documentation

\texttt{class sage.schemes.elliptic_curves.ell_curve_isogeny.EllipticCurveIsogeny(E, kernel, codomain=None, degree=None, model=None, check=True)}

\texttt{Bases: sage.schemes.elliptic_curves.hom.EllipticCurveHom}

This class implements separable isogenies of elliptic curves.

Several different algorithms for computing isogenies are available. These include:

- Vélu’s Formulas: Vélu’s original formulas for computing isogenies. This algorithm is selected by giving as the \texttt{kernel} parameter a single point, or a list of points, generating a finite subgroup.
- Kohel’s Formulas: Kohel’s original formulas for computing isogenies. This algorithm is selected by giving as the \texttt{kernel} parameter a monic polynomial (or a coefficient list) which will define the kernel of the isogeny. Kohel’s algorithm is currently only implemented for cyclic isogenies, with the exception of [2].

INPUT:

- \texttt{E} – an elliptic curve, the domain of the isogeny to initialize.
- \texttt{kernel} – a kernel: either a point on \texttt{E}, a list of points on \texttt{E}, a monic kernel polynomial, or \texttt{None}. If initializing from a domain/codomain, this must be \texttt{None}.
- \texttt{codomain} – an elliptic curve (default: \texttt{None}).
  - If \texttt{kernel} is \texttt{None}, then \texttt{degree} must be given as well and the given \texttt{codomain} must be the codomain of a cyclic, separable, normalized isogeny of the given degree.
  - If \texttt{kernel} is not \texttt{None}, then this must be isomorphic to the codomain of the separable isogeny defined by \texttt{kernel}; in this case, the isogeny is post-composed with an isomorphism so that the codomain equals the given curve.
- \texttt{degree} – an integer (default: \texttt{None}).
  - If \texttt{kernel} is \texttt{None}, then this is the degree of the isogeny from \texttt{E} to \texttt{codomain}.
  - If \texttt{kernel} is not \texttt{None}, then this is used to determine whether or not to skip a \texttt{gcd} of the given kernel polynomial with the two-torsion polynomial of \texttt{E}.
- \texttt{model} – a string (default: \texttt{None}). Supported values (cf. \texttt{compute_model()}):
  - "minimal": If \texttt{E} is a curve over the rationals or over a number field, then the codomain is a global minimal model where this exists.
  - "short_weierstrass": The codomain is a short Weierstrass curve, assuming one exists.
- "montgomery": The codomain is an (untwisted) Montgomery curve, assuming one exists over this field.

• check (default: True) – check whether the input is valid. Setting this to False can lead to significant speedups.

EXAMPLES:

A simple example of creating an isogeny of a field of small characteristic:

```
sage: E = EllipticCurve(GF(7), [0,0,0,1,0])
sage: phi = EllipticCurveIsogeny(E, E((0,0))); phi
Isogeny of degree 2 from Elliptic Curve defined by y^2 = x^3 + x over Finite Field of size 7 to Elliptic Curve defined by y^2 = x^3 + 3*x over Finite Field of size 7
sage: phi.degree() == 2
True
sage: phi.kernel_polynomial()
x
sage: phi.rational_maps()
((x^2 + 1)/x, (x^2*y - y)/x^2)
sage: phi == loads(dumps(phi))  # known bug
True
```

A more complicated example of a characteristic-2 field:

```
sage: E = EllipticCurve(GF(2^4,'alpha'), [0,0,1,0,1])
sage: P = E((1,1))
sage: phi_v = EllipticCurveIsogeny(E, P); phi_v
Isogeny of degree 3 from Elliptic Curve defined by y^2 + y = x^3 + 1 over Finite Field in alpha of size 2^4 to Elliptic Curve defined by y^2 + y = x^3 over Finite Field in alpha of size 2^4
sage: phi_ker_poly = phi_v.kernel_polynomial()
sage: phi_ker_poly
x + 1
sage: phi_k = EllipticCurveIsogeny(E, phi_ker_poly)
sage: phi_k == phi_v
True
sage: phi_k.rational_maps()
((x^3 + x + 1)/(x^2 + 1), (x^3*y + x^2*y + x*y + x + y)/(x^3 + x^2 + x + 1))
sage: phi_k.degree() == phi_v.degree() == 3
True
sage: phi_k.is_separable()
True
sage: phi_v(E(0))
(0 : 1 : 0)
sage: alpha = E.base_field().gen()
sage: Q = E((0, alpha*(alpha + 1)))
sage: phi_v(Q)
(1 : alpha^2 + alpha : 1)
sage: phi_v(P) == phi_k(P)
True
sage: phi_k(P) == phi_v.codomain()(0)
True
```
We can create an isogeny whose kernel equals the full 2-torsion:

```
sage: E = EllipticCurve(GF((3,2)), [0,0,0,1,1])
sage: ker_poly = E.division_polynomial(2)
sage: phi = EllipticCurveIsogeny(E, ker_poly); phi
Isogeny of degree 4 from Elliptic Curve defined by y^2 = x^3 + x + 1 over Finite Field in z2 of size 3^2 to Elliptic Curve defined by y^2 = x^3 + x + 1 over Finite Field in z2 of size 3^2
sage: P1,P2,P3 = filter(bool, E(0).division_points(2))
sage: phi(P1)
(0 : 1 : 0)
sage: phi(P2)
(0 : 1 : 0)
sage: phi(P3)
(0 : 1 : 0)
sage: phi.degree()
4
```

We can also create trivial isogenies with the trivial kernel:

```
sage: E = EllipticCurve(GF(17), [11, 11, 4, 12, 10])
sage: phi_v = EllipticCurveIsogeny(E, E(0))
sage: phi_v.degree()
1
sage: phi_v.rational_maps()
(x, y)
sage: E == phi_v.codomain()
True
sage: P = E.random_point()
sage: phi_v(P) == P
True
sage: E = EllipticCurve(GF(31), [23, 1, 22, 7, 18])
sage: phi_k = EllipticCurveIsogeny(E, [1]); phi_k
Isogeny of degree 1 from Elliptic Curve defined by y^2 + 23*x*y + 22*y = x^3 + x^2 + 7*x + 18 over Finite Field of size 31 to Elliptic Curve defined by y^2 + 23*x*y + 22*y = x^3 + x^2 + 7*x + 18 over Finite Field of size 31
sage: phi_k.degree()
1
sage: phi_k.rational_maps()
(x, y)
sage: phi_k.codomain() == E
True
sage: phi_k.kernel_polynomial()
1
sage: P = E.random_point(); P == phi_k(P)
True
```

Vélu and Kohel also work in characteristic 0:

```
sage: E = EllipticCurve(QQ, [0,0,0,3,4])
sage: P_list = E.torsion_points()
sage: phi = EllipticCurveIsogeny(E, P_list); phi
Isogeny of degree 2 from Elliptic Curve defined by y^2 = x^3 + 3*x + 4 over Rational Field to Elliptic Curve defined by y^2 = x^3 - 27*x + 46 over Rational Field
```
sage: P = E((0, 2))
sage: phi(P)
(6 : -10 : 1)
sage: phi_ker_poly = phi.kernel_polynomial()
sage: phi_ker_poly
x + 1
sage: phi_k = EllipticCurveIsogeny(E, phi_ker_poly); phi_k
Isogeny of degree 2 from Elliptic Curve defined by y^2 = x^3 + 3*x + 4 over Rational Field to Elliptic Curve defined by y^2 = x^3 - 27*x + 46 over Rational Field
sage: phi_k(P) == phi(P)
True
sage: phi_k == phi
True
sage: phi_k.degree()
2
sage: phi_k.is_separable()
True

A more complicated example over the rationals (of odd degree):

sage: E = EllipticCurve('11a1')
sage: P_list = E.torsion_points()
sage: phi_v = EllipticCurveIsogeny(E, P_list); phi_v
Isogeny of degree 5 from Elliptic Curve defined by y^2 + y = x^3 - x^2 - 10*x - 20 over Rational Field to Elliptic Curve defined by y^2 + y = x^3 - x^2 - 7820*x - 263580 over Rational Field
sage: P = E((16, -61))
sage: phi_v(P)
(0 : 1 : 0)
sage: ker_poly = phi_v.kernel_polynomial(); ker_poly
x^2 - 21*x + 80
sage: phi_k = EllipticCurveIsogeny(E, ker_poly); phi_k
Isogeny of degree 5 from Elliptic Curve defined by y^2 + y = x^3 + (-1)*x^2 + (-10)*x + (-20) over Number Field in alpha with defining polynomial x^3 - 2*x^2 - 40*x - 158 to Elliptic Curve defined by y^2 + y = x^3 + (-1)*x^2 + (-7820)*x + (-263580) over Number Field in alpha with defining polynomial x^3 - 2*x^2 - 40*x - 158

We can also do this same example over the number field defined by the irreducible two-torsion polynomial of E:

sage: E = EllipticCurve('11a1')
sage: P_list = E.torsion_points()
sage: K.<alpha> = NumberField(x^3 - 2*x^2 - 40*x - 158)
sage: EK = E.change_ring(K)
sage: P_list = [EK(P) for P in P_list]
sage: phi_v = EllipticCurveIsogeny(EK, P_list); phi_v
Isogeny of degree 5 from Elliptic Curve defined by y^2 + y = x^3 - x^2 - 10*x - 20 over Number Field in alpha with defining polynomial x^3 - 2*x^2 - 40*x - 158 to Elliptic Curve defined by y^2 + y = x^3 - x^2 - 7820*x - 263580 over Number Field in alpha with defining polynomial x^3 - 2*x^2 - 40*x - 158

sage: phi_v(P) == phi_k(P)
True
sage: phi_k.is_separable()
True
sage: P = EK((alpha/2,-1/2))
sage: phi_v(P)
(122/121*alpha^2 + 1633/242*alpha - 3920/121 : -1/2 : 1)
sage: ker_poly = phi_v.kernel_polynomial()
sage: ker_poly
x^2 - 21*x + 80
sage: phi_k = EllipticCurveIsogeny(EK, ker_poly)
sage: phi_k
Isogeny of degree 5 from Elliptic Curve defined by y^2 + y = x^3 + (-1)*x^2 + (-10)*x + (-20) over Number Field in alpha with defining polynomial x^3 - 2*x^2 - 40*x - 158 to Elliptic Curve defined by y^2 + y = x^3 + (-1)*x^2 + (-7820)*x + (-263580) over Number Field in alpha with defining polynomial x^3 - 2*x^2 - 40*x - 158
sage: phi_v == phi_k
True
sage: phi_k(P) == phi_v(P)
True
sage: phi_k == phi_v
True
sage: phi_k.degree()
5
sage: phi_v.is_separable()
True

The following example shows how to specify an isogeny from domain and codomain:

sage: E = EllipticCurve('11a1')
sage: R.<x> = QQ[]
sage: f = x^2 - 21*x + 80
sage: phi = E.isogeny(f)
sage: E2 = phi.codomain()
sage: phi_s = EllipticCurveIsogeny(E, None, E2, 5)
sage: phi_s
Isogeny of degree 5 from Elliptic Curve defined by y^2 + y = x^3 - x^2 - 10*x - 20 over Rational Field to Elliptic Curve defined by y^2 + y = x^3 - x^2 - 7820*x - 263580 over Rational Field
sage: phi_s == phi
True
sage: phi_s.rational_maps() == phi.rational_maps()
True

However, only cyclic normalized isogenies can be constructed this way. The non-cyclic multiplication-by-3 isogeny won't be found:

sage: E.isogeny(None, codomain=E, degree=9)
Traceback (most recent call last):
... ValueError: the two curves are not linked by a cyclic normalized isogeny of degree 9

Non-normalized isogeny also won't be found:

sage: E2.isogeny(None, codomain=E, degree=5)
Traceback (most recent call last):
... Value ERROR: the two curves are not linked by a cyclic normalized isogeny of degree 5

```
sage: phihat = phi.dual(); phihat
Isogeny of degree 5 from Elliptic Curve defined by y^2 + y = x^3 - x^2 - 7820*x - 263580 over Rational Field to Elliptic Curve defined by y^2 + y = x^3 - x^2 - 10*x - 20 over Rational Field
```

```
sage: phihat.is_normalized()
False
```

Here an example of a construction of endomorphisms with cyclic kernel on a CM-curve:

```
sage: K.<i> = NumberField(x^2+1)
sage: E = EllipticCurve(K, [1,0])
sage: RK.<X> = K[]
sage: f = X^2 - 2/5*i + 1/5
sage: phi= E.isogeny(f)
sage: isom = phi.codomain().isomorphism_to(E)
sage: phi = isom * phi
sage: phi.codomain() == phi.domain()
True
sage: phi.rational_maps()
(((4/25*i + 3/25)*x^5 + (4/5*i - 2/5)*x^3 - x)/(x^4 + (-4/5*i + 2/5)*x^2 + (-4/25*i - 3/25)), ((11/125*i + 2/125)*x^6*y + (-23/125*i + 64/125)*x^4*y + (141/125*i + 162/125)*x^2*y + (3/25*i - 4/25)*y)/(x^6 + (-6/5*i + 3/5)*x^4 + (-12/25*i - 9/25)*x^2 + (2/125*i - 11/125)))
```

```

as_morphism() Return this isogeny as a morphism of projective schemes.

```

```
sage: k = GF(11)
sage: E = EllipticCurve(k, [1,1])
sage: Q = E(6,5)
sage: phi = E.isogeny(Q)
sage: mor = phi.as_morphism()
sage: mor.domain() == E
True
sage: mor.codomain() == phi.codomain()
True
sage: mor(Q) == phi(Q)
True
```

dual() Return the isogeny dual to this isogeny.

```

Note: If \( \varphi: E \rightarrow E' \) is the given isogeny and \( n \) is its degree, then the dual is by definition the unique isogeny \( \hat{\varphi}: E' \rightarrow E \) such that the compositions \( \hat{\varphi} \circ \varphi \) and \( \varphi \circ \hat{\varphi} \) are the multiplication-by-\( n \) maps on \( E \) and \( E' \), respectively.

```

EXAMPLES:
```python
sage: E = EllipticCurve('11a1')
sage: R.<x> = QQ[]
sage: f = x^2 - 21*x + 80
sage: phi = EllipticCurveIsogeny(E, f)
sage: phi_hat = phi.dual()
sage: phi_hat.domain() == phi.codomain()
True
sage: phi_hat.codomain() == phi.domain()
True
sage: (X, Y) = phi.rational_maps()
sage: (Xhat, Yhat) = phi_hat.rational_maps()
sage: Xm = Xhat.subs(x=X, y=Y)
sage: Ym = Yhat.subs(x=X, y=Y)
sage: (Xm, Ym) == E.multiplication_by_m(5)
True
```

```python
sage: E = EllipticCurve(GF(37), [0,0,0,1,8])
sage: R.<x> = GF(37)[]
sage: f = x^3 + x^2 + 28*x + 33
sage: phi = EllipticCurveIsogeny(E, f)
sage: phi_hat = phi.dual()
sage: phi_hat.domain() == phi.codomain()
True
sage: phi_hat.codomain() == phi.domain()
True
sage: (X, Y) = phi.rational_maps()
sage: (Xhat, Yhat) = phi_hat.rational_maps()
sage: Xm = Xhat.subs(x=X, y=Y)
sage: Ym = Yhat.subs(x=X, y=Y)
sage: (Xm, Ym) == E.multiplication_by_m(7)
True
```

```python
sage: E = EllipticCurve(GF(31), [0,0,0,1,8])
sage: R.<x> = GF(31)[]
sage: f = x^2 + 17*x + 29
sage: phi = EllipticCurveIsogeny(E, f)
sage: phi_hat = phi.dual()
sage: phi_hat.domain() == phi.codomain()
True
sage: phi_hat.codomain() == phi.domain()
True
sage: (X, Y) = phi.rational_maps()
sage: (Xhat, Yhat) = phi_hat.rational_maps()
sage: Xm = Xhat.subs(x=X, y=Y)
sage: Ym = Yhat.subs(x=X, y=Y)
sage: (Xm, Ym) == E.multiplication_by_m(5)
True
```

`get_post_isomorphism()`

Return the post-isomorphism of this isogeny, or None.

**Note:** Pre- and post-isomorphisms are an implementation detail of how isogenies are currently represented in Sage. They have limited inherent mathematical meaning and this method may disappear in a future version of Sage.
EXAMPLES:

```python
sage: E = EllipticCurve(j=GF(31)(0))
sage: R.<x> = GF(31)[]
sage: phi = EllipticCurveIsogeny(E, x+18)
sage: phi.get_post_isomorphism()
sage: from sage.schemes.elliptic_curves.weierstrass_morphism import WeierstrassIsomorphism
sage: isom = WeierstrassIsomorphism(phi.codomain(), (6,8,10,12))
sage: phi.set_post_isomorphism(isom)
...
sage: isom == phi.get_post_isomorphism()
True

sage: E = EllipticCurve(GF(83), [1,0,1,1,0])
sage: R.<x> = GF(83)[]; f = x+24
sage: phi = EllipticCurveIsogeny(E, f)
sage: E2 = phi.codomain()
sage: phi2 = EllipticCurveIsogeny(E, None, E2, 2)
sage: phi2.get_post_isomorphism()
Elliptic-curve morphism:
From: Elliptic Curve defined by y^2 = x^3 + 65*x + 69 over Finite Field of size 83
To: Elliptic Curve defined by y^2 + x*y + y = x^3 + 4*x + 16 over Finite Field of size 83
Via: (u,r,s,t) = (1, 7, 42, 42)
```

**get_pre_isomorphism()**

Return the pre-isomorphism of this isogeny, or None.

**Note:** Pre- and post-isomorphisms are an implementation detail of how isogenies are currently represented in Sage. They have limited inherent mathematical meaning and this method may disappear in a future release.

EXAMPLES:

```python
sage: E = EllipticCurve(GF(31), [1,1,0,1,-1])
sage: R.<x> = GF(31)[]
sage: f = x^3 + 9*x^2 + x + 30
sage: phi = EllipticCurveIsogeny(E, f)
sage: phi.get_post_isomorphism()
sage: Epr = E.short_weierstrass_model()
sage: isom = Epr.isomorphism_to(E)
sage: phi.set_pre_isomorphism(isom)
...
sage: isom == phi.get_pre_isomorphism()
True

sage: E = EllipticCurve(GF(83), [1,0,1,1,0])
sage: R.<x> = GF(83)[]; f = x+24
```
Elliptic curves, Release 9.7

```python
sage: phi = EllipticCurveIsogeny(E, f)
sage: E2 = phi.codomain()
sage: phi2 = EllipticCurveIsogeny(E, None, E2, 2)
sage: phi2.get_pre_isomorphism()
```

Elliptic-curve morphism:

From: Elliptic Curve defined by y^2 + x*y + y = x^3 + x over Finite Field of size 83
To: Elliptic Curve defined by y^2 = x^3 + 62*x + 74 over Finite Field of size 83
Via: (u,r,s,t) = (1, 76, 41, 3)


```
kernel_polynomial()

Return the kernel polynomial of this isogeny.

EXAMPLES:
```
```
sage: E = EllipticCurve(QQ, [0,0,2,0])
sage: phi = EllipticCurveIsogeny(E, E((0,0)))
sage: phi.kernel_polynomial()
x
```
```
sage: E = EllipticCurve('11a1')
sage: phi = EllipticCurveIsogeny(E, E.torsion_points())
sage: phi.kernel_polynomial()
x^2 - 21*x + 80
```
```
sage: E = EllipticCurve(GF(17), [1,-1,1,-1,1])
sage: phi = EllipticCurveIsogeny(E, [1])
sage: phi.kernel_polynomial()
1
```
```
sage: E = EllipticCurve(GF(31), [0,0,3,0])
sage: phi = EllipticCurveIsogeny(E, [0,3,0,1])
sage: phi.kernel_polynomial()
x^3 + 3*x
```

```
rational_maps()

Return the pair of rational maps defining this isogeny.

Note: Both components are returned as elements of the function field F(x, y) in two variables over the base field F, though the first only involves x. To obtain the x-coordinate function as a rational function in F(x), use x_rational_map().

EXAMPLES:
```
```
sage: E = EllipticCurve(QQ, [0,2,0,1,-1])
sage: phi = EllipticCurveIsogeny(E, [1])
sage: phi.rational_maps()
(x, y)
```
```
sage: E = EllipticCurve(GF(17), [0,0,3,0])
sage: phi = EllipticCurveIsogeny(E, E((0,0)))
```

(continues on next page)
sage: phi.rational_maps()
((x^2 + 3)/x, (x^2*y - 3*y)/x^2)

scaling_factor()
Return the Weierstrass scaling factor associated to this elliptic-curve isogeny.

The scaling factor is the constant \( u \) (in the base field) such that \( \varphi^* \omega_2 = u \omega_1 \), where \( \varphi : E_1 \to E_2 \) is this isogeny and \( \omega_i \) are the standard Weierstrass differentials on \( E_i \) defined by \( \frac{dx}{(2y + a_1x + a_3)} \).

EXAMPLES:

sage: E = EllipticCurve(GF(257^2), [0,1])
sage: phi = E.isogeny(E.lift_x(240))
sage: phi.degree()
43
sage: phi.scaling_factor()
1
sage: phi.dual().scaling_factor()
43

ALGORITHM: The “inner” isogeny is normalized by construction, so we only need to account for the scaling factors of a pre- and post-isomorphism.

set_post_isomorphism(postWI)
Modify this isogeny by postcomposing with a Weierstrass isomorphism.

Warning: Isogenies will be immutable in a future release of Sage. This method is deprecated in favor of using the * operator to compose elliptic-curve morphisms.

EXAMPLES:

sage: E = EllipticCurve(j=GF(31)(0))
sage: R.<x> = GF(31)[]
sage: phi = EllipticCurveIsogeny(E, x+18)
sage: from sage.schemes.elliptic_curves.weierstrass_morphism import WeierstrassIsomorphism
sage: phi.set_post_isomorphism(WeierstrassIsomorphism(phi.codomain(), (6,8,10, 12)))
...
sage: phi
Isogeny of degree 3 from Elliptic Curve defined by y^2 = x^3 + 1 over Finite Field of size 31 to Elliptic Curve defined by y^2 + 24*x*y + 7*y = x^3 + 22*x^2 + 16*x + 20 over Finite Field of size 31
sage: E = EllipticCurve(j=GF(47)(0))
sage: f = E.torsion_polynomial(3)/3
sage: phi = EllipticCurveIsogeny(E, f)
sage: E2 = phi.codomain()
sage: post_isom = E2.isomorphism_to(E)
sage: phi.set_post_isomorphism(post_isom)
...
sage: phi.rational_maps() == E.multiplication_by_m(3)
Elliptic curves, Release 9.7

(continued from previous page)

False
\begin{verbatim}
sage: phi.switch_sign()
...
sage: phi.rational_maps() == E.multiplication_by_m(3)
True
\end{verbatim}

Example over a number field:

\begin{verbatim}
sage: R.<x> = QQ[]
sage: K.<a> = NumberField(x^2 + 2)
sage: E = EllipticCurve(j=K(1728))
sage: ker_list = E.torsion_points()
sage: phi = EllipticCurveIsogeny(E, ker_list)
sage: from sage.schemes.elliptic_curves.weierstrass_morphism import WeierstrassIsomorphism
sage: post_isom = WeierstrassIsomorphism(phi.codomain(), (a,2,3,5))
sage: phi
Isogeny of degree 4 from Elliptic Curve defined by y^2 = x^3 + x over Number Field in a with defining polynomial x^2 + 2 to Elliptic Curve defined by y^2 = x^3 + (-44)*x + 112 over Number Field in a with defining polynomial x^2 + 2
\end{verbatim}

\texttt{set_pre_isomorphism}(\texttt{preWI})

Modify this isogeny by precomposing with a Weierstrass isomorphism.

\textbf{Warning}: Isogenies will be immutable in a future release of Sage. This method is deprecated in favor of using the * operator to compose elliptic-curve morphisms.

\textbf{EXAMPIES}:

\begin{verbatim}
sage: E = EllipticCurve(GF(31), [1,1,0,1,-1])
sage: R.<x> = GF(31)[]
sage: f = x^3 + 9*x^2 + x + 30
sage: phi = EllipticCurveIsogeny(E, f)
sage: Epr = E.short_weierstrass_model()
sage: isom = Epr.isomorphism_to(E)
sage: phi.set_pre_isomorphism(isom)
...
sage: phi.rational_maps()
((-6*x^4 - 3*x^3 + 12*x^2 + 10*x - 1)/(x^3 + x - 12), (3*x^7 + x^6*y - 14*x^6 - 1 - 3*x^5 + 5*x^4*y + 7*x^4 + 8*x^3*y - 8*x^3 - 5*x^2*y + 5*x^2 - 14*x*y + 14*x - 6*y - 6)/(x^6 + 2*x^4 + 7*x^3 + x^2 + 7*x - 11))
sage: phi(Epr((0,22)))
(13 : 21 : 1)
sage: phi(Epr((3,7)))
(14 : 17 : 1)
sage: E = EllipticCurve(GF(29), [0,0,0,1,0])
sage: R.<x> = GF(29)[]
sage: f = x^2 + 5
sage: phi = EllipticCurveIsogeny(E, f)
sage: phi
\end{verbatim}

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Isogeny of degree 5 from Elliptic Curve defined by $y^2 = x^3 + x$ over Finite Field of size 29 to Elliptic Curve defined by $y^2 = x^3 + 20*x$ over Finite Field of size 29

```
sage: from sage.schemes.elliptic_curves.weierstrass_morphism import WeierstrassIsomorphism
sage: inv_isom = WeierstrassIsomorphism(E, (1,-2,5,10))
sage: Epr = inv_isom.codomain()
sage: isom = Epr.isomorphism_to(E)
sage: phi.set_pre_isomorphism(isom)
...
sage: phi
Isogeny of degree 5 from Elliptic Curve defined by $y^2 + 10*x*y + 20*y = x^3 + 27*x^2 + 6$ over Finite Field of size 29 to Elliptic Curve defined by $y^2 = x^3 + 20*x$ over Finite Field of size 29
```

```
sage: phi(Epr((12,1)))
(26 : 0 : 1)
sage: phi(Epr((2,9)))
(0 : 0 : 1)
sage: phi(Epr((21,12)))
(3 : 0 : 1)
sage: phi.rational_maps()[0]
(x^5 - 10*x^4 - 6*x^3 - 7*x^2 - x + 3)/(x^4 - 8*x^3 + 5*x^2 - 14*x - 6)
```

```
sage: E = EllipticCurve('11a1')
sage: R.<x> = QQ[]
sage: f = x^2 - 21*x + 80
sage: phi = EllipticCurveIsogeny(E, f); phi
Isogeny of degree 5 from Elliptic Curve defined by $y^2 + y = x^3 - x^2 - 10*x - 20$ over Rational Field to Elliptic Curve defined by $y^2 + y = x^3 - x^2 - 7820*x - 263580$ over Rational Field
```

```
sage: from sage.schemes.elliptic_curves.weierstrass_morphism import WeierstrassIsomorphism
sage: Epr = E.short_weierstrass_model()
sage: isom = Epr.isomorphism_to(E)
sage: phi.set_pre_isomorphism(isom)
...
sage: phi
Isogeny of degree 5 from Elliptic Curve defined by $y^2 = x^3 - 13392*x - 1080432$ over Rational Field to Elliptic Curve defined by $y^2 + y = x^3 - x^2 - 7820*x - 263580$ over Rational Field
```

```
sage: phi(Epr((168,1188)))
(0 : 1 : 0)
```

```
switch_sign()

Compose this isogeny with $[-1]$ (negation).

Warning: Isogenies will be immutable in a future version of Sage. This method is deprecated in favor of using the unary - operator to negate elliptic-curve morphisms.

EXAMPLES:
sage: E = EllipticCurve(GF(23), [0,0,0,1,0])
sage: f = E.torsion_polynomial(3)/3
sage: phi = EllipticCurveIsogeny(E, f, E)
sage: phi.rational_maps() == E.multiplication_by_m(3)
False
sage: phi.switch_sign()

sage: phi.rational_maps() == E.multiplication_by_m(3)
True

sage: E = EllipticCurve(GF(17), [-2, 3, -5, 7, -11])
sage: R.<x> = GF(17)[]
sage: f = x+6
sage: phi = EllipticCurveIsogeny(E, f)

Isogeny of degree 2 from Elliptic Curve defined by y^2 + 15*x*y + 12*y = x^3 + 3*x^2 + 7*x + 6 over Finite Field of size 17 to Elliptic Curve defined by y^2 + 15*x*y + 12*y = x^3 + 3*x^2 + 4*x + 8 over Finite Field of size 17

sage: phi.rational_maps()
((x^2 + 6*x + 4)/(x + 6), (x^2*y - 5*x*y + 8*x - 2*y)/(x^2 - 5*x + 2))

sage: phi.switch_sign()

sage: phi.rational_maps()
((x^2 + 6*x + 4)/(x + 6), (2*x^3 - x^2*y - 5*x^2 + 5*x*y - 4*x + 2*y + 7)/(x^2 - 5*x + 2))

sage: E = EllipticCurve('11a1')
sage: R.<x> = QQ[]
sage: f = x^2 - 21*x + 80
sage: phi = EllipticCurveIsogeny(E, f)

sage: (xmap1, ymap1) = phi.rational_maps()

sage: phi.switch_sign()

sage: (xmap2, ymap2) = phi.rational_maps()

sage: xmap1 == xmap2
True

sage: ymap1 == -ymap2 - E.a1()*xmap2 - E.a3()
True

sage: K.<a> = NumberField(x^2 + 1)
sage: E = EllipticCurve(K, [0,0,0,1,0])
sage: R.<x> = K[]
sage: phi = EllipticCurveIsogeny(E, x-a)

sage: phi.rational_maps()
((x^2 + (-a)*x - 2)/(x + (-a)), (x^2*y + (-2*a)*x*y + y)/(x^2 + (-2*a)*x - 1))

sage: phi.switch_sign()

sage: phi.rational_maps()
((x^2 + (-a)*x - 2)/(x + (-a)), (-x^2*y + (2*a)*x*y - y)/(x^2 + (-2*a)*x - 1))
**x_rational_map()**

Return the rational map giving the $x$-coordinate of this isogeny.

**Note:** This function returns the $x$-coordinate component of the isogeny as a rational function in $F(x)$, where $F$ is the base field. To obtain both coordinate functions as elements of the function field $F(x,y)$ in two variables, use `rational_maps()`.

**EXAMPLES:**

```
sage: E = EllipticCurve(QQ, [0,2,0,1,-1])
sage: phi = EllipticCurveIsogeny(E, [1])
sage: phi.x_rational_map()
x
sage: E = EllipticCurve(GF(17), [0,0,0,3,0])
sage: phi = EllipticCurveIsogeny(E, E((0,0)))
sage: phi.x_rational_map()
(x^2 + 3)/x
```

sage.schemes.elliptic_curves.ell_curve_isogeny.compute_codomain_formula($E, v, w$)

Compute the codomain curve given parameters $v$ and $w$ (as in Vélu/Kohel/etc. formulas).

**INPUT:**

- $E$ – an elliptic curve
- $v, w$ – elements of the base field of $E$

**OUTPUT:**

The elliptic curve with invariants $[a_1, a_2, a_3, a_4 - 5v, a_6 - (a_1^2 + 4a_2)v - 7w]$ where $E = [a_1, a_2, a_3, a_4, a_6]$.

**EXAMPLES:**

This formula is used by every invocation of the `EllipticCurveIsogeny` constructor:

```
sage: E = EllipticCurve(GF(19), [1,2,3,4,5])
sage: phi = EllipticCurveIsogeny(E, E((1,2)))
sage: phi.codomain()  # Elliptic Curve defined by y^2 + x*y + 3*y = x^3 + x^2 + 9*x + 13 over Finite...
Field of size 19
sage: from sage.schemes.elliptic_curves.ell_curve_isogeny import compute_codomain_formula
sage: v = phi._EllipticCurveIsogeny__v
sage: w = phi._EllipticCurveIsogeny__w
sage: compute_codomain_formula(E, v, w) == phi.codomain()
True
```

sage.schemes.elliptic_curves.ell_curve_isogeny.compute_codomain_kohel($E, kernel$)

Compute the codomain from the kernel polynomial using Kohel’s formulas.

**INPUT:**

- $E$ – domain elliptic curve
- $kernel$ (polynomial or list) – the kernel polynomial, or a list of its coefficients

**OUTPUT:**
(elliptic curve) The codomain elliptic curve of the isogeny defined by kernel.

EXAMPLES:

```python
sage: from sage.schemes.elliptic_curves.ell_curve_isogeny import compute_codomain_kohel
sage: E = EllipticCurve(GF(19), [1,2,3,4,5])
```

```python
case: phi = EllipticCurveIsogeny(E, [9,1])
sage: phi.codomain() == isogeny_codomain_from_kernel(E, [9,1])
True
sage: compute_codomain_kohel(E, [9,1])
Elliptic Curve defined by y^2 + x*y + 3*y = x^3 + 2*x^2 + 9*x + 8 over Finite Field of size 19
```

```python
sage: R.<x> = GF(19)[]
```

```python
sage: E = EllipticCurve(GF(19), [18,17,16,15,14])
```

```python
case: phi = EllipticCurveIsogeny(E, x^3 + 14*x^2 + 3*x + 11)
sage: phi.codomain() == isogeny_codomain_from_kernel(E, x^3 + 14*x^2 + 3*x + 11)
True
sage: compute_codomain_kohel(E, x^3 + 14*x^2 + 3*x + 11)
Elliptic Curve defined by y^2 + 18*x*y + 16*y = x^3 + 17*x^2 + 18*x + 18 over Finite Field of size 19
```

```python
sage: E = EllipticCurve(GF(19), [1,2,3,4,5])
```

```python
case: phi = EllipticCurveIsogeny(E, x^3 + 7*x^2 + 15*x + 12)
```

```python
sage: isogeny_codomain_from_kernel(E, x^3 + 7*x^2 + 15*x + 12) == phi.codomain()
True
sage: compute_codomain_kohel(E, x^3 + 7*x^2 + 15*x + 12)
Elliptic Curve defined by y^2 + x*y + 3*y = x^3 + 2*x^2 + 3*x + 15 over Finite Field of size 19
```

ALGORITHM:

This function uses the formulas of Section 2.4 of [Koh1996].

```python
sage.schemes.elliptic_curves.ell_curve_isogeny.compute_intermediate_curves(E1, E2)
```

Return intermediate curves and isomorphisms.

Note: This is used to compute \( \wp \) functions from the short Weierstrass model more easily.

Warning: The base field must be of characteristic not equal to 2 or 3.

INPUT:

- E1, E2 – elliptic curves

OUTPUT:

A tuple `(pre_isomorphism, post_isomorphism, intermediate_domain, intermediate_codomain)` where:

- `intermediate_domain` is a short Weierstrass curve isomorphic to E1;
- `intermediate_codomain` is a short Weierstrass curve isomorphic to E2;
- `pre_isomorphism` is a normalized isomorphism from E1 to `intermediate_domain`;
- `post_isomorphism` is a normalized isomorphism from `intermediate_codomain` to E2.
EXAMPLES:

```python
sage: from sage.schemes.elliptic_curves.ell_curve_isogeny import compute_intermediate_curves
sage: E = EllipticCurve(GF(83), [1,0,1,1,0])
sage: R.<x> = GF(83)[]; f = x+24
sage: phi = EllipticCurveIsogeny(E, f)
sage: E2 = phi.codomain()
sage: compute_intermediate_curves(E, E2)
(Elliptic Curve defined by y^2 = x^3 + 62*x + 74 over Finite Field of size 83,
Elliptic Curve defined by y^2 = x^3 + 65*x + 69 over Finite Field of size 83,
Elliptic-curve morphism:
  From: Elliptic Curve defined by y^2 + x*y + y = x^3 + x over Finite Field of size 83
  To:  Elliptic Curve defined by y^2 = x^3 + 62*x + 74 over Finite Field of size 83
    Via: (u,r,s,t) = (1, 76, 41, 3),
Elliptic-curve morphism:
  From: Elliptic Curve defined by y^2 = x^3 + 65*x + 69 over Finite Field of size 83
  To:  Elliptic Curve defined by y^2 + x*y + y = x^3 + 4*x + 16 over Finite Field of size 83
    Via: (u,r,s,t) = (1, 7, 42, 42))
```

```python
sage: R.<x> = QQ[]
sage: K.<i> = NumberField(x^2 + 1)
sage: E = EllipticCurve(K, [0,0,0,1,0])
sage: E2 = EllipticCurve(K, [0,0,0,16,0])
sage: compute_intermediate_curves(E, E2)
(Elliptic Curve defined by y^2 = x^3 + x over Number Field in i with defining polynomial x^2 + 1,
Elliptic Curve defined by y^2 = x^3 + 16*x over Number Field in i with defining polynomial x^2 + 1,
Elliptic-curve endomorphism of Elliptic Curve defined by y^2 = x^3 + x over Number Field in i with defining polynomial x^2 + 1
  Via: (u,r,s,t) = (1, 0, 0, 0),
Elliptic-curve endomorphism of Elliptic Curve defined by y^2 = x^3 + 16*x over Number Field in i with defining polynomial x^2 + 1
  Via: (u,r,s,t) = (1, 0, 0, 0))
```

`sage.schemes.elliptic_curves.ell_curve_isogeny.compute_isogeny_kernel_polynomial(E1, E2, ell, algorithm='starks')`

Return the kernel polynomial of an isogeny of degree `ell` from `E1` to `E2`.

INPUT:
- `E1` – domain elliptic curve in short Weierstrass form
- `E2` – codomain elliptic curve in short Weierstrass form
- `ell` – the degree of an isogeny from `E1` to `E2`
- `algorithm` – currently only "starks" (default) is implemented

OUTPUT:
The kernel polynomial of an isogeny from `E1` to `E2`.
Note: If there is no degree-\(\ell\), cyclic, separable, normalized isogeny from \(E_1\) to \(E_2\), a \texttt{ValueError} will be raised.

EXAMPLES:

```python
sage: from sage.schemes.elliptic_curves.ell_curve_isogeny import compute_isogeny_kernel_polynomial

sage: E = EllipticCurve(GF(37), [0,0,1,8])

sage: R.<x> = GF(37)[]

sage: f = (x + 14) * (x + 30)

sage: phi = EllipticCurveIsogeny(E, f)

sage: E2 = phi.codomain()

sage: compute_isogeny_kernel_polynomial(E, E2, 5)
\(x^2 + 7x + 13\)

sage: f
\(x^2 + 7x + 13\)

sage: R.<x> = QQ[]

sage: K.<i> = NumberField(x^2 + 1)

sage: E = EllipticCurve(K, [0,0,1,0])

sage: E2 = EllipticCurve(K, [0,0,16,0])

sage: compute_isogeny_kernel_polynomial(E, E2, 4)
\(x^3 + x\)
```

\texttt{sage.schemes.elliptic_curves.ell_curve_isogeny.compute_isogeny_starks}(\texttt{E1}, \texttt{E2}, \texttt{ell})

Return the kernel polynomial of an isogeny of degree \(\ell\) from \(E_1\) to \(E_2\).

INPUT:

- \(E_1\) – domain elliptic curve in short Weierstrass form
- \(E_2\) – codomain elliptic curve in short Weierstrass form
- \(\ell\) – the degree of an isogeny from \(E_1\) to \(E_2\)

OUTPUT:

The kernel polynomial of an isogeny from \(E_1\) to \(E_2\).

Note: If there is no degree-\(\ell\), cyclic, separable, normalized isogeny from \(E_1\) to \(E_2\), a \texttt{ValueError} will be raised.

ALGORITHM:

This function uses Starks’ algorithm as presented in Section 6.2 of [BMSS2006].

Note: As published in [BMSS2006], the algorithm is incorrect, and a correct version (with slightly different notation) can be found in [Mo2009]. The algorithm originates in [Sta1973].

EXAMPLES:
```python
sage: from sage.schemes.elliptic_curves.ell_curve_isogeny import compute_isogeny_starks, compute_sequence_of_maps

sage: E = EllipticCurve(GF(97), [1,0,1,1,0])

sage: R.<x> = GF(97)[ ]; f = x^5 + 27*x^4 + 61*x^3 + 58*x^2 + 28*x + 21

sage: phi = EllipticCurveIsogeny(E, f)

sage: E2 = phi.codomain()

sage: (isom1, isom2, E1pr, E2pr, ker_poly) = compute_sequence_of_maps(E, E2, 11)

sage: compute_isogeny_starks(E1pr, E2pr, 11)

x^10 + 37*x^9 + 53*x^8 + 66*x^7 + 66*x^6 + 17*x^5 + 57*x^4 + 6*x^3 + 89*x^2 + 53*x + 8

sage: E = EllipticCurve(GF(37), [0,0,0,1,8])

sage: R.<x> = GF(37)[ ]

sage: f = (x + 14) * (x + 30)

sage: phi = EllipticCurveIsogeny(E, f)

sage: E2 = phi.codomain()

sage: compute_isogeny_starks(E, E2, 5)

x^4 + 14*x^3 + x^2 + 34*x + 21

sage: f**2

x^4 + 14*x^3 + x^2 + 34*x + 21

sage: E = EllipticCurve(QQ, [0,0,0,1,0])

sage: R.<x> = QQ[ ]

sage: f = x

sage: phi = EllipticCurveIsogeny(E, f)

sage: E2 = phi.codomain()

sage: compute_isogeny_starks(E, E2, 2)

x
```

```

Elliptic curves, Release 9.7

```

`sage.schemes.elliptic_curves.ell_curve_isogeny.computer_sequence_of_maps(E1, E2, ell)`

Return intermediate curves, isomorphisms and kernel polynomial.

**INPUT:**

- `E1, E2` – elliptic curves
- `ell` – a prime such that there is a degree-`ell` separable normalized isogeny from `E1` to `E2`

**OUTPUT:**

A tuple `(pre_isom, post_isom, E1pr, E2pr, ker_poly)` where:

- `E1pr` is an elliptic curve in short Weierstrass form isomorphic to `E1`;
- `E2pr` is an elliptic curve in short Weierstrass form isomorphic to `E2`;
- `pre_isom` is a normalized isomorphism from `E1` to `E1pr`;
- `post_isom` is a normalized isomorphism from `E2pr` to `E2`;
- `ker_poly` is the kernel polynomial of an `ell`-isogeny from `E1pr` to `E2pr`.

**EXAMPLES:**

```python
sage: from sage.schemes.elliptic_curves.ell_curve_isogeny import compute_sequence_of_maps

sage: E = EllipticCurve('11a1')

(continues on next page)```
sage: R.<x> = QQ[]; f = x^2 - 21*x + 80
sage: phi = EllipticCurveIsogeny(E, f)
sage: E2 = phi.codomain()
sage: compute_sequence_of_maps(E, E2, 5)

(Elliptic-curve morphism:
  From: Elliptic Curve defined by y^2 + y = x^3 - x^2 - 10*x - 20 over Rational Field
  To:  Elliptic Curve defined by y^2 = x^3 - 31/3*x - 2501/108 over Rational Field
    Via: (u,r,s,t) = (1, 1/3, 0, -1/2),
Elliptic-curve morphism:
  From: Elliptic Curve defined by y^2 = x^3 - 23461/3*x - 28748141/108 over Rational Field
  To:  Elliptic Curve defined by y^2 = x^3 - 31/3*x - 2501/108 over Rational Field
    Via: (u,r,s,t) = (1, -1/3, 0, 1/2),
Elliptic Curve defined by y^2 = x^3 - 23461/3*x - 28748141/108 over Rational Field,
x^2 - 61/3*x + 658/9)
sage: K.<i> = NumberField(x^2 + 1)
sage: E = EllipticCurve(K, [0,0,0,1,0])
sage: E2 = EllipticCurve(K, [0,0,0,16,0])
sage: compute_sequence_of_maps(E, E2, 4)

(Elliptic-curve endomorphism of Elliptic Curve defined by y^2 = x^3 + x over Number Field in i with defining polynomial x^2 + 1
  Via: (u,r,s,t) = (1, 0, 0, 0),
Elliptic-curve endomorphism of Elliptic Curve defined by y^2 = x^3 + 16*x over Number Field in i with defining polynomial x^2 + 1
  Via: (u,r,s,t) = (1, 0, 0, 0),
Elliptic Curve defined by y^2 = x^3 + x over Number Field in i with defining polynomial x^2 + 1,
x^3 + x)
sage: E = EllipticCurve(GF(97), [1,0,1,1,0])
sage: R.<x> = GF(97)[ ]; f = x^5 + 27*x^4 + 61*x^3 + 58*x^2 + 28*x + 21
sage: phi = EllipticCurveIsogeny(E, f)
sage: E2 = phi.codomain()
sage: compute_sequence_of_maps(E, E2, 11)

(Elliptic-curve morphism:
  From: Elliptic Curve defined by y^2 + x*y + y = x^3 + x over Finite Field of size 97
  To:  Elliptic Curve defined by y^2 = x^3 + 52*x + 31 over Finite Field of size 97
    Via: (u,r,s,t) = (1, 8, 48, 44),
Elliptic-curve morphism:
  From: Elliptic Curve defined by y^2 = x^3 + 41*x + 66 over Finite Field of size 97
  To:  Elliptic Curve defined by y^2 + x*y + y = x^3 + 87*x + 26 over Finite Field of size 97
    Via: (u,r,s,t) = (1, 89, 49, 49),
Elliptic Curve defined by y^2 = x^3 + 52*x + 31 over Finite Field of size 97,
Elliptic Curve defined by y^2 = x^3 + 41*x + 66 over Finite Field of size 97,
sage.schemes.elliptic_curves.ell_curve_isogeny.compute_vw_kohel_even_deg1(x0, y0, a1, a2, a4)
Compute Vélu's \((v, w)\) using Kohel's formulas for isogenies of degree exactly divisible by 2.

**INPUT:**

- \(x0, y0\) – coordinates of a 2-torsion point on an elliptic curve \(E\)
- \(a1, a2, a4\) – invariants of \(E\)

**OUTPUT:**

(tuple) Vélu's isogeny parameters \((v, w)\).

**EXAMPLES:**

This function will be implicitly called by the following example:

```python
sage: E = EllipticCurve(GF(19), [1,2,3,4,5])
sage: phi = EllipticCurveIsogeny(E, [9,1]); phi
Isogeny of degree 2 from Elliptic Curve defined by y^2 + x*y + 3*y = x^3 + 2*x^2 + 4*x + 5 over Finite Field of size 19 to Elliptic Curve defined by y^2 + x*y + 3*y = x^3 + 2*x^2 + 9*x + 8 over Finite Field of size 19
sage: from sage.schemes.elliptic_curves.ell_curve_isogeny import compute_vw_kohel_even_deg1
sage: a1,a2,a3,a4,a6 = E.a_invariants()
sage: x0 = -9
sage: y0 = -(a1*x0 + a3)/2
sage: compute_vw_kohel_even_deg1(x0, y0, a1, a2, a4)
(18, 9)
```

sage.schemes.elliptic_curves.ell_curve_isogeny.compute_vw_kohel_even_deg3(b2, b4, s1, s2, s3)
Compute Vélu's \((v, w)\) using Kohel's formulas for isogenies of degree divisible by 4.

**INPUT:**

- \(b2, b4\) – invariants of an elliptic curve \(E\)
- \(s1, s2, s3\) – signed coefficients of the 2-division polynomial of \(E\)

**OUTPUT:**

(tuple) Vélu's isogeny parameters \((v, w)\).

**EXAMPLES:**

This function will be implicitly called by the following example:

```python
sage: E = EllipticCurve(GF(19), [1,2,3,4,5])
sage: R.<x> = GF(19)[]
sage: phi = EllipticCurveIsogeny(E, x^3 + 7*x^2 + 15*x + 12); phi
Isogeny of degree 4 from Elliptic Curve defined by y^2 + x*y + 3*y = x^3 + 2*x^2 + 4*x + 5 over Finite Field of size 19 to Elliptic Curve defined by y^2 + x*y + 3*y = x^3 + 2*x^2 + 3*x + 15 over Finite Field of size 19
sage: from sage.schemes.elliptic_curves.ell_curve_isogeny import compute_vw_kohel_even_deg3
sage: b2,b4 = E.b2(), E.b4()
sage: s1, s2, s3 = -7, 15, -12
sage: compute_vw_kohel_even_deg3(b2, b4, s1, s2, s3)
(18, 9)
```
sage: compute_vw_kohel_even_deg3(b2, b4, s1, s2, s3)
(4, 7)

sage.schemes.elliptic_curves.ell_curve_isogeny.compute_vw_kohel_odd(b2, b4, b6, s1, s2, s3, n)
Compute Vélu’s \((v, w)\) using Kohel’s formulas for isogenies of odd degree.

INPUT:

- \(b2, b4, b6\) – invariants of an elliptic curve \(E\)
- \(s1, s2, s3\) – signed coefficients of lowest powers of \(x\) in the kernel polynomial
- \(n\) (integer) – the degree

OUTPUT:

(tuple) Vélu’s isogeny parameters \((v, w)\).

EXAMPLES:

This function will be implicitly called by the following example:

```
sage: E = EllipticCurve(GF(19), [18,17,16,15,14])
sage: R.<x> = GF(19)[]
sage: phi = EllipticCurveIsogeny(E, x^3 + 14*x^2 + 3*x + 11); phi
Isogeny of degree 7 from Elliptic Curve defined by y^2 + 18*x*y + 16*y = x^3 + 17*x^2 + 18*x + 18 over Finite Field of size 19 to Elliptic Curve defined by y^2 + 18*x*y + 16*y = x^3 + 17*x^2 + 18*x + 18 over Finite Field of size 19
sage: from sage.schemes.elliptic_curves.ell_curve_isogeny import compute_vw_kohel_odd
sage: b2,b4,b6 = E.b2(), E.b4(), E.b6()
sage: s1,s2,s3 = -14,3,-11
sage: compute_vw_kohel_odd(b2,b4,b6,s1,s2,s3,3)
(7, 1)
```

sage.schemes.elliptic_curves.ell_curve_isogeny.fill_isogeny_matrix(M)
Return a filled isogeny matrix giving all degrees from one giving only prime degrees.

INPUT:

- \(M\) – a square symmetric matrix whose off-diagonal \(i, j\) entry is either a prime \(l\) if the \(i\)’th and \(j\)’th curves have an \(l\)-isogeny between them, otherwise 0

OUTPUT:

(matrix) A square matrix with entries 1 on the diagonal, and in general the \(i, j\) entry is \(d > 0\) if \(d\) is the minimal degree of an isogeny from the \(i\)’th to the \(j\)’th curve.

EXAMPLES:

```
sage: M = Matrix([[0, 2, 3, 3, 0, 0], [2, 0, 0, 0, 3, 3], [3, 0, 0, 0, 2, 0], [3, 0, 0, 0, 2, 0], [0, 3, 0, 0, 0, 0]])
sage: from sage.schemes.elliptic_curves.ell_curve_isogeny import fill_isogeny_matrix
```
sage: fill_isogeny_matrix(M)

\[
\begin{bmatrix}
1 & 2 & 3 & 3 & 6 & 6 \\
2 & 1 & 6 & 6 & 3 & 3 \\
3 & 6 & 1 & 9 & 2 & 18 \\
3 & 6 & 9 & 1 & 18 & 2 \\
6 & 3 & 2 & 18 & 1 & 9 \\
6 & 3 & 18 & 2 & 9 & 1
\end{bmatrix}
\]

sage.schemes.elliptic_curves.ell_curve_isogeny.isogeny_codomain_from_kernel(E, kernel, degree=None)

Compute the isogeny codomain given a kernel.

INPUT:

- E – domain elliptic curve
- kernel – either a list of points in the kernel of the isogeny, or a kernel polynomial (specified as either a univariate polynomial or a coefficient list)

OUTPUT:

(elliptic curve) The codomain of the separable normalized isogeny defined by this kernel.

EXAMPLES:

sage: from sage.schemes.elliptic_curves.ell_curve_isogeny import isogeny_codomain_from_kernel

sage: E = EllipticCurve(GF(7), [1,0,1,0,1])
sage: R.<x> = GF(7)[]
sage: isogeny_codomain_from_kernel(E, [4,1])
Elliptic Curve defined by y^2 + x*y + y = x^3 + 4*x + 6 over Finite Field of size 7
sage: EllipticCurveIsogeny(E, [4,1]).codomain() == isogeny_codomain_from_kernel(E, [4,1])
True
sage: isogeny_codomain_from_kernel(E, x^3 + x^2 + 4*x + 3)
Elliptic Curve defined by y^2 + x*y + y = x^3 + 4*x + 6 over Finite Field of size 7
sage: EllipticCurveIsogeny(E, x^3 + 2*x^2 + 4*x + 3)
Elliptic Curve defined by y^2 + x*y + y = x^3 + 5*x + 2 over Finite Field of size 7

sage: E = EllipticCurve(GF(19), [1,2,3,4,5])
sage: kernel_list = [E((15,10)), E((10,3)), E((6,5))]
sage: isogeny_codomain_from_kernel(E, kernel_list)
Elliptic Curve defined by y^2 + x*y + 3*y = x^3 + 2*x^2 + 3*y + 15 over Finite Field of size 19

sage.schemes.elliptic_curves.ell_curve_isogeny.split_kernel_polynomial(poly)

Obsolete internal helper function formerly used by compute_isogeny_kernel_polynomial().

Use radical() instead.

INPUT:

- poly – a nonzero univariate polynomial

OUTPUT:

The maximum separable divisor of poly. If the input is a full kernel polynomial where the roots which are x-coordinates of points of order greater than 2 have multiplicity 1, the output will be a polynomial with the same
roots, all of multiplicity 1.

EXAMPLES:

Check that this behaves identically to \texttt{.radical()}:

```python
sage: from sage.schemes.elliptic_curves.ell_curve_isogeny import split_kernel_polynomial
sage: q = next_prime(randrange(3,10^3))
```

```python
sage: e = randrange(1,5)
```

```python
sage: R = GF(q^e, 'a')['x']
```

```python
sage: f = R.random_element(randrange(10,100)).monic()
```

```python
sage: split_kernel_polynomial(f) == f.radical()
```

doctest:warning ...
DeprecationWarning: ...
True
```

\texttt{sage.schemes.elliptic_curves.ell_curve_isogeny.two_torsion_part}(\texttt{E, psi})

Return the greatest common divisor of \texttt{psi} and the 2-torsion polynomial of \texttt{E}.

**INPUT:**

- \texttt{E} – an elliptic curve
- \texttt{psi} – a univariate polynomial over the base field of \texttt{E}

**OUTPUT:**

(polynomial) The gcd of \texttt{psi} and the 2-torsion polynomial of \texttt{E}.

**EXAMPLES:**

Every function that computes the kernel polynomial via Kohel’s formulas will call this function:

```python
sage: E = EllipticCurve(GF(19), [1,2,3,4,5])
```

```python
sage: R.<x> = GF(19)[]
```

```python
sage: phi = EllipticCurveIsogeny(E, x + 13)
```

```python
sage: isogeny_codomain_from_kernel(E, x + 13) == phi.codomain()
```

```python
True
```

```python
sage: from sage.schemes.elliptic_curves.ell_curve_isogeny import two_torsion_part
```

```python
sage: two_torsion_part(E, x+13)
```

x + 13

\texttt{sage.schemes.elliptic_curves.ell_curve_isogeny.unfill_isogeny_matrix}(\texttt{M})

Reverses the action of \texttt{fill_isogeny_matrix}.

**INPUT:**

- \texttt{M} – a square symmetric matrix of integers

**OUTPUT:**

(matrix) A square symmetric matrix obtained from \texttt{M} by replacing non-prime entries with 0.

**EXAMPLES:**

```python
sage: M = Matrix([[0, 2, 3, 0, 0], [2, 0, 0, 0, 2], [3, 0, 0, 2, 0], [0, 3, 2, 0, 0], [0, 0, 0, 3, 0]]); M
```

```
(continues on next page)


```python
[3 0 0 0 0 2]
[0 3 2 0 0 0]
[0 3 0 2 0 0]

sage: from sage.schemes.elliptic_curves.ell_curve_isogeny import fill_isogeny_matrix, unfill_isogeny_matrix

sage: M1 = fill_isogeny_matrix(M); M1
[[1 2 3 3 6 6]
 [2 1 6 6 3 3]
 [3 6 1 9 2 18]
 [3 6 9 1 18 2]
 [6 3 2 18 1 9]
 [6 3 18 2 9 1]]

sage: unfill_isogeny_matrix(M1)
[0 2 3 3 0 0]
[2 0 0 0 3 3]
[3 0 0 0 2 0]
[3 0 0 0 0 2]
[0 3 2 0 0 0]
[0 3 0 2 0 0]

sage: unfill_isogeny_matrix(M1) == M
True
```
√ÉLU ALGORITHM FOR ELLIPTIC-CURVE ISOGENIES

The √élü algorithm computes isogenies of elliptic curves in time $\tilde{O}(\sqrt{\ell})$ rather than naïvely $O(\ell)$, where $\ell$ is the degree.

The core idea is to reindex the points in the kernel subgroup in a baby-step-giant-step manner, then use fast resultant computations to evaluate “elliptic polynomials” (see FastEllipticPolynomial) in essentially square-root time.

Based on experiments with Sage version 9.7, the isogeny degree where EllipticCurveHom_velusqrt begins to outperform EllipticCurveIsogeny can be as low as $\approx 100$, but is typically closer to $\approx 1000$, depending on the exact situation.

REFERENCES: [BDLS2020]

EXAMPLES:

```
sage: from sage.schemes.elliptic_curves.hom_velusqrt import EllipticCurveHom_velusqrt
sage: E = EllipticCurve(GF(6666679), [5,5])
sage: K = E(9970, 1003793, 1)
sage: K.order()
10009
sage: phi = EllipticCurveHom_velusqrt(E, K)
sage: phi
Elliptic-curve isogeny (using √élü) of degree 10009:
  From: Elliptic Curve defined by y^2 = x^3 + 5*x + 5 over Finite Field of size 6666679
  To:   Elliptic Curve defined by y^2 = x^3 + 227975*x + 3596133 over Finite Field of size 6666679

sage: phi.codomain()
Elliptic Curve defined by y^2 = x^3 + 227975*x + 3596133 over Finite Field of size 6666679
```

Note that the isogeny is usually not identical to the one computed by EllipticCurveIsogeny:

```
sage: psi = EllipticCurveIsogeny(E, K)
sage: psi
Isogeny of degree 10009
  from Elliptic Curve defined by y^2 = x^3 + 5*x + 5 over Finite Field of size 6666679
to Elliptic Curve defined by y^2 = x^3 + 5344836*x + 3950273 over Finite Field of size 6666679

sage: isos = psi.codomain().isomorphisms(phi.codomain())
sage: sum(iso * psi == phi for iso in isos)
1
```

However, they are certainly separable isogenies with the same kernel and must therefore be equal up to post-isomorphism:
Just like \textit{EllipticCurveIsogeny}, the constructor supports a \texttt{model} keyword argument:

\begin{verbatim}
sage: E = EllipticCurve(GF(6666679), [1,1])
sage: K = E(9091, 517864)
sage: phi = EllipticCurveHom_velusqrt(E, K, model='montgomery')
sage: phi
Elliptic-curve isogeny (using $\sqrt{\text{elu}}$) of degree 2999:
  From: Elliptic Curve defined by y^2 = x^3 + x + 1 over Finite Field of size 6666679
  To:  Elliptic Curve defined by y^2 = x^3 + 1559358*x^2 + x over Finite Field of size 6666679

Internally, \textit{EllipticCurveHom_velusqrt} works on short Weierstraß curves, but it performs the conversion automatically:

\begin{verbatim}
sage: E = EllipticCurve(GF(101), [1,2,3,4,5])
sage: K = E(1, 2)
sage: K.order()
37
sage: EllipticCurveHom_velusqrt(E, K)
Elliptic-curve isogeny (using $\sqrt{\text{elu}}$) of degree 37:
  From: Elliptic Curve defined by y^2 + x*y + 3*y = x^3 + 2*x^2 + 4*x + 5 over Finite Field of size 101
  To:  Elliptic Curve defined by y^2 = x^3 + 66*x + 86 over Finite Field of size 101
\end{verbatim}

However, this does imply not all elliptic curves are supported. Curves without a short Weierstraß model exist in characteristics 2 and 3:

\begin{verbatim}
sage: F.<t> = GF(3^3)
sage: E = EllipticCurve(F, [1,1,1,1,1])
sage: P = E(t^2+2, 1)
sage: P.order()
19
sage: EllipticCurveHom_velusqrt(E, P)
Traceback (most recent call last):
  ... NotImplementedError: only implemented for curves having a short Weierstrass model
\end{verbatim}

Furthermore, the implementation is restricted to finite fields, since this appears to be the most relevant application for the $\sqrt{\text{elu}}$ algorithm:

\begin{verbatim}
sage: E = EllipticCurve('26b1')
sage: P = E(1,0)
sage: P.order()
7
sage: EllipticCurveHom_velusqrt(E, P)
Traceback (most recent call last):
  ... NotImplementedError: only implemented for elliptic curves over finite fields
\end{verbatim}

\textbf{Note:} Currently \textit{EllipticCurveHom_velusqrt} does not implement all methods of \textit{EllipticCurveHom}. This will hopefully change in the future.

\textbf{AUTHORS:}
class sage.schemes.elliptic_curves.hom_velusqrt.EllipticCurveHom_velusqrt(E, P, codomain, model, Q)

Bases: sage.schemes.elliptic_curves.hom.EllipticCurveHom

This class implements separable odd-degree isogenies of elliptic curves over finite fields using the \(\sqrt{\text{elu}}\) algorithm.

The complexity is \(O(\sqrt{\ell})\) base-field operations, where \(\ell\) is the degree.

REFERENCES: [BDLS2020]

INPUT:

• E – an elliptic curve over a finite field
• P – a point on \(E\) of odd order \(\geq 5\)
• codomain – codomain elliptic curve (optional)
• model – string (optional); input to compute_model()
• Q – a point on \(E\) outside \(\langle P\rangle\), or None

EXAMPLES:

```python
sage: from sage.schemes.elliptic_curves.hom_velusqrt import EllipticCurveHom_velusqrt
sage: F.<t> = GF(10009^3)
sage: E = EllipticCurve(F, [t,t])
sage: K = E(2154*t^2 + 5711*t + 2899, 7340*t^2 + 4653*t + 6935)
sage: phi = EllipticCurveHom_velusqrt(E, K); phi
Elliptic-curve isogeny (using \(\sqrt{\text{elu}}\)) of degree 601:
  From: Elliptic Curve defined by y^2 = x^3 + t*x + t over Finite Field in t of size 10009^3
  To:  Elliptic Curve defined by y^2 = x^3 + (263*t^2+3173*t+4759)*x + (3898*t^2+6111*t+9443) over Finite Field in t of size 10009^3
sage: phi(K)
(0 : 1 : 0)
sage: P = E(2, 3163*t^2 + 7293*t + 5999)
sage: phi(P)
(6085*t^2 + 855*t + 8720 : 8078*t^2 + 9889*t + 6030 : 1)
sage: Q = E(6, 5575*t^2 + 6607*t + 9991)
sage: phi(Q)
(626*t^2 + 9749*t + 1291 : 5931*t^2 + 8549*t + 3111 : 1)
sage: phi(P) + phi(Q)
(983*t^2 + 4894*t + 4072 : 5047*t^2 + 9325*t + 336 : 1)
```

See also:

EllipticCurveIsogeny

class sage.schemes.elliptic_curves.hom_velusqrt.FastEllipticPolynomial(E, n, P, Q=None)

Bases: object

A class to represent and evaluate an elliptic polynomial, and optionally its derivative, in essentially square-root time.
The elliptic polynomials computed by this class are of the form

\[ h_S(Z) = \prod_{i \in S} (Z - x(Q + [i]P)) \]

where \( P \) is a point of odd order \( n \geq 5 \) and \( Q \) is either None, in which case it is assumed to be \( \infty \), or an arbitrary point which is not a multiple of \( P \).

The index set \( S \) is chosen as follows:

- If \( Q \) is given, then \( S = \{0, 1, 2, 3, ..., n - 1\} \).
- If \( Q \) is omitted, then \( S = \{1, 3, 5, ..., n - 2\} \). Note that in this case, \( h_{\{1,3,5,\ldots,n-1\}} \) can be computed as \( h_S^3 \) since \( n \) is odd.

**INPUT:**
- \( E \) – an elliptic curve in short Weierstraß form
- \( n \) – an odd integer \( \geq 5 \)
- \( P \) – a point on \( E \)
- \( Q \) – a point on \( E \), or None

**ALGORITHM:** [BDLS2020], Algorithm 2

**Note:** Currently only implemented for short Weierstraß curves.

**EXAMPLES:**

```python
sage: from sage.schemes.elliptic_curves.hom_velusqrt import FastEllipticPolynomial
sage: E = EllipticCurve(GF(71), [5,5])
sage: P = E(4, 35)

sage: hP = FastEllipticPolynomial(E, P.order(), P); hP
Fast elliptic polynomial prod(Z - x[i*P] for i in range(1,n,2)) with n = 19, P = (4 → 35 : 1)

sage: hP(7)
19

sage: prod(7 - (i*P).xy()[0] for i in range(1,P.order(),2))
19
```

Passing \( Q \) changes the index set:

```python
sage: Q = E(0, 17)

sage: hPQ = FastEllipticPolynomial(E, P.order(), P, Q)

sage: hPQ(7)
58

sage: prod(7 - (Q+i*P).xy()[0] for i in range(P.order()))
58
```

The call syntax has an optional keyword argument derivative, which will make the function return the pair \((h_S(\alpha), h_S'(\alpha))\) instead of just \(h_S(\alpha)\):

```python
sage: hP(7, derivative=True)
(19, 15)

sage: R.<Z> = E.base_field()

sage: HP = prod(Z - (i*P).xy()[0] for i in range(1,P.order(),2))
```

(continues on next page)
sage: HP
Z^9 + 16*Z^8 + 57*Z^7 + 6*Z^6 + 45*Z^5 + 31*Z^4 + 46*Z^3 + 10*Z^2 + 28*Z + 41
sage: HP(7)
19
sage: HP.derivative()(7)
15

sage: hPQ(7, derivative=True)
(58, 62)
sage: R.<Z> = E.base_field()

sage: HPQ = prod(Z - (Q+i*P).xy()[0] for i in range(P.order()))
sage: HPQ
→ + 29*Z^10 + 38*Z^9 + 48*Z^8 + 38*Z^7 + 43*Z^6 + 21*Z^5 + 25*Z^4 + 33*Z^3 + 49*Z^2
→ + 60*Z
sage: HPQ(7)
58
sage: HPQ.derivative()(7)
62

The input can be an element of any algebra over the base ring:

sage: R.<T> = GF(71)[]
sage: S.<t> = R.quotient(T^2)
sage: hP(7 + t)
15*t + 19

class sage.schemes.elliptic_curves.hom_velusqrt.ProductTree(leaves)

Bases: object

A simple product tree.

INPUT:

• leaves – a sequence of elements in a common ring

EXAMPLES:

sage: from sage.schemes.elliptic_curves.hom_velusqrt import ProductTree
sage: R.<x> = GF(101)[]
sage: vs = [x - i for i in range(1,10)]
sage: tree = ProductTree(vs)
sage: tree.value()
x^9 + 56*x^8 + 62*x^7 + 44*x^6 + 47*x^5 + 42*x^4 + 15*x^3 + 11*x^2 + 12*x + 13
sage: tree.remainders(x^7 + x + 1)
[3, 30, 70, 27, 58, 72, 98, 98, 23]
sage: tree.remainders(x^100)
[1, 1, 1, 1, 1, 1, 1, 1, 1, 1]

sage: vs = prime_range(100)
sage: tree = ProductTree(vs)
sage: tree.value().factor()
2 * 3 * 5 * 7 * 11 * 13 * 17 * 19 * 23 * 29 * 31 * 37 * 41 * 43 * 47 * 53 * 59 * 61
→ * 67 * 71 * 73 * 79 * 83 * 89 * 97
We can access the individual layers of the tree:

```
sage: tree.layers
[(2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41, 43, 47, 53, 59, 61, 67, 71, 73, 79, 83, 89, 97),
 (6, 35, 143, 323, 667, 1147, 1763, 2491, 3599, 4757, 5767, 7387, 97),
 (210, 46189, 765049, 4391633, 17120443, 42600829, 97),
 (9699690, 3359814435017, 729345064647247, 97),
 (32589158477190044730, 70746471270782959),
 (2305567963945518424753102147331756070, )]
```

**Note:** Use this class if you need the `remainders()` method. To compute just the product, `prod()` is likely faster.

`remainders(x)`

Given a value $x$, return a list of all remainders of $x$ modulo the leaves of this product tree.

The base ring must support the `%` operator for this method to work.

**INPUT:**

- $x$ – an element of the base ring of this product tree

**EXAMPLES:**

```
sage: from sage.schemes.elliptic_curves.hom_velusqrt import ProductTree
sage: vs = prime_range(100)
sage: tree = ProductTree(vs)
sage: n = 1085749272376749812331712967
sage: tree.remainders(n)
[1, 1, 2, 1, 9, 1, 7, 15, 8, 20, 15, 6, 27, 11, 2, 6, 0, 25, 49, 5, 51, 4, 19, 74, 13]
sage: [n % v for v in vs]
[1, 1, 2, 1, 9, 1, 7, 15, 8, 20, 15, 6, 27, 11, 2, 6, 0, 25, 49, 5, 51, 4, 19, 74, 13]
```

`value()`

Return the value represented by this product tree (i.e., the product of all leaves).

**EXAMPLES:**

```
sage: from sage.schemes.elliptic_curves.hom_velusqrt import ProductTree
sage: R.<x> = GF(101)[]
sage: vs = [x - i for i in range(1,10)]
sage: tree = ProductTree(vs)
sage: tree.value()
x^9 + 56*x^8 + 62*x^7 + 44*x^6 + 47*x^5 + 42*x^4 + 15*x^3 + 11*x^2 + 12*x + 13
sage: tree.value() == prod(vs)
True
```
sage.schemes.elliptic_curves.hom_velusqrt.prod_with_derivative(pairs)
Given a list of pairs \((f, \partial f)\) of ring elements, return the pair \((\prod f, \partial \prod f)\), assuming \(\partial\) is an operator obeying the standard product rule.

This function is entirely algebraic, hence still works when the elements \(f\) and \(\partial f\) are all passed through some ring homomorphism first. (See the polynomial-evaluation example below.)

INPUT:

- pairs – a sequence of tuples \((f, \partial f)\) of elements of a common ring

ALGORITHM:

This function wraps the given pairs in a thin helper class that automatically applies the product rule whenever multiplication is invoked, then calls \texttt{prod()} on the wrapped pairs.

EXAMPLES:

\begin{verbatim}
sage: from sage.schemes.elliptic_curves.hom_velusqrt import prod_with_derivative
sage: R.<x> = ZZ[]
sage: fs = [x^2 + 2*x + 3, 4*x + 5, 6*x^7 + 8*x + 9]
sage: prod(fs)
24*x^10 + 78*x^9 + 132*x^8 + 90*x^7 + 32*x^4 + 140*x^3 + 293*x^2 + 318*x + 135
sage: prod(fs).derivative()
240*x^9 + 702*x^8 + 1056*x^7 + 630*x^6 + 128*x^3 + 420*x^2 + 586*x + 318
sage: F, dF = prod_with_derivative((f, f.derivative()) for f in fs)
sage: F
24*x^10 + 78*x^9 + 132*x^8 + 90*x^7 + 32*x^4 + 140*x^3 + 293*x^2 + 318*x + 135
sage: dF
240*x^9 + 702*x^8 + 1056*x^7 + 630*x^6 + 128*x^3 + 420*x^2 + 586*x + 318
\end{verbatim}

The main reason for this function to exist is that it allows us to \textit{evaluate} the derivative of a product of polynomials at a point \(\alpha\) without ever fully expanding the product as \textit{a polynomial}:

\begin{verbatim}
sage: alpha = 42
sage: F(alpha)
442943981574522759
sage: dF(alpha)
104645261461514994
sage: us = [f(alpha) for f in fs]
sage: vs = [f.derivative()(alpha) for f in fs]
sage: prod_with_derivative(zip(us, vs))
(442943981574522759, 104645261461514994)
\end{verbatim}
COMPOSITE MORPHISMS OF ELLIPTIC CURVES

It is often computationally convenient (for example, in cryptography) to factor an isogeny of large degree into a composition of isogenies of smaller (prime) degree. This class implements such a decomposition while exposing (close to) the same interface as “normal”, unfactored elliptic-curve isogenies.

Warning: This module is currently considered experimental. It may change in a future release without prior warning, or even be removed altogether if things turn out to be unfixably broken.

EXAMPLES:
The following example would take quite literally forever with the straightforward \texttt{EllipticCurveIsogeny} implementation, but decomposing into prime steps is exponentially faster:

\begin{verbatim}
from sage.schemes.elliptic_curves.hom_composite import EllipticCurveHom_composite
doctest:warning...
...
sage: p = 3 * 2^143 - 1
sage: GF(p^2).inject_variables()
Defining z2
sage: E = EllipticCurve(GF(p^2), [1,0])
sage: P = E.lift_x(31415926535897932384626433832795028841971 - z2)
sage: P.order().factor()
2^143
sage: EllipticCurveHom_composite(E, P)
Composite morphism of degree 11150372599265311570767859136324180752990208 = 2^143:
  From: Elliptic Curve defined by y^2 = x^3 + x over Finite Field in z2 of size 33451117797795934712303577408972542258970623^2
  To:   Elliptic Curve defined by y^2 = (18676616761632593484576727486205473216172067*z2+326901995859749251932927863118141241821898308)*x over Finite Field in z2 of size 33451117797795934712303577408972542258970623^2

Yet, the interface provided by \texttt{EllipticCurveHom_composite} is identical to \texttt{EllipticCurveIsogeny} and other instantiations of \texttt{EllipticCurveHom}:

\begin{verbatim}
sage: E = EllipticCurve(GF(419), [0,1])
sage: P = E.lift_x(33); P.order()
35
sage: psi = EllipticCurveHom_composite(E, P); psi
Composite morphism of degree 35 = 5*7:
\end{verbatim}
\end{verbatim}
From: Elliptic Curve defined by $y^2 = x^3 + 1$ over Finite Field of size 419
To: Elliptic Curve defined by $y^2 = x^3 + 101x + 285$ over Finite Field of size 419

```
sage: psi(E.lift_x(11))
(352 : 73 : 1)
sage: psi.rational_maps()
((x^35 + 162*x^34 + 186*x^33 + 92*x^32 - ... + 44*x^3 + 190*x^2 + 80*x - 72)/(x^34 + -162*x^33 - 129*x^32 + 41*x^31 + ... + 66*x^3 - 191*x^2 + 119*x + 21),
(x^51*y - 176*x^50*y + 115*x^49*y - 120*x^48*y + ... + 72*x^3*y + 129*x^2*y + 163*x*y + -178*y)/(x^51 - 176*x^50 + 11*x^49 + 26*x^48 - ... - 77*x^3 + 185*x^2 + 169*x - 128))
sage: psi.kernel_polynomial()
x^17 + 81*x^16 + 7*x^15 + 82*x^14 + 49*x^13 + 68*x^12 + 109*x^11 + 326*x^10 + 117*x^9 + -136*x^8 + 111*x^7 + 292*x^6 + 55*x^5 + 389*x^4 + 175*x^3 + 43*x^2 + 149*x + 373
sage: psi.dual()
Composite morphism of degree 35 = 7*5:
  From: Elliptic Curve defined by $y^2 = x^3 + 101x + 285$ over Finite Field of size 419
  To: Elliptic Curve defined by $y^2 = x^3 + 1$ over Finite Field of size 419
sage: psi.formal()
t + 211*t^5 + 417*t^7 + 159*t^9 + 360*t^11 + 224*t^15 + 296*t^17 + 139*t^19 + -222*t^21 + O(t^23)
```

Equality is decided correctly (and, in some cases, much faster than comparing `EllipticCurveHom.rational_maps()`) even when distinct factorizations of the same isogeny are compared:

```
sage: psi == EllipticCurveIsogeny(E, P)
True
```

We can easily obtain the individual factors of the composite map:

```
sage: psi.factors()
(Isogeny of degree 5 from Elliptic Curve defined by $y^2 = x^3 + 1$ over Finite Field of...
  Isogeny of degree 7 from Elliptic Curve defined by $y^2 = x^3 + 140x + 214$ over Finite...
  Field of size 419 to Elliptic Curve defined by $y^2 = x^3 + 101x + 285$ over Finite...
  Field of size 419)
```

AUTHORS:

- Lukas Zobernig (2020): initial proof-of-concept version
- Lorenz Panny (2021): `EllipticCurveHom` interface, documentation and tests, equality testing

```python
class sage.schemes.elliptic_curves.hom_composite.EllipticCurveHom_composite(E, kernel, codomain=None, model=None)
Bases: sage.schemes.elliptic_curves.hom.EllipticCurveHom

Construct a composite isogeny with given kernel (and optionally, prescribed codomain curve). The isogeny is decomposed into steps of prime degree.

The codomain and model parameters have the same meaning as for `EllipticCurveIsogeny`.

EXAMPLES:
```
sage: from sage.schemes.elliptic_curves.hom_composite import EllipticCurveHom_composite
sage: E = EllipticCurve(GF(419), [1,0])
sage: EllipticCurveHom_composite(E, E.lift_x(23))
Composite morphism of degree 105 = 3*5*7:
  From: Elliptic Curve defined by y^2 = x^3 + x over Finite Field of size 419
  To:   Elliptic Curve defined by y^2 = x^3 + 373*x + 126 over Finite Field of size 419

The given kernel generators need not be independent:
sage: K.<a> = NumberField(x^2 - x - 5)
sage: E = EllipticCurve('210.b6').change_ring(K)
sage: E.torsion_subgroup()
Torsion Subgroup isomorphic to Z/12 + Z/2 associated to the Elliptic Curve defined by y^2 + x*y + y = x^3 + (-578)*x + 2756 over Number Field in a with defining polynomial x^2 - x - 5
sage: EllipticCurveHom_composite(E, E.torsion_points())
Composite morphism of degree 24 = 2^3*3:
  From: Elliptic Curve defined by y^2 + x*y + y = x^3 + (-578)*x + 2756 over Number Field in a with defining polynomial x^2 - x - 5
  To:   Elliptic Curve defined by y^2 + x*y + y = x^3 + (-89915533/16)*x + (-328200928141/64) over Number Field in a with defining polynomial x^2 - x - 5
dual()
Return the dual of this composite isogeny.

EXAMPLES:
sage: from sage.schemes.elliptic_curves.hom_composite import EllipticCurveHom_composite
sage: E = EllipticCurve(GF(65537), [1,2,3,4,5])
sage: P = E.lift_x(7321)
sage: phi = EllipticCurveHom_composite(E, P); phi
Composite morphism of degree 9 = 3^2:
  From: Elliptic Curve defined by y^2 + x*y + 3*y = x^3 + 2*x^2 + 4*x + 5 over Finite Field of size 65537
  To:   Elliptic Curve defined by y^2 + x*y + 3*y = x^3 + 2*x^2 + 28339*x + 59518 over Finite Field of size 65537
sage: psi = phi.dual(); psi
Composite morphism of degree 9 = 3^2:
  From: Elliptic Curve defined by y^2 + x*y + 3*y = x^3 + 2*x^2 + 28339*x + 59518 over Finite Field of size 65537
  To:   Elliptic Curve defined by y^2 + x*y + 3*y = x^3 + 2*x^2 + 4*x + 5 over Finite Field of size 65537
sage: psi * phi == phi.domain().multiplication_by_m_isogeny(phi.degree())
True
sage: phi * psi == psi.domain().multiplication_by_m_isogeny(psi.degree())
True
factors()
Return the factors of this composite isogeny as a tuple.
The isogenies are returned in left-to-right order, i.e., the returned tuple (f_1, ..., f_n) corresponds to the map f_n \circ \cdots \circ f_1.
EXAMPLES:

```python
sage: from sage.schemes.elliptic_curves.hom_composite import EllipticCurveHom_composite
sage: E = EllipticCurve(GF(43), [1,0])
sage: P, = E.gens()

sage: phi = EllipticCurveHom_composite(E, P)
sage: phi.factors()
(Isogeny of degree 2 from Elliptic Curve defined by y^2 = x^3 + x over Finite Field of size 43 to Elliptic Curve defined by y^2 = x^3 + 39*x over Finite Field of size 43,
Isogeny of degree 2 from Elliptic Curve defined by y^2 = x^3 + 39*x over Finite Field of size 43 to Elliptic Curve defined by y^2 = x^3 + 42*x + 26 over Finite Field of size 43,
Isogeny of degree 11 from Elliptic Curve defined by y^2 = x^3 + 42*x + 26 over Finite Field of size 43 to Elliptic Curve defined by y^2 = x^3 + x over Finite Field of size 43)
```

`formal(prec=20)`

Return the formal isogeny corresponding to this composite isogeny as a power series in the variable \( t = -x/y \) on the domain curve.

EXAMPLES:

```python
sage: from sage.schemes.elliptic_curves.hom_composite import EllipticCurveHom_composite
sage: E = EllipticCurve(GF(65537), [1,2,3,4,5])

sage: P = E.lift_x(7321)

sage: phi = EllipticCurveHom_composite(E, P)

sage: phi.factors()
\( t + 54203*t^5 + 48536*t^6 + 40698*t^7 + 37808*t^8 + 21111*t^9 + 42381*t^{10} + \ldots + 46688*t^{11} + 657*t^{12} + 38916*t^{13} + 62261*t^{14} + 59707*t^{15} + 30767*t^{16} + \ldots + 7248*t^{17} + 60287*t^{18} + 50451*t^{19} + 38305*t^{20} + 12312*t^{21} + 31329*t^{22} + \ldots + O(t^{23}) \)

sage: (phi.dual() * phi).formal(prec=5)
\( 9*t + 65501*t^2 + 65141*t^3 + 59183*t^4 + 21491*t^5 + 8957*t^6 + 999*t^7 + O(t^8) \)
```

`classmethod from_factors(maps, E=None, strict=True)`

This method constructs a `EllipticCurveHom_composite` object encapsulating a given sequence of compatible isogenies.

The isogenies are composed in left-to-right order, i.e., the resulting composite map equals \( f_{n-1} \circ \cdots \circ f_0 \) where \( f_i \) denotes `maps[i]`.

INPUT:

- `maps` – sequence of `EllipticCurveHom` objects
- `E` (optional) – the domain elliptic curve
- `strict` (optional, default: True) – if True, always return an `EllipticCurveHom_composite` object; else may return another `EllipticCurveHom` type

OUTPUT: the composite of maps

EXAMPLES:
```python
sage: from sage.schemes.elliptic_curves.hom_composite import EllipticCurveHom_composite
sage: E = EllipticCurve(GF(43), [1,0])
sage: P, = E.gens()
sage: phi = EllipticCurveHom_composite(E, P)
sage: psi = EllipticCurveHom_composite.from_factors(phi.factors())
```

`is_injective()`
Determine whether this composite morphism has trivial kernel.

In other words, return `True` if and only if `self` is a purely inseparable isogeny.

**EXAMPLES:**

```python
sage: from sage.schemes.elliptic_curves.hom_composite import EllipticCurveHom_composite
sage: E = EllipticCurve([1,0])
sage: phi = EllipticCurveHom_composite(E, E(0,0))
```

`is_separable()`
Determine whether this composite isogeny is separable.

A composition of isogenies is separable if and only if all factors are.

**EXAMPLES:**

```python
sage: from sage.schemes.elliptic_curves.hom_composite import EllipticCurveHom_composite
sage: E = EllipticCurve(GF(7^2), [3,2])
```

`kernel_polynomial()`
Return the kernel polynomial of this composite isogeny.

```python
sage: from sage.schemes.elliptic_curves.hom_composite import EllipticCurveHom_composite
sage: E = EllipticCurve(GF(7^2), [3,2])
```
EXAMPLES:

```python
sage: from sage.schemes.elliptic_curves.hom_composite import EllipticCurveHom_composite
sage: E = EllipticCurve(GF(65537), [1,2,3,4,5])
sage: P = E.lift_x(7321)

sage: phi = EllipticCurveHom_composite(E, P); phi

Composite morphism of degree 9 = 3^2:
  From: Elliptic Curve defined by y^2 + x*y + 3*y = x^3 + 2*x^2 + 4*x + 5 over
           Finite Field of size 65537
  To:   Elliptic Curve defined by y^2 + x*y + 3*y = x^3 + 2*x^2 + 28339*x +
           59518 over Finite Field of size 65537

sage: phi.kernel_polynomial()

x^4 + 46500*x^3 + 19556*x^2 + 7643*x + 15952
```

**static make_default()**

Calling this method will override the composition method of `EllipticCurveHom` such that it constructs a `EllipticCurveHom_composite` object by default, rather than a `sage.categories.map.FormalCompositeMap`.

**Warning:** This method exists only temporarily to make testing more convenient while `EllipticCurveHom_composite` is experimental.

EXAMPLES:

```python
sage: from sage.schemes.elliptic_curves.hom_composite import EllipticCurveHom_composite
sage: E = EllipticCurve(GF(587), [1,0])

sage: P = E(3,404)

sage: phi = E.isogeny(7*P)

sage: psi = phi.codomain().isogeny(phi(P))

sage: psi * phi

Composite map:
  From: Elliptic Curve defined by y^2 = x^3 + x over Finite Field of size 587
  To:   Elliptic Curve defined by y^2 = x^3 + 126*x + 500 over Finite Field of size 587

then

  Isogeny of degree 7 from Elliptic Curve defined by y^2 = x^3 + x over Finite Field of size 587
  to Elliptic Curve defined by y^2 = x^3 + 126*x + 500 over Finite Field of size 587

sage: EllipticCurveHom_composite.make_default()

sage: psi * phi

Composite morphism of degree 49 = 7^2:
  From: Elliptic Curve defined by y^2 = x^3 + x over Finite Field of size 587
  To:   Elliptic Curve defined by y^2 = x^3 + 126*x + 500 over Finite Field of size 587

sage: (psi * phi).factors()

(Isogeny of degree 7 from Elliptic Curve defined by y^2 = x^3 + x over Finite Field of size 587
to Elliptic Curve defined by y^2 = x^3 + 126*x + 500 over Finite Field of size 587,
Isogeny of degree 7 from Elliptic Curve defined by y^2 = x^3 + 126*x + 500 over Finite Field of size 587,
Isogeny of degree 7 from Elliptic Curve defined by $y^2 = x^3 + 126x + 500$ over Finite Field of size 587 to Elliptic Curve defined by $y^2 = x^3 + 296x + 164$ over Finite Field of size 587

**rational_maps()**
Return the pair of explicit rational maps defining this composite isogeny.

**EXAMPLES:**

```python
sage: from sage.schemes.elliptic_curves.hom_composite import EllipticCurveHom_composite
sage: E = EllipticCurve(GF(65537), [1,2,3,4,5])
sage: P = E.lift_x(7321)
sage: phi = EllipticCurveHom_composite(E, P)
sage: phi.rational_maps()
((x^9 + 27463*x^8 + 21204*x^7 - 5750*x^6 + 14440*x^4 + 26605*x^3 - 15569*x^2 - 3341*x + 1267)/(x^8 + 27463*x^7 + 26871*x^6 + 5999*x^5 - 20194*x^4 - 6310*x^3 - 24366*x^2 - 20905*x - 13867),
(x^12*y + 8426*x^11*y + 5667*x^11 + 27612*x^10*y + 26124*x^10 + 9688*x^9*y - 22715*x^9 + 19864*x^8*y + 498*x^8 + 22466*x^7*y - 14036*x^7 + 8078*x^6*y + 19955*x^6 - 20765*x^5*y - 12481*x^5 + 12672*x^4*y + 24142*x^4 - 23695*x^3*y + 26667*x^3 + 23780*x^2*y + 17864*x^2 + 15053*x*y - 30118*x + 17539*y - 23609)/
(x^12 + 8426*x^11 + 21945*x^10 - 22587*x^9 + 22094*x^8 + 14603*x^7 - 26255*x^6 + 6 + 11171*x^5 - 16508*x^4 - 14435*x^3 - 2170*x^2 + 29081*x - 19009))
```

**scaling_factor()**
Return the Weierstrass scaling factor associated to this composite morphism.

The scaling factor is the constant $u$ (in the base field) such that $\varphi^{*}\omega_2 = u\omega_1$, where $\varphi : E_1 \rightarrow E_2$ is this morphism and $\omega_i$ are the standard Weierstrass differentials on $E_i$ defined by $dx/(2y+a_1x+a_3)$.

**EXAMPLES:**

```python
sage: from sage.schemes.elliptic_curves.hom_composite import EllipticCurveHom_composite
sage: from sage.schemes.elliptic_curves.weierstrass_morphism import WeierstrassIsomorphism
sage: E = EllipticCurve(GF(65537), [1,2,3,4,5])
sage: P = E.lift_x(7321)
sage: phi = EllipticCurveHom_composite(E, P)
sage: phi = WeierstrassIsomorphism(phi.codomain(), [7,8,9,10]) * phi
sage: phi.formal()
7*t + 65474*t^2 + 511*t^3 + 61316*t^4 + 20548*t^5 + 45511*t^6 + 37285*t^7 +
-48414*t^8 + 9022*t^9 + 24025*t^10 + 35986*t^11 + 55397*t^12 + 25199*t^13 +
-18744*t^14 + 46142*t^15 + 9978*t^16 + 18030*t^17 + 47599*t^18 + 12158*t^19 +
-50630*t^20 + 56449*t^21 + 43320*t^22 + O(t^23)
sage: phi.scaling_factor()
7
```

**ALGORITHM:** The scaling factor is multiplicative under composition, so we return the product of the individual scaling factors associated to each factor.

**x_rational_map()**
Return the $x$-coordinate rational map of this composite isogeny.

**EXAMPLES:**
Elliptic curves, Release 9.7

```
sage: from sage.schemes.elliptic_curves.hom_composite import EllipticCurveHom_composite
sage: E = EllipticCurve(GF(65537), [1,2,3,4,5])
sage: P = E.lift_x(7321)
sage: phi = EllipticCurveHom_composite(E, P)
sage: phi.x_rational_map() == phi.rational_maps()[0]
True
```
CHAPTER
THIRTEEN

ISOGENIES OF SMALL PRIME DEGREE

Functions for the computation of isogenies of small primes degree. First: \( l = 2, 3, 5, 7, \) or 13, where the modular curve \( X_0(l) \) has genus 0. Second: \( l = 11, 17, 19, 23, 29, 31, 41, 47, 59, \) or 71, where \( X_0^+(l) \) has genus 0 and \( X_0(l) \) is elliptic or hyperelliptic. Also: \( l = 11, 17, 19, 37, 43, 67 \) or 163 over \( \mathbb{Q} \) (the sporadic cases with only finitely many \( j \)-invariants each). All the above only require factorization of a polynomial of degree \( l + 1 \). Finally, a generic function which works for arbitrary odd primes \( l \) (including the characteristic), but requires factorization of the \( l \)-division polynomial, of degree \( (l^2 - 1)/2 \).

AUTHORS:

- John Cremona and Jenny Cooley: 2009-07..11: the genus 0 cases the sporadic cases over \( \mathbb{Q} \).
- Kimi Tsukazaki and John Cremona: 2013-07: The 10 (hyper)-elliptic cases and the generic algorithm. See [KT2013].

```
sage.schemes.elliptic_curves.isogeny_small_degree.Fricke_module(l)
```

Fricke module for \( l = 2, 3, 5, 7, 13 \).

For these primes (and these only) the modular curve \( X_0(l) \) has genus zero, and its field is generated by a single modular function called the Fricke module (or Hauptmodul), \( t \). There is a classical choice of such a generator \( t \) in each case, and the \( j \)-function is a rational function of \( t \) of degree \( l + 1 \) of the form \( P(t)/t \) where \( P \) is a polynomial of degree \( l + 1 \). Up to scaling, \( t \) is determined by the condition that the ramification points above \( j = \infty \) are \( t = 0 \) (with ramification degree 1) and \( t = \infty \) (with degree \( l \)). The ramification above \( j = 0 \) and \( j = 1728 \) may be seen in the factorizations of \( j(t) \) and \( k(t) \) where \( k = j - 1728 \).

OUTPUT:
The rational function \( P(t)/t \).

```
sage.schemes.elliptic_curves.isogeny_small_degree.Fricke_polynomial(l)
```

Fricke polynomial for \( l = 2, 3, 5, 7, 13 \).

For these primes (and these only) the modular curve \( X_0(l) \) has genus zero, and its field is generated by a single modular function called the Fricke module (or Hauptmodul), \( t \). There is a classical choice of such a generator \( t \) in each case, and the \( j \)-function is a rational function of \( t \) of degree \( l + 1 \) of the form \( P(t)/t \) where \( P \) is a polynomial of degree \( l + 1 \). Up to scaling, \( t \) is determined by the condition that the ramification points above \( j = \infty \) are \( t = 0 \) (with ramification degree 1) and \( t = \infty \) (with degree \( l \)). The ramification above \( j = 0 \) and \( j = 1728 \) may be seen in the factorizations of \( j(t) \) and \( k(t) \) where \( k = j - 1728 \).

OUTPUT:
The polynomial \( P(t) \) as an element of \( \mathbb{Z}[t] \).

```
sage.schemes.elliptic_curves.isogeny_small_degree.Psi(l, use_stored= True)
```

Generic kernel polynomial for genus zero primes.

For each of the primes \( l \) for which \( X_0(l) \) has genus zero (namely \( l = 2, 3, 5, 7, 13 \)), we may define an elliptic curve \( E_l \) over \( \mathbb{Q}(t) \), with coefficients in \( \mathbb{Z}[t] \), which has good reduction except at \( t = 0 \) and \( t = \infty \) (which lie
above $j = \infty$) and at certain other values of $t$ above $j = 0$ when $l = 3$ (one value) or $l \equiv 1 \pmod{3}$ (two values) and above $j = 1728$ when $l = 2$ (one value) or $l \equiv 1 \pmod{4}$ (two values). (These exceptional values correspond to endomorphisms of $E_t$ of degree $l$.) The $l$-division polynomial of $E_t$ has a unique factor of degree $(l - 1)/2$ (or 1 when $l = 2$), with coefficients in $\mathbb{Z}[t]$, which we call the Generic Kernel Polynomial for $l$. These are used, by specialising $t$, in the function `isogenies_prime_degree_genus_0()`, which also has to take into account the twisting factor between $E_t$ for a specific value of $t$ and the short Weierstrass form of an elliptic curve with $j$-invariant $j(t)$. This enables the computation of the kernel polynomials of isogenies without having to compute and factor division polynomials.

All of this data is quickly computed from the Fricke modules, except that for $l = 13$ the factorization of the Generic Division Polynomial takes a long time, so the value have been precomputed and cached; by default the cached values are used, but the code here will recompute them when `use_stored` is `False`, as in the doctests.

**INPUT:**
- $l$ – either 2, 3, 5, 7, or 13.
- `use_stored` (boolean, default True) – If True, use precomputed values, otherwise compute them on the fly.

**Note:** This computation takes a negligible time for $l = 2, 3, 5, 7$ but more than 100s for $l = 13$. The reason for allowing dynamic computation here instead of just using precomputed values is for testing.

```python
sage.schemes.elliptic_curves.isogeny_small_degree.Psi2(l)
```

Return the generic kernel polynomial for hyperelliptic $l$-isogenies.

**INPUT:**
- $l$ – either 11, 17, 19, 23, 29, 31, 41, 47, 59, or 71.

**OUTPUT:**
The generic $l$-kernel polynomial.

**EXAMPLES:**

```python
sage: from sage.schemes.elliptic_curves.isogeny_small_degree import Psi2
sage: Psi2(11)
-x^5 + 55*x^4*u + 994*x^3*u^2 - 8774*x^2*u^3 + 41453*x*u^4 - 928945/11*u^5 + 33*x^4 + 276*x^3*u + 7794*x^2*u^2 + 4452*x*u^3 + 1319331/11*u^4 + 216*x^3*v - 4536*x^2*u*v - 185976*x*u^2*v - 842616/11*u^3*v + 610578*x^2*u^2 + 38718*x*u^3 + 3343694/11*u^3 + 4536*x^2*v + 73872*x*u*v - 2745576/11*u^2*v - 16470*x^2 + 580068*x*u - 67821354/11*u^2 - 185976*x*v + 14143896/11*u*v + 733*x - 20437029/11*u - 12389112/11*v + 19964151/11
```

```python
sage: p = Psi2(71) # long time
```

```python
sage: (x,u,v) = p.variables() # long time
sage: p.coefficient({x: 0, u: 210, v: 0}) # long time
-2209380711722505179506258739515288584116147237398315266666670643652/71
```

```python
sage: p.coefficient({x: 0, u: 0, v: 0}) # long time
-1479073958643831539456739330199076967815742561944064678252277649/71
```

```python
sage: from sage.schemes.elliptic_curves.isogeny_small_degree import is_kernel_polynomial
sage: is_kernel_polynomial(E, m, f)
```

Test whether $E$ has a cyclic isogeny of degree $m$ with kernel polynomial $f$.

**INPUT:**
- $E$ – an elliptic curve.
- $m$ – a positive integer.
• \( f \) – a polynomial over the base field of \( E \).

OUTPUT:

(\text{bool}) \ \text{True} \ \text{if} \ \ E \ \text{has a cyclic isogeny of degree} \ m \ \text{with kernel polynomial} \ f, \ \text{else} \ \text{False}.

ALGORITHM:

\( f \) \ \text{must have degree} \ (m - 1)/2 \ (\text{if} \ m \ \text{is odd}) \ \text{or degree} \ m/2 \ (\text{if} \ m \ \text{is even}), \ \text{and have the property that for each root} \ x \ \text{of} \ f, \ \mu(x) \ \text{is also a root where} \ \mu \ \text{is the multiplication-by-}m \ \text{map on} \ E \ \text{and} \ m \ \text{runs over a set of generators of} \ (\mathbb{Z}/m\mathbb{Z})^*\{/1, -1\}.

EXAMPLES:

```python
sage: from sage.schemes.elliptic_curves.isogeny_small_degree import is_kernel_polynomial
sage: E = EllipticCurve([0, -1, 1, -10, -20])
\sage: x = polygen(QQ)
\sage: is_kernel_polynomial(E, 5, x^2 + x - 29/5)
True
\sage: is_kernel_polynomial(E, 5, (x - 16) * (x - 5))
True
```

An example from [KT2013], where the 13-division polynomial splits into 14 factors each of degree 6, but only two of these is a kernel polynomial for a 13-isogeny:

```python
sage: F = GF(3)
\sage: E = EllipticCurve(F, [0, 0, 0, -1, 0])
\sage: f13 = E.division_polynomial(13)
\sage: factors = [f for f, e in f13.factor()]
\sage: all(f.degree() == 6 for f in factors)
True
\sage: [is_kernel_polynomial(E, 13, f) for f in factors]
[True,
 True,
 False,
 False,
 False,
 False,
 False,
 False,
 False,
 False,
 False,
 False]
```

See trac ticket #22232:

```python
sage: K = GF(47^2)
\sage: E = EllipticCurve([0, K.gen()])
\sage: psi7 = E.division_polynomial(7)
\sage: f = psi7.factor()[4][0]
\sage: f
x^3 + (7*z2 + 11)*x^2 + (25*z2 + 33)*x + 25*z2
```

(continues on next page)
sage: f.divides(psi7)
True
sage: is_kernel_polynomial(E, 7, f)
False

sage.schemes.elliptic_curves.isogeny_small_degree.isogenies_13_0(E, minimal_models=True)

Return list of all 13-isogenies from E when the j-invariant is 0.

INPUT:

- E – an elliptic curve with j-invariant 0.
- minimal_models (bool, default True) – if True, all curves computed will be minimal or semi-minimal models. Over fields of larger degree it can be expensive to compute these so set to False.

OUTPUT:

(list) 13-isogenies with codomain E. In general these are normalised; but if $-3$ is a square then there are two endomorphisms of degree 13, for which the codomain is the same as the domain.

**Note:** This implementation requires that the characteristic is not 2, 3 or 13.

**Note:** This function would normally be invoked indirectly via E.isogenies_prime_degree(13).

**EXAMPLES:**

sage: from sage.schemes.elliptic_curves.isogeny_small_degree import isogenies_13_0

Endomorphisms of degree 13 will exist when $-3$ is a square:

sage: K.<r> = QuadraticField(-3)
sage: E = EllipticCurve(K, [0, r]); E
Elliptic Curve defined by y^2 = x^3 + r over Number Field in r with defining polynomial x^2 + 3 with r = 1.732050807568878*I
sage: isogenies_13_0(E)
[Isogeny of degree 13 from Elliptic Curve defined by y^2 = x^3 + r over Number Field in r with defining polynomial x^2 + 3 with r = 1.732050807568878*I to Elliptic Curve defined by y^2 = x^3 + r over Number Field in r with defining polynomial x^2 + 3 with r = 1.732050807568878*I, Isogeny of degree 13 from Elliptic Curve defined by y^2 = x^3 + r over Number Field in r with defining polynomial x^2 + 3 with r = 1.732050807568878*I to Elliptic Curve defined by y^2 = x^3 + r over Number Field in r with defining polynomial x^2 + 3 with r = 1.732050807568878*I]
An example of endomorphisms over a finite field:

\begin{verbatim}
    sage: K = GF(19^2, 'a')
    sage: E = EllipticCurve(j=K(0)); E
    Elliptic Curve defined by y^2 = x^3 + 1 over Finite Field in a of size 19^2
    sage: isogenies_13_0(E)
    [Isogeny of degree 13 from Elliptic Curve defined by y^2 = x^3 + 1 over Finite Field in a of size 19^2 to Elliptic Curve defined by y^2 = x^3 + 1 over Finite Field in a of size 19^2, Isogeny of degree 13 from Elliptic Curve defined by y^2 = x^3 + 1 over Finite Field in a of size 19^2 to Elliptic Curve defined by y^2 = x^3 + 1 over Finite Field in a of size 19^2]
    sage: isogenies_13_0(E)[0].rational_maps()
    ((6*x^13 - 6*x^10 - 3*x^7 + 6*x^4 + x)/(x^12 - 5*x^9 - 9*x^6 - 7*x^3 + 5), (-8*x^18*y - 9*x^15*y + 9*x^12*y - 5*x^9*y + 5*x^6*y - 7*x^3*y + 7*y)/(x^18 + 2*x^15 + 3*x^12 - x^9 + 8*x^6 - 9*x^3 + 7))
\end{verbatim}

A previous implementation did not work in some characteristics:

\begin{verbatim}
    sage: K = GF(29)
    sage: E = EllipticCurve(j=K(0))
    sage: isogenies_13_0(E)
    [Isogeny of degree 13 from Elliptic Curve defined by y^2 = x^3 + 1 over Finite Field of size 29 to Elliptic Curve defined by y^2 = x^3 + 26*x + 12 over Finite Field of size 29, Isogeny of degree 13 from Elliptic Curve defined by y^2 = x^3 + 1 over Finite Field of size 29 to Elliptic Curve defined by y^2 = x^3 + 16*x + 28 over Finite Field of size 29]
    sage: K.<a> = NumberField(f)
    sage: E = EllipticCurve(j=K(0)); E.ainvs()
    (0, 0, 0, 1)
    sage: [phi.codomain().ainvs() for phi in isogenies_13_0(E)]
    [(0, 0, 20360599/165164973653422080*a^11 - 3643073/41291243413355520*a^10 - 101/8789110986240*a^9 + 5557619461/573489491852160*a^8 - 82824971/11947697746920*a^7 - 19487/21127670640*a^6 - 475752603733/29409717530880*a^5 + 87205112531/5732429382720*a^4 + 3849/521670880*a^3 + 5857444881/12764634345*a^2 - 1858703809/2836585410*a + 58759402/48906645, -139861295/2656795873499984*a^11 - 3455957/5664093746688*a^10 - 34531057/5097684372192*a^9 - 506530795/118001953056*a^8 - 12860048113/265504394376*a^7 - 25007420461/44250732396*a^6 + 458134176455/1416023436672*a^5 + 16701886031/907783312*a^4 + 155941666417/9677073312*a^3 + 34993101115/378211388*a^2 - 737674863/94552847*a - 21954102381/94552847, 579363345221/13763747804451840*a^11 + 371192377511/860234237778240*a^10 + 885509636557/1146978937804320*a^9 + 5367261541663/1633873196190*a^8 - 193)
\end{verbatim}
sage.schemes.elliptic_curves.isogeny_small_degree.isogenies_13_1728(E, minimal_models=True)

Return list of all 13-isogenies from E when the j-invariant is 1728.

INPUT:

• E – an elliptic curve with j-invariant 1728.

• minimal_models (bool, default True) – if True, all curves computed will be minimal or semi-minimal models. Over fields of larger degree it can be expensive to compute these so set to False.

OUTPUT:

(list) 13-isogenies with codomain E. In general these are normalised; but if \(-1\) is a square then there are two endomorphisms of degree 13, for which the codomain is the same as the domain; and over \(\mathbb{Q}\) or a number field, the codomain is a global minimal model where possible.

Note: This implementation requires that the characteristic is not 2, 3 or 13.

Note: This function would normally be invoked indirectly via E.isogenies_prime_degree(13).

EXAMPLES:

sage: from sage.schemes.elliptic_curves.isogeny_small_degree import isogenies_13_1728
sage: isogenies_13_1728

sage: K.<i> = QuadraticField(-1)
sage: E = EllipticCurve([0,0,0,i,0]); E.ainvs()

(0, 0, 0, i, 0)

sage: isogenies_13_1728(E)

(Isogeny of degree 13 from Elliptic Curve defined by y^2 = x^3 + i*x over Number Field in i with defining polynomial x^2 + 1 with i = 1*I to Elliptic Curve defined by y^2 = x^3 + 1*x over Number Field in i with defining polynomial x^2 + 1 with i = 1*I,
Isogeny of degree 13 from Elliptic Curve defined by $y^2 = x^3 + i\cdot x$ over Number Field in $i$ with defining polynomial $x^2 + 1$ with $i = 1 + i$

defined by $y^2 = x^3 + i\cdot x$ over Number Field in $i$ with defining polynomial $x^2 + 1$ with $i = 1 + i$

sage: K = GF(83)
sage: E = EllipticCurve(K, [0,0,0,5,0]); E.ainvs()
(0, 0, 0, 5, 0)
sage: isogenies_13_1728(E)
[]
sage: K = GF(89)
sage: E = EllipticCurve(K, [0,0,0,5,0]); E.ainvs()
(0, 0, 0, 5, 0)
sage: isogenies_13_1728(E)
[Isogeny of degree 13 from Elliptic Curve defined by $y^2 = x^3 + 5\cdot x$ over Finite Field of size 89 to Elliptic Curve defined by $y^2 = x^3 + 5\cdot x$ over Finite Field of size 89,
Isogeny of degree 13 from Elliptic Curve defined by $y^2 = x^3 + 5\cdot x$ over Finite Field of size 89 to Elliptic Curve defined by $y^2 = x^3 + 5\cdot x$ over Finite Field of size 89]

sage: K = GF(23)
sage: E = EllipticCurve(K, [1,0])
sage: isogenies_13_1728(E)
Isogeny of degree 13 from Elliptic Curve defined by $y^2 = x^3 + x$ over Finite Field of size 23 to Elliptic Curve defined by $y^2 = x^3 + 16$ over Finite Field of size 23, Isogeny of degree 13 from Elliptic Curve defined by $y^2 = x^3 + x$ over Finite Field of size 23 to Elliptic Curve defined by $y^2 = x^3 + 7$ over Finite Field of size 23

sage: x = polygen(QQ)
sage: f = x^12 + 1092*x^10 - 432432*x^8 + 6641024*x^6 - 282896640*x^4 - 149879808*x^2 - 349360128
sage: K.<a> = NumberField(f)
sage: E = EllipticCurve(K, [1,0])
sage: [phi.codomain().ainvs() for phi in isogenies_13_1728(E)]
# long time (3s)
[(0, 0, 0, -4225010072113/3063768069807341568*a^10 - 24841071989413/15957125363579904*a^8 + 11179537789374271/21276167151439872*a^6 - 407474562289492049/4787137698739712*a^4 + 1608052769560747/4522994717568*a^2 + 7786720245212809/36937790193472, -36359427751/57445651308887654*a^11 - 7213386922793/2991961005671232*a^9 - 2810978361185589/1329760556880492049/8975838017913696*a^7 + 28159383688846061/8975838017913696*a^5 - 1287313166530075/848061509544*a^3 + 9768837984886039/6925835661276*a), (0, 0, 0, -4225010072113/3063768069807341568*a^10 - 24841071989413/15957125363579904*a^8 + 11179537789374271/21276167151439872*a^6 - 407474562289492049/4787137698739712*a^4 + 1608052769560747/4522994717568*a^2 + 7786720245212809/36937790193472, -36359427751/57445651308887654*a^11 - 7213386922793/2991961005671232*a^9 - 2810978361185589/1329760556880492049/8975838017913696*a^7 + 28159383688846061/8975838017913696*a^5 - 1287313166530075/848061509544*a^3 + 9768837984886039/6925835661276*a), (0, 0, 0, -4225010072113/3063768069807341568*a^10 - 24841071989413/15957125363579904*a^8 + 11179537789374271/21276167151439872*a^6 - 407474562289492049/4787137698739712*a^4 + 1608052769560747/4522994717568*a^2 + 7786720245212809/36937790193472, -36359427751/57445651308887654*a^11 - 7213386922793/2991961005671232*a^9 - 2810978361185589/1329760556880492049/8975838017913696*a^7 + 28159383688846061/8975838017913696*a^5 - 1287313166530075/848061509544*a^3 + 9768837984886039/6925835661276*a), ...]
sage.schemes.elliptic_curves.isogeny_small_degree.isogenies_2(E, minimal_models=True)
Return a list of all 2-isogenies with domain E.
INPUT:
• E – an elliptic curve.
• minimal_models (bool, default True) – if True, all curves computed will be minimal or semi-minimal models. Over fields of larger degree it can be expensive to compute these so set to False.
OUTPUT:
(list) 2-isogenies with domain E. In general these are normalised, but over \( \mathbb{Q} \) and other number fields, the codomain is a minimal model where possible.
EXAMPLES:

```
sage: from sage.schemes.elliptic_curves.isogeny_small_degree import isogenies_2
sage: E = EllipticCurve('14a1'); E
Elliptic Curve defined by y^2 + x*y + y = x^3 + 4*x - 6 over Rational Field
sage: [phi.codomain().ainvs() for phi in isogenies_2(E)]
[(1, 0, 1, -36, -70)]
sage: E = EllipticCurve([1,2,3,4,5]); E
Elliptic Curve defined by y^2 + x*y + 3*y = x^3 + 2*x^2 + 4*x + 5 over Rational Field
sage: [phi.codomain().ainvs() for phi in isogenies_2(E)]
[]
sage: E = EllipticCurve(QQbar, [9,8]); E
Elliptic Curve defined by y^2 = x^3 + 9*x + 8 over Algebraic Field
sage: isogenies_2(E) # not implemented
```

sage.schemes.elliptic_curves.isogeny_small_degree.isogenies_3(E, minimal_models=True)
Return a list of all 3-isogenies with domain E.
INPUT:
• E – an elliptic curve.
• minimal_models (bool, default True) – if True, all curves computed will be minimal or semi-minimal models. Over fields of larger degree it can be expensive to compute these so set to False.
OUTPUT:
(list) 3-isogenies with domain E. In general these are normalised, but over \( \mathbb{Q} \) or a number field, the codomain is a global minimal model where possible.
EXAMPLES:

```
sage: from sage.schemes.elliptic_curves.isogeny_small_degree import isogenies_3
sage: E = EllipticCurve(GF(17), [1,1])
sage: [phi.codomain().ainvs() for phi in isogenies_3(E)]
[(0, 0, 0, 9, 7), (0, 0, 0, 0, 1)]
```
sage: E = EllipticCurve(GF(17^2,'a'), [1,1])
sage: [phi.codomain().ainvs() for phi in isogenies_3(E)]
[(0, 0, 0, 9, 7), (0, 0, 0, 0, 1), (0, 0, 0, 5*a + 1, a + 13), (0, 0, 0, 12*a + 6, 16*a + 14)]
sage: E = EllipticCurve('19a1')
sage: [phi.codomain().ainvs() for phi in isogenies_3(E)]
[(0, 1, 1, 1, 0), (0, 1, 1, -769, -8470)]
sage: E = EllipticCurve([1,1])
sage: [phi.codomain().ainvs() for phi in isogenies_3(E)]
[]

sage.schemes.elliptic_curves.isogeny_small_degree.isogenies_5_0(E, minimal_models=True)

Return a list of all the 5-isogenies with domain E when the j-invariant is 0.

INPUT:

- E – an elliptic curve with j-invariant 0.
- minimal_models (bool, default True) – if True, all curves computed will be minimal or semi-minimal models. Over fields of larger degree it can be expensive to compute these so set to False.

OUTPUT:

(list) 5-isogenies with codomain E. In general these are normalised, but over Q or a number field, the codomain is a global minimal model where possible.

**Note:** This implementation requires that the characteristic is not 2, 3 or 5.

**Note:** This function would normally be invoked indirectly via E.isogenies_prime_degree(5).

**EXAMPLES:**

sage: from sage.schemes.elliptic_curves.isogeny_small_degree import isogenies_5_0
sage: E = EllipticCurve([0,12])
sage: isogenies_5_0(E)
[]
sage: E = EllipticCurve(GF(13^2,'a'),[0,-3])
sage: isogenies_5_0(E)
[Isogeny of degree 5 from Elliptic Curve defined by y^2 = x^3 + 10 over Finite Field in a of size 13^2 to Elliptic Curve defined by y^2 = x^3 + (4*a+6)*x + (2*a+10) over Finite Field in a of size 13^2, Isogeny of degree 5 from Elliptic Curve defined by y^2 = x^3 + (12*a+5)*x + (2*a+10) over Finite Field in a of size 13^2 to Elliptic Curve defined by y^2 = x^3 + (10*a+2)*x + (2*a+10) over Finite Field in a of size 13^2, Isogeny of degree 5 from Elliptic Curve defined by y^2 = x^3 + (3*a+12)*x + (11*a+12) over Finite Field in a of size 13^2 to Elliptic Curve defined by y^2 = x^3 + (a+4)*x + (11*a+12) over Finite Field in a of size 13^2, Isogeny of degree 5 from Elliptic Curve defined by y^2 = x^3 + (9*a+10)*x + (11*a+12) over Finite Field in a of size 13^2 to Elliptic Curve defined by y^2 = x^3 + (11*a+12) over Finite Field in a of size 13^2, Isogeny of degree 5 from Elliptic Curve defined by y^2 = x^3 + (9*a+10)*x + (11*a+12) over Finite Field in a of size 13^2 to Elliptic Curve defined by y^2 = x^3 + (10*a+2)*x + (2*a+10) over Finite Field in a of size 13^2, Isogeny of degree 5 from Elliptic Curve defined by y^2 = x^3 + (4*a+6)*x + (2*a+10) over Finite Field in a of size 13^2 to Elliptic Curve defined by y^2 = x^3 + (3*a+12)*x + (11*a+12) over Finite Field in a of size 13^2, Isogeny of degree 5 from Elliptic Curve defined by y^2 = x^3 + (2*a+10) over Finite Field in a of size 13^2 to Elliptic Curve defined by y^2 = x^3 + (a+4)*x + (11*a+12) over Finite Field in a of size 13^2]
sage: K.<a> = NumberField(x**6-320*x**3-320)
sage: E = EllipticCurve(K,[0,0,1,0,0])
sage: isogenies_5_0(E)
[Isogeny of degree 5 from Elliptic Curve defined by y^2 + y = x^3 over Number Field in a with defining polynomial x^6 - 320*x^3 - 320 to Elliptic Curve defined by y^2 + y = x^3 + (241565/32*a^5-362149/48*a^4+180281/24*a^3-9693307/4*a^2+14524871/6*a-7254985/3)*x + (1668391123/192*a^5-829315373/96*a^4+77680504/9*a^3-66622345345/24*a^2+33276655441/12*a-2493165912/9) over Number Field in a with defining polynomial x^6 - 320*x^3 - 320,
Isogeny of degree 5 from Elliptic Curve defined by y^2 + y = x^3 over Number Field in a with defining polynomial x^6 - 320*x^3 - 320 to Elliptic Curve defined by y^2 + y = x^3 + (47519/32*a^5-72103/48*a^4+32939/24*a^3-1909753/4*a^2+2861549/6*a-1429675/3)*x + (-131678717/192*a^5+65520419/96*a^4-12594215/18*a^3+5280985135/24*a^2-2637787519/12*a+1976130088/9) over Number Field in a with defining polynomial x^6 - 320*x^3 - 320]

sage.schemes.elliptic_curves.isogeny_small_degree.isogenies_5_1728(E, minimal_models=True)
Return a list of 5-isogenies with domain $E$ when the j-invariant is 1728.

INPUT:

- $E$ – an elliptic curve with j-invariant 1728.
- minimal_models (bool, default True) – if True, all curves computed will be minimal or semi-minimal models. Over fields of larger degree it can be expensive to compute these so set to False.

OUTPUT:

(list) 5-isogenies with codomain $E$. In general these are normalised; but if $-1$ is a square then there are two endomorphisms of degree 5, for which the codomain is the same as the domain curve; and over $\mathbb{Q}$ or a number field, the codomain is a global minimal model where possible.

Note: This implementation requires that the characteristic is not 2, 3 or 5.

Note: This function would normally be invoked indirectly via $E$.isogenies_prime_degree(5).

EXAMPLES:

sage: from sage.schemes.elliptic_curves.isogeny_small_degree import isogenies_5_1728
sage: E = EllipticCurve([7,0])
sage: isogenies_5_1728(E)
[]
sage: E = EllipticCurve(GF(13),[11,0])
sage: isogenies_5_1728(E)
[Isogeny of degree 5 from Elliptic Curve defined by y^2 = x^3 + 11*x over Finite Field of size 13 to Elliptic Curve defined by y^2 = x^3 + 11*x over Finite Field of size 13,
Isogeny of degree 5 from Elliptic Curve defined by y^2 = x^3 + 11*x over Finite Field of size 13 to Elliptic Curve defined by y^2 = x^3 + 11*x over Finite Field of size 13]
An example of endomorphisms of degree 5:

```
sage: K.<i> = QuadraticField(-1)
```
```
sage: E = EllipticCurve(K,[0,0,0,1,0])
```
```
sage: isogenies_5_1728(E)
```
```
[Isogeny of degree 5 from Elliptic Curve defined by y^2 = x^3 + x over Number Field in i with defining polynomial x^2 + 1 with i = 1*I to Elliptic Curve defined by y^2 = x^3 + x over Number Field in i with defining polynomial x^2 + 1 with i = 1*I, Isogeny of degree 5 from Elliptic Curve defined by y^2 = x^3 + x over Number Field in i with defining polynomial x^2 + 1 with i = 1*I to Elliptic Curve defined by y^2 = x^3 + x over Number Field in i with defining polynomial x^2 + 1 with i = 1*I]
```
```
sage: _.rational_maps()
```
```
(((4/25*i + 3/25)*x^5 + (4/5*i - 2/5)*x^3 - x)/(x^4 + (-4/5*i + 2/5)*x^2 + (-4/25*i - 3/25)),
(11/125*i + 2/125)*x^6*y + (-23/125*i + 64/125)*x^4*y + (141/125*i + 162/125)*x^2*y + (3/25*i - 4/25)*y)/(x^6 + (-6/5*i + 3/5)*x^4 + (-12/25*i - 9/25)*x^2 + (2/125*i - 11/125)))
```
```
```
An example of 5-isogenies over a number field:

```
sage: K.<a> = NumberField(x**4+20*x**2-80)
```
```
sage: K(5).is_square() #necessary but not sufficient!
```
```
True
```
```
sage: E = EllipticCurve(K,[0,0,0,1,0])
```
```
sage: isogenies_5_1728(E)
```
```
[Isogeny of degree 5 from Elliptic Curve defined by y^2 = x^3 + x over Number Field in a with defining polynomial x^4 + 20*x^2 - 80 to Elliptic Curve defined by y^2 = x^3 + (-753/4*a^2-4399)*x + (2779*a^3+65072*a) over Number Field in a with defining polynomial x^4 + 20*x^2 - 80, Isogeny of degree 5 from Elliptic Curve defined by y^2 = x^3 + x over Number Field in a with defining polynomial x^4 + 20*x^2 - 80 to Elliptic Curve defined by y^2 = x^3 + (-753/4*a^2-4399)*x + (-2779*a^3-65072*a) over Number Field in a with defining polynomial x^4 + 20*x^2 - 80]
```
```
```
See trac ticket #19840:

```
sage: K.<a> = NumberField(x^4 - 5*x^2 + 5)
```
```
sage: E = EllipticCurve([a^2 + a + 1, a^3 + a^2 + a + 1, a^2 + a, 17*a^3 + 34*a^2 - 16*a - 37, 54*a^3 + 105*a^2 - 66*a - 135])
```
```
sage: len(E.isogenies_prime_degree(5))
```
```
2
```
```
sage: from sage.schemes.elliptic_curves.isogeny_small_degree import isogenies_5_1728
```
```
sage: [phi.codomain().j_invariant() for phi in isogenies_5_1728(E)]
```
```
[19691491018752*a^2 - 27212977933632, 19691491018752*a^2 - 27212977933632]
```
```
```
```
Elliptic curves, Release 9.7

7-isogenies with codomain \( E \). In general these are normalised; but if \(-3\) is a square then there are two endomorphisms of degree 7, for which the codomain is the same as the domain; and over \( \mathbb{Q} \) or a number field, the codomain is a global minimal model where possible.

**Note:** This implementation requires that the characteristic is not 2, 3 or 7.

**Note:** This function would normally be invoked indirectly via \( E \).isogenies_prime_degree(7)\).

**EXAMPLES:**

First some examples of endomorphisms:

```sage
sage: from sage.schemes.elliptic_curves.isogeny_small_degree import isogenies_7_0
sage: K.<r> = QuadraticField(-3)
sage: E = EllipticCurve(K, [0,1])
sage: isogenies_7_0(E)
[Isogeny of degree 7 from Elliptic Curve defined by y^2 = x^3 + 1 over Number Field in r with defining polynomial x^2 + 3 with r = 1.732050807568878?*I to EllipticCurve defined by y^2 = x^3 + 1 over Number Field in r with defining polynomial x^2 + 3 with r = 1.732050807568878?*I, Isogeny of degree 7 from Elliptic Curve defined by y^2 = x^3 + 1 over Number Field in r with defining polynomial x^2 + 3 with r = 1.732050807568878?*I to EllipticCurve defined by y^2 = x^3 + 1 over Number Field in r with defining polynomial x^2 + 3 with r = 1.732050807568878?*I]
```

```sage
sage: E = EllipticCurve(GF(13^2,'a'),[0,-3])
sage: isogenies_7_0(E)
[Isogeny of degree 7 from Elliptic Curve defined by y^2 = x^3 + 10 over Finite Field of size 13^2 to Elliptic Curve defined by y^2 = x^3 + 10 over Finite Field of size 13^2, Isogeny of degree 7 from Elliptic Curve defined by y^2 = x^3 + 10 over Finite Field of size 13^2 to Elliptic Curve defined by y^2 = x^3 + 10 over Finite Field of size 13^2]
```

Now some examples of 7-isogenies which are not endomorphisms:

```sage
sage: K = GF(101)
sage: E = EllipticCurve(K, [0,1])
sage: isogenies_7_0(E)
[Isogeny of degree 7 from Elliptic Curve defined by y^2 = x^3 + 1 over Finite Field of size 101 to Elliptic Curve defined by y^2 = x^3 + 1 over Finite Field of size 101, Isogeny of degree 7 from Elliptic Curve defined by y^2 = x^3 + 1 over Finite Field of size 101 to Elliptic Curve defined by y^2 = x^3 + 1 over Finite Field of size 101]
```

Examples over a number field:

```sage
sage: from sage.schemes.elliptic_curves.isogeny_small_degree import isogenies_7_0
sage: E = EllipticCurve('27a1').change_ring(QuadraticField(-3,'r'))
sage: isogenies_7_0(E)
[Isogeny of degree 7 from Elliptic Curve defined by y^2 + y = x^3 + (-7) over Number Field in r with defining polynomial x^2 + 3 with r = 1.732050807568878?*I to Elliptic Curve defined by y^2 + y = x^3 + (-7) over Number Field in r with defining polynomial x^2 + 3 with r = 1.732050807568878?*I, (continues on next page)
```
Isogeny of degree 7 from Elliptic Curve defined by $y^2 + y = x^3 + (-7)$ over Number Field in $r$ with defining polynomial $x^2 + 3$ with $r = 1.732050807568878?*I$

to Elliptic Curve defined by $y^2 + y = x^3 + (-7)$ over Number Field in $r$ with defining polynomial $x^2 + 3$ with $r = 1.732050807568878?*I$

```
sage: K.<a> = NumberField(x^6 + 1512*x^3 - 21168)
sage: E = EllipticCurve(K, [0,1])
sage: isogs = isogenies_7_0(E)
sage: [phi.codomain().a_invariants() for phi in isogs]
[(0, 0, 0),
 -415/98*a^5 - 675/14*a^4 - 2255/7*a^3 - 74700/7*a^2 - 25110*a - 66420,
 -141163/56*a^5 + 1443453/112*a^4 - 374275/2*a^3 - 3500211/2*a^2 - 17871975/4*a - 7710065),
 (0, 0, 0),
 -24485/392*a^5 - 1080/7*a^4 - 2255/7*a^3 - 1340865/14*a^2 - 230040*a - 553500,
 1753837/56*a^5 + 8345733/112*a^4 + 374275/2*a^3 + 95377029/2*a^2 + 458385345/4*a - 275241835)]
sage: [phi.codomain().j_invariant() for phi in isogs]
[158428486656000/7*a^3 - 313976217600000,
 -158428486656000/7*a^3 - 34534529335296000]
```

```
sage.schemes.elliptic_curves.isogeny_small_degree.isogenies_7_1728(E, minimal_models=True)

Return list of all 7-isogenies from $E$ when the j-invariant is 1728.

INPUT:

- $E$ – an elliptic curve with j-invariant 1728.
- minimal_models (bool, default True) – if True, all curves computed will be minimal or semi-minimal models. Over fields of larger degree it can be expensive to compute these so set to False.

OUTPUT:

(list) 7-isogenies with codomain $E$. In general these are normalised; but over $\mathbb{Q}$ or a number field, the codomain is a global minimal model where possible.

Note: This implementation requires that the characteristic is not 2, 3, or 7.

Note: This function would normally be invoked indirectly via $E$.isogenies_prime_degree(7).

EXAMPLES:

```
sage: from sage.schemes.elliptic_curves.isogeny_small_degree import isogenies_7_1728
sage: E = EllipticCurve(GF(47), [1, 0])
sage: isogenies_7_1728(E)
```

(continues on next page)
Isogeny of degree 7 from Elliptic Curve defined by $y^2 = x^3 + x$ over Finite Field of size 47 to Elliptic Curve defined by $y^2 = x^3 + 21$ over Finite Field of size 47

An example in characteristic 53 (for which an earlier implementation did not work):

```python
sage: from sage.schemes.elliptic_curves.isogeny_small_degree import isogenies_7_1728
sage: E = EllipticCurve(GF(53), [1, 0])
```

```python
sage: len(isogenies_7_1728(E))
```

```python
0
```

```python
sage: E = EllipticCurve(GF(53^2, 'a'), [1, 0])
```

```python
sage: [iso.codomain().ainvs() for iso in isogenies_7_1728(E)]
```

```python
[(0, 0, 0, 36, 19*a + 15), (0, 0, 0, 36, 34*a + 38), (0, 0, 0, 33, 39*a + 28), (0, 0, 0, 33, 14*a + 25), (0, 0, 0, 19, 45*a + 16), (0, 0, 0, 19, 8*a + 37), (0, 0, 3, 45*a + 16), (0, 0, 3, 8*a + 37)]
```

```python
sage: K.<a> = NumberField(x^8 + 84*x^6 - 1890*x^4 + 644*x^2 - 567)
```

```python
sage: E = EllipticCurve(K, [1, 0])
```

```python
sage: isogs = isogenies_7_1728(E)
```

```python
sage: [phi.codomain().j_invariant() for phi in isogs]
```

```python
[-526110256146528/53*a^6 + 183649373229024*a^4 - 333381559996576/53*a^2 + 2910267397643616/53, -526110256146528/53*a^6 + 183649373229024*a^4 - 333381559996576/53*a^2 + 2910267397643616/53]
```

```python
sage: E1 = isogs[0].codomain()
sage: E2 = isogs[1].codomain()
sage: E1.is_isomorphic(E2)
False
sage: E1.is_quadratic_twist(E2)
-1
```

```
Return all separable 1-isogenies with domain E.

**INPUT:**

- E – an elliptic curve.
- l – a prime.
- minimal_models (bool, default True) – if True, all curves computed will be minimal or semi-minimal models. Over fields of larger degree it can be expensive to compute these so set to False. Ignored except over number fields other than $\mathbb{Q}$.

**OUTPUT:**

A list of all separable isogenies of degree $l$ with domain E.

**EXAMPLES:**

```python
sage: from sage.schemes.elliptic_curves.isogeny_small_degree import isogenies_prime_degree
```

```python
sage: isogenies_prime_degree(E, 1)
```

(continues on next page)
[Isogeny of degree 7 from Elliptic Curve defined by $y^2 + x^3 + 1$ over Finite Field of size 2^6 to Elliptic Curve defined by $y^2 + x^3 + x$ over Finite Field of size 2^6]

sage: E = EllipticCurve_from_j(GF(3^12,'a')(2))
sage: isogenies_prime_degree(E, 17)
[Isogeny of degree 17 from Elliptic Curve defined by $y^2 = x^3 + 2x^2 + 2$ over Finite Field of size 3^12 to Elliptic Curve defined by $y^2 = x^3 + 2x^2 + x + 2$ over Finite Field of size 3^12]

sage: E = EllipticCurve([0, 0, 1, -1862, -30956])
sage: isogenies_prime_degree(E, 19)
[Isogeny of degree 19 from Elliptic Curve defined by $y^2 + y = x^3 - 1862x - 30956$ over Finite Field of size 19 to Elliptic Curve defined by $y^2 + y = x^3 - 163137088x - 801950801728$ over Finite Field of size 19]

Isogenies of degree equal to the characteristic are computed (but only the separable isogeny). In the following example we consider an elliptic curve which is supersingular in characteristic 2 only:

[Isogeny of degree 3 from Elliptic Curve defined by $y^2 + y = x^3 + 1$ over Finite Field of size 3 to Elliptic Curve defined by $y^2 + y = x^3 + x$ over Finite Field of size 3]

sage: from sage.schemes.elliptic_curves.isogeny_small_degree import isogenies_prime_degree
sage: ainvs = (0,1,1,-1,-1)
sage: for l in prime_range(50):
  ....:     E = EllipticCurve(GF(l),ainvs)
  ....:     isogenies_prime_degree(E, l)
[]

(continues on next page)
[Isogeny of degree 13 from Elliptic Curve defined by \(y^2 + y = x^3 + x^2 + 12x + \ldots\) over Finite Field of size 13 to Elliptic Curve defined by \(y^2 + y = x^3 + x^2 + 12x + \ldots\) over Finite Field of size 13]
[Isogeny of degree 17 from Elliptic Curve defined by \(y^2 + y = x^3 + x^2 + 16x + \ldots\) over Finite Field of size 17 to Elliptic Curve defined by \(y^2 + y = x^3 + x^2 + 16x + \ldots\) over Finite Field of size 17]
[Isogeny of degree 19 from Elliptic Curve defined by \(y^2 + y = x^3 + x^2 + 18x + \ldots\) over Finite Field of size 19 to Elliptic Curve defined by \(y^2 + y = x^3 + x^2 + 18x + \ldots\) over Finite Field of size 19]
[Isogeny of degree 23 from Elliptic Curve defined by \(y^2 + y = x^3 + x^2 + 22x + \ldots\) over Finite Field of size 23 to Elliptic Curve defined by \(y^2 + y = x^3 + x^2 + 22x + \ldots\) over Finite Field of size 23]
[Isogeny of degree 29 from Elliptic Curve defined by \(y^2 + y = x^3 + x^2 + 28x + \ldots\) over Finite Field of size 29 to Elliptic Curve defined by \(y^2 + y = x^3 + x^2 + 28x + \ldots\) over Finite Field of size 29]
[Isogeny of degree 31 from Elliptic Curve defined by \(y^2 + y = x^3 + x^2 + 30x + \ldots\) over Finite Field of size 31 to Elliptic Curve defined by \(y^2 + y = x^3 + x^2 + 30x + \ldots\) over Finite Field of size 31]
[Isogeny of degree 37 from Elliptic Curve defined by \(y^2 + y = x^3 + x^2 + 36x + \ldots\) over Finite Field of size 37 to Elliptic Curve defined by \(y^2 + y = x^3 + x^2 + 36x + \ldots\) over Finite Field of size 37]
[Isogeny of degree 41 from Elliptic Curve defined by \(y^2 + y = x^3 + x^2 + 40x + \ldots\) over Finite Field of size 41 to Elliptic Curve defined by \(y^2 + y = x^3 + x^2 + 40x + \ldots\) over Finite Field of size 41]
[Isogeny of degree 43 from Elliptic Curve defined by \(y^2 + y = x^3 + x^2 + 42x + \ldots\) over Finite Field of size 43 to Elliptic Curve defined by \(y^2 + y = x^3 + x^2 + 42x + \ldots\) over Finite Field of size 43]
[Isogeny of degree 47 from Elliptic Curve defined by \(y^2 + y = x^3 + x^2 + 46x + \ldots\) over Finite Field of size 47 to Elliptic Curve defined by \(y^2 + y = x^3 + x^2 + 46x + \ldots\) over Finite Field of size 47]

Note that the computation is faster for degrees equal to one of the genus 0 primes (2, 3, 5, 7, 13) or one of the hyperelliptic primes (11, 17, 19, 23, 29, 31, 41, 47, 59, 71) than when the generic code must be used:

```python
sage: E = EllipticCurve(GF(101), [-3440, 77658])
sage: E.isogenies_prime_degree(71) # fast
[]
sage: E.isogenies_prime_degree(73) # long time (2s)
[]
```

Test that trac ticket #32269 is fixed:

```python
sage: K = QuadraticField(-11)
sage: E = EllipticCurve(K, [0,1,0,-117,-541])
sage: E.isogenies_prime_degree(37) # long time (9s)
[Isogeny of degree 37 from Elliptic Curve defined by \(y^2 = x^3 + x^2 + (-117)*x + (-541)\) over Number Field in a with defining polynomial \(x^2 + 11\) with a = 3.166247903554007*I to Elliptic Curve defined by \(y^2 = x^3 + x^2 + (-117)*x + (-541)\) over Number Field in a with defining polynomial \(x^2 + 11\) with a = 3.166247903554007*I, Isogeny of degree 37 from Elliptic Curve defined by \(y^2 = x^3 + x^2 + (-117)*x + (-541)\) over Number Field in a with defining polynomial \(x^2 + 11\) with a = 3.166247903554007*I, Isogeny of degree 37 from Elliptic Curve defined by \(y^2 = x^3 + x^2 + (-117)*x + (-541)\) over Number Field in a with defining polynomial \(x^2 + 11\) with a = 3.166247903554007*I, Isogeny of degree 37 from Elliptic Curve defined by \(y^2 = x^3 + x^2 + (-117)*x + (-541)\) over Number Field in a with defining polynomial \(x^2 + 11\) with a = 3.166247903554007*I]
```
sage.schemes.elliptic_curves.isogeny_small_degree.isogenies_prime_degree_general($E$, $l$, minimal_models=True)

Return all separable $l$-isogenies with domain $E$.

**INPUT:**
- $E$ – an elliptic curve.
- $l$ – a prime.
- minimal_models (bool, default True) – if True, all curves computed will be minimal or semi-minimal models. Over fields of larger degree it can be expensive to compute these so set to False.

**OUTPUT:**
A list of all separable isogenies of degree $l$ with domain $E$.

**ALGORITHM:**
This algorithm factors the $l$-division polynomial, then combines its factors to obtain kernels. See [KT2013], Chapter 3.

**Note:** This function works for any prime $l$. Normally one should use the function isogenies_prime_degree() which uses special functions for certain small primes.

**EXAMPLES:**

```
sage: from sage.schemes.elliptic_curves.isogeny_small_degree import isogenies_prime_degree
sage: E = EllipticCurve_from_j(GF(2^6, 'a')(1))
sage: isogenies_prime_degree_general(E, 7)
[Isogeny of degree 7 from Elliptic Curve defined by y^2 + x*y = x^3 + 1 over Finite Field in a of size 2^6 to Elliptic Curve defined by y^2 + x*y = x^3 + x over Finite Field in a of size 2^6]
sage: E = EllipticCurve_from_j(GF(3^12, 'a')(2))
sage: isogenies_prime_degree_general(E, 17)
[Isogeny of degree 17 from Elliptic Curve defined by y^2 = x^3 + 2*x^2 + 2 over Finite Field in a of size 3^12 to Elliptic Curve defined by y^2 = x^3 + 2*x^2 + x + 2 over Finite Field in a of size 3^12]
sage: E = EllipticCurve('50a1')
sage: isogenies_prime_degree_general(E, 3)
[Isogeny of degree 3 from Elliptic Curve defined by y^2 + x*y + y = x^3 - x - 2 over Rational Field to Elliptic Curve defined by y^2 + x*y + y = x^3 - 126*x - 552 over Rational Field]
sage: isogenies_prime_degree_general(E, 5)
[Isogeny of degree 5 from Elliptic Curve defined by y^2 + x*y + y = x^3 - x - 2 over Rational Field to Elliptic Curve defined by y^2 + x*y + y = x^3 - 76*x + 298 over Rational Field]
sage: E = EllipticCurve([0, 0, 1, -1862, -30956])
sage: isogenies_prime_degree_general(E, 19)
[Isogeny of degree 19 from Elliptic Curve defined by y^2 + y = x^3 - 1862*x - 30956 over Rational Field to Elliptic Curve defined by y^2 + y = x^3 - 672182*x + 21235489 over Rational Field]
```
Isogenies of degree equal to the characteristic are computed (but only the separable isogeny). In the following example we consider an elliptic curve which is supersingular in characteristic 2 only:

```python
code: from sage.schemes.elliptic_curves.isogeny_small_degree import isogenies_prime_degree_general
code: ainv = (0,1,1,-1,-1)
code: for l in prime_range(50):
    ....: E = EllipticCurve(GF(l),ainv)
    ....: isogenies_prime_degree_general(E,l)

[Isogeny of degree 3 from Elliptic Curve defined by y^2 + y = x^3 + x + 2 over Finite Field of size 3 to Elliptic Curve defined by y^2 + y = x^3 + x^2 + x over Finite Field of size 3]
[Isogeny of degree 5 from Elliptic Curve defined by y^2 + y = x^3 + x^2 + 4*x + 4 over Finite Field of size 5 to Elliptic Curve defined by y^2 + y = x^3 + x^2 + 4*x + 4 over Finite Field of size 5]
[Isogeny of degree 7 from Elliptic Curve defined by y^2 + y = x^3 + x^2 + 6*x + 6 over Finite Field of size 7 to Elliptic Curve defined by y^2 + y = x^3 + x^2 + 6*x + 6 over Finite Field of size 7]
[Isogeny of degree 11 from Elliptic Curve defined by y^2 + y = x^3 + x^2 + 10*x + 10 over Finite Field of size 11 to Elliptic Curve defined by y^2 + y = x^3 + x^2 + 10*x + 10 over Finite Field of size 11]
[Isogeny of degree 13 from Elliptic Curve defined by y^2 + y = x^3 + x^2 + 12*x + 12 over Finite Field of size 13 to Elliptic Curve defined by y^2 + y = x^3 + x^2 + 12*x + 12 over Finite Field of size 13]
[Isogeny of degree 17 from Elliptic Curve defined by y^2 + y = x^3 + x^2 + 16*x + 16 over Finite Field of size 17 to Elliptic Curve defined by y^2 + y = x^3 + x^2 + 16*x + 16 over Finite Field of size 17]
[Isogeny of degree 19 from Elliptic Curve defined by y^2 + y = x^3 + x^2 + 18*x + 18 over Finite Field of size 19 to Elliptic Curve defined by y^2 + y = x^3 + x^2 + 18*x + 18 over Finite Field of size 19]
[Isogeny of degree 23 from Elliptic Curve defined by y^2 + y = x^3 + x^2 + 22*x + 22 over Finite Field of size 23 to Elliptic Curve defined by y^2 + y = x^3 + x^2 + 22*x + 22 over Finite Field of size 23]
[Isogeny of degree 29 from Elliptic Curve defined by y^2 + y = x^3 + x^2 + 28*x + 28 over Finite Field of size 29 to Elliptic Curve defined by y^2 + y = x^3 + x^2 + 28*x + 28 over Finite Field of size 29]
[Isogeny of degree 31 from Elliptic Curve defined by y^2 + y = x^3 + x^2 + 30*x + 30 over Finite Field of size 31 to Elliptic Curve defined by y^2 + y = x^3 + x^2 + 30*x + 30 over Finite Field of size 31]
```

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[Isogeny of degree 37 from Elliptic Curve defined by \(y^2 + y = x^3 + x^2 + 36x + 36\) over Finite Field of size 37 to Elliptic Curve defined by \(y^2 + y = x^3 + x^2 + 16x + 17\) over Finite Field of size 37]

[Isogeny of degree 41 from Elliptic Curve defined by \(y^2 + y = x^3 + x^2 + 40x + 40\) over Finite Field of size 41 to Elliptic Curve defined by \(y^2 + y = x^3 + x^2 + 33x + 16\) over Finite Field of size 41]

[Isogeny of degree 43 from Elliptic Curve defined by \(y^2 + y = x^3 + x^2 + 42x + 42\) over Finite Field of size 43 to Elliptic Curve defined by \(y^2 + y = x^3 + x^2 + 36\) over Finite Field of size 43]

[Isogeny of degree 47 from Elliptic Curve defined by \(y^2 + y = x^3 + x^2 + 46x + 46\) over Finite Field of size 47 to Elliptic Curve defined by \(y^2 + y = x^3 + x^2 + 42x + 34\) over Finite Field of size 47]

Note that not all factors of degree \((l-1)/2\) of the \(l\)-division polynomial are kernel polynomials. In this example, the 13-division polynomial factors as a product of 14 irreducible factors of degree 6 each, but only two those are kernel polynomials:

\[
\text{sage: } F3 = \text{GF}(3) \\
\text{sage: } E = \text{EllipticCurve}(F3,[0,0,0,-1,0]) \\
\text{sage: } Psi13 = E.division_polynomial(13) \\
\text{sage: } \text{len([f for f,e in Psi13.factor() if f.degree()==6])} \\
14 \\
\text{sage: } \text{len(E.isogenies_prime_degree(13))} \\
2 \\
\]

Over GF(9) the other factors of degree 6 split into pairs of cubics which can be rearranged to give the remaining 12 kernel polynomials:

\[
\text{sage: } \text{len(E.change_ring(GF(3^2,'a')).isogenies_prime_degree(13))} \\
14 \\
\]

See trac ticket #18589: the following example took 20s before, now only 4s:

\[
\text{sage: } K.<i> = \text{QuadraticField(-1)} \\
\text{sage: } E = \text{EllipticCurve}(K,[0,0,0,1,0]) \\
\text{sage: } \text{[phi.codomain().ainvs() for phi in E.isogenies_prime_degree(37)]} # long time \\
\rightarrow (6s) \\
[0, 0, 0, -840*i + 1081, 0], (0, 0, 0, 840*i + 1081, 0)]
\]

\[
\text{sage.schemes.elliptic_curves.isogeny_small_degree.isogenies_prime_degree_genus_0(E, l=None, minimal_models=True)}
\]

Return list of \(l\)-isogenies with domain \(E\).

INPUT:

- \(E\) – an elliptic curve.
- \(l\) – either None or 2, 3, 5, 7, or 13.
- \(\text{minimal_models}\) (bool, default True) – if True, all curves computed will be minimal or semi-minimal models. Over fields of larger degree it can be expensive to compute these so set to False.

OUTPUT:
(list) When \( l \) is None a list of all isogenies of degree 2, 3, 5, 7 and 13, otherwise a list of isogenies of the given degree.

**Note:** This function would normally be invoked indirectly via \( E.isogenies_prime_degree(1) \), which automatically calls the appropriate function.

**ALGORITHM:**

Cremona and Watkins [CW2005]. See also [KT2013], Chapter 4.

**EXAMPLES:**

```python
sage: from sage.schemes.elliptic_curves.isogeny_small_degree import isogenies_prime_degree_genus_0
sage: E = EllipticCurve([0,12])
\[
\]
sage: isogenies_prime_degree_genus_0(E, 5)
\[
\]
sage: E = EllipticCurve('1450c1')
\[
\]
sage: isogenies_prime_degree_genus_0(E)
\[
\]
\[\text{Isogeny of degree 3 from Elliptic Curve defined by } y^2 + x*y = x^3 + x^2 + 300*x - 1000 \text{ over Rational Field to Elliptic Curve defined by } y^2 + x*y = x^3 + x^2 - 5950*x - 182250 \text{ over Rational Field}\]

sage: E = EllipticCurve('50a1')
\[
\]
sage: isogenies_prime_degree_genus_0(E)
\[
\]
\[\text{Isogeny of degree 3 from Elliptic Curve defined by } y^2 + x*y + y = x^3 - x - 2 \text{ over Rational Field to Elliptic Curve defined by } y^2 + x*y + y = x^3 - 126*x - 552 \text{ over Rational Field},
\]
\[\text{Isogeny of degree 5 from Elliptic Curve defined by } y^2 + x*y + y = x^3 - x - 2 \text{ over Rational Field to Elliptic Curve defined by } y^2 + x*y + y = x^3 - 76*x + 298 \text{ over Rational Field}\]
```

sage.schemes.elliptic_curves.isogeny_small_degree.isogenies_prime_degree_genus_0(\( E, l=None, \)
\[\text{minimal_models=True}\)

Return list of \(-l\)-isogenies with domain \( E \).

**INPUT:**

- \( E \) – an elliptic curve.
- \( l \) – either None or 11, 17, 19, 23, 29, 31, 41, 47, 59, or 71.
- \text{minimal_models} (bool, default \text{True}) – if \text{True}, all curves computed will be minimal or semi-minimal models. Over fields of larger degree it can be expensive to compute these so set to False.

**OUTPUT:**

(list) When \( l \) is None a list of all isogenies of degree 11, 17, 19, 23, 29, 31, 41, 47, 59, or 71, otherwise a list of isogenies of the given degree.

**Note:** This function would normally be invoked indirectly via \( E.isogenies_prime_degree(1) \), which automatically calls the appropriate function.
ALGORITHM:
See [KT2013], Chapter 5.

EXAMPLES:

```python
from sage.schemes.elliptic_curves.isogeny_small_degree import isogenies_prime_degree_genus_plus_0

E = EllipticCurve('121a1')

isogenies_prime_degree_genus_plus_0(E, 11)

E = EllipticCurve([1, 1, 0, -660, -7600])

isogenies_prime_degree_genus_plus_0(E, 17)

E = EllipticCurve([0, 0, 1, -1862, -30956])

isogenies_prime_degree_genus_plus_0(E, 19)

K = QuadraticField(-295, 'a')

a = K.gen()

E = EllipticCurve_from_j(-484650135/16777216*a + 4549855725/16777216)

isogenies_prime_degree_genus_plus_0(E, 23)

K = QuadraticField(-199, 'a')

a = K.gen()

E = EllipticCurve_from_j(-484650135/16777216*a + 4549855725/16777216)

isogenies_prime_degree_genus_plus_0(E, 29)
```

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sage: K = QuadraticField(253, 'a')
sage: a = K.gen()
sage: E = EllipticCurve_from_j((208438034112000*a - 3315409892960000)
    )
sage: isogenies_prime_degree_genus_plus_0(E, 31)
[Isogeny of degree 31 from Elliptic Curve defined by y^2 = x^3 +
    →(41643545221854369346779566680000*a-659516654996503729563480640000)*x + (-
    →18329111156447347458342539369824580252416000*a+29154236611038392836651036806420447260129280000)*a-
    →9059737205868677 to Elliptic Curve defined by y^2 = x^3 + 253 with a = 15.
    →9059737205868677 over Number Field in a with defining polynomial x^2 - 253 with a = 15.905973720586867? to Elliptic Curve defined by y^2 = x^3 +
    →(200339763852548615776123686912000*a-318659901902716904280948275200000)*x +
    →(7443671791411479291172172601822862948502077440000*a-
    →118938947898864757209685951728838388594516865360000) over Number Field in a with
    →defining polynomial x^2 - 253 with a = 15.905973720586867?]
sage: E = EllipticCurve_from_j(GF(5)(1))
sage: isogenies_prime_degree_genus_plus_0(E, 41)
[Isogeny of degree 41 from Elliptic Curve defined by y^2 = x^3 + x + 2 over Finite
    →Field of size 5 to Elliptic Curve defined by y^2 = x^3 + x + 3 over Finite Field
    →of size 5, Isogeny of degree 41 from Elliptic Curve defined by y^2 = x^3 + x + 2
    →over Finite Field of size 5 to Elliptic Curve defined by y^2 = x^3 + x + 3 over
    →Finite Field of size 5]
sage: K = QuadraticField(5, 'a')
sage: a = K.gen()
sage: E = EllipticCurve_from_j((184068066743177379840*a - 41158870972471296000)
    )
sage: isogenies_prime_degree_genus_plus_0(E, 47)
# long time (2s)
[Isogeny of degree 47 from Elliptic Curve defined by y^2 = x^3 +
    →(45456202855408355857852804984997595490560*a-
    →10164315983712411466868928167511361024000)*x + (-
    →2494567984298600881440540950893713303830363999480094280965120*a+55780235873871044345127332022752
    →over Number Field in a with defining polynomial x^2 - 5 with a = 2.
    →236079777499790 to Elliptic Curve defined by y^2 = x^3 +
    →(3953311844236101370577638493619665245992960*a-
    →8839748079969828340617478832005245173760000)*x + (+
    →(214930321479466610282305286115623686938301058305553630618032537600*a-
    →4785863480742206699676163232666163722904497458452316582576128000) over Number
    →Field in a with defining polynomial x^2 - 5 with a = 2.2360679794799790?]
sage: K = QuadraticField(-66827, 'a')
sage: a = K.gen()
sage: E = EllipticCurve_from_j((-98669236224000*a + 4401720074240000)
    )
sage: isogenies_prime_degree_genus_plus_0(E, 59)
# long time (5s)
[Isogeny of degree 59 from Elliptic Curve defined by y^2 = x^3 +
    →(26058861467821447622997974784000*a+189368104891277363494634716160000)*x + (-
    →116918454256410782232296183190067568744071168000*a+1701204353829466402718588235851401130481287168
    →over Number Field in a with defining polynomial x^2 - 66827 with a = 258.
    →50918745762217*I to Elliptic Curve defined by y^2 = x^3 + (-
    →19387084027159786821400775093868000*a-4882059104868154225052787156713472000)*x + (-
    →(25659860101014542871331477227179429538847260672000*a-
    →2596038148441293485938798119003462978248081839846880000) over Number Field in a
    →with defining polynomial x^2 - 66827 with a = 258.50918745762217?I]
sage: E = EllipticCurve_from_j(GF(13)(5))
sage: isogenies_prime_degree_genus_plus_0(E, 71)
[Isogeny of degree 71 from Elliptic Curve defined by \( y^2 = x^3 + x + 4 \) over Finite Field of size 13 to Elliptic Curve defined by \( y^2 = x^3 + 10x + 7 \) over Finite Field of size 13, Isogeny of degree 71 from Elliptic Curve defined by \( y^2 = x^3 + x + 4 \) over Finite Field of size 13 to Elliptic Curve defined by \( y^2 = x^3 + 10x + 7 \) over Finite Field of size 13]

sage: E = EllipticCurve(GF(13),[0,1,1,1,0])
sage: isogenies_prime_degree_genus_plus_0(E)
[Isogeny of degree 17 from Elliptic Curve defined by \( y^2 + y = x^3 + x^2 + x \) over Finite Field of size 13 to Elliptic Curve defined by \( y^2 + y = x^3 + x^2 + 10x + 1 \) over Finite Field of size 13, Isogeny of degree 17 from Elliptic Curve defined by \( y^2 + y = x^3 + x^2 + x \) over Finite Field of size 13 to Elliptic Curve defined by \( y^2 + y = x^3 + x^2 + 12x + 4 \) over Finite Field of size 13, Isogeny of degree 29 from Elliptic Curve defined by \( y^2 + y = x^3 + x^2 + x \) over Finite Field of size 13 to Elliptic Curve defined by \( y^2 + y = x^3 + x^2 + 12x + 4 \) over Finite Field of size 13, Isogeny of degree 29 from Elliptic Curve defined by \( y^2 + y = x^3 + x^2 + x \) over Finite Field of size 13 to Elliptic Curve defined by \( y^2 + y = x^3 + x^2 + 12x + 6 \) over Finite Field of size 13, Isogeny of degree 41 from Elliptic Curve defined by \( y^2 + y = x^3 + x^2 + x \) over Finite Field of size 13 to Elliptic Curve defined by \( y^2 + y = x^3 + x^2 + 12x + 4 \) over Finite Field of size 13, Isogeny of degree 41 from Elliptic Curve defined by \( y^2 + y = x^3 + x^2 + x \) over Finite Field of size 13 to Elliptic Curve defined by \( y^2 + y = x^3 + x^2 + 5x + 6 \) over Finite Field of size 13, lsage.schemes.elliptic_curves.isogeny_small_degree.isogenies_prime_degree_genus_plus_0_j0(E, l, minimal_models=True)

Return a list of hyperelliptic \( l \)-isogenies with domain \( E \) when \( j(E) = 0 \).

INPUT:

- \( E \) – an elliptic curve with j-invariant 0.
- \( l \) – 11, 17, 19, 23, 29, 31, 41, 47, 59, or 71.
- \( \text{minimal\_models} \) (bool, default True) – if True, all curves computed will be minimal or semi-minimal models. Over fields of larger degree it can be expensive to compute these so set to False.

OUTPUT:

(list) a list of all isogenies of degree 11, 17, 19, 23, 29, 31, 41, 47, 59, or 71.

Note: This implementation requires that the characteristic is not 2, 3 or 1.

Note: This function would normally be invoked indirectly via \( E.isogenies_prime_degree(l) \).
EXAMPLES:

```python
sage: from sage.schemes.elliptic_curves.isogeny_small_degree import isogenies_prime_degree_genus_plus_0_j0

sage: E = EllipticCurve(GF(5^6,
  degree_genus_plus_0_j0(E,17)
[Isogeny of degree 17 from Elliptic Curve defined by y^2 = x^3 + (-121/5*a^3-20691/
  5*a^2-29403/5*a+3267) over Number Field in a with defining polynomial x^4 + 228*x^3 +
  486*x^2 - 540*x + 225 to Elliptic Curve defined by y^2 = x^3 + (-44286*a^3-
  740157*a^2+600039*a-277695)*x + (-17863351/5*a^3+125072739/5*a^2-74353653/5*a-
  682803) over Number Field in a with defining polynomial x^4 + 228*x^3 + 486*x^2 -
  540*x + 225]

sage: isogenies_prime_degree_genus_plus_0_j0(E,11)
[Isogeny of degree 11 from Elliptic Curve defined by y^2 = x^3 + (-121/5*a^3-20691/
  5*a^2-29403/5*a+3267) over Number Field in a with defining polynomial x^4 + 228*x^3 +
  486*x^2 - 540*x + 225 to Elliptic Curve defined by y^2 = x^3 + (-3267*a^3-
  740157*a^2+600039*a-277695)*x + (-17863351/5*a^3-4171554981/5*a^2+3769467867/5*a-
  272366523) over Number Field in a with defining polynomial x^4 + 228*x^3 + 486*x^2 -
  540*x + 225]

sage: E = EllipticCurve(K,[0,-121/5*a^3-20691/5*a^2-29403/5*a+3267])

K.<a> = NumberField(u^4+228*u^3+486*u^2-540*u+225)

sage: u = polygen(QQ)

sage: E = EllipticCurve(K,[0,-121/5*a^3-20691/5*a^2-29403/5*a+3267])

[Isogeny of degree 17 from Elliptic Curve defined by y^2 = x^3 + (-121/5*a^3-20691/
  5*a^2-29403/5*a+3267) over Number Field in a with defining polynomial x^4 + 228*x^3 +
  486*x^2 - 540*x + 225 to Elliptic Curve defined by y^2 = x^3 + (-44286*a^3-
  740157*a^2+600039*a-277695)*x + (-17863351/5*a^3+125072739/5*a^2-74353653/5*a-
  682803) over Number Field in a with defining polynomial x^4 + 228*x^3 + 486*x^2 -
  540*x + 225]
```

(continues on next page)
sage.schemes.elliptic_curves.isogeny_small_degree.isogenies_prime_degree_genus_plus_0_j1728(E, l, minimal_models=True)

Return a list of \( l \)-isogenies with domain \( E \) when \( j(E) = 1728 \).

**INPUT:**
- \( E \) – an elliptic curve with j-invariant 1728.
- \( l \) – 11, 17, 19, 23, 29, 31, 41, 47, 59, or 71.
- \texttt{minimal\_models} (bool, default True) – if True, all curves computed will be minimal or semi-minimal models. Over fields of larger degree it can be expensive to compute these so set to False.

**OUTPUT:**
(list) a list of all isogenies of degree 11, 17, 19, 23, 29, 31, 41, 47, 59, or 71.

**Note:** This implementation requires that the characteristic is not 2, 3 or \( l \).

**Note:** This function would normally be invoked indirectly via \( E.isogenies\_prime\_degree(l) \).

**EXAMPLES:**

```python
sage: from sage.schemes.elliptic_curves.isogeny_small_degree import isogenies_prime_degree_genus_plus_0_j1728
sage: u = polygen(QQ)
sage: K.<a> = NumberField(u^6 - 522*u^5 - 10017*u^4 + 2484*u^3 - 5265*u^2 + 12150*u - 5103)
sage: E = EllipticCurve(K,[-75295/1335852*a^5+13066735/445284*a^4+44903485/74214*a^3+17086861/24738*a^2+11373021/16492*a-1246245/2356,0])
sage: isogenies_prime_degree_genus_plus_0_j1728(E,11)
```

[Isogeny of degree 11 from Elliptic Curve defined by \( y^2 = x^3 + (-75295/1335852*a^5+13066735/445284*a^4+44903485/74214*a^3+17086861/24738*a^2+11373021/16492*a-1246245/2356)*x \) over Number Field in \( a \) with defining polynomial \( x^6 - 522*x^5 - 10017*x^4 + 2484*x^3 - 5265*x^2 + 12150*x - 5103 \) to Elliptic Curve defined by \( y^2 = x^3 + (9110695/1335852*a^5-1581074935/445284*a^4-5433321685/74214*a^3+3163057249/24738*a^2+1569269691/16492*a+73825125/2356)*x + (3540460*a^3-30522492*a^2-7043652*a+5031180) \) over Number Field in \( a \) with defining polynomial \( x^6 - 522*x^5 - 10017*x^4 + 2484*x^3 - 5265*x^2 + 12150*x - 5103 \), Isogeny of degree 11 from Elliptic Curve defined by \( y^2 = x^3 + (-75295/1335852*a^5+13066735/445284*a^4+44903485/74214*a^3+17086861/24738*a^2+11373021/16492*a-1246245/2356)*x \) over Number Field in \( a \) with defining polynomial \( x^6 - 522*x^5 - 10017*x^4 + 2484*x^3 - 5265*x^2 + 12150*x - 5103 \) to Elliptic Curve defined by \( y^2 = x^3 + (9110695/1335852*a^5-1581074935/445284*a^4-5433321685/74214*a^3+3163057249/24738*a^2+1569269691/16492*a+73825125/2356)*x + (3540460*a^3-30522492*a^2-7043652*a+5031180) \) over Number Field in \( a \) with defining polynomial \( x^6 - 522*x^5 - 10017*x^4 + 2484*x^3 - 5265*x^2 + 12150*x - 5103 \)]
sage: i = QuadraticField(-1,'i').gen()
sage: E = EllipticCurve([-1-2*i,0])
sage: isogenies_prime_degree_genus_plus_0_j1728(E,17)
[Isogeny of degree 17 from Elliptic Curve defined by y^2 = x^3 + (-2*i-1)*x over Number Field in i with defining polynomial x^2 + 1 with i = 1*I to Elliptic Curve defined by y^2 = x^3 + (-82*i-641)*x over Number Field in i with defining polynomial x^2 + 1 with i = 1*I, Isogeny of degree 17 from Elliptic Curve defined by y^2 = x^3 + (-2*i-1)*x over Number Field in i with defining polynomial x^2 + 1 with i = 1*I to Elliptic Curve defined by y^2 = x^3 + (-562*i+319)*x over Number Field in i with defining polynomial x^2 + 1 with i = 1*I]
sage: Emin = E.global_minimal_model()
sage: [(p,len(isogenies_prime_degree_genus_plus_0_j1728(Emin,p))) for p in [17, 29, 41]]
[(17, 2), (29, 2), (41, 2)]

sage.schemes.elliptic_curves.isogeny_small_degree.isogenies_sporadic_Q(E, l=None, minimal_models=True)

Return a list of sporadic l-isogenies from E (l = 11, 17, 19, 37, 43, 67 or 163). Only for elliptic curves over Q.

INPUT:

• E – an elliptic curve defined over Q.
• l – either None or a prime number.

OUTPUT:

(list) If l is None, a list of all isogenies with domain E and of degree 11, 17, 19, 37, 43, 67 or 163; otherwise a list of isogenies of the given degree.

Note: This function would normally be invoked indirectly via E.isogenies_prime_degree(1), which automatically calls the appropriate function.

EXAMPLES:

sage: from sage.schemes.elliptic_curves.isogeny_small_degree import isogenies_sporadic_Q
sage: E = EllipticCurve('121a1')
sage: isogenies_sporadic_Q(E, 11)
[]
sage: isogenies_sporadic_Q(E, 17)
[]
sage: isogenies_sporadic_Q(E)
[]
sage: E = EllipticCurve([1, 1, 0, -660, -7600])
sage: isogenies_sporadic_Q(E, 17)
Elliptic curves, Release 9.7

[Isogeny of degree 17 from Elliptic Curve defined by $y^2 + x*y = x^3 + x^2 - 660*x - 7600$ over Rational Field to Elliptic Curve defined by $y^2 + x*y = x^3 + x^2 - 878710*x + 31667750$ over Rational Field]
sage: isogenies_sporadic_Q(E)

[Isogeny of degree 17 from Elliptic Curve defined by $y^2 + x*y = x^3 + x^2 - 660*x - 7600$ over Rational Field to Elliptic Curve defined by $y^2 + x*y = x^3 + x^2 - 878710*x + 31667750$ over Rational Field]
sage: isogenies_sporadic_Q(E, 11)
[]
sage: E = EllipticCurve([0, 0, 1, -1862, -30956])
sage: isogenies_sporadic_Q(E, 11)
[]
sage: isogenies_sporadic_Q(E, 19)

[Isogeny of degree 19 from Elliptic Curve defined by $y^2 + y = x^3 - 1862*x - 30956$ over Rational Field to Elliptic Curve defined by $y^2 + y = x^3 - 672182*x + 212325489$ over Rational Field]
sage: isogenies_sporadic_Q(E)

[Isogeny of degree 19 from Elliptic Curve defined by $y^2 + y = x^3 - 1862*x - 30956$ over Rational Field to Elliptic Curve defined by $y^2 + y = x^3 - 672182*x + 212325489$ over Rational Field]
sage: E = EllipticCurve([0, -1, 0, -6288, 211072])
sage: E.conductor()
19600
sage: isogenies_sporadic_Q(E,37)

[Isogeny of degree 37 from Elliptic Curve defined by $y^2 = x^3 - x^2 - 6288*x + 211072$ over Rational Field to Elliptic Curve defined by $y^2 = x^3 - x^2 - 163137088*x - 801950801728$ over Rational Field]
sage: E = EllipticCurve([1, 1, 0, -25178045, 48616918750])
sage: E.conductor()
148225
sage: isogenies_sporadic_Q(E,37)

[Isogeny of degree 37 from Elliptic Curve defined by $y^2 + x*y = x^3 + x^2 - 25178045*x + 48616918750$ over Rational Field to Elliptic Curve defined by $y^2 + x*y = x^3 + x^2 - 970*x - 13075$ over Rational Field]
sage: E = EllipticCurve([-3440, 77658])
sage: E.conductor()
118336
sage: isogenies_sporadic_Q(E,43)

[Isogeny of degree 43 from Elliptic Curve defined by $y^2 = x^3 - x^2 - 3440*x + 77658$ over Rational Field to Elliptic Curve defined by $y^2 = x^3 - 6360560*x - 6174354606$ over Rational Field]
sage: E = EllipticCurve([-29480, -1948226])
sage: E.conductor()
287296
sage: isogenies_sporadic_Q(E,67)

[Isogeny of degree 67 from Elliptic Curve defined by $y^2 = x^3 - 29480*x - 1948226$ over Rational Field to Elliptic Curve defined by $y^2 = x^3 - 132335720*x + 58594296438$ over Rational Field]

(continues on next page)
sage: E = EllipticCurve([-34790720, -78984748304])
sage: E.conductor()
425104
sage: isogenies_sporadic_Q(E, 163)
[Isogeny of degree 163 from Elliptic Curve defined by y^2 = x^3 - 34790720*x - 78984748304 over Rational Field to Elliptic Curve defined by y^2 = x^3 - 924354639680*x + 342062961763303088 over Rational Field]
14.1 Elliptic curves over the rational numbers

AUTHORS:
- William Stein (2005): first version
- David Harvey (2006-09): Added padic_E2, padic_sigma, padic_height, padic_regulator methods.
- David Harvey (2007-02): reworked padic-height related code
- Christian Wuthrich (2007): added p-adic sha computation
- David Roe (2007-09): moved sha, l-series and p-adic functionality to separate files.
- John Cremona (2008-01)
- Tobias Nagel and Michael Mardaus (2008-07): added integral_points
- John Cremona (2008-07): further work on integral_points
- Christian Wuthrich (2010-01): moved Galois reps and modular parametrization in a separate file
- Simon Spicer (2013-03): Added code for modular degrees and congruence numbers of higher level
- Simon Spicer (2014-08): Added new analytic rank computation functionality

```python
class sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field(ainvs, **kwds)
```

**Bases:** `sage.schemes.elliptic_curves.ell_number_field.EllipticCurve_number_field`

Elliptic curve over the Rational Field.

**INPUT:**
- `ainvs` – a list or tuple \([a_1, a_2, a_3, a_4, a_6]\) of Weierstrass coefficients

**Note:** This class should not be called directly; use `sage.constructor.EllipticCurve` to construct elliptic curves.

**EXAMPLES:**
Construction from Weierstrass coefficients (\(a\)-invariants), long form:
```
sage: E = EllipticCurve([1,2,3,4,5]); E
Elliptic Curve defined by y^2 + x*y + 3*y = x^3 + 2*x^2 + 4*x + 5 over Rational Field
```
Construction from Weierstrass coefficients ($a$-invariants), short form (sets $a_1 = a_2 = a_3 = 0$):

```sage
sage: EllipticCurve([4,5]).ainvs()
(0, 0, 0, 4, 5)
```

Constructor from a Cremona label:

```sage
sage: EllipticCurve('389a1')
Elliptic Curve defined by y^2 + y = x^3 + x^2 - 2*x over Rational Field
```

Constructor from an LMFDB label:

```sage
sage: EllipticCurve('462.f3')
Elliptic Curve defined by y^2 + x*y = x^3 - 363*x + 1305 over Rational Field
```

**CPS_height_bound()**

Return the Cremona-Prickett-Siksek height bound. This is a floating point number $B$ such that if $P$ is a rational point on the curve, then $h(P) \leq \hat{h}(P) + B$, where $h(P)$ is the naive logarithmic height of $P$ and $\hat{h}(P)$ is the canonical height.

See also:  
`silverman_height_bound()` for a bound that also works for points over number fields.

**EXAMPLES:**

```sage
sage: E = EllipticCurve("11a")
sage: E.CPS_height_bound()
2.8774743273580445
sage: E = EllipticCurve("5077a")
sage: E.CPS_height_bound()
0.0
sage: E = EllipticCurve([1,2,3,4,1])
sage: E.CPS_height_bound()
Traceback (most recent call last):
  ...
RuntimeError: curve must be minimal.
sage: F = E.quadratic_twist(-19)
sage: F
Elliptic Curve defined by y^2 + x*y + y = x^3 - x^2 + 1376*x - 130 over Rational Field
sage: F.CPS_height_bound()
0.6555158376972852
```

**IMPLEMENTATION:**

Call the corresponding mwrank C++ library function. Note that the formula in the [CPS2006] paper is given for number fields. It is only the implementation in Sage that restricts to the rational field.

**Lambda($s$, prec)**

Return the value of the Lambda-series of the elliptic curve $E$ at $s$, where $s$ can be any complex number.

**IMPLEMENTATION:**

Fairly slow computation using the definitions implemented in Python.
Uses \texttt{prec} terms of the power series.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: E = EllipticCurve('389a')
sage: E.Lambda(1.4+0.5*I, 50)
-0.354172680517... + 0.874518681720...*I
\end{verbatim}

\texttt{Np}(p)

The number of points on \( E \) modulo \( p \).

\textbf{INPUT:}

\begin{itemize}
  \item \( p \) (int) – a prime, not necessarily of good reduction
\end{itemize}

\textbf{OUTPUT:}

(int) The number of points on the reduction of \( E \) modulo \( p \) (including the singular point when \( p \) is a prime of bad reduction).

\textbf{EXAMPLES:}

\begin{verbatim}
sage: E = EllipticCurve([0, -1, 1, -10, -20])
sage: E.Np(2)
5
sage: E.Np(3)
5
sage: E.conductor()
11
sage: E.Np(11)
11
\end{verbatim}

This even works when the prime is large:

\begin{verbatim}
sage: E = EllipticCurve('37a')
sage: E.Np(next_prime(10^30))
100000000000001426441464441649
\end{verbatim}

\texttt{S_integral_points}(\( S \), \texttt{mw_base='auto'}, \texttt{both_signs=False}, \texttt{verbose=False}, \texttt{proof=None})

Compute all S-integral points (up to sign) on this elliptic curve.

\textbf{INPUT:}

\begin{itemize}
  \item \( S \) – list of primes
  \item \texttt{mw_base} – (default: 'auto' - calls \texttt{gens()}) list of EllipticCurvePoint generating the Mordell-Weil group of \( E \)
  \item \texttt{both_signs} – boolean (default: False); if True the output contains both \( P \) and \(-P\), otherwise only one of each pair
  \item \texttt{verbose} – boolean (default: False); if True, some details of the computation are output
  \item \texttt{proof} – boolean (default: True); if True ALL S-integral points will be returned. If False, the MW basis will be computed with the proof=False flag, and also the time-consuming final call to \texttt{S_integral_x_coords_with_abs_bounded_by(abs_bound)} is omitted. Use this only if the computation takes too long, but be warned that then it cannot be guaranteed that all S-integral points will be found.
\end{itemize}

\textbf{OUTPUT:}

A sorted list of all the S-integral points on \( E \) (up to sign unless both_signs is True)
Note: The complexity increases exponentially in the rank of curve E and in the length of S. The computation time (but not the output!) depends on the Mordell-Weil basis. If mw_base is given but is not a basis for the Mordell-Weil group (modulo torsion), S-integral points which are not in the subgroup generated by the given points will almost certainly not be listed.

EXAMPLES:

A curve of rank 3 with no torsion points:

```python
sage: E = EllipticCurve([0,0,1,-7,6])
sage: P1 = E.point((2,0))
sage: P2 = E.point((-1,3))
sage: P3 = E.point((4,6))
sage: a = E.S_integral_points(S=[2,3], mw_base=[P1,P2,P3], verbose=True);a
max_S: 3 len_S: 3 len_tors: 1
lambda 0.485997517468...
```

```python
k1,k2,k3,k4 7.65200453902598e234 1.31952866480763 3.54035317966420e9 2.
-> 42767548272846e17
p= 2 : trying with p_prec = 30
mw_base_p_log_val = [2, 2, 1]
min_psi = 2 + 2^3 + 2^6 + 2^7 + 2^8 + 2^9 + 2^11 + 2^12 + 2^13 + 2^16 + 2^17 +...
-> 2^19 + 2^20 + 2^21 + 2^23 + 2^24 + 2^28 + 0(2^30)
p= 3 : trying with p_prec = 30
mw_base_p_log_val = [1, 2, 1]
min_psi = 3 + 3^2 + 2*3^3 + 3^6 + 2*3^7 + 2*3^8 + 3^9 + 2*3^11 + 2*3^12 + 2*3^...
-> 13 + 3*15 + 2*3^16 + 3*18 + 2*3^19 + 2*3^22 + 2*3^23 + 2*3^24 + 2*3^27 + 3*28...
-> + 3^29 + 0(3^30)
mw_base [(1 : -1 : 1), (2 : 0 : 1), (0 : -3 : 1)]
mw_base_log [0.667789378224099, 0.552642660712417, 0.81847722895703]
mp [5, 7]
mw_base_p_log [[2^2 + 2^3 + 2^6 + 2^7 + 2^8 + 2^9 + 2^14 + 2^15 + 2^18 + 2^19 +...
-> 2^24 + 2^29 + 0(2^30)], 2^2 + 2^3 + 2^5 + 2^6 + 2^9 + 2^11 + 2^12 + 2^14 + 2^...
-> 15 + 2^16 + 2^18 + 2^20 + 2^22 + 2^23 + 2^26 + 2^27 + 2^29 + 0(2^30), 2 + 2^3 +...
-> + 2^6 + 2^7 + 2^8 + 2^9 + 2^11 + 2^12 + 2^13 + 2^16 + 2^17 + 2^19 + 2^20 + 2^...
-> 21 + 2^23 + 2^24 + 2^28 + 0(2^30)], [2^3*2 + 2*3^5 + 2*3^6 + 2^7 + 3*8 + 3^...
-> 9 + 2*3^10 + 3*12 + 2*3^14 + 3^15 + 3^17 + 2*3^19 + 2*3^23 + 3*25 + 3*28 +...
-> 0(3^30), 2*3 + 2*3^2 + 2*3^3 + 2*3^4 + 2*3^6 + 2*3^7 + 2*3^8 + 3^10 + 2*3^12 +...
-> + 3^13 + 2*3^14 + 3^15 + 3^18 + 3^22 + 3^25 + 2*3^26 + 3^27 + 3*28 + 0(3^30), 3...
-> 3 + 3^2 + 2*3^3 + 3^6 + 2*3^7 + 2^3^8 + 3^9 + 2*3^11 + 2*3^12 + 2*3^13 + 3*15 +...
-> + 2*3^16 + 3^18 + 2*3^19 + 2*3^22 + 2*3^23 + 2*3^24 + 2*3^27 + 3*28 + 3*29 +...
-> 0(3^30)]]
k5,k6,k7 0.321154513240... 1.55246328915... 0.161999172489...
initial bound 2.8057927340...e117
bound_list [58, 58, 58]
bound_list [8, 9, 9]
bound_list [9, 7, 7]
starting search of points using coefficient bound 9
x-coords of S-integral points via linear combination of mw_base and torsion:
[-3, -26/9, -8159/2916, -2759/1024, -151/64, -1343/576, -2, -7/4, -1, -47/256, 9, 1/4, 4/9, 9/16, 58/81, 7/9, 6169/6561, 1, 17/16, 2, 33/16, 172/81, 9/4, 25/9, 3, 31/9, 4, 25/4, 1793/256, 8, 625/64, 11, 14, 21, 37, 52, 6142/81, 93, 4537/36, 342, 406, 816, 207331217/4096]
```
starting search of extra S-integer points with absolute value bounded by 3.

89321964979420

x-coords of points with bounded absolute value

[-3, -2, -1, 0, 1, 2]

Total number of S-integral points: 43


It is not necessary to specify mw_base; if it is not provided, then the Mordell-Weil basis must be computed, which may take much longer.

```sage```
a = E.S_integral_points([2,3])
len(a)
```

An example with negative discriminant:

```sage```
E = EllipticCurve('900d1').S_integral_points([17], both_signs=True)
```

Output checked with Magma (corrected in 3 cases):

```sage```
[len(E.S_integral_points([2], both_signs=False)) for E in cremona_curves([11..100])]
```

An example from [PZGH1999]:

```sage```
E = EllipticCurve([0,0,0,-172,505])
E.rank(), len(E.S_integral_points([3,5,7]))
```

(continues on next page)
Elliptic curves, Release 9.7

(continued from previous page)

(4, 72)

This is curve “7690e1” which failed until trac ticket #4805 was fixed:

```
sage: EllipticCurve([1,1,1,-301,-1821]).S_integral_points([13,2])
[(-13 : 16 : 1),
  (-9 : 20 : 1),
  (-7 : 4 : 1),
  (21 : 30 : 1),
  (23 : 52 : 1),
  (63 : 452 : 1),
  (71 : 548 : 1),
  (87 : 756 : 1),
  (2711 : 139828 : 1),
  (7323 : 623052 : 1),
  (17687 : 2343476 : 1)]
```

- Some parts of this implementation are partially based on the function integral_points()

AUTHORS:

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- Michael Mardaus (2008-12)
- John Cremona (2008-12)

**abelian_variety()**

Return self as a modular abelian variety.

OUTPUT:

- a modular abelian variety

EXAMPLES:

```
sage: E = EllipticCurve('11a')
sage: E.abelian_variety()
Abelian variety J0(11) of dimension 1
sage: E = EllipticCurve('33a')
sage: E.abelian_variety()
Abelian subvariety of dimension 1 of J0(33)
```

**an(n)**

The n-th Fourier coefficient of the modular form corresponding to this elliptic curve, where n is a positive integer.

EXAMPLES:

```
sage: E = EllipticCurve('37a1')
sage: [E.an(n) for n in range(20) if n>0]
[1, -2, -3, 2, -2, 6, -1, 0, 6, 4, -5, -6, -2, 2, 6, -4, 0, -12, 0]
```

**analytic_rank(algorithm='pari', leading_coefficient=False)**

Return an integer that is probably the analytic rank of this elliptic curve.
INPUT:

- **algorithm** – (default: 'pari'), String
  - 'pari' – use the PARI library function.
  - 'sympow' – use Watkins’s program sympow
  - 'rubinstein' – use Rubinstein’s L-function C++ program lcalc.
  - 'magma' – use MAGMA
  - 'zero_sum' – Use the rank bounding zero sum method implemented in self.analytic_rank_upper_bound()
  - 'all' – compute with PARI, sympow and lcalc, check that the answers agree, and return the common answer.

- **leading_coefficient** – (default: False) Boolean; if set to True, return a tuple (rank, lead) where lead is the value of the first non-zero derivative of the L-function of the elliptic curve. Only implemented for algorithm='pari'.

**Note:** If the curve is loaded from the large Cremona database, then the modular degree is taken from the database.

Of the first three algorithms above, probably Rubinstein’s is the most efficient (in some limited testing done). The zero sum method is often much faster, but can return a value which is strictly larger than the analytic rank. For curves with conductor <=10^9 using default parameters, testing indicates that for 99.75% of curves the returned rank bound is the true rank.

**Note:** If you use set_verbose(1), extra information about the computation will be printed when algorithm='zero_sum'.

**Note:** It is an open problem to prove that any particular elliptic curve has analytic rank ≥ 4.

**EXAMPLES:**

```python
sage: E = EllipticCurve('389a')
sage: E.analytic_rank(algorithm='pari')
2
sage: E.analytic_rank(algorithm='rubinstein')
2
sage: E.analytic_rank(algorithm='sympow')
2
sage: E.analytic_rank(algorithm='magma')  # optional - magma
2
sage: E.analytic_rank(algorithm='zero_sum')
2
sage: E.analytic_rank(algorithm='all')
2
```

With the optional parameter leading_coefficient set to True, a tuple of both the analytic rank and the leading term of the L-series at s = 1 is returned. This only works for algorithm='pari':
sage: EllipticCurve([0,-1,1,-10,-20]).analytic_rank(leading_coefficient=True)
(0, 0.25384186085591068...)
sage: EllipticCurve([0,0,1,-1,0]).analytic_rank(leading_coefficient=True)
(1, 0.30599977383405230...)
sage: EllipticCurve([0,1,1,-2,0]).analytic_rank(leading_coefficient=True)
(2, 1.518633000576853...)
sage: EllipticCurve([0,0,1,-7,6]).analytic_rank(leading_coefficient=True)
(3, 10.39109940071580...)
sage: EllipticCurve([0,0,1,-7,36]).analytic_rank(leading_coefficient=True)
(4, 196.170903794579...)

analytic_rank_upper_bound(max_Delta=None, adaptive=True, N=None, root_number='compute',
                          bad_primes=None, ncpus=None)

Return an upper bound for the analytic rank of self, conditional on the Generalized Riemann Hypothesis,
via computing the zero sum \( \sum \gamma f(\Delta \gamma) \), where \( \gamma \) ranges over the imaginary parts of the zeros of \( L(E, s) \)
along the critical strip, \( f(x) = (\sin(\pi x)/(\pi x))^2 \), and \( \Delta \) is the tightness parameter whose maximum value
is specified by \( \text{max}_\Delta \). This computation can be run on curves with very large conductor (so long as
the conductor is known or quickly computable) when \( \Delta \) is not too large (see below). Uses Bober’s rank
bounding method as described in [Bob2013].

INPUT:

- \text{max}_\Delta – (default: None) If not None, a positive real value specifying the maximum Delta value
  used in the zero sum; larger values of Delta yield better bounds - but runtime is exponential in Delta. If
  left as None, Delta is set to \( \min \{ \frac{1}{2} \log(N + 1000)/2 - \log(2\pi) - \eta, 2.5 \} \), where \( N \) is the conductor
  of the curve attached to self, and \( \eta \) is the Euler-Mascheroni constant \( \approx 0.5772... \); the crossover point
  is at conductor around \( 8.3 \cdot 10^8 \). For the former value, empirical results show that for about 99.7% of
  all curves the returned value is the actual analytic rank.

- \text{adaptive} – (default: True) boolean
  - True – the computation is first run with small and then successively larger \( \Delta \) values up to
    \text{max}_\Delta. If at any point the computed bound is 0 (or 1 when \text{root_number} is -1 or True),
    the computation halts and that value is returned; otherwise the minimum of the computed bounds
    is returned.
  - False – the computation is run a single time with \( \Delta \) equal to \text{max}_\Delta, and the resulting bound
    returned.

- \text{N} – (default: None) If not None, a positive integer equal to the conductor of \text{self}. This is passable so
  that rank estimation can be done for curves whose (large) conductor has been precomputed.

- \text{root_number} – (default: “compute”) string or integer
  - "compute" – the root number of \text{self} is computed and used to (possibly) lower the analytic rank
    estimate by 1.
  - "ignore" – the above step is omitted
  - 1 – this value is assumed to be the root number of \text{self}. This is passable so that rank estimation
    can be done for curves whose root number has been precomputed.
  - -1 – this value is assumed to be the root number of \text{self}. This is passable so that rank estimation
    can be done for curves whose root number has been precomputed.

- \text{bad_primes} – (default: None) If not None, a list of the primes of bad reduction for the curve attached
to \text{self}. This is passable so that rank estimation can be done for curves of large conductor whose bad
primes have been precomputed.
• ncpus – (default: None) If not None, a positive integer defining the maximum number of CPUs to be used for the computation. If left as None, the maximum available number of CPUs will be used. Note: Due to parallelization overhead, multiple processors will only be used for Delta values $\geq 1.75$.

**Note:** Output will be incorrect if the incorrect conductor or root number is specified.

**Warning:** Zero sum computation time is exponential in the tightness parameter $\Delta$, roughly doubling for every increase of 0.1 thereof. Using $\Delta = 1$ (and adaptive=False) will yield a runtime of a few milliseconds; $\Delta = 2$ takes a few seconds, and $\Delta = 3$ may take upwards of an hour. Increase beyond this at your own risk!

**OUTPUT:**
A non-negative integer greater than or equal to the analytic rank of self.

**Note:** If you use set_verbose(1), extra information about the computation will be printed.

**See also:**
LFunctionZeroSum() root_number() set_verbose()

**EXAMPLES:**
For most elliptic curves with small conductor the central zero(s) of $L_E(s)$ are fairly isolated, so small values of $\Delta$ will yield tight rank estimates.

```python
sage: E = EllipticCurve("11a")
sage: E.rank()
0
sage: E.analytic_rank_upper_bound(max_Delta=1,adaptive=False)
0
sage: E = EllipticCurve([-39,123])
sage: E.rank()
1
sage: E.analytic_rank_upper_bound(max_Delta=1,adaptive=True)
1
```

This is especially true for elliptic curves with large rank.

```python
sage: for r in range(9):
    ....:     E = elliptic_curves.rank(r)[0]
    ....:     print((r, E.analytic_rank_upper_bound(max_Delta=1,
    ....:         adaptive=False,root_number="ignore")))
(0, 0)
(1, 1)
(2, 2)
(3, 3)
(4, 4)
(5, 5)
(6, 6)
(7, 7)
(8, 8)
```

14.1. Elliptic curves over the rational numbers
However, some curves have $L$-functions with low-lying zeroes, and for these larger values of $\Delta$ must be used to get tight estimates.

```python
sage: E = EllipticCurve("974b1")
sage: r = E.rank(); r
0
sage: E.analytic_rank_upper_bound(max_Delta=1,root_number="ignore")
1
sage: E.analytic_rank_upper_bound(max_Delta=1.3,root_number="ignore")
0
```

Knowing the root number of $E$ allows us to use smaller Delta values to get tight bounds, thus speeding up runtime considerably.

```python
sage: E.analytic_rank_upper_bound(max_Delta=0.6,root_number="compute")
0
```

There are a small number of curves which have pathologically low-lying zeroes. For these curves, this method will produce a bound that is strictly larger than the analytic rank, unless very large values of Delta are used. The following curve ("256944c1" in the Cremona tables) is a rank 0 curve with a zero at 0.0256...; the smallest Delta value for which the zero sum is strictly less than 2 is ~2.815.

```python
sage: E = EllipticCurve([0, -1, 0, -7460362000712, -7842981500851012704])
sage: N,r = E.conductor(),E.analytic_rank(); N, r
(256944, 0)
sage: E.analytic_rank_upper_bound(max_Delta=1,adaptive=False)
2
sage: E.analytic_rank_upper_bound(max_Delta=2,adaptive=False)
2
```

This method is can be called on curves with large conductor.

```python
sage: E = EllipticCurve([-2934,19238])
sage: E.analytic_rank_upper_bound()
1
```

And it can bound rank on curves with very large conductor, so long as you know beforehand/can easily compute the conductor and primes of bad reduction less than $e^{2\pi\Delta}$. The example below is of the rank 28 curve discovered by Elkies that is the elliptic curve of (currently) largest known rank.

```python
sage: a4 = -200677624155755265850332082093385427509302312178956502
sage: a6 = 34481611795030556467032985690390720374855944359319180361266008296291939448732243429
sage: E = EllipticCurve([1,-1,1,a4,a6])
sage: bad_primes = [2,3,5,7,11,13,17,19,48463]
sage: N = 34556011083575473415322538649016052311985115057937331389005951894721447247814563353801541498711930950197
sage: E.analytic_rank_upper_bound(max_Delta=2.37,adaptive=False, # long time
    ....:     N=N,root_number=1,bad_primes=bad_primes,ncpus=2) # long time
32
```

`anlist(n, python_ints=False)`

The Fourier coefficients up to and including $a_n$ of the modular form attached to this elliptic curve. The $i$-th element of the return list is $a[i]$.

INPUT:
• $n$ – integer
• python_ints – bool (default: False); if True return a list of Python ints instead of Sage integers

OUTPUT: list of integers

EXAMPLES:

```
sage: E = EllipticCurve([0, -1, 1, -10, -20])
sage: E.anlist(3)
[0, 1, -2, -1]
```

```
sage: E = EllipticCurve([0,1])
sage: E.anlist(20)
[0, 1, 0, 0, 0, 0, 0, -4, 0, 0, 0, 0, 0, 2, 0, 0, 0, 0, 0, 8, 0]
```

**antilogarithm**($z$, max_denominator=None)

Return the rational point (if any) associated to this complex number; the inverse of the elliptic logarithm function.

INPUT:

• $z$ – a complex number representing an element of $C/L$ where $L$ is the period lattice of the elliptic curve

• max_denominator – integer (optional); parameter controlling the attempted conversion of real numbers to rationals. If not given, simplest_rational() will be used; otherwise, nearby_rational() will be used with this value of max_denominator

OUTPUT:

• point on the curve: the rational point which is the image of $z$ under the Weierstrass parametrization, if it exists and can be determined from $z$ and the given value of max_denominator (if any); otherwise a ValueError exception is raised.

EXAMPLES:

```
sage: E = EllipticCurve('389a')
sage: P = E(-1,1)
sage: z = P.elliptic_logarithm()
sage: E.antilogarithm(z)
(-1 : 1 : 1)
```

```
sage: Q = E(0,-1)
sage: z = Q.elliptic_logarithm()
sage: E.antilogarithm(z)
Traceback (most recent call last):
  ...ValueError: approximated point not on the curve
```

```
sage: E = EllipticCurve('11a1')
sage: w1,w2 = E.period_lattice().basis()
sage: [E.antilogarithm(a*w1/5,1) for a in range(5)]
[(0 : 1 : 0), (16 : -61 : 1), (5 : -6 : 1), (5 : 5 : 1), (16 : 60 : 1)]
```

**ap**($p$)

The $p$-th Fourier coefficient of the modular form corresponding to this elliptic curve, where $p$ is prime.
EXAMPLES:

```python
sage: E = EllipticCurve('37a1')
sage: [E.ap(p) for p in prime_range(50)]
[-2, -3, -2, -1, -5, 0, 0, 2, -4, -1, -9, 2, -9]
```

`aplist(n, python_ints=False)`

The Fourier coefficients $a_p$ of the modular form attached to this elliptic curve, for all primes $p \leq n$.

**INPUT:**

- $n$ – integer
- `python_ints` – bool (default: `False`); if True return a list of Python ints instead of Sage integers

**OUTPUT:** list of integers

**EXAMPLES:**

```python
sage: e = EllipticCurve('37a1')
sage: e.aplist(1)
[]
sage: e.aplist(2)
[-2]
sage: e.aplist(10)
[-2, -3, -2, -1]
sage: v = e.aplist(13); v
[-2, -3, -2, -1, -5, -2]
sage: type(v[0])
<... 'sage.rings.integer.Integer'>
sage: type(e.aplist(13, python_ints=True)[0])
<... 'int'>
```

`cm_discriminant()`

Return the associated quadratic discriminant if this elliptic curve has Complex Multiplication over the algebraic closure.

A `ValueError` is raised if the curve does not have CM (see the function `has_cm()`).

**EXAMPLES:**

```python
sage: E = EllipticCurve('32a1')
sage: E.cm_discriminant()
-4
sage: E = EllipticCurve('121b1')
sage: E.cm_discriminant()
-11
sage: E = EllipticCurve('37a1')
sage: E.cm_discriminant()
Traceback (most recent call last):
...
ValueError: Elliptic Curve defined by y^2 + y = x^3 - x over Rational Field does not have CM
```

`conductor(algorithm='pari')`

Return the conductor of the elliptic curve.

**INPUT:**
• algorithm -- str, (default: “pari”)

  - "pari" – use the PARI C-library pari:ellglobalred implementation of Tate’s algorithm
  - "mwrank" – use Cremona’s mwrank implementation of Tate’s algorithm; can be faster if the curve has integer coefficients (TODO: limited to small conductor until mwrank gets integer factorization)
  - "gp" – use the GP interpreter
  - "generic" – use the general number field implementation
  - "all" – use all four implementations, verify that the results are the same (or raise an error), and output the common value

EXAMPLES:

```
sage: E = EllipticCurve([1, -1, 1, -29372, -1932937])
sage: E.conductor(algorithm="pari")
3006
sage: E.conductor(algorithm="mwrank")
3006
sage: E.conductor(algorithm="gp")
3006
sage: E.conductor(algorithm="generic")
3006
sage: E.conductor(algorithm="all")
3006
```

Note: The conductor computed using each algorithm is cached separately. Thus calling `E.conductor('pari')`, then `E.conductor('mwrank')` and getting the same result checks that both systems compute the same answer.

**congruence_number**(M=1)

The case $M = 1$ corresponds to the classical definition of congruence number: Let $X$ be the subspace of $S_2(\Gamma_0(N))$ spanned by the newform associated with this elliptic curve, and $Y$ be orthogonal complement of $X$ under the Petersson inner product. Let $S_X$ and $S_Y$ be the intersections of $X$ and $Y$ with $S_2(\Gamma_0(N), \mathbb{Z})$. The congruence number is defined to be $[S_X \oplus S_Y : S_2(\Gamma_0(N), \mathbb{Z})]$. It measures congruences between $f$ and elements of $S_2(\Gamma_0(N), \mathbb{Z})$ orthogonal to $f$.

The congruence number for higher levels, when $M>1$, is defined as above, but instead considers $X$ to be the subspace of $S_2(\Gamma_0(MN))$ spanned by embeddings into $S_2(\Gamma_0(MN))$ of the newform associated with this elliptic curve; this subspace has dimension $\sigma_0(M)$, i.e. the number of divisors of $M$. Let $Y$ be the orthogonal complement in $S_2(\Gamma_0(MN))$ of $X$ under the Petersson inner product, and $S_X$ and $S_Y$ the intersections of $X$ and $Y$ with $S_2(\Gamma_0(MN), \mathbb{Z})$ respectively. Then the congruence number at level $MN$ is $[S_X \oplus S_Y : S_2(\Gamma_0(MN), \mathbb{Z})]$.

INPUT:

• $M$ – non-negative integer; congruence number is computed at level $MN$, where $N$ is the conductor of self

EXAMPLES:

```
sage: E = EllipticCurve('37a')
sage: E.congruence_number()
2
sage: E.congruence_number()
(continues on next page)
```
2
\begin{verbatim}
sage: E = EllipticCurve('54b')
sage: E.congruence_number()
6
sage: E.modular_degree()
2
sage: E = EllipticCurve('242a1')
sage: E.modular_degree()
16
sage: E.congruence_number()  # long time (4s on sage.math, 2011)
176
\end{verbatim}

Higher level cases:
\begin{verbatim}
sage: E = EllipticCurve('11a')
sage: for M in range(1,11): print(E.congruence_number(M))  # long time (20s on ˓→2009 MBP)
1
1
3
2
7
45
12
4
18
245
\end{verbatim}

It is a theorem of Ribet that the congruence number (at level $N$) is equal to the modular degree in the case of square free conductor. It is a conjecture of Agashe, Ribet, and Stein that $\operatorname{ord}_p(c_f/m_f) \leq \operatorname{ord}_p(N)/2$.

\textbf{cremona_label}(\texttt{space=False})  
Return the Cremona label associated to (the minimal model) of this curve, if it is known. If not, raise a \texttt{LookupError} exception.

\textbf{EXAMPLES}:
\begin{verbatim}
sage: E = EllipticCurve('389a1')
sage: E.cremona_label()
'389a1'
\end{verbatim}

The default database only contains conductors up to 10000, so any curve with conductor greater than that will cause an error to be raised. The optional package \texttt{database_cremona_ellcurve} contains many more curves.

\begin{verbatim}
sage: E = EllipticCurve([1, -1, 0, -79, 289])
sage: E.conductor()
234446
sage: E.cremona_label()  # optional - database_cremona_ellcurve
'234446a1'
sage: E = EllipticCurve([0, 0, 1, -79, 342])
sage: E.conductor()
19047851
sage: E.cremona_label()
\end{verbatim}
Traceback (most recent call last):
...
LookupError: Cremona database does not contain entry for Elliptic Curve defined by y^2 + y = x^3 - 79*x + 342 over Rational Field

**database_attributes()**

Return a dictionary containing information about self in the elliptic curve database.

If there is no elliptic curve isomorphic to self in the database, a LookupError is raised.

**EXAMPLES:**

```
sage: E = EllipticCurve((0, 0, 1, -1, 0))
sage: data = E.database_attributes()
sage: data['conductor']
37
sage: data['cremona_label']
'37a1'
sage: data['rank']
1
sage: data['torsion_order']
1

sage: E = EllipticCurve((8, 13, 21, 34, 55))
sage: E.database_attributes()
Traceback (most recent call last):
...
LookupError: Cremona database does not contain entry for Elliptic Curve defined by y^2 + 8*x*y + 21*y = x^3 + 13*x^2 + 34*x + 55 over Rational Field
```

**database_curve()**

Return the curve in the elliptic curve database isomorphic to this curve, if possible. Otherwise raise a LookupError exception.

Since ticket #11474, this returns exactly the same curve as *minimal_model()*; the only difference is the additional work of checking whether the curve is in the database.

**EXAMPLES:**

```
sage: E = EllipticCurve([0,1,2,3,4])
sage: E.database_curve()
Elliptic Curve defined by y^2 = x^3 + x^2 + 3*x + 5 over Rational Field
```

**Note:** The model of the curve in the database can be different from the Weierstrass model for this curve, e.g., database models are always minimal.

**elliptic_exponential(z, embedding=None)**

Compute the elliptic exponential of a complex number with respect to the elliptic curve.

**INPUT:**

- `z` – a complex number
- `embedding` – ignored (for compatibility with the period_lattice function for elliptic_curve_number_field)
OUTPUT:

The image of $z$ modulo $L$ under the Weierstrass parametrization $C/L \to E(C)$.

**Note:** The precision is that of the input $z$, or the default precision of 53 bits if $z$ is exact.

**EXAMPLES:**

```python
sage: E = EllipticCurve([1,1,1,-8,6])
sage: P = E([1,-2])
sage: z = P.elliptic_logarithm()  # default precision is 100 here
sage: E.elliptic_exponential(z)
(1.0000000000000000000000000000 : -2.0000000000000000000000000000 : 1.0000000000000000000000000000)

sage: z = E([1,-2]).elliptic_logarithm(precision=201)
sage: E.elliptic_exponential(z)
(1.00000000000000000000000000000000000000000000000000000000000 : -2.00000000000000000000000000000000000000000000000000000000000 : 1.00000000000000000000000000000000000000000000000000000000000)
```

```python
sage: E = EllipticCurve('389a')
sage: Q = E([3,5])
sage: E.elliptic_exponential(Q.elliptic_logarithm())
(3.0000000000000000000000000000 : 5.0000000000000000000000000000 : 1.0000000000000000000000000000)

sage: P = E([-1,1])
sage: P.elliptic_logarithm()
0.47934825019021931612953301006 + 0.98586885077582410221120384908*I
sage: E.elliptic_exponential(P.elliptic_logarithm())
(-1.0000000000000000000000000000 : 1.0000000000000000000000000000 : 1.0000000000000000000000000000)
```

Some torsion examples:

```python
sage: w1, w2 = E.period_lattice().basis()
sage: E.division_polynomial(3).roots(CC,multiplicities=False)
[-2.88288879135333..., 1.3922799513..., 0.078313731444316... - 0.4928409917099*I, 0.078313731444316... + 0.4928409917099*I]
sage: [E.elliptic_exponential((a*w1+b*w2)/3)[0] for a,b in [(0,1),(1,0),(1,1),(2,1)]]
[-2.8828887913533..., 1.3922799513..., 0.0783137314443... - 0.4928409917099*I, 0.0783137314443... + 0.4928409917099*I]
```

Observe that this is a group homomorphism (modulo rounding error):
Elliptic curves, Release 9.7

```python
sage: z = CC.random_element()
sage: v = 2 * E.elliptic_exponential(z)
sage: w = E.elliptic_exponential(2 * z)
sage: def err(a, b):
....:     err = abs(a - b)
....:     if a + b:
....:         err = min(err, err / abs(a + b))
....:     return err
sage: err(v[0], w[0]) + err(v[1], w[1])  # abs tol 1e-13
0.0
```

**eval_modular_form** *(points, order)*

Evaluate the modular form of this elliptic curve at points in C.

**INPUT:**
- points – a list of points in the upper half-plane
- order – a nonnegative integer

The order parameter is the number of terms used in the summation.

**OUTPUT:** A list of values for s in points

**EXAMPLES:**

```python
sage: E = EllipticCurve('37a1')
sage: E.eval_modular_form([1.5+I,2.0+I,2.5+I],100)
[-0.0018743978548152085...,
  0.0018604485340371083..., 
 0.0018743978548152085...]
sage: E.eval_modular_form(2.1+I, 100)  # abs tol 1e-16
[0.00150864362757267079 + 0.00109100341113449845*I]
```

**faltings_height**(stable=False, prec=None)

Return the Faltings height (stable or unstable) of this elliptic curve.

**INPUT:**
- stable – boolean (default: False); if True, return the stable Faltings height, otherwise the unstable height
- prec – integer (default: None); bit precision of output; if None, use standard precision (53 bits)

**OUTPUT:**
(real) the Faltings height of this elliptic curve.

**Note:** Different authors normalise the Faltings height differently. We use the formula $-\frac{1}{2} \log(A)$, where $A$ is the area of the fundamental period parallelogram; some authors use $-\frac{1}{2\pi} \log(A)$ instead.

The unstable Faltings height does depend on the model. The stable Faltings height is defined to be

$$\frac{1}{12} \log \text{denom}(j) - \frac{1}{12} \log |\Delta| - \frac{1}{2} \log A,$$

This is independent of the model. For the minimal model of a semistable elliptic curve, we have $\text{denom}(j) = |\Delta|$, and the stable and unstable heights agree.
EXAMPLES:

```python
sage: E = EllipticCurve('32a1')
sage: E.faltings_height()
-0.617385745351564
sage: E.faltings_height(stable=True)
-1.31053292591151
```

These differ since the curve is not semistable:

```python
sage: E.is_semistable()
False
```

If the model is changed, the Faltings height changes but the stable height does not. It is reduced by \(\log(u)\) where \(u\) is the scale factor:

```python
sage: E1 = E.change_weierstrass_model([10,0,0,0])
sage: E1.faltings_height()
-2.9197083834561
sage: E1.faltings_height(stable=True)
-1.31053292591151
sage: E.faltings_height() - log(10.0)
-2.9197083834561
```

For a semistable curve (that is, one with squarefree conductor), the stable and unstable heights are equal. Here we also show that one can specify the (bit) precision of the result:

```python
sage: E = EllipticCurve('210a1')
sage: E.is_semistable()
True
sage: E.faltings_height(prec=100)
-0.043427311858075396288912139225
sage: E.faltings_height(stable=True, prec=100)
-0.043427311858075396288912139225
```

`galois_representation()`

The compatible family of the Galois representation attached to this elliptic curve.

Given an elliptic curve \(E\) over \(\mathbb{Q}\) and a rational prime number \(p\), the \(p^n\)-torsion \(E[p^n]\) points of \(E\) is a representation of the absolute Galois group of \(\mathbb{Q}\). As \(n\) varies we obtain the Tate module \(T_pE\) which is a representation of \(G_K\) on a free \(\mathbb{Z}_p\)-module of rank 2. As \(p\) varies the representations are compatible.

EXAMPLES:

```python
sage: rho = EllipticCurve('11a1').galois_representation()
sage: rho
Compatible family of Galois representations associated to the Elliptic Curve
˓→defined by y^2 + y = x^3 - x^2 - 10*x - 20 over Rational Field
sage: rho.is_irreducible(7)
True
sage: rho.is_irreducible(5)
False
sage: rho.is_surjective(11)
True
sage: rho.non_surjective()
```

(continues on next page)
Elliptic curves, Release 9.7

(continued from previous page)

\[\text{sage: rho} = \text{EllipticCurve('37a1').galois_representation()}
\text{sage: rho.non_surjective()}
[]\]
\text{sage: rho} = \text{EllipticCurve('27a1').galois_representation()}
\text{sage: rho.is_irreducible(7)}
True
\text{sage: rho.non_surjective()} # cm-curve
[0]

\text{gens(proof=\text{None}, **\text{kwds})}

Return generators for the Mordell-Weil group \(E(Q)\) modulo torsion.

INPUT:

- \text{proof} – \text{bool or None (default None), see proof.elliptic_curve or sage.structure.proof}
- \text{verbose} – (default: None), if specified changes the verbosity of mwrank computations
- \text{rank1_search} – (default: 10), if the curve has analytic rank 1, try to find a generator by a direct search up to this logarithmic height. If this fails, the usual mwrank procedure is called.
- \text{algorithm} – one of the following:
  - 'mwrank_shell' (default) – call mwrank shell command
  - 'mwrank_lib' – call mwrank C library
- \text{only_use_mwrank} – \text{bool (default True) if False, first attempts to use more naive, natively implemented methods}
- \text{use_database} – \text{bool (default True) if True, attempts to find curve and gens in the (optional) database}
- \text{descent_second_limit} – (default: 12) used in 2-descent
- \text{sat_bound} – (default: 1000) bound on primes used in saturation. If the computed bound on the index of the points found by two-descent in the Mordell-Weil group is greater than this, a warning message will be displayed.

OUTPUT:

- \text{generators} – list of generators for the Mordell-Weil group modulo torsion

\text{Note:} If you call this with \text{proof=\text{False}}, then you can use the \text{gens\_certain()} method to find out afterwards whether the generators were proved.

\text{IMPLEMENTATION: Uses Cremona’s mwrank C library.}

\text{EXAMPLES:}

\text{sage: E = EllipticCurve('389a')}
\text{sage: E.gens()}
# random output
\[\left[\left(-1 : 1 : 1\right), \left(0 : 0 : 1\right)\right]\]

A non-integral example:

\text{sage: E = EllipticCurve([-3/8,-2/3])}
\text{sage: E.gens()} # random (up to sign)
\[\left[\left(10/9 : 29/54 : 1\right)\right]\]
A non-minimal example:

```python
sage: E = EllipticCurve('389a1')
sage: E1 = E.change_weierstrass_model([1/20,0,0,0]); E1
Elliptic Curve defined by y^2 + 8000*y = x^3 + 400*x^2 - 320000*x over Rational Field
sage: E1.gens() # random (if database not used)
[(-400 : 8000 : 1), (0 : -8000 : 1)]
```

gens_certain()
Return True if the generators have been proven correct.

EXAMPLES:

```python
sage: E = EllipticCurve('37a1')
sage: E.gens() # random (up to sign)
[(0 : -1 : 1)]
sage: E.gens_certain()
True
```

global_integral_model()
Return a model of self which is integral at all primes.

EXAMPLES:

```python
sage: E = EllipticCurve([0, 0, 1/216, -7/1296, 1/7776])
sage: F = E.global_integral_model(); F
Elliptic Curve defined by y^2 + y = x^3 - 7*x + 6 over Rational Field
sage: F == EllipticCurve('5077a1')
True
```

has_cm()
Return whether or not this curve has a CM $j$-invariant.

OUTPUT:
True if the $j$-invariant of this curve is the $j$-invariant of an imaginary quadratic order, otherwise False.

See also:
`cm_discriminant()` and `has_rational_cm()`

Note: Even if $E$ has CM in this sense (that its $j$-invariant is a CM $j$-invariant), since the associated negative discriminant $D$ is not a square in $\mathbb{Q}$, the extra endomorphisms will not be defined over $\mathbb{Q}$. See also the method `has_rational_cm()` which tests whether $E$ has extra endomorphisms defined over $\mathbb{Q}$ or a given extension of $\mathbb{Q}$.

EXAMPLES:

```python
sage: E = EllipticCurve('37a1')
sage: E.has_cm()
False
sage: E = EllipticCurve('32a1')
sage: E.has_cm()
True
```
\textbf{sage: }\texttt{E.j_invariant()}
\begin{verbatim}
1728
\end{verbatim}

\textbf{has\_good\_reduction\_outside\_S(S=None)}
Test if this elliptic curve has good reduction outside \( S \).

\textbf{INPUT:}
- \( S \) – list of primes (default: []).

\textbf{Note:} Primality of elements of \( S \) is not checked, and the output is undefined if \( S \) is not a list or contains non-primes.

This only tests the given model, so should only be applied to minimal models.

\textbf{EXAMPLES:}
\begin{verbatim}
sage: EllipticCurve('11a1').has_good_reduction_outside_S([11])
True
sage: EllipticCurve('11a1').has_good_reduction_outside_S([2])
False
sage: EllipticCurve('2310a1').has_good_reduction_outside_S([2,3,5,7])
False
sage: EllipticCurve('2310a1').has_good_reduction_outside_S([2,3,5,7,11])
True
\end{verbatim}

\textbf{has\_rational\_cm(field=None)}
Return whether or not this curve has CM defined over \( \mathbb{Q} \) or the given field.

\textbf{INPUT:}
- \texttt{field} – (default: \( \mathbb{Q} \)) a field, which should be an extension of \( \mathbb{Q} \);

\textbf{OUTPUT:}
True if the ring of endomorphisms of this curve over the given field is larger than \( \mathbb{Z} \); otherwise False. If \texttt{field} is None the output will always be False. See also \texttt{cm\_discriminant()} and \texttt{has\_cm()}.

\textbf{Note:} If \( E \) has CM but the discriminant \( D \) is not a square in the given field \( K \), which will certainly be the case for \( K = \mathbb{Q} \) since \( D < 0 \), then the extra endomorphisms will not be defined over \( K \), and this function will return False. See also \texttt{has\_cm()}. To obtain the CM discriminant, use \texttt{cm\_discriminant()}. 

\textbf{EXAMPLES:}
\begin{verbatim}
sage: E = EllipticCurve(j=0)
sage: E.has_cm()
True
sage: E.has_rational_cm()
False
sage: D = E.cm_discriminant(); D
-3
\end{verbatim}

If we extend scalars to a field in which the discriminant is a square, the CM becomes rational:
sage: E.has_rational_cm(QuadraticField(-3))
True
sage: E = EllipticCurve(j=8000)
\sage: E.has_cm()
True
\sage: E.has_rational_cm()
False
\sage: D = E.cm_discriminant(); D
-8

Again, we may extend scalars to a field in which the discriminant is a square, where the CM becomes rational:

sage: E.has_rational_cm(QuadraticField(-2))
True

The field need not be a number field provided that it is an extension of \(\mathbb{Q}\):

sage: E.has_rational_cm(RR)
False
sage: E.has_rational_cm(CC)
True

An error is raised if a field is given which is not an extension of \(\mathbb{Q}\), i.e., not of characteristic 0:

sage: E.has_rational_cm(GF(2))
Traceback (most recent call last):
...
ValueError: Error in has_rational_cm: Finite Field of size 2 is not an extension field of \(\mathbb{Q}\)

**heegner_discriminants**\((bound)\)

Return the list of self’s Heegner discriminants between \(-1\) and \(-bound\).

**INPUT:**

\* bound (int) – upper bound for \(-discriminant\)

**OUTPUT:** The list of Heegner discriminants between \(-1\) and \(-bound\) for the given elliptic curve.

**EXAMPLES:**

sage: E=EllipticCurve('11a')
sage: E.heegner_discriminants(30)  # indirect doctest
[-7, -8, -19, -24]

**heegner_discriminants_list**(\(n\))

Return the list of self’s first \(n\) Heegner discriminants smaller than \(-5\).

**INPUT:**

\* n (int) – the number of discriminants to compute

**OUTPUT:** The list of the first \(n\) Heegner discriminants smaller than \(-5\) for the given elliptic curve.

**EXAMPLES:**
Elliptic curves, Release 9.7

```python
sage: E = EllipticCurve('11a')
sage: E.heegner_discriminants_list(4)  # indirect doctest
[-7, -8, -19, -24]
```

**heegner_index**\((D, \text{min}_p=2, \text{prec}=5, \text{descent}_\text{second}_\text{limit}=12, \text{verbose}_\text{mwrank}=\text{False}, \text{check}_\text{rank}=\text{True})\)

Return an interval that contains the index of the Heegner point \(y_K\) in the group of \(K\)-rational points modulo torsion on this elliptic curve, computed using the Gross-Zagier formula and/or a point search, or possibly half the index if the rank is greater than one.

If the curve has rank > 1, then the returned index is infinity.

**Note:** If \(\text{min}_p\) is bigger than 2 then the index can be off by any prime less than \(\text{min}_p\). This function returns the index divided by 2 exactly when the rank of \(E(K)\) is greater than 1 and \(E(Q)_{\text{tor}} \oplus E_D(Q)_{\text{tor}}\) has index 2 in \(E(K)_{\text{tor}}\), where the second factor undergoes a twist.

**INPUT:**
- \(D\) (int) – Heegner discriminant
- \(\text{min}_p\) (int) – (default: 2) only rule out primes = \(\text{min}_p\) dividing the index.
- \(\text{verbose}_\text{mwrank}\) (bool) – (default: \text{False}); print lots of mwrank search status information when computing regulator
- \(\text{prec}\) (int) – (default: 5), use \(\text{prec}\*\text{sqrt}(N) + 20\) terms of \(L\)-series in computations, where \(N\) is the conductor.
- \(\text{descent}_\text{second}_\text{limit}\) – (default: 12)- used in 2-descent when computing regulator of the twist
- \(\text{check}_\text{rank}\) – whether to check if the rank is at least 2 by computing the Mordell-Weil rank directly.

**OUTPUT:** an interval that contains the index, or half the index

**EXAMPLES:**

```python
sage: E = EllipticCurve('11a')
sage: E.heegner_discriminants(50)
[-7, -8, -19, -24, -35, -39, -40, -43]
sage: E.heegner_index(-7)
1.00000?
sage: E = EllipticCurve('37b')
sage: E.heegner_discriminants(100)
[-3, -4, -7, -11, -40, -47, -67, -71, -83, -84, -95]
sage: E.heegner_index(-95)  # long time (1 second)
2.00000?
```

This tests doing direct computation of the Mordell-Weil group.

```python
sage: EllipticCurve('675b').heegner_index(-11)
3.0000?
```

Currently discriminants -3 and -4 are not supported:

```python
sage: E.heegner_index(-3)
Traceback (most recent call last):
(continues on next page)```
The curve 681b returns the true index, which is 3:

```
sage: E = EllipticCurve('681b')
sage: I = E.heegner_index(-8); I
3.0000?
```

In fact, whenever the returned index has a denominator of 2, the true index is got by multiplying the returned index by 2. Unfortunately, this is not an if and only if condition, i.e., sometimes the index must be multiplied by 2 even though the denominator is not 2.

This example demonstrates the `descent_second_limit` option, which can be used to fine tune the 2-descent used to compute the regulator of the twist:

```
sage: E = EllipticCurve([1,-1,0,-1228,-16267])
sage: E.heegner_index(-8)
Traceback (most recent call last):
...
RuntimeError: ...
```

However when we search higher, we find the points we need:

```
sage: E.heegner_index(-8, descent_second_limit=16, check_rank=False) # long
˓→time
2.00000?
```

Two higher rank examples (of ranks 2 and 3):

```
sage: E = EllipticCurve('389a')
sage: E.heegner_index(-7)
+Infinity
sage: E = EllipticCurve('5077a')
sage: E.heegner_index(-7)
+Infinity
sage: E.heegner_index(-7, check_rank=False)
0.001?
```

```
sage: E.heegner_index(-7, check_rank=False).lower() == 0
True
```

The function `heegner_index_bound(D=0, prec=5, max_height=None)`

Assume self has rank 0.

Return a list $v$ of primes such that if an odd prime $p$ divides the index of the Heegner point in the group of rational points modulo torsion, then $p$ is in $v$.

If 0 is in the interval of the height of the Heegner point computed to the given prec, then this function returns $v = 0$. This does not mean that the Heegner point is torsion, just that it is very likely torsion.

If we obtain no information from a search up to `max_height`, e.g., if the Sijse et al. bound is bigger than `max_height`, then we return $v = -1$.

INPUT:

- `D` (int) – (default: 0) Heegner discriminant; if 0, use the first discriminant -4 that satisfies the Heegner hypothesis
Elliptic curves, Release 9.7

- `verbose` (bool) – (default: True)

- `prec` (int) – (default: 5), use $prec \cdot \sqrt{N} + 20$ terms of $L$-series in computations, where $N$ is the conductor.

- `max_height` (float) – should be $= 21$; bound on logarithmic naive height used in point searches. Make smaller to make this function faster, at the expense of possibly obtaining a worse answer. A good range is between 13 and 21.

**OUTPUT:**

- `$v$` – list or int (bad primes or 0 or -1)
- `$D$` – the discriminant that was used (this is useful if $D$ was automatically selected).
- `exact` – either False, or the exact Heegner index (up to factors of 2)

**EXAMPLES:**

```python
sage: E = EllipticCurve('11a1')
sage: E.heegner_index_bound()
([2], -7, 2)
```

**heegner_point**($D, c=1, f=None, check=True$)

Returns the Heegner point on this curve associated to the quadratic imaginary field $K = \mathbb{Q}(\sqrt{D})$.

If the optional parameter $c$ is given, returns the higher Heegner point associated to the order of conductor $c$.

**INPUT:**

- `$D$` – a Heegner discriminant
- `$c$` – (default: 1) conductor, must be coprime to $DN$
- `$f$` – binary quadratic form or 3-tuple $(A, B, C)$ of coefficients of $AX^2 + BXY + CY^2$
- `check` – bool (default: True)

**OUTPUT:**

The Heegner point $y_c$.

**EXAMPLES:**

```python
sage: E = EllipticCurve('37a1')
sage: E.heegner_discriminants_list(10)
[-7, -11, -40, -47, -67, -71, -83, -84, -95, -104]
sage: P = E.heegner_point(-7); P
# indirect doctest
Heegner point of discriminant -7 on elliptic curve of conductor 37
sage: P.point_exact()
(0 : 0 : 1)
sage: P.curve()
Elliptic Curve defined by $y^2 + y = x^3 - x$ over Rational Field
sage: P = E.heegner_point(-40).point_exact(); P
(a : -a + 1 : 1)
sage: P = E.heegner_point(-47).point_exact(); P
(a : a^4 + a - 1 : 1)
sage: P[0].parent()
Number Field in a with defining polynomial $x^5 - x^4 + x^3 + x^2 - 2x + 1$
```

Working out the details manually:

14.1. Elliptic curves over the rational numbers 241
Elliptic curves, Release 9.7

```python
sage: P = E.heegner_point(-47).numerical_approx(prec=200)
sage: f = algdep(P[0], 5); f
x^5 - x^4 + x^3 + x^2 - 2*x + 1
sage: f.discriminant().factor()
47^2
```

The Heegner hypothesis is checked:

```python
sage: E = EllipticCurve('389a'); P = E.heegner_point(-5,7);
Traceback (most recent call last):
...
ValueError: N (=389) and D (=5) must satisfy the Heegner hypothesis
```

We can specify the quadratic form:

```python
sage: P = EllipticCurve('389a').heegner_point(-7, 5, (778,925,275)); P
Heegner point of discriminant -7 and conductor 5 on elliptic curve of conductor 389
sage: P.quadratic_form()
778*x^2 + 925*x*y + 275*y^2
```

**heegner_point_height**(\(D, \text{prec}=2, \text{check\_rank}=\text{True}\))

Use the Gross-Zagier formula to compute the Neron-Tate canonical height over \(K\) of the Heegner point corresponding to \(D\), as an interval (it is computed to some precision using \(L\)-functions).

If the curve has rank at least 2, then the returned height is the exact Sage integer 0.

**INPUT:**

- \(D\) (int) – fundamental discriminant (=\(-3, -4\))
- \(\text{prec}\) (int) – (default: 2), use \(\text{prec} \cdot \sqrt{(N)} + 20\) terms of \(L\)-series in computations, where \(N\) is the conductor.
- \(\text{check\_rank}\) – whether to check if the rank is at least 2 by computing the Mordell-Weil rank directly.

**OUTPUT:** Interval that contains the height of the Heegner point.

**EXAMPLES:**

```python
sage: E = EllipticCurve('11a')
sage: E.heegner_point_height(-7)
0.22227?
```

Some higher rank examples:

```python
sage: E = EllipticCurve('389a')
sage: E.heegner_point_height(-7)
0
sage: E = EllipticCurve('5077a')
sage: E.heegner_point_height(-7)
0
sage: E.heegner_point_height(-7,check_rank=False)
0.0000?
```

**heegner_sha_an**(\(D, \text{prec}=53\))

Return the conjectural (analytic) order of Sha for \(E\) over the field \(K = \mathbb{Q}(\sqrt{D})\).
INPUT:
- $D$ – negative integer; the Heegner discriminant
- prec – integer (default: 53); bits of precision to compute analytic order of Sha

OUTPUT:
(floating point number) an approximation to the conjectural order of Sha.

Note: Often you’ll want to do `proof.elliptic_curve(False)` when using this function, since often the twisted elliptic curves that come up have enormous conductor, and Sha is nontrivial, which makes provably finding the Mordell-Weil group using 2-descent difficult.

EXAMPLES:
An example where $E$ has conductor 11:

```sage
E = EllipticCurve('11a')
E.heegner_sha_an(-7) # long time
1.00000000000000
```

The cache works:

```sage
E.heegner_sha_an(-7) is E.heegner_sha_an(-7) # long time
True
```

Lower precision:

```sage
E.heegner_sha_an(-7, 10) # long time
1.0
```

Checking that the cache works for any precision:

```sage
E.heegner_sha_an(-7, 10) is E.heegner_sha_an(-7, 10) # long time
True
```

Next we consider a rank 1 curve with nontrivial Sha over the quadratic imaginary field $K$; however, there is no Sha for $E$ over $Q$ or for the quadratic twist of $E$:

```sage
E = EllipticCurve('37a')
E.heegner_sha_an(-40) # long time
4.00000000000000
E.quadratic_twist(-40).sha().an() # long time
1
E.sha().an() # long time
1
```

A rank 2 curve:

```sage
E = EllipticCurve('389a') # long time
E.heegner_sha_an(-7) # long time
1.00000000000000
```

If we remove the hypothesis that $E(K)$ has rank 1 in Conjecture 2.3 in [GZ1986] page 311, then that conjecture is false, as the following example shows:
Elliptic curves, Release 9.7

```
sage: E = EllipticCurve('65a')  # long time
sage: E.heegner_sha_an(-56)   # long time
1.00000000000000
sage: E.torsion_order()       # long time
2
sage: E.tamagawa_product()    # long time
1
sage: E.quadratic_twist(-56).rank() # long time
2
```

**height**(precision=None)

Return the real height of this elliptic curve.

This is used in `integral_points()`.

**INPUT:**

- **precision** – desired real precision of the result (default real precision if None)

**EXAMPLES:**

```
sage: E = EllipticCurve('5077a1')
sage: E.height()
17.4513334798896
sage: E.height(100)
17.451333479889612702508579399
sage: E = EllipticCurve([0,0,0,0,1])
sage: E.height()
1.38629436111989
sage: E = EllipticCurve([0,0,0,1,0])
sage: E.height()
7.45471994936400
```

**integral_model()**

Return a model of self which is integral at all primes.

**EXAMPLES:**

```
sage: E = EllipticCurve([0,0,1/216,-7/1296,1/7776])
sage: F = E.global_integral_model(); F
Elliptic Curve defined by y^2 + y = x^3 - 7*x + 6 over Rational Field
sage: F == EllipticCurve('5077a1')
True
```

**integral_points**(mw_base='auto', both_signs=False, verbose=False)

Compute all integral points (up to sign) on this elliptic curve.

**INPUT:**

- **mw_base** – (default: 'auto') - calls `gens()`) list of EllipticCurvePoint generating the Mordell-Weil group of E
- **both_signs** – boolean (default: False); if True the output contains both P and -P, otherwise only one of each pair
- **verbose** – boolean (default: False); if True, some details of the computation are output

**OUTPUT:** A sorted list of all the integral points on E (up to sign unless both_signs is True)
**Note:** The complexity increases exponentially in the rank of curve E. The computation time (but not the output!) depends on the Mordell-Weil basis. If mw_base is given but is not a basis for the Mordell-Weil group (modulo torsion), integral points which are not in the subgroup generated by the given points will almost certainly not be listed.

**EXAMPLES:** A curve of rank 3 with no torsion points:

```python
sage: E = EllipticCurve([0,0,1,-7,6])
sage: P1=E.point((2,0)); P2=E.point((-1,3)); P3=E.point((4,6))
sage: a=E.integral_points([P1,P2,P3]); a
sage: a = E.integral_points([P1,P2,P3], verbose=True)
Using mw_basis [ (2 : 0 : 1), (3 : -4 : 1), (8 : -22 : 1)]
e1,e2,e3: -3.0124303725933...,1.0658205476962...,1.94660982489710
Minimal and maximal eigenvalues of height pairing matrix: 0.637920814585005, 2.31982967525725
x-coords of points on compact component with -3 <= x <= 1
[-3, -2, -1, 0, 1]
x-coords of points on non-compact component with 2 <= x <= 6
[2, 3, 4]
starting search of remaining points using coefficient bound 5 and |x| bound 1.
53897183921009e25
x-coords of extra integral points:
[2, 3, 4, 8, 11, 14, 21, 37, 52, 93, 342, 406, 816]
Total number of integral points: 18
```

It is not necessary to specify mw_base; if it is not provided, then the Mordell-Weil basis must be computed, which may take much longer.

```python
sage: E = EllipticCurve([0,0,1,-7,6])
sage: a=E.integral_points(both_signs=True); a
```

An example with negative discriminant:

```python
sage: EllipticCurve('900d1').integral_points()
[(-11 : 27 : 1), (-4 : 34 : 1), (4 : 18 : 1), (16 : 54 : 1)]
```

Another example with rank 5 and no torsion points:
Elliptic curves, Release 9.7

```
sage: E = EllipticCurve([-879984,319138704])
sage: P1=E.point((540,1188)); P2=E.point((576,1836))
sage: P3=E.point((468,3132)); P4=E.point((612,3132))
sage: P5=E.point((432,4428))
sage: a=E.integral_points([P1,P2,P3,P4,P5]); len(a)  # long time (18s on sage. ˓→math, 2011)
54
```

ALGORITHM:

This function uses the algorithm given in [Coh2007I].

AUTHORS:

• Michael Mardaus (2008-07)
• Tobias Nagel (2008-07)
• John Cremona (2008-07)

```
integral_short_weierstrass_model()

Return a model of the form $y^2 = x^3 + ax + b$ for this curve with $a, b \in \mathbb{Z}$.

EXAMPLES:

```
sage: E = EllipticCurve('17a1')
sage: E.integral_short_weierstrass_model()
Elliptic Curve defined by y^2 = x^3 - 11*x - 890 over Rational Field
```

```
integral_x_coords_in_interval(xmin, xmax)

Return the set of integers $x$ with $xmin \leq x \leq xmax$ which are $x$-coordinates of rational points on this curve.

INPUT:

• xmin, xmax (integers) – two integers

OUTPUT:

(set) The set of integers $x$ with $xmin \leq x \leq xmax$ which are $x$-coordinates of rational points on the elliptic curve.

EXAMPLES:

```
sage: E = EllipticCurve([0, 0, 1, -7, 6])
sage: xset = E.integral_x_coords_in_interval(-100,100)
sage: sorted(xset)
[-3, -2, -1, 0, 1, 2, 3, 4, 8, 11, 14, 21, 37, 52, 93]
sage: xset = E.integral_x_coords_in_interval(-100,0)
sage: sorted(xset)
[-3, -2, -1, 0]
```

```
is_global_integral_model()

Return True iff self is integral at all primes.

EXAMPLES:

```
sage: E = EllipticCurve([1/2,1/5,1/5,1/5,1/5])
sage: E.is_global_integral_model()
False
```
Elliptic curves, Release 9.7

sage: Emin=E.global_integral_model()
sage: Emin.is_global_integral_model()
True

\textbf{is\_good}(p, check=True)

Return True if \( p \) is a prime of good reduction for \( E \).

\textbf{INPUT:}

\begin{itemize}
  \item \( p \) – a prime
\end{itemize}

\textbf{OUTPUT:} bool

\textbf{EXAMPLES:}

\begin{verbatim}
sage: e = EllipticCurve('11a')
sage: e.is_good(-8)
Traceback (most recent call last):
...
ValueError: p must be prime
sage: e.is_good(-8, check=False)
True
\end{verbatim}

\textbf{is\_integral}()

Return True if this elliptic curve has integral coefficients (in \( \mathbb{Z} \)).

\textbf{EXAMPLES:}

\begin{verbatim}
sage: E = EllipticCurve(QQ,[1,1]); E
Elliptic Curve defined by \( y^2 = x^3 + x + 1 \) over Rational Field
sage: E.is_integral()  
True
sage: E2=E.change_weierstrass_model(2,0,0,0); E2
Elliptic Curve defined by \( y^2 = x^3 + 1/16*x + 1/64 \) over Rational Field
sage: E2.is_integral() 
False
\end{verbatim}

\textbf{is\_isogenous}(other, proof=True, maxp=200)

Return whether or not \( \text{self} \) is isogenous to \( \text{other} \).

\textbf{INPUT:}

\begin{itemize}
  \item \( \text{other} \) – another elliptic curve
  \item \( \text{proof} \) – (default: True) if False, the function will return True whenever the two curves have the same conductor and are isogenous modulo \( p \) for \( p \) up to \( \text{maxp} \); otherwise this test is followed by a rigorous test (which may be more time-consuming)
  \item \( \text{maxp} \) – (default: 200) the maximum prime \( p \) for which isogeny modulo \( p \) will be checked
\end{itemize}

\textbf{OUTPUT:}

(bool) True if there is an isogeny from curve \( \text{self} \) to curve \( \text{other} \).

\textbf{ALGORITHM:}

First the conductors are compared as well as the Traces of Frobenius for good primes up to \( \text{maxp} \). If any of these tests fail, False is returned. If they all pass and \( \text{proof} \) is False then True is returned, otherwise a complete set of curves isogenous to \( \text{self} \) is computed and \( \text{other} \) is checked for isomorphism with any of these,
EXAMPLES:

```python
sage: E1 = EllipticCurve('14a1')
sage: E6 = EllipticCurve('14a6')
sage: E1.is_isogenous(E6)
True
sage: E1.is_isogenous(EllipticCurve('11a1'))
False
sage: EllipticCurve('37a1').is_isogenous(EllipticCurve('37b1'))
False
```

```python
sage: E = EllipticCurve([2, 16])
sage: EE = EllipticCurve([87, 45])
sage: E.is_isogenous(EE)
False
```

```python
sage: def is_local_integral_model(*p):
    Tests if self is integral at the prime p, or at all the primes if p is a list or tuple of primes.

    EXAMPLES:

    sage: E = EllipticCurve([1/2,1/5,1/5,1/5,1/5])
    sage: [E.is_local_integral_model(p) for p in (2,3,5)]
    [False, True, False]
    sage: E.is_local_integral_model(2,3,5)
    False
    sage: Eint2=E.local_integral_model(2)
    sage: Eint2.is_local_integral_model(2)
    True

```

```python
sage: def is_minimal():
    Return True iff this elliptic curve is a reduced minimal model.

    The unique minimal Weierstrass equation for this elliptic curve. This is the model with minimal discriminant and \( a_1, a_2, a_3 \in \{0, \pm 1\} \).

    Todo: This is not very efficient since it just computes the minimal model and compares. A better implementation using the Kraus conditions would be preferable.

    EXAMPLES:

    sage: E = EllipticCurve([10,100,1000,10000,1000000])
    sage: E.is_minimal()
    False
    sage: E = E.minimal_model()
    sage: E.is_minimal()
    True

```

```python
sage: def is_ordinary(p, ell=None):
    Return True precisely when the mod-p representation attached to this elliptic curve is ordinary at ell.

    INPUT:
    • p – a prime
```


- ell -- a prime (default: p)

OUTPUT: bool

EXAMPLES:

```
sage: E = EllipticCurve('37a1')
sage: E.is_ordinary(37)
True
sage: E = EllipticCurve('32a1')
sage: E.is_ordinary(2)
False
sage: [p for p in prime_range(50) if E.is_ordinary(p)]
[5, 13, 17, 29, 37, 41]
```

**is_p_integral** *(p)*

Return True if this elliptic curve has \( p \)-integral coefficients.

INPUT:

- \( p \) -- a prime integer

EXAMPLES:

```
sage: E = EllipticCurve(QQ,[1,1]); E
Elliptic Curve defined by y^2 = x^3 + x + 1 over Rational Field
sage: E.is_p_integral(2)
True
sage: E2=E.change_weierstrass_model(2,0,0,0); E2
Elliptic Curve defined by y^2 = x^3 + 1/16*x + 1/64 over Rational Field
sage: E2.is_p_integral(2)
False
sage: E2.is_p_integral(3)
True
```

**is_p_minimal** *(p)*

Tests if curve is \( p \)-minimal at a given prime \( p \).

INPUT:

- \( p \) -- a prime

OUTPUT:

- True -- if curve is \( p \)-minimal
- False -- if curve is not \( p \)-minimal

EXAMPLES:

```
sage: E = EllipticCurve('441a2')
sage: E.is_p_minimal(7)
True
sage: E = EllipticCurve([0,0,0,(2*5*11)**10])
sage: [E.is_p_minimal(p) for p in prime_range(2,24)]
[False, True, False, True, False, True, True, True]
```

**is_semistable**

Return True iff this elliptic curve is semi-stable at all primes.
EXAMPLES:

```python
sage: E = EllipticCurve('37a1')
sage: E.is_semistable()
True
sage: E = EllipticCurve('90a1')
sage: E.is_semistable()
False
```

**is_supersingular**\((p, ell=None)\)

Return True precisely when \(p\) is a prime of good reduction and the mod-\(p\) representation attached to this elliptic curve is supersingular at \(ell\).

**INPUT:**

- \(p\) – a prime
- \(ell\) – a prime (default: \(p\))

**OUTPUT:** bool

**EXAMPLES:**

```python
sage: E = EllipticCurve('37a1')
sage: E.is_supersingular(37)
False
sage: E = EllipticCurve('32a1')
sage: E.is_supersingular(2)
False
sage: E.is_supersingular(7)
True
sage: [p for p in prime_range(50) if E.is_supersingular(p)]
[3, 7, 11, 19, 23, 31, 43, 47]
```

**isogenies_prime_degree**\((l=None)\)

Return a list of \(\ell\)-isogenies from self, where \(\ell\) is a prime.

**INPUT:**

- \(l\) – either None or a prime or a list of primes

**OUTPUT:** (list) \(\ell\)-isogenies for the given \(\ell\) or if \(\ell\) is None, all \(\ell\)-isogenies.

**Note:** The codomains of the isogenies returned are standard minimal models. This is because the functions `isogenies_prime_degree_genus_0()` and `isogenies_sporadic_Q()` are implemented that way for curves defined over \(Q\).

**EXAMPLES:**

```python
sage: E = EllipticCurve([45,32])
sage: E.isogenies_prime_degree()[]
sage: E = EllipticCurve(j = -262537412640768000)
sage: E.isogenies_prime_degree()[]
```

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Elliptic curves, Release 9.7

sage: E1 = E.quadratic_twist(6584935282)
sage: E1.isogenies_prime_degree()
[Isogeny of degree 163 from Elliptic Curve defined by $y^2 = x^3 - 942853859570317979813768080x + 352385311612420041387338054224547830898$ over $\mathbb{Q}$ to Elliptic Curve defined by $y^2 = x^3 - 25050803755423778405671810669520x - 1526091631109553256978090116318797845018020806$ over $\mathbb{Q}$]

sage: E = EllipticCurve('14a1')
sage: E.isogenies_prime_degree(2)
[Isogeny of degree 2 from Elliptic Curve defined by $y^2 + x*y + y = x^3 + 4*x - 6$ over $\mathbb{Q}$ to Elliptic Curve defined by $y^2 + x*y + y = x^3 - 36*x - 70$ over $\mathbb{Q}$]

sage: E.isogenies_prime_degree(3)
[Isogeny of degree 3 from Elliptic Curve defined by $y^2 + x*y + y = x^3 + 4*x - 6$ over $\mathbb{Q}$ to Elliptic Curve defined by $y^2 + x*y + y = x^3 - x$ over $\mathbb{Q}$, Isogeny of degree 3 from Elliptic Curve defined by $y^2 + x*y + y = x^3 + 4*x - 6$ over $\mathbb{Q}$ to Elliptic Curve defined by $y^2 + x*y + y = x^3 - 171*x - 874$ over $\mathbb{Q}$]

sage: E.isogenies_prime_degree(5)
[]
sage: E.isogenies_prime_degree(11)
[]
sage: E.isogenies_prime_degree(29)
[]
sage: E.isogenies_prime_degree(4)
Traceback (most recent call last):
  ...
ValueError: 4 is not prime.

```
isogeny_class(algorithm='sage', order=None)
```

Return the $\mathbb{Q}$-isogeny class of this elliptic curve.

**INPUT:**

- **algorithm** – string: one of the following:
  - “database” – use the Cremona database (only works if curve is isomorphic to a curve in the database)
  - “sage” (default) – use the native Sage implementation.

- **order** – None, string, or list of curves (default: None): If not None then the curves in the class are reordered after being computed. Note that if the order is None then the resulting order will depend on the algorithm.
  - If order is “database” or “sage”, then the reordering is so that the order of curves matches the order produced by that algorithm.
  - If order is “lmfdb” then the curves are sorted lexicographically by a-invariants, in the LMFDB database.
  - If order is a list of curves, then the curves in the class are reordered to be isomorphic with the specified list of curves.

**OUTPUT:**
An instance of the class `sage.schemes.elliptic_curves.isogeny_class.IsogenyClass_EC_Rational`. This object models a list of minimal models (with containment, index, etc based on isomorphism classes). It also has methods for computing the isogeny matrix and the list of isogenies between curves in this class.

**Note:** The curves in the isogeny class will all be standard minimal models.

### EXAMPLES:

```python
sage: isocls = EllipticCurve('37b').isogeny_class(order="lmfdb")
sage: isocls
Elliptic curve isogeny class 37b
sage: isocls.curves
(Elliptic Curve defined by y^2 + y = x^3 + x^2 - 1873*x - 31833 over Rational Field,
 Elliptic Curve defined by y^2 + y = x^3 + x^2 - 23*x - 50 over Rational Field,
 Elliptic Curve defined by y^2 + y = x^3 + x^2 - 3*x + 1 over Rational Field)
sage: isocls.matrix()
[1 3 9]
[3 1 3]
[9 3 1]
```

```python
sage: isocls = EllipticCurve('37b').isogeny_class('database', order="lmfdb");

isocls.curves
(Elliptic Curve defined by y^2 + y = x^3 + x^2 - 1873*x - 31833 over Rational Field,
 Elliptic Curve defined by y^2 + y = x^3 + x^2 - 23*x - 50 over Rational Field,
 Elliptic Curve defined by y^2 + y = x^3 + x^2 - 3*x + 1 over Rational Field)
```

This is an example of a curve with a 37-isogeny:

```python
sage: E = EllipticCurve([1,1,1,-8,6])
sage: isocls = E.isogeny_class(); isocls
Isogeny class of Elliptic Curve defined by y^2 + x*y + y = x^3 + x^2 - 8*x + 6 over Rational Field
sage: isocls.matrix()
[ 1 37]
[37 1]
sage: print("\n".join(repr(E) for E in isocls.curves))
Elliptic Curve defined by y^2 + x*y + y = x^3 + x^2 - 8*x + 6 over Rational Field
Elliptic Curve defined by y^2 + x*y + y = x^3 + x^2 - 208083*x - 36621194 over Rational Field
```

This curve had numerous 2-isogenies:

```python
sage: e = EllipticCurve([1,0,0,-39,90])
sage: isocls = e.isogeny_class(); isocls.matrix()
[1 2 4 4 8 8]
[2 1 2 2 4 4]
[4 2 1 4 8 8]
[4 2 4 1 2 2]
```

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See [http://math.harvard.edu/~elkies/nature.html](http://math.harvard.edu/~elkies/nature.html) for more interesting examples of isogeny structures.

```python
sage: E = EllipticCurve(j = -262537412640768000)
sage: isocls = E.isogeny_class(); isocls.matrix()
[ 1 163]
[163  1]
sage: print("\n.join(repr(C) for C in isocls.curves))
Elliptic Curve defined by y^2 + y = x^3 - 2174420*x + 1234136692 over Rational Field
Elliptic Curve defined by y^2 + y = x^3 - 57772164980*x - 5344733777551611 over Rational Field
```

The degrees of isogenies are invariant under twists:

```python
sage: E = EllipticCurve(j = -262537412640768000)
sage: E1 = E.quadratic_twist(6584935282)
sage: isocls = E1.isogeny_class(); isocls.matrix()
[ 1 163]
[163  1]
sage: E1.conductor()
1843300296671263653330496
```

```python
sage: E = EllipticCurve('14a1')
sage: isocls = E.isogeny_class(); isocls.matrix()
[ 1 2 3 3 6 6]
[ 2 1 6 6 3 3]
[ 3 6 1 9 2 18]
[ 3 6 9 1 18 2]
[ 6 3 2 18 1 9]
[ 6 3 18 2 9 1]
sage: print("\n.join(repr(C) for C in isocls.curves))
Elliptic Curve defined by y^2 + x*y + y = x^3 + 4*x - 6 over Rational Field
Elliptic Curve defined by y^2 + x*y + y = x^3 - 36*x - 70 over Rational Field
Elliptic Curve defined by y^2 + x*y + y = x^3 - x over Rational Field
Elliptic Curve defined by y^2 + x*y + y = x^3 - 171*x - 874 over Rational Field
Elliptic Curve defined by y^2 + x*y + y = x^3 - 11*x + 12 over Rational Field
Elliptic Curve defined by y^2 + x*y + y = x^3 - 2731*x - 55146 over Rational Field
```

```python
sage: isocls2 = isocls.reorder('lmfdb'); isocls2.matrix()
[ 1 2 3 9 18 6]
[ 2 1 6 18 9 3]
[ 3 6 1 3 6 2]
[ 9 18 3 1 2 6]
[18 9 6 2 1 3]
[ 6 3 2 6 3 1]
sage: print("\n.join(repr(C) for C in isocls2.curves))
Elliptic Curve defined by y^2 + x*y + y = x^3 - 2731*x - 55146 over Rational Field
Elliptic Curve defined by y^2 + x*y + y = x^3 - 171*x - 874 over Rational Field
```

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Elliptic Curves defined by:
- \( y^2 + x*y + y = x^3 - 36*x - 70 \) over Rational Field
- \( y^2 + x*y + y = x^3 - 11*x + 12 \) over Rational Field
- \( y^2 + x*y + y = x^3 - x \) over Rational Field
- \( y^2 + x*y + y = x^3 + 4*x - 6 \) over Rational Field

```python
sage: E = EllipticCurve('11a1')
sage: isocls = E.isogeny_class(); isocls.matrix()
[[1 5 5]
 [5 1 25]
 [5 25 1]]
sage: f = isocls.isogenies()[0][1]; f.kernel_polynomial()
x^2 + x - 29/5
```

**isogeny_degree**(*other*)

Return the minimal degree of an isogeny between `self` and `other`.

**INPUT:**
- `other` – another elliptic curve

**OUTPUT:**

The minimal degree of an isogeny from `self` to `other`, or 0 if the curves are not isogenous.

**EXAMPLES:**

```python
sage: E = EllipticCurve([-1056, 13552])
sage: E2 = EllipticCurve([-127776, -18037712])
sage: E.isogeny_degree(E2)
11

sage: E1 = EllipticCurve('14a1')
sage: E2 = EllipticCurve('14a2')
sage: E3 = EllipticCurve('14a3')
sage: E4 = EllipticCurve('14a4')
sage: E5 = EllipticCurve('14a5')
sage: E6 = EllipticCurve('14a6')
sage: E3.isogeny_degree(E1)
3
sage: E3.isogeny_degree(E2)
6
sage: E3.isogeny_degree(E3)
1
sage: E3.isogeny_degree(E4)
9
sage: E3.isogeny_degree(E5)
2
sage: E3.isogeny_degree(E6)
18
```

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Elliptic curves, Release 9.7

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```
sage: E5 = EllipticCurve('30a5')
sage: E6 = EllipticCurve('30a6')
sage: E7 = EllipticCurve('30a7')
sage: E8 = EllipticCurve('30a8')
sage: E1.isogeny_degree(E1)
1
sage: E1.isogeny_degree(E2)
2
sage: E1.isogeny_degree(E3)
3
sage: E1.isogeny_degree(E4)
4
sage: E1.isogeny_degree(E5)
4
sage: E1.isogeny_degree(E6)
6
sage: E1.isogeny_degree(E7)
12
sage: E1.isogeny_degree(E8)
12
```

```
sage: E1 = EllipticCurve('15a1')
sage: E2 = EllipticCurve('15a2')
sage: E3 = EllipticCurve('15a3')
sage: E4 = EllipticCurve('15a4')
sage: E5 = EllipticCurve('15a5')
sage: E6 = EllipticCurve('15a6')
sage: E7 = EllipticCurve('15a7')
sage: E8 = EllipticCurve('15a8')
sage: E1.isogeny_degree(E1)
1
sage: E7.isogeny_degree(E2)
8
sage: E7.isogeny_degree(E3)
2
sage: E7.isogeny_degree(E4)
8
sage: E7.isogeny_degree(E5)
16
sage: E7.isogeny_degree(E6)
16
sage: E7.isogeny_degree(E8)
4
```

0 is returned when the curves are not isogenous:

```
sage: A = EllipticCurve('37a1')
sage: B = EllipticCurve('37b1')
sage: A.isogeny_degree(B)
0
sage: A.is_isogenous(B)
False
```
**isogeny_graph**(order=None)

Return a graph representing the isogeny class of this elliptic curve, where the vertices are isogenous curves over \( \mathbb{Q} \) and the edges are prime degree isogenies.

**Note:** The vertices are labeled 1 to \( n \) rather than 0 to \( n - 1 \) to correspond to LMFDB and Cremona labels.

**EXAMPLES:**

```python
sage: LL = []
sage: for e in cremona_optimal_curves(range(1, 38)):  # long time
    ...:     G = e.isogeny_graph()
    ...:     already = False
    ...:     for H in LL:
    ...:         if G.is_isomorphic(H):
    ...:             already = True
    ...:             break
    ...:     if not already:
    ...:         LL.append(G)
sage: graphs_list.show_graphs(LL)  # long time
```

```python
sage: E = EllipticCurve('195a')
sage: G = E.isogeny_graph()
sage: for v in G: print("{} ",format(v, G.get_vertex(v)))
1 Elliptic Curve defined by y^2 + x*y = x^3 - 110*x + 435 over Rational Field
2 Elliptic Curve defined by y^2 + x*y = x^3 - 115*x + 392 over Rational Field
3 Elliptic Curve defined by y^2 + x*y = x^3 + 210*x + 2277 over Rational Field
4 Elliptic Curve defined by y^2 + x*y = x^3 - 520*x - 4225 over Rational Field
5 Elliptic Curve defined by y^2 + x*y = x^3 + 605*x - 19750 over Rational Field
6 Elliptic Curve defined by y^2 + x*y = x^3 - 8125*x - 282568 over Rational Field
7 Elliptic Curve defined by y^2 + x*y = x^3 - 7930*x - 296725 over Rational Field
8 Elliptic Curve defined by y^2 + x*y = x^3 - 130000*x - 18051943 over Rational Field
sage: G.plot(edge_labels=True)
Graphics object consisting of 23 graphics primitives
```

**kodaira_symbol**(\( p \))

Local Kodaira type of the elliptic curve at \( p \).

**INPUT:**

- \( p \) – an integral prime

**OUTPUT:**

- the Kodaira type of this elliptic curve at \( p \), as a `KodairaSymbol`

**EXAMPLES:**

```python
sage: E = EllipticCurve('124a')
sage: E.kodaira_type(2)
IV
```

**kodaira_type**(\( p \))

Local Kodaira type of the elliptic curve at \( p \).
INPUT:
  • $p$ – an integral prime
OUTPUT:
  • the Kodaira type of this elliptic curve at $p$, as a *KodairaSymbol*
EXAMPLES:
```
sage: E = EllipticCurve('124a')
sage: E.kodaira_type(2)
IV
```

**kodaira_type_old($p$)**
Local Kodaira type of the elliptic curve at $p$.

INPUT:
  • $p$ – an integral prime
OUTPUT:
  • the Kodaira type of this elliptic curve at $p$, as a *KodairaSymbol*
EXAMPLES:
```
sage: E = EllipticCurve('124a')
sage: E.kodaira_type_old(2)
IV
```

**kolyvagin_point($D$, $c=1$, check=True)**
Return the Kolyvagin point on this curve associated to the quadratic imaginary field $K = \mathbb{Q}(\sqrt{D})$ and conductor $c$.

INPUT:
  • $D$ – a Heegner discriminant
  • $c$ – (default: 1) conductor, must be coprime to $DN$
  • check – bool (default: True)
OUTPUT:
  The Kolyvagin point $P$ of conductor $c$.
EXAMPLES:
```
sage: E = EllipticCurve('37a1')
sage: P = E.kolyvagin_point(-67); P
Kolyvagin point of discriminant -67 on elliptic curve of conductor 37
sage: P.numerical_approx()  # abs tol 1e-14
(6.00000000000000 : -15.0000000000000 : 1.00000000000000)
sage: P.index()
6
sage: g = E((0,-1,1))  # a generator
sage: E.regulator() == E.regulator_of_points([g])
True
sage: 6*g
(6 : -15 : 1)
```

14.1. Elliptic curves over the rational numbers
**label** *(space=False)*

Return the Cremona label associated to (the minimal model) of this curve, if it is known. If not, raise a `LookupError` exception.

**EXAMPLES:**

```
sage: E = EllipticCurve('389a1')
sage: E.cremona_label()
'389a1'
```

The default database only contains conductors up to 10000, so any curve with conductor greater than that will cause an error to be raised. The optional package `database_cremona_ellcurve` contains many more curves.

```
sage: E = EllipticCurve([1, -1, 0, -79, 289])
sage: E.cremona_label()  # optional - database_cremona_ellcurve
'234446a1'
sage: E = EllipticCurve((0, 0, 1, -79, 342))
sage: E.cremona_label()  # optional -- webbrowser
Traceback (most recent call last):
  ...
LookupError: Cremona database does not contain entry for Elliptic Curve defined by y^2 + y = x^3 - 79*x + 342 over Rational Field
```

**lmfdb_page()**

Open the LMFDB web page of the elliptic curve in a browser.

See [http://www.lmfdb.org](http://www.lmfdb.org)

**EXAMPLES:**

```
sage: E = EllipticCurve('5077a1')
sage: E.lmfdb_page()  # optional -- webbrowser
```

**local_integral_model**(p)

Return a model of self which is integral at the prime p.

**EXAMPLES:**

```
sage: E = EllipticCurve([0, 0, 1/216, -7/1296, 1/7776])
sage: E.local_integral_model(2)
Elliptic Curve defined by y^2 + 1/27*y = x^3 - 7/81*x + 2/243 over Rational Field
sage: E.local_integral_model(3)
Elliptic Curve defined by y^2 + 1/8*y = x^3 - 7/16*x + 3/32 over Rational Field
sage: E.local_integral_model(2).local_integral_model(3) == EllipticCurve('5077a1')
True
```

**lseries()**

Return the L-series of this elliptic curve.

Further documentation is available for the functions which apply to the L-series.
EXAMPLES:

```
sage: E = EllipticCurve('37a1')
sage: E.lseries()
Complex L-series of the Elliptic Curve defined by y^2 + y = x^3 - x over Rational Field
```

\texttt{lseries\_gross\_zagier}(A)

Return the Gross-Zagier L-series attached to \texttt{self} and an ideal class \texttt{A}.

\textbf{INPUT:}

- \texttt{A} – an ideal class in an imaginary quadratic number field \texttt{K}

This L-series \(L(E, A, s)\) is defined as the product of a shifted L-function of the quadratic character associated to \(K\) and the Dirichlet series whose \(n\)-th coefficient is the product of the \(n\)-th factor of the L-series of \(E\) and the number of integral ideal in \(A\) of norm \(n\). For any character \(\chi\) on the class group of \(K\), one gets

\[L_K(E, \chi, s) = \sum_{A} \chi(A)L(E, A, s)\]

where \(A\) runs through the class group of \(K\).

For the exact definition see section IV of [GZ1986].

EXAMPLES:

```
sage: E = EllipticCurve('37a1')
sage: K.<a> = QuadraticField(-40)
sage: A = K.class_group().gen(0); A
Fractional ideal class (2, 1/2*a)
sage: L = E.lseries_gross_zagier(A) ; L
Gross Zagier L-series attached to Elliptic Curve defined by y^2 + y = x^3 - x over Rational Field with ideal class Fractional ideal class (2, 1/2*a)
sage: L(1)
0.000000000000000
sage: L.taylor_series(1, 5)
0.000000000000000 - 5.51899839494458*z + 13.6297841350649*z^2 - 16.22292417817675*z^3 + 7.94288823727125*z^4 + O(z^5)
```

These should be equal:

```
sage: L(2) + E.lseries_gross_zagier(A^2)(2)
0.502803417587467
sage: E.lseries()(2) * E.quadratic_twist(-40).lseries()(2)
0.502803417587467
```

\texttt{manin\_constant}()

Return the Manin constant of this elliptic curve.

If \(\phi : X_0(N) \to E\) is the modular parametrization of minimal degree, then the Manin constant \(c\) is defined to be the rational number \(c\) such that \(\phi^*(\omega_E) = c \cdot \omega_f\) where \(\omega_E\) is a Néron differential and \(\omega_f = f(q) dq / q\) is the differential on \(X_0(N)\) corresponding to the newform \(f\) attached to the isogeny class of \(E\).

It is known that the Manin constant is an integer. It is conjectured that in each class there is at least one, more precisely the so-called strong Weil curve or \(X_0(N)\)-optimal curve, that has Manin constant 1.

\textbf{OUTPUT:}

an integer

This function only works if the curve is in the installed Cremona database. Sage includes by default a small database; for the full database you have to install an optional package.
EXAMPLES:

```
sage: EllipticCurve('11a1').manin_constant()
1
sage: EllipticCurve('11a2').manin_constant()
1
sage: EllipticCurve('11a3').manin_constant()
5
```

Check that it works even if the curve is non-minimal:

```
sage: EllipticCurve('11a3').change_weierstrass_model([1/35,0,0,0]).manin_constant()
5
```

Rather complicated examples (see trac ticket #12080)

```
sage: [ EllipticCurve('27a%s%i').manin_constant() for i in [1,2,3,4] ]
[1, 1, 3, 3]
sage: [ EllipticCurve('80b%s%i').manin_constant() for i in [1,2,3,4] ]
[1, 2, 1, 2]
```

`matrix_of_frobenius(p, prec=20, check=False, check_hypotheses=True, algorithm='auto')`

Returns the matrix of Frobenius on the Monsky Washnitzer cohomology of the short Weierstrass model of the minimal model of the elliptic curve.

**INPUT:**

- `p` – prime (>= 3) for which $E$ is good and ordinary
- `prec` – (relative) $p$-adic precision for result (default 20)
- `check` – boolean (default: False), whether to perform a consistency check. This will slow down the computation by a constant factor 2. (The consistency check is to verify that its trace is correct to the specified precision. Otherwise, the trace is used to compute one column from the other one (possibly after a change of basis).)
- `check_hypotheses` – boolean, whether to check that this is a curve for which the $p$-adic sigma function makes sense
- `algorithm` – one of “standard”, “sqrtp”, or “auto”. This selects which version of Kedlaya’s algorithm is used. The “standard” one is the one described in Kedlaya’s paper. The “sqrtp” one has better performance for large $p$, but only works when $p > 6N$ ($N = prec$). The “auto” option selects “sqrtp” whenever possible.

Note that if the “sqrtp” algorithm is used, a consistency check will automatically be applied, regardless of the setting of the “check” flag.

**OUTPUT:** a matrix of $p$-adic number to precision `prec`

See also the documentation of `padic_E2`.

**EXAMPLES:**

```
sage: E = EllipticCurve('37a1')
sage: E.matrix_of_frobenius(7)
[ 2^7 + 4*7^2 + 5*7^4 + 6*7^5 + 6*7^6 + 7^8 + 4*7^9 + 3*7^10 + 2*7^11 + 5*7^12 + 4*7^14 + 7^16 + 2*7^17 + 3*7^18 + 4*7^19 + 3*7^20 + O(7^21)  2 + 3*7 + 6*7^2 + 7^3 + 3*7^4 + 5*7^5 + 3*7^7 + 3*7^8 + 6*7^9 + 7^10 + 7^11 + 7^13 + 7^14 + 7^16 + 5*7^17 + 4*7^18 + 7^19 + O(7^20)]
```

(continues on next page)
Elliptic curves, Release 9.7

[2*7 + 3*7^2 + 7*3 + 3*7^4 + 6*7^5 + 2*7^6 + 3*7^7 + 5*7^8 + 3*7^9 + 2*7^11 +... + 6*7^12 + 5*7^13 + 4*7^16 + 4*7^17 + 6*7^18 + 6*7^19 + 4*7^20 + 0(7^21)]
\[\rightarrow\]
\[+ 4*7 + 2*7^2 + 6*7^3 + 7^4 + 6*7^7 + 5*7^8 + 2*7^9 + 3*7^10 + 4*7^11 + 7^12 +... + 6*7^13 + 2*7^14 + 6*7^15 + 5*7^16 + 4*7^17 + 3*7^18 + 2*7^19 + 0(7^20)]\]

sage: M = E.matrix_of_frobenius(11, prec=3); M
\[\begin{bmatrix}
9*11 + 9*11^3 + O(11^4) & 10 + 11 + 0(11^3) \\
2*11 + 11^2 + O(11^4) & 6 + 11 + 10*11^2 + O(11^3)
\end{bmatrix}\]

sage: M.det()
11 + 0(11^4)
sage: M.trace()
6 + 10*11 + 10*11^2 + 0(11^3)
sage: E.ap(11)
-5

minimial_model()  
Return the unique minimal Weierstrass equation for this elliptic curve.  
This is the model with minimal discriminant and \(a_1, a_2, a_3 \in \{0, \pm 1\}\).

EXAMPLES:

sage: E = EllipticCurve([10,100,1000,10000,100000])

E.minimal_model()
Elliptic Curve defined by y^2 + x*y + y = x^3 + x^2 + x + 1 over Rational Field

minimal_quadratic_twist()  
Determine a quadratic twist with minimal conductor. Return a global minimal model of the twist and the fundamental discriminant of the quadratic field over which they are isomorphic.

Note: If there is more than one curve with minimal conductor, the one returned is the one with smallest label (if in the database), or the one with minimal \(a\)-invariant list (otherwise).

Note: For curves with \(j\)-invariant 0 or 1728 the curve returned is the minimal quadratic twist, not necessarily the minimal twist (which would have conductor 27 or 32 respectively).

EXAMPLES:

sage: E = EllipticCurve('121d1')

E.minimal_quadratic_twist()
(Elliptic Curve defined by y^2 + x*y + y = x^3 + x^2 + x + 1 over Rational Field, -11)
sage: E, D = EllipticCurve('32a1').minimal_quadratic_twist()
sage: D
1

sage: E = EllipticCurve('11a1')
Elliptic curves, Release 9.7

sage: Et, D = E.quadratic_twist(-24).minimal_quadratic_twist()
sage: E == Et
True
sage: D
-24

sage: E = EllipticCurve([0,0,0,0,1000])
sage: E.minimal_quadratic_twist()
(Elliptic Curve defined by y^2 = x^3 + 1 over Rational Field, 40)

sage: E = EllipticCurve([0,0,0,1600,0])
sage: E.minimal_quadratic_twist()
(Elliptic Curve defined by y^2 = x^3 + 4*x over Rational Field, 5)

If the curve has square-free conductor then it is already minimal (see trac ticket #14060):

sage: E = next(cremona_optimal_curves([2*3*5*7*11]))
sage: (E, 1) == E.minimal_quadratic_twist()
True

An example where the minimal quadratic twist is not the minimal twist (which has conductor 27):

sage: E = EllipticCurve([0,0,0,0,7])
sage: E.j_invariant()
0
sage: E.minimal_quadratic_twist()[0].conductor()
5292

mod5family()

Return the family of all elliptic curves with the same mod-5 representation as self.

EXAMPLES:

sage: E = EllipticCurve('32a1')
sage: E.mod5family()
Elliptic Curve defined by y^2 = x^3 + 4*x over Fraction Field of Univariate Polynomial Ring in t over Rational Field

modular_degree(algorithm='sympow', M=1)

Return the modular degree at level $MN$ of this elliptic curve. The case $M == 1$ corresponds to the classical definition of modular degree.

When $M > 1$, the function returns the degree of the map from $X_0(MN) \to A$, where A is the abelian variety generated by embeddings of $E$ into $J_0(MN)$.

The result is cached. Subsequent calls, even with a different algorithm, just returned the cached result. The algorithm argument is ignored when $M > 1$.

INPUT:

- algorithm -- string:
  - 'sympow' - (default) use Mark Watkin's (newer) C program sympow
  - 'magma' - requires that MAGMA be installed (also implemented by Mark Watkins)
- M -- non-negative integer; the modular degree at level $MN$ is returned (see above)
**Note:** On 64-bit computers ec does not work, so Sage uses sympow even if ec is selected on a 64-bit computer.

The correctness of this function when called with algorithm “sympow” is subject to the following three hypothesis:

- Manin’s conjecture: the Manin constant is 1
- Steven’s conjecture: the $X_1(N)$-optimal quotient is the curve with minimal Faltings height. (This is proved in most cases.)
- The modular degree fits in a machine double, so it better be less than about 50-some bits. (If you use sympow this constraint does not apply.)

Moreover for all algorithms, computing a certain value of an $L$-function ‘uses a heuristic method that discerns when the real-number approximation to the modular degree is within epsilon [=0.01 for algorithm='sympow’] of the same integer for 3 consecutive trials (which occur maybe every 25000 coefficients or so). Probably it could just round at some point. For rigour, you would need to bound the tail by assuming (essentially) that all the $a_n$ are as large as possible, but in practice they exhibit significant (square root) cancellation. One difficulty is that it doesn’t do the sum in 1-2-3-4 order; it uses 1-2-4-8–3-6-12-24-9-18- (Euler product style) instead, and so you have to guess ahead of time at what point to curtail this expansion.’ (Quote from an email of Mark Watkins.)

**Note:** If the curve is loaded from the large Cremona database, then the modular degree is taken from the database.

**EXAMPLES:**

```sage
sage: E = EllipticCurve([0, -1, 1, -10, -20])
sage: E
Elliptic Curve defined by y^2 + y = x^3 - x^2 - 10*x - 20 over Rational Field
sage: E.modular_degree()
1
sage: E = EllipticCurve('5077a')
sage: E.modular_degree()
1984
sage: factor(1984)
2^6 * 31
sage: EllipticCurve([0, 0, 1, -7, 6]).modular_degree()
1984
sage: EllipticCurve([0, 0, 1, -7, 6]).modular_degree(algorithm='sympow')
1984
sage: EllipticCurve([0, 0, 1, -7, 6]).modular_degree(algorithm='magma')  # optional - magma
1984
```

We compute the modular degree of the curve with rank 4 having smallest (known) conductor:

```sage
sage: E = EllipticCurve([1, -1, 0, -79, 289])
sage: factor(E.conductor())  # conductor is 234446
2 * 117223
```
Elliptic curves, Release 9.7

\begin{verbatim}
sage: factor(E.modular_degree())
2^7 * 2617

Higher level cases:

sage: E = EllipticCurve('11a')
sage: for M in range(1,11): print(E.modular_degree(M=M)) # long time (20s on 2009 MBP)
1
1
3
2
7
45
12
16
54
245

modular_form()  
  Return the cuspidal modular form associated to this elliptic curve.  

EXAMPLES:

sage: E = EllipticCurve('37a')
sage: f = E.modular_form()  
sage: f
q - 2*q^2 - 3*q^3 + 2*q^4 - 2*q^5 + O(q^6)

If you need to see more terms in the \( q \)-expansion:

sage: f.q_expansion(20)
q - 2*q^2 - 3*q^3 + 2*q^4 - 2*q^5 + 6*q^6 - q^7 + 6*q^9 + 4*q^10
  - 5*q^11 - 6*q^12 - 2*q^13 + 2*q^14 + 6*q^15 - 4*q^16 - 12*q^18 + O(q^20)

Note: If you just want the \( q \)-expansion, use \texttt{q_expansion}().

modular_parametrization()  
  Return the modular parametrization of this elliptic curve, which is a map from \( X_0(N) \) to self, where \( N \) is the conductor of self.  

EXAMPLES:

sage: E = EllipticCurve('15a')
sage: phi = E.modular_parametrization(); phi
Modular parameterization from the upper half plane to \Elliptic Curve defined by
.. math::
   y^2 + x*y + y = x^3 + x^2 - 10*x - 10
over Rational Field

sage: z = 0.1 + 0.2j
sage: phi(z)
(8.20822465478531 - 13.1562816054682*I : -8.79855099049364 + 69.4006129342200*I : 1.0)
\end{verbatim}
This map is actually a map on $X_0(N)$, so equivalent representatives in the upper half plane map to the same point:

```
sage: phi((-7*z-1)/(15*z+2))
(8.20822465478524 - 13.1562816054681*I : -8.79855099049... + 69.4006129342...*I
  ↠: 1.00000000000000)
```

We can also get a series expansion of this modular parameterization:

```
sage: E = EllipticCurve('389a1')
sage: X,Y=E.modular_parametrization().power_series()
sage: X
q^-2 + 2*q^-1 + 4 + 7*q + 13*q^2 + 18*q^3 + 31*q^4 + 49*q^5 + 74*q^6 + 111*q^7
  ↠ 173*q^8 + 251*q^9 + 379*q^10 + 560*q^11 + 824*q^12 + 1199*q^13 + 1773*q^14
  ↠ 2548*q^15 + 3722*q^16 + 5374*q^17 + 0(q^18)
sage: Y
-q^-3 - 3*q^-2 - 8*q^-1 - 17 - 33*q - 61*q^2 - 110*q^3 - 186*q^4 - 320*q^5
  ↠ 528*q^6 - 861*q^7 - 1383*q^8 - 2218*q^9 - 3472*q^10 - 5451*q^11 - 8447*q^12
  ↠ 13020*q^13 - 19923*q^14 - 30403*q^15 - 46003*q^16 + 0(q^17)
```

The following should give 0, but only approximately:

```
sage: q = X.parent().gen()
sage: E.defining_polynomial()(X,Y,1) + O(q^11) == 0
True
```

```
modular_symbol(sign=1, normalize=None, implementation='eclib', nap=0)
```

Return the modular symbol map associated to this elliptic curve with given sign.

**INPUT:**

- `sign` – +1 (default) or -1.
- `normalize` – (default: None); either ‘L_ratio’, ‘period’, or ‘none’; ignored unless `implementation` is ‘sage’. For ‘L_ratio’, the modular symbol tries to normalize correctly as explained below by comparing it to $L$-ratio for the curve and some small twists. The normalization ‘period’ uses the `integral_period_map` for modular symbols which is known to be equal to the desired normalization, up to the sign and a possible power of 2. With normalization ‘none’, the modular symbol is almost certainly not correctly normalized, i.e. all values will be a fixed scalar multiple of what they should be.

- `implementation` – either ‘eclib’ (default), ‘sage’ or ‘num’. Here, ‘eclib’ uses Cremona’s C++ implementation in the `eclib` library, ‘sage’ uses an implementation within Sage which is often quite a bit slower, and ‘num’ uses Wuthrich’s implementation of numerical modular symbols.

- `nap` – (int, default 0); ignored unless implementation is ‘eclib’. The number of ap of $E$ to use in determining the normalisation of the modular symbols. If 0 (the default), then the value of $100 \cdot E$.conductor().isqrt() is used. Using too small a value can lead to incorrect normalisation.

**DEFINITION:**

The modular symbol map sends any rational number $r$ to the rational number which is the ratio of the real or imaginary part (depending on the sign) of the integral of $2\pi i f(z)dz$ from $\infty$ to $r$, where $f$ is the newform attached to $E$, to the real or imaginary period of $E$.

More precisely: If the sign is +1, then the value returned is the quotient of the real part of this integral by the least positive period $\Omega^+_E$ of $E$. In particular for $r = 0$, the value is equal to $L(E,1)/\Omega^+_E$ (unlike in `L_ratio` of `lseries()`), where the value is also divided by the number of connected components of $E(\mathbb{R})$. In particular the modular symbol depends on $E$ and not only the isogeny class of $E$. For sign
−1, it is the quotient of the imaginary part of the integral divided by the purely imaginary period of $E$
with smallest positive imaginary part. Note however there is an issue about these normalizations, hence the
optional argument normalize explained below

ALGORITHM:

For the implementations ‘sage’ and ‘eclib’, the used algorithm starts by finding the space of modular sym-
ols within the full space of all modular symbols of that level. This initial step will take a very long time if
the conductor is large (e.g. minutes for five digit conductors). Once the space is determined, each evaluation
is very fast (logarithmic in the denominator of $r$).

The implementation ‘num’ uses a different algorithm. It uses numerical integration along paths in the
upper half plane. The bounds are rigorously proved so that the outcome is known to be correct. The initial
step costs no time, instead each evaluation will take more time than in the above. More information in the
documentation of the class ModularSymbolNumerical.

See also:

modular_symbol_numerical()

EXAMPLES:

```sage
sage: E = EllipticCurve('37a1')
sage: M = E.modular_symbol(); M
Modular symbol with sign 1 over Rational Field attached to Elliptic Curve
  --> defined by y^2 + y = x^3 - x over Rational Field
sage: M(1/2)
0
sage: M(1/5)
1
```

```
sage: E = EllipticCurve('121b1')
sage: M = E.modular_symbol(implementation="sage")
Warning : Could not normalize the modular symbols, maybe all further results
  --> will be multiplied by -1 and a power of 2
sage: M(1/7)
-1/2
```

With the numerical version, rather high conductors can be computed:

```
sage: E = EllipticCurve([999,997])
sage: E.conductor()
16059409956
sage: m = E.modular_symbol(implementation="num")
sage: m(0) # long time
16
```

Different curves in an isogeny class have modular symbols which differ by a nonzero rational factor:

```
sage: E1 = EllipticCurve('11a1')
sage: M1 = E1.modular_symbol()
sage: M1(0)
1/5
sage: E2 = EllipticCurve('11a2')
sage: M2 = E2.modular_symbol()
sage: M2(0)
```

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Elliptic curves, Release 9.7

With the default implementation using eclib, the symbols are correctly normalized automatically. With the Sage implementation we can choose to normalize using the L-ratio, unless that is 0 (for curves of positive rank) or using periods. Here is an example where the symbol is already normalized:

```python
sage: E = EllipticCurve('11a2')
sage: E.modular_symbol(implementation = 'eclib')(0)
1
sage: E.modular_symbol(implementation = 'sage', normalize='L_ratio')(0)
1
sage: E.modular_symbol(implementation = 'sage', normalize='none')(0)
1
sage: E.modular_symbol(implementation = 'sage', normalize='period')(0)
1
```

Here is an example where both normalization methods work, while the non-normalized symbol is incorrect:

```python
sage: E = EllipticCurve('11a3')
sage: E.modular_symbol(implementation = 'eclib')(0)
1/25
sage: E.modular_symbol(implementation = 'sage', normalize='L_ratio')(0)
1/25
sage: E.modular_symbol(implementation = 'sage', normalize='none')(0)
1
sage: E.modular_symbol(implementation = 'sage', normalize='period')(0)
1/25
```

Since trac ticket #10256, the interface for negative modular symbols in eclib is available:

```python
sage: E = EllipticCurve('11a1')
sage: Mplus = E.modular_symbol(+1); Mplus
Modular symbol with sign 1 over Rational Field attached to Elliptic Curve...
    defined by y^2 + y = x^3 - x^2 - 10*x - 20 over Rational Field
sage: [Mplus(1/i) for i in [1..11]]
[1/5, -4/5, -3/10, 7/10, 6/5, 6/5, 7/10, -3/10, -4/5, 1/5, 0]

sage: Mminus = E.modular_symbol(-1); Mminus
Modular symbol with sign -1 over Rational Field attached to Elliptic Curve...
    defined by y^2 + y = x^3 - x^2 - 10*x - 20 over Rational Field
sage: [Mminus(1/i) for i in [1..11]]
[0, 0, 1/2, 1/2, 0, 0, -1/2, -1/2, 0, 0, 0]
```

With older version of eclib, in the default ‘eclib’ implementation, if nap is too small, the normalization may be computed incorrectly (see trac ticket #31317). This was fixed in eclib version v20210310, since now eclib increase nap automatically. The following used to give incorrect results. See trac ticket #31443:
sage: E = EllipticCurve('1590g1')
sage: m = E.modular_symbol(nap=300)
sage: [m(a/5) for a in [1..4]]
[13/2, -13/2, -13/2, 13/2]

These values are correct, as verified by the numerical implementation:

sage: m = E.modular_symbol(implementation='num')
sage: [m(a/5) for a in [1..4]]
[13/2, -13/2, -13/2, 13/2]

**modular_symbol_numerical**(sign=1, prec=20)

Return the modular symbol as a numerical function.

Just as in `modular_symbol()` this returns a function that maps any rational \( r \) to a real number that should be equal to the rational number with an error smaller than the given binary precision. In practice the precision is often much higher. See the examples below. The normalisation is the same.

**INPUT:**

- sign – either +1 (default) or -1
- prec – an integer (default 20)

**OUTPUT:**

- a real number

**ALGORITHM:**

This method does not compute spaces of modular symbols, so it is suitable for curves of larger conductor than can be handled by `modular_symbol()`. It is essentially the same implementation as `modular_symbol` with implementation set to ‘num’. However the precision is not automatically chosen to be certain that the output is equal to the rational number it approximates.

For large conductors one should set the prec very small.

**EXAMPLES:**

sage: E = EllipticCurve('19a1')
sage: f = E.modular_symbol_numerical(1)
sage: g = E.modular_symbol(1)
sage: f(0), g(0)  # abs tol 1e-11
(0.333333333333333, 1/3)

sage: E = EllipticCurve('5077a1')
sage: f = E.modular_symbol_numerical(-1, prec=2)
sage: f(0)  # abs tol 1e-11
0.000000000000000
sage: f(1/7)  # abs tol 1e-11
0.999844176260303

sage: E = EllipticCurve([123,456])
sage: E.conductor()
104461920
sage: f = E.modular_symbol_numerical(prec=2)
sage: f(0)  # abs tol 1e-11
2.00001004772210
modular_symbol_space(sign=1, base_ring=Rational Field, bound=None)

Return the space of cuspidal modular symbols associated to this elliptic curve, with given sign and base ring.

INPUT:

• sign – 0, -1, or 1

• base_ring – a ring

EXAMPLES:

```
sage: f = EllipticCurve('37b')
sage: f.modular_symbol_space()
Modular Symbols subspace of dimension 1 of Modular Symbols space of dimension 3 → for Gamma_0(37) of weight 2 with sign 1 over Rational Field
sage: f.modular_symbol_space(-1)
Modular Symbols subspace of dimension 1 of Modular Symbols space of dimension 2 → for Gamma_0(37) of weight 2 with sign -1 over Rational Field
sage: f.modular_symbol_space(0, bound=3)
Modular Symbols subspace of dimension 2 of Modular Symbols space of dimension 5 → for Gamma_0(37) of weight 2 with sign 0 over Rational Field
```

Note: If you just want the \( q \)-expansion, use \texttt{q_expansion()}.  

mwrank(options='')

Run Cremona’s mwrank program on this elliptic curve and return the result as a string.

INPUT:

• options (string) – run-time options passed when starting mwrank. The format is as follows (see below for examples of usage):
  - -v n (verbosity level) sets verbosity to n (default=1)
  - -o (PARI/GP style output flag) turns ON extra PARI/GP short output (default is OFF)
  - -p n (precision) sets precision to \( n \) decimals (default=15)
  - -b n (quartic bound) bound on quartic point search (default=10)
  - -x n (n_aux) number of aux primes used for sieving (default=6)
  - -l (generator list flag) turns ON listing of points (default ON unless v=0)
  - -s (selmer_only flag) if set, computes Selmer rank only (default: not set)
  - -d (skip_2nd_descent flag) if set, skips the second descent for curves with 2-torsion (default: not set)
  - -S n (sat_bd) upper bound on saturation primes (default=100, -1 for automatic)

OUTPUT:

• (string) – output of mwrank on this curve

Note: The output is a raw string and completely illegible using automatic display, so it is recommended to use print for legible output.

EXAMPLES:
sage: E = EllipticCurve('37a1')
sage: E.mwrank()  # random
...
sage: print(E.mwrank())  
Curve [0,0,1,-1,0] : Basic pair: I=48, J=-432
disc=255744
...
Generator 1 is [0:-1:1]; height 0.05111...
Regulator = 0.05111...

The rank and full Mordell-Weil basis have been determined unconditionally.
...

Options to mwrank can be passed:

sage: E = EllipticCurve([0,0,0,877,0])
Run mwrank with 'verbose' flag set to 0 but list generators if found:

sage: print(E.mwrank('-v0 -l'))
Curve [0,0,0,877,0] : 0 <= rank <= 1
Regulator = 1
Run mwrank again, this time with a higher bound for point searching on homogeneous spaces:

sage: print(E.mwrank('-v0 -l -b11'))
Curve [0,0,0,877,0] : Rank = 1
Generator 1 is [29604565394828237474403861024284371796799791624792913256602210:-25625626798892680938776834045513089648669153204356603464786949:49007802321978758895980293399:
=> height 95.98037...
Regulator = 95.98037...

mwrank_curve(verbos=False)

Construct an mwrank_EllipticCurve from this elliptic curve
The resulting mwrank_EllipticCurve has available methods from John Cremona’s eclib library.
EXAMPLES:

sage: E = EllipticCurve('11a1')
sage: EE = E.mwrank_curve()
sage: EE
y^2 + y = x^3 - x^2 - 10 x - 20
sage: type(EE)
<class 'sage.libs eclib interface mwrank EllipticCurve'>
sage: EE.isogeny_class()([
[[0, -1, 1, -10, -20], [0, -1, 1, -7820, -263580], [0, -1, 1, 0, 0]],
[[0, 5, 5], [5, 0, 0], [5, 0, 0]]
newform()

Same as self.modular_form().
EXAMPLES:
```python
sage: E = EllipticCurve('37a1')
sage: E.newform()
q - 2*q^2 - 3*q^3 + 2*q^4 - 2*q^5 + O(q^6)
sage: E.newform() == E.modular_form()
True
```

**ngens** *(proof=None)*

Return the number of generators of this elliptic curve.

**Note:** See *gens()* for further documentation. The function *ngens()* calls *gens()* if not already done, but only with default parameters. Better results may be obtained by calling *mwrank()* with carefully chosen parameters.

**EXAMPLES:**

```python
sage: E = EllipticCurve('37a1')
sage: E.ngens()
1
sage: E = EllipticCurve([0,0,0,877,0])
sage: E.ngens()
1
sage: print(E.mwrank('-v0 -b12 -l'))
Curve [0,0,0,877,0] : Rank = 1
Generator 1 is [2960456539482823740386102484371796799791624792913256602210:-2562562679889268093887768340455130896486691532043566034647866949:49007802321978758895980293390];
→ height 95.98037...
Regulator = 95.980...```

**optimal_curve()**

Given an elliptic curve that is in the installed Cremona database, return the optimal curve isogenous to it.

**EXAMPLES:**

The following curve is not optimal:

```python
sage: E = EllipticCurve('11a2'); E
Elliptic Curve defined by y^2 + y = x^3 - x^2 + 6112*x - 41533 over Rational Field
sage: E.optimal_curve()
Elliptic Curve defined by y^2 + x*y + y = x^3 - x^2 - 1568*x - 4669 over Rational Field
sage: E.optimal_curve().cremona_label()
'11a1'
```

Note that 990h is the special case where the optimal curve isn’t the first in the Cremona labeling:

```python
sage: E = EllipticCurve('990b4'); E
Elliptic Curve defined by y^2 + x*y + y = x^3 - x^2 + 6112*x - 41533 over Rational Field
sage: F = E.optimal_curve(); F
Elliptic Curve defined by y^2 + x*y + y = x^3 - x^2 - 1568*x - 4669 over Rational Field
```

(continues on next page)
Elliptic curves, Release 9.7

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```
sage: F.cremona_label()
'990h3'
sage: EllipticCurve('990a1').optimal_curve().cremona_label()  # a isn't h.
'990a1'
```

If the input curve is optimal, this function returns that curve (not just a copy of it or a curve isomorphic to it):

```
sage: E = EllipticCurve('37a1')
sage: E.optimal_curve() is E
True
```

Also, if this curve is optimal but not given by a minimal model, this curve will still be returned, so this function need not return a minimal model in general.

```
sage: F = E.short_weierstrass_model(); F
Elliptic Curve defined by y^2 = x^3 - 16*x + 16 over Rational Field
sage: F.optimal_curve()
Elliptic Curve defined by y^2 = x^3 - 16*x + 16 over Rational Field
```

**ordinary_primes**(\(B\))

Return a list of all ordinary primes for this elliptic curve up to and possibly including \(B\).

**EXAMPLES:**

```
sage: e = EllipticCurve('11a')
sage: e.aplist(20)
[-2, -1, 1, -2, 1, 4, -2, 0]
sage: e.ordinary_primes(97)
sage: e = EllipticCurve('49a')
sage: e.aplist(20)
[1, 0, 0, 0, 4, 0, 0, 0]
sage: e.supersingular_primes(97)
[3, 5, 13, 17, 19, 31, 41, 47, 59, 61, 73, 83, 89, 97]
sage: e.ordinary_primes(97)
sage: e.ordinary_primes(3)
[2]
sage: e.ordinary_primes(2)
[2]
sage: e.ordinary_primes(1)
[]
```

**padic_E2**(\(p\), \(prec=20\), \(check=False\), \(check_hypotheses=True\), \(algorithm='auto'\))

Returns the value of the \(p\)-adic modular form \(E2\) for \((E, \omega)\) where \(\omega\) is the usual invariant differential \(dx/(2y + a_1 x + a_3)\).

**INPUT:**

- \(p\) – prime (= 5) for which \(E\) is good and ordinary
- \(prec\) – (relative) \(p\)-adic precision (= 1) for result
Elliptic curves, Release 9.7

- **check** – boolean, whether to perform a consistency check. This will slow down the computation by a constant factor 2. (The consistency check is to compute the whole matrix of frobenius on Monsky-Washnitzer cohomology, and verify that its trace is correct to the specified precision. Otherwise, the trace is used to compute one column from the other one (possibly after a change of basis).)

- **check_hypotheses** – boolean, whether to check that this is a curve for which the p-adic sigma function makes sense

- **algorithm** – one of “standard”, “sqrtp”, or “auto”. This selects which version of Kedlaya’s algorithm is used. The “standard” one is the one described in Kedlaya’s paper. The “sqrtp” one has better performance for large \( p \), but only works when \( p > 6N (N = \text{prec}) \). The “auto” option selects “sqrtp” whenever possible.

Note that if the “sqrtp” algorithm is used, a consistency check will automatically be applied, regardless of the setting of the “check” flag.

**OUTPUT:** p-adic number to precision \( \text{prec} \)

**Note:** If the discriminant of the curve has nonzero valuation at \( p \), then the result will not be returned mod \( p^{\text{prec}} \), but it still will have \( \text{prec} \) digits of precision.

**Todo:** Once we have a better implementation of the “standard” algorithm, the algorithm selection strategy for “auto” needs to be revisited.

**AUTHORS:**
- David Harvey (2006-09-01): partly based on code written by Robert Bradshaw at the MSRI 2006 modular forms workshop

**ACKNOWLEDGMENT:** - discussion with Eyal Goren that led to the trace trick.

**EXAMPLES:** Here is the example discussed in the paper “Computation of p-adic Heights and Log Convergence” (Mazur, Stein, Tate):

```python
sage: EllipticCurve([-1, 1/4]).padic_E2(5)
2 + 4*5 + 2*5^3 + 5^4 + 3*5^5 + 2*5^6 + 5^8 + 3*5^9 + 4*5^10 + 2*5^11 + 2*5^12
\rightarrow 2*5^14 + 3*5^15 + 3*5^16 + 3*5^17 + 4*5^18 + 2*5^19 + O(5^20)
```

Let’s try to higher precision (this is the same answer the MAGMA implementation gives):

```python
sage: EllipticCurve([-1, 1/4]).padic_E2(5, 100)
2 + 4*5 + 2*5^3 + 5^4 + 3*5^5 + 2*5^6 + 5^8 + 3*5^9 + 4*5^10 + 2*5^11 + 2*5^12
\rightarrow 2*5^14 + 3*5^15 + 3*5^16 + 3*5^17 + 4*5^18 + 2*5^19 + 5^21 + 4*5^22
\rightarrow 22 + 2*5^23 + 3*5^24 + 3*5^26 + 2*5^27 + 3*5^28 + 2*5^30 + 5^31 + 4*5^33 + ...
\rightarrow 3*5^34 + 4*5^35 + 5^36 + 4*5^37 + 4*5^38 + 3*5^39 + 4*5^41 + 2*5^42 + 3*5^43
\rightarrow + 2*5^44 + 2*5^48 + 3*5^49 + 4*5^50 + 2*5^51 + 5^52 + 4*5^53 + 4*5^54 + 3*5^5
\rightarrow + 55 + 2*5^56 + 3*5^57 + 4*5^58 + 4*5^59 + 5^60 + 3*5^61 + 5^62 + 4*5^63 + 5^65
\rightarrow + 3*5^66 + 2*5^67 + 5^69 + 2*5^70 + 3*5^71 + 3*5^72 + 5^74 + 5^75 + 5^76 + ...
\rightarrow + 3*5^77 + 4*5^78 + 4*5^79 + 2*5^80 + 3*5^81 + 5^82 + 5^83 + 4*5^84 + 3*5^85 + ...
\rightarrow + 2*5^86 + 3*5^87 + 5^88 + 2*5^89 + 4*5^90 + 4*5^92 + 3*5^93 + 4*5^94 + 3*5^95
\rightarrow + 2*5^96 + 4*5^97 + 4*5^98 + 2*5^99 + O(5^100)
```

Check it works at low precision too:

---

14.1. Elliptic curves over the rational numbers 273
Elliptic curves, Release 9.7

```python
sage: EllipticCurve([-1, 1/4]).padic_E2(5, 1)
2 + 0(5)
sage: EllipticCurve([-1, 1/4]).padic_E2(5, 2)
2 + 4*5 + O(5^2)
sage: EllipticCurve([-1, 1/4]).padic_E2(5, 3)
2 + 4*5 + O(5^3)
```

TODO: With the old(-er), i.e., = sage-2.4 p-adics we got $5 + O(5^2)$ as output, i.e., relative precision 1, but with the newer p-adics we get relative precision 0 and absolute precision 1.

```python
sage: EllipticCurve([1, 1, 1, 1, 1]).padic_E2(5, 1)
O(5)
```

Check it works for different models of the same curve (37a), even when the discriminant changes by a power of $p$ (note that E2 depends on the differential too, which is why it gets scaled in some of the examples below):

```python
sage: X1 = EllipticCurve([-1, 1/4])
sage: X1.j_invariant(), X1.discriminant()
(110592/37, 37)
sage: X1.padic_E2(5, 10)
2 + 4*5 + 2*5^3 + 5^4 + 3*5^5 + 2*5^6 + 5^8 + 3*5^9 + O(5^10)
```

```python
sage: X2 = EllipticCurve([0, 0, 1, -1, 0])
sage: X2.j_invariant(), X2.discriminant()
(110592/37, 37)
sage: X2.padic_E2(5, 10)
2 + 4*5 + 2*5^3 + 5^4 + 3*5^5 + 2*5^6 + 5^8 + 3*5^9 + O(5^10)
```

```python
sage: X3 = EllipticCurve([-1*(2**4), 1/4*(2**6)])
sage: X3.j_invariant(), X3.discriminant() / 2**12
(110592/37, 37)
sage: 2**(2*(-2)) * X3.padic_E2(5, 10)
2 + 4*5 + 2*5^3 + 5^4 + 3*5^5 + 2*5^6 + 5^8 + 3*5^9 + O(5^10)
```

```python
sage: X4 = EllipticCurve([-1*(7**4), 1/4*(7**6)])
sage: X4.j_invariant(), X4.discriminant() / 7**12
(110592/37, 37)
sage: 7**(2*(-2)) * X4.padic_E2(5, 10)
2 + 4*5 + 2*5^3 + 5^4 + 3*5^5 + 2*5^6 + 5^8 + 3*5^9 + O(5^10)
```

```python
sage: X5 = EllipticCurve([-1*(5**4), 1/4*(5**6)])
sage: X5.j_invariant(), X5.discriminant() / 5**12
(110592/37, 37)
sage: 5**(2*(-2)) * X5.padic_E2(5, 10)
2 + 4*5 + 2*5^3 + 5^4 + 3*5^5 + 2*5^6 + 5^8 + 3*5^9 + O(5^10)
```

```python
sage: X6 = EllipticCurve([-1/(5**4), 1/4/(5**6)])
sage: X6.j_invariant(), X6.discriminant() * 5**12
(110592/37, 37)
sage: 5**(2*(-2)) * X6.padic_E2(5, 10)
2 + 4*5 + 2*5^3 + 5^4 + 3*5^5 + 2*5^6 + 5^8 + 3*5^9 + O(5^10)
```

Test check=True vs check=False:
Elliptic curves, Release 9.7

```sage
sage: EllipticCurve([-1, 1/4]).padic_E2(5, 1, check=False)
2 + O(5)
sage: EllipticCurve([-1, 1/4]).padic_E2(5, 1, check=True)
2 + O(5)
sage: EllipticCurve([-1, 1/4]).padic_E2(5, 30, check=False)
2 + 4*5 + 2*5^3 + 5^4 + 3*5^5 + 2*5^6 + 5^8 + 3*5^9 + 4*5^10 + 2*5^11 + 2*5^12 +
    2*5^14 + 3*5^15 + 3*5^16 + 3*5^17 + 4*5^18 + 2*5^19 + 4*5^20 + 5^21 + 4*5^22 + 2*5^23 + 3*5^24 + 3*5^26 + 2*5^27 + 3*5^28 + O(5^30)
sage: EllipticCurve([-1, 1/4]).padic_E2(5, 30, check=True)
2 + 4*5 + 2*5^3 + 5^4 + 3*5^5 + 2*5^6 + 5^8 + 3*5^9 + 4*5^10 + 2*5^11 + 2*5^12 +
    2*5^14 + 3*5^15 + 3*5^16 + 3*5^17 + 4*5^18 + 2*5^19 + 4*5^20 + 5^21 + 4*5^22 + 2*5^23 + 3*5^24 + 3*5^26 + 2*5^27 + 3*5^28 + O(5^30)
```

Here’s one using the $p^{1/2}$ algorithm:

```sage
sage: EllipticCurve([-1, 1/4]).padic_E2(3001, 3, algorithm="sqrtp")
1907 + 2819*3001 + 1124*3001^2 + O(3001^3)
```

`padic_height(p, prec=20, sigma=None, check_hypotheses=True)`

Compute the cyclotomic p-adic height.

The equation of the curve must be minimal at $p$.

**INPUT:**

- $p$ – prime $\geq 5$ for which the curve has semi-stable reduction
- $\text{prec}$ – integer $\geq 1$ (default 20), desired precision of result
- $\text{sigma}$ – precomputed value of sigma. If not supplied, this function will call `padic_sigma` to compute it.
- $\text{check_hypotheses}$ – boolean, whether to check that this is a curve for which the p-adic height makes sense

**OUTPUT:** A function that accepts two parameters:

- a Q-rational point on the curve whose height should be computed
- optional boolean flag 'check': if False, it skips some input checking, and returns the p-adic height of that point to the desired precision.

The normalization (sign and a factor 1/2 with respect to some other normalizations that appear in the literature) is chosen in such a way as to make the p-adic Birch Swinnerton-Dyer conjecture hold as stated in [Mazur-Tate-Teitelbaum].

**AUTHORS:**

- Jennifer Balakrishnan: original code developed at the 2006 MSRI graduate workshop on modular forms
- David Harvey (2006-09-13): integrated into Sage, optimised to speed up repeated evaluations of the returned height function, addressed some thorny precision questions
- David Harvey (2006-09-30): rewrote to use division polynomials for computing denominator of $nP$.
- David Harvey (2007-02): cleaned up according to algorithms in “Efficient Computation of p-adic Heights”
- Chris Wuthrich (2007-05): added supersingular and multiplicative heights

**EXAMPLES:**
Elliptic curves, Release 9.7

```python
sage: E = EllipticCurve("37a")
sage: P = E.gens()[0]
sage: h = E.padic_height(5, 10)
sage: h(P)
5 + 5^2 + 5^3 + 3*5^6 + 4*5^7 + 5^9 + O(5^10)
```

An anomalous case:

```python
sage: h = E.padic_height(53, 10)
sage: h(P)
26*53^-1 + 30 + 20*53 + 47*53^2 + 10*53^3 + 32*53^4 + 9*53^5 + 22*53^6 + 35*53^7 + 30*53^8 + 17*53^9 + O(53^10)
```

Boundary case:

```python
sage: E.padic_height(5, 3)(P)
5 + 5^2 + O(5^3)
```

A case that works the division polynomial code a little harder:

```python
sage: E.padic_height(5, 10)(5*P)
5^3 + 5^4 + 5^5 + 3*5^8 + 4*5^9 + O(5^10)
```

Check that answers agree over a range of precisions:

```python
sage: max_prec = 30  # make sure we get past p^2  # long time
sage: full = E.padic_height(5, max_prec)(P)  # long time
sage: for prec in range(1, max_prec):
    # long time
    ....: assert E.padic_height(5, prec)(P) == full  # long time
```

A supersingular prime for a curve:

```python
sage: E = EllipticCurve('37a')
sage: E.is_supersingular(3)
True
sage: h = E.padic_height(3, 5)
sage: h(E.gens()[0])
(3 + 3^3 + O(3^6), 2*3^2 + 3^3 + 3^4 + 3^5 + 2*3^6 + O(3^7))
```

A torsion point in both the good and supersingular cases:

```python
sage: E = EllipticCurve('11a')
sage: P = E.torsion_subgroup().gen(0).element(); P
(5 : 5 : 1)
sage: h = E.padic_height(19, 5)
sage: h(P)
0
```

(continues on next page)
The result is not dependent on the model for the curve:

```python
sage: E = EllipticCurve([0,0,0,0,2^12*17])
sage: Em = E.minimal_model()
sage: P = E.gens()[0]
sage: Pm = Em.gens()[0]
sage: h = E.padic_height(7)
sage: hm = Em.padic_height(7)
sage: h(P) == hm(Pm)
True
```

**padic_height_pairing_matrix**($p$, $\text{prec}=20$, $\text{height}=\text{None}$, $\text{check_hypotheses}=\text{True}$)

Computes the cyclotomic $p$-adic height pairing matrix of this curve with respect to the basis self.gens() for the Mordell-Weil group for a given odd prime $p$ of good ordinary reduction.

**INPUT:**
- $p$ – prime $\geq 5$
- $\text{prec}$ – answer will be returned modulo $p^{\text{prec}}$
- $\text{height}$ – precomputed height function. If not supplied, this function will call padic_height to compute it.
- $\text{check_hypotheses}$ – boolean, whether to check that this is a curve for which the $p$-adic height makes sense

**OUTPUT:** The $p$-adic cyclotomic height pairing matrix of this curve to the given precision.

**Todo:** remove restriction that curve must be in minimal Weierstrass form. This is currently required for $E.gens()$.

**AUTHORS:**
- David Harvey, Liang Xiao, Robert Bradshaw, Jennifer Balakrishnan: original implementation at the 2006 MSRI graduate workshop on modular forms
- David Harvey (2006-09-13): cleaned up and integrated into Sage, removed some redundant height computations

**EXAMPLES:**

```python
sage: E = EllipticCurve("37a")
sage: E.padic_height_pairing_matrix(5, 10)
[5 + 5^2 + 5^3 + 3*5^6 + 4*5^7 + 5^9 + O(5^10)]
```

A rank two example:

```python
sage: e = EllipticCurve('389a')
sage: e._set_gens([e(-1, 1), e(1, 0)])  # avoid platform dependent gens
sage: e.padic_height_pairing_matrix(5, 10)
```

(continues on next page)
An anomalous rank 3 example:

\[
\text{sage: } e = \text{EllipticCurve("5077a")}
\text{sage: } e._set_gens([e(-1,3), e(2,0), e(4,6)])
\text{sage: } e.padic_height_pairing_matrix(5,4)
\[
\begin{bmatrix}
3*5 + 2*5^2 + 5^4 + 5^5 + 5^7 + 4*5^9 + 0(5^10) & 5 + 4*5^\rightarrow \\
\downarrow 2 + 5^3 + 2*5^4 + 3*5^5 + 4*5^6 + 5^7 + 5^8 + 2*5^9 + 0(5^10) & [5 + 4*5^2 + 5^3 + 2*5^4 + 3*5^5 + 4*5^6 + 5^7 + 5^8 + 2*5^9 + 0(5^10) \downarrow \\
\downarrow 4*5 + 2*5^4 + 3*5^6 + 4*5^7 + 4*5^8 + 0(5^10)]
\end{bmatrix}
\]

\text{padic_height_via_multiply}(p, \text{prec}=20, E2=None, \text{check_hypotheses}=True)
Computes the cyclotomic p-adic height.

The equation of the curve must be minimal at \( p \).

**INPUT:**

- \( p \) – prime \( \geq 5 \) for which the curve has good ordinary reduction
- \( \text{prec} \) – integer \( \geq 2 \) (default 20), desired precision of result
- \( E2 \) – precomputed value of \( E2 \). If not supplied, this function will call \text{padic_E2} to compute it. The value supplied must be correct mod \( p^{\text{prec} - 2} \) (or slightly higher in the anomalous case; see the code for details).
- \( \text{check_hypotheses} \) – boolean, whether to check that this is a curve for which the p-adic height makes sense

**OUTPUT:** A function that accepts two parameters:

- a Q-rational point on the curve whose height should be computed
- optional boolean flag ‘check’: if False, it skips some input checking, and returns the p-adic height of that point to the desired precision.

The normalization (sign and a factor 1/2 with respect to some other normalizations that appear in the literature) is chosen in such a way as to make the p-adic Birch Swinnerton-Dyer conjecture hold as stated in [Mazur-Tate-Teitelbaum].

**AUTHORS:**

- David Harvey (2008-01): based on the \text{padic_height()} function, using the algorithm of “Computing p-adic heights via point multiplication”

**EXAMPLES:**

\[
\text{sage: } E = \text{EllipticCurve("37a")}
\text{sage: } P = E.gens()[0]
\text{sage: } h = E.padic_height_via_multiply(5, 10)
\text{sage: } h(P)
5 + 5^2 + 5^3 + 3*5^6 + 4*5^7 + 5^9 + 0(5^10)
\]

An anomalous case:
Elliptic curves, Release 9.7

```
sage: h = E.padic_height_via_multiply(53, 10)
sage: h(P)
26*53^-1 + 30 + 20*53 + 47*53^2 + 10*53^3 + 32*53^4 + 9*53^5 + 22*53^6 + 35*53^7 + 30*53^8 + 17*53^9 + O(53^10)
```

Supply the value of E2 manually:

```
sage: E2 = E.padic_E2(5, 8)
sage: E2
2 + 4*5 + 2*5^3 + 5^4 + 3*5^5 + 2*5^6 + O(5^8)
sage: h = E.padic_height_via_multiply(5, 10, E2=E2)
sage: h(P)
5 + 5^2 + 5^3 + 3*5^6 + 4*5^7 + 5^9 + O(5^10)
```

Boundary case:

```
sage: E.padic_height_via_multiply(5, 3)(P)
5 + 5^2 + O(5^3)
```

Check that answers agree over a range of precisions:

```
sage: max_prec = 30  # make sure we get past p^2    # long time
sage: full = E.padic_height(5, max_prec)(P)       # long time
sage: for prec in range(2, max_prec):             # long time
....: assert E.padic_height_via_multiply(5, prec)(P) == full  # long time
```

`padic_lseries(p, normalize=None, implementation='eclib', precision=None)`

Return the \( p \)-adic \( L \)-series of self at \( p \), which is an object whose approx method computes approximation to the true \( p \)-adic \( L \)-series to any desired precision.

**INPUT:**

- \( p \) – prime
- `normalize` – ‘L_ratio’ (default), ‘period’ or ‘none’; this is describes the way the modular symbols are normalized. See `modular_symbol` for more details.
- `implementation` – ‘eclib’ (default), ‘sage’, ‘num’ or ‘pollackstevens’; Whether to use John Cremona’s eclib, the Sage implementation, numerical modular symbols or Pollack-Stevens’ implementation of overconvergent modular symbols.

**EXAMPLES:**

```
sage: E = EllipticCurve('37a')
sage: L = E.padic_lseries(5); L
5-adic L-series of Elliptic Curve defined by y^2 + y = x^3 - x over Rational Field
sage: type(L)
<class 'sage.schemes.elliptic_curves.padic_lseries.pAdicLseriesOrdinary'>
```

We compute the 3-adic \( L \)-series of two curves of rank 0 and in each case verify the interpolation property for their leading coefficient (i.e., value at 0):

```
sage: e = EllipticCurve('11a')
sage: ms = e.modular_symbol()
sage: [ms(1/11), ms(1/3), ms(0), ms(oo)]
(continues on next page)```
Next consider the curve 37b:

\[
\text{sage: } e = \text{EllipticCurve('37b')}
\]
\[
\text{sage: } L = e.padic_lseries(3)
\]
\[
\text{sage: } P = L.series(5)
\]
\[
\text{sage: } \alpha = L.alpha(9); \alpha
\]
\[
1 + 2 + 3 + 3^2 + 2 \cdot 3^3 + 2 \cdot 3^5 + 3^6 + 3^7 + O(3^9)
\]
\[
\text{sage: } r = e.lseries().L_ratio(); r
\]
\[
1/3
\]
\[
(1 - \alpha^{(-1)})^2 \cdot r
\]
\[
3 + 3^2 + 2 \cdot 3^4 + 2 \cdot 3^5 + 2 \cdot 3^6 + 3^7 + O(3^9)
\]
\[
\text{sage: } P(0)
\]
\[
3 + 3^2 + 2 \cdot 3^4 + 2 \cdot 3^5 + 0(3^6)
\]

We can use Sage modular symbols instead to compute the $L$-series:

\[
\text{sage: } e = \text{EllipticCurve('11a')}
\]
\[
\text{sage: } L = e.padic_lseries(3, \text{implementation = 'sage'})
\]
\[
\text{sage: } L.series(5, \text{prec}=10)
\]
\[
2 + 3 + 3^2 + 2 \cdot 3^3 + 2 \cdot 3^5 + 3^6 + 0(3^7) + (1 + 3 + 2 \cdot 3^2 + 3^3 + 0(3^4)) \cdot T + \ldots
\]
\[
\ldots \rightarrow (1 + 2 \cdot 3 + 0(3^4)) \cdot T^2 + (3 + 2 \cdot 3^2 + 0(3^3)) \cdot T^3 + (2 \cdot 3 + 3^2 + 0(3^3)) \cdot T^4 + \ldots
\]
\[
\ldots \rightarrow (2 + 2 \cdot 3 + 2 \cdot 3^2 + 0(3^3)) \cdot T^5 + (1 + 3^2 + 0(3^3)) \cdot T^6 + (2 + 3^2 + 0(3^3)) \cdot T^7 + (2 + 2 \cdot 3 + 2 \cdot 3^2 + 0(3^3)) \cdot T^8 + (2 + 0(3^2)) \cdot T^9 + O(T^{10})
\]

Also the numerical modular symbols can be used. This may allow for much larger conductor in some instances:

\[
\text{sage: } E = \text{EllipticCurve([[101,103]])}
\]
\[
\text{sage: } L = E.padic_lseries(5, \text{implementation=\text{\textquoteleft}num\textquoteleft\})}
\]
\[
\text{sage: } L.series(2)
\]
\[
O(5^4) + (3 + O(5)) \cdot T + (1 + O(5)) \cdot T^2 + (3 + O(5)) \cdot T^3 + O(5) \cdot T^4 + O(T^5)
\]

Finally, we can use the overconvergent method of Pollack-Stevens:
sage: e = EllipticCurve('11a')
sage: L = e.padic_lseries(3, implementation = 'pollackstevens', precision = 6)
sage: L.series(5)
2 + 3 + 3^2 + 2*3^3 + 2*3^5 + O(3^6) + (1 + 3 + 2*3^2 + 3^3 + O(3^4))*T + (1 +
→2*3 + O(3^2))*T^2 + (3 + O(3^2))*T^3 + O(3^0)*T^4 + O(T^5)
sage: L[3]
3 + O(3^2)

Another example with a semistable prime:

sage: E = EllipticCurve("11a1")
sage: L = E.padic_lseries(11, implementation = 'pollackstevens', precision=3)
sage: L[1]
10 + 3*11 + O(11^2)
sage: L[3]
O(11^0)

padic_regulator($p$, $prec=20$, height=None, check_hypotheses=True)
Compute the cyclotomic $p$-adic regulator of this curve.

INPUT:

- $p$ – prime $\geq 5$
- $prec$ – answer will be returned modulo $p^{prec}$
- $height$ – precomputed height function. If not supplied, this function will call padic_height to compute it.
- $check_hypotheses$ – boolean, whether to check that this is a curve for which the $p$-adic height makes sense

OUTPUT: The $p$-adic cyclotomic regulator of this curve, to the requested precision.

If the rank is 0, we output 1.

Todo: Remove restriction that curve must be in minimal Weierstrass form. This is currently required for E.gens().

AUTHORS:

- Liang Xiao: original implementation at the 2006 MSRI graduate workshop on modular forms
- David Harvey (2006-09-13): cleaned up and integrated into Sage, removed some redundant height computations
- Chris Wuthrich (2007-05-22): added multiplicative and supersingular cases
- David Harvey (2007-09-20): fixed some precision loss that was occurring

EXAMPLES:

sage: E = EllipticCurve("37a")
sage: E.padic_regulator(5, 10)
5 + 5^2 + 5*3 + 3*5^6 + 4*5^7 + 5^9 + O(5^10)

An anomalous case:
Elliptic curves, Release 9.7

```
sage: E.padic_regulator(53, 10)
26*53^-1 + 30 + 20*53 + 47*53^2 + 10*53^3 + 32*53^4 + 9*53^5 + 22*53^6 + 35*53^7 + 30*53^8 + O(53^9)
```

An anomalous case where the precision drops some:

```
sage: E = EllipticCurve("5077a")
sage: E.padic_regulator(5, 10)
5 + 5^2 + 4*5^3 + 2*5^4 + 2*5^5 + 2*5^6 + 4*5^7 + 2*5^8 + 5^9 + O(5^10)
```

Check that answers agree over a range of precisions:

```
sage: max_prec = 30 # make sure we get past p^2 # long time
sage: full = E.padic_regulator(5, max_prec) # long time
sage: for prec in range(1, max_prec):
    # long time
    ....: assert E.padic_regulator(5, prec) == full # long time
```

A case where the generator belongs to the formal group already (trac ticket #3632):

```
sage: E = EllipticCurve([37,0])
sage: E.padic_regulator(5,10)
2*5^2 + 2*5^3 + 5^4 + 5^5 + 4*5^6 + 3*5^8 + 4*5^9 + O(5^10)
```

The result is not dependent on the model for the curve:

```
sage: E = EllipticCurve([0,0,0,0,2^12*17])
sage: Em = E.minimal_model()
sage: E.padic_regulator(7) == Em.padic_regulator(7)
True
```

Allow a Python int as input:

```
sage: E = EllipticCurve('37a')
sage: E.padic_regulator(int(5))
5 + 5^2 + 5^3 + 3*5^6 + 4*5^7 + 5^9 + 5^10 + 3*5^11 + 3*5^12 + 5^13 + 4*5^14 + 5^15 + 2*5^16 + 5^17 + 2*5^18 + 4*5^19 + O(5^20)
```

```
\textbf{padic}\_\textbf{sigma}(p, N=20, E2=None, check=False, check_hypotheses=True)
```

Computes the p-adic sigma function with respect to the standard invariant differential $dx/(2y + a_1 x + a_3)$, as defined by Mazur and Tate, as a power series in the usual uniformiser $t$ at the origin.

The equation of the curve must be minimal at $p$.

**INPUT:**

- $p$ – prime $\geq 5$ for which the curve has good ordinary reduction
- $N$ – integer $\geq 1$ (default 20), indicates precision of result; see OUTPUT section for description
- $E2$ – precomputed value of $E2$. If not supplied, this function will call padic\_E2 to compute it. The value supplied must be correct mod $p^{N-2}$.
- $\text{check}$ – boolean, whether to perform a consistency check (i.e. verify that the computed sigma satisfies the defining
- $\text{differential\ equation}$ – note that this does NOT guarantee correctness of all the returned digits, but it comes pretty close :-))
• check_hypotheses – boolean, whether to check that this is a curve for which the p-adic sigma function makes sense

OUTPUT: A power series \( t + \cdots \) with coefficients in \( \mathbb{Z}_p \).

The output series will be truncated at \( O(t^{N+1}) \), and the coefficient of \( t^n \) for \( n \geq 1 \) will be correct to precision \( O(p^{N-n+1}) \).

In practice this means the following. If \( t_0 = p^k u \), where \( u \) is a p-adic unit with at least \( N \) digits of precision, and \( k \geq 1 \), then the returned series may be used to compute \( \sigma(t_0) \) correctly modulo \( p^{N+k} \) (i.e. with \( N \) correct p-adic digits).

ALGORITHM: Described in “Efficient Computation of p-adic Heights” (David Harvey), which is basically an optimised version of the algorithm from “p-adic Heights and Log Convergence” (Mazur, Stein, Tate).

Running time is soft-\( O(N^2 \log p) \), plus whatever time is necessary to compute \( E_2 \).

AUTHORS:
• David Harvey (2006-09-12)
• David Harvey (2007-02): rewrote

EXAMPLES:

```python
sage: EllipticCurve([-1, 1/4]).padic_sigma(5, 10)
O(5^11) + (1 + O(5^10))*t + O(5^9)*t^2 + (3 + 2*5^2 + 3*5^3 + 3*5^6 + 4*5^7 + O(5^8))*t^3 + (2 + 4*5^2 + 4*5^3 + 5*4 + 5*5 + O(5^6))*t^4 + O(5^5)*t^5
```

Run it with a consistency check:

```python
sage: EllipticCurve("37a").padic_sigma(5, 10, check=True)
O(5^11) + (1 + O(5^10))*t + O(5^9)*t^2 + (3 + 2*5^2 + 3*5^3 + 3*5^6 + O(5^7))*t^3 + (2 + 3*5 + O(5^6))*t^4 + O(5^3)*t^5
```

Boundary cases:

```python
sage: EllipticCurve([1, 1, 1, 1, 1]).padic_sigma(5, 1)
(1 + O(5))*t + O(t^2)
sage: EllipticCurve([1, 1, 1, 1, 1]).padic_sigma(5, 2)
(1 + O(5^2))*t + (3 + O(5))*t^2 + O(t^3)
```

Supply your very own value of \( E_2 \):

```python
sage: X = EllipticCurve("37a")
sage: my_E2 = X.padic_E2(5, 8)
sage: my_E2 = my_E2 + 5**5  # oops!!!
sage: X.padic_sigma(5, 10, E2=my_E2)
```

```
O(5^11) + (1 + O(5^10))*t + O(5^9)*t^2 + (3 + 2*5^2 + 3*5^3 + 3*5^6 + 4*5^7 + O(5^8))*t^3 + (2 + 4*5^2 + 4*5^3 + 5*4 + 5*5 + O(5^6))*t^4 + O(5^5)*t^5 + (2 + 3*5 + 5*4 + O(5^3))*t^6
```

Check that sigma is “weight 1”.

```python
sage: f = EllipticCurve([-1, 3]).padic_sigma(5, 10)
sage: g = EllipticCurve([-1*(2**4), 3*(2**6)]).padic_sigma(5, 10)
sage: t = f.parent().gen()
sage: f(2*t)/2
(1 + O(5^10))*t + (4 + 3*5 + 3*5^2 + 3*5^3 + 4*5^4 + 4*5^5 + 3*5^6 + 5^7 + O(5^8))*t^3 + (3 + 3*5^2 + 5^4 + 2*5^5 + O(5^6))*t^5 + (4 + 5 + 3*5^3 + O(5^4))*t^7 + (4 + 2*5 + O(5^2))*t^9 + O(5)*t^10 + O(t^11)
sage: g
0(5^11) + (1 + O(5^10))*t + O(5^9)*t^2 + (4 + 3*5 + 3*5^2 + 3*5^3 + 4*5^4 + 4*5^5 + 5 + 3*5^6 + 5^7 + O(5^8))*t^3 + (3 + 3*5^2 + 5^4 + 2*5^5 + O(5^6))*t^5 + (4 + 5 + 3*5^3 + O(5^4))*t^7 + (4 + 2*5 + O(5^2))*t^9 + O(5)*t^10 + O(t^11)
sage: f(2*t)/2 -g
O(t^11)
```

Test that it returns consistent results over a range of precision:

```python
sage: max_N = 30  # get up to at least p^2  # long time
sage: E = EllipticCurve([1, 1, 1, 1, 1])  # long time
sage: p = 5  # long time
sage: E2 = E.padic_E2(5, max_N)  # long time
sage: max_sigma = E.padic_sigma(p, max_N, E2=E2)  # long time
sage: for N in range(3, max_N):
    # long time
    sigma = E.padic_sigma(p, N, E2=E2)
    assert sigma == max_sigma
    ....: assert sigma == max_sigma
```

\textbf{padic\_sigma\_truncated}(p, N=20, lamb=0, E2=None, check\_hypotheses=True)

Compute the p-adic sigma function with respect to the standard invariant differential $dx/(2y + a_1 x + a_3)$, as defined by Mazur and Tate, as a power series in the usual uniformiser $t$ at the origin.

The equation of the curve must be minimal at $p$.

This function differs from \textbf{padic\_sigma()} in the precision profile of the returned power series; see OUTPUT below.

**INPUT:**

- \texttt{p} – prime $\geq 5$ for which the curve has good ordinary reduction
- \texttt{N} – integer $\geq 2$ (default 20), indicates precision of result; see OUTPUT section for description
- \texttt{lamb} – integer $\geq 0$, see OUTPUT section for description
- \texttt{E2} – precomputed value of E2. If not supplied, this function will call \texttt{padic\_E2} to compute it. The value supplied must be correct mod $p^{N-2}$.

- \texttt{check\_hypotheses} – boolean, whether to check that this is a curve for which the p-adic sigma function makes sense

**OUTPUT:** A power series $t + \cdots$ with coefficients in $\mathbb{Z}_p$.

The coefficient of $t^j$ for $j \geq 1$ will be correct to precision $O(p^{N-2+(3-j)(\text{lamb}+1)})$.

**ALGORITHM:** Described in “Efficient Computation of p-adic Heights” (David Harvey, to appear in LMS JCM), which is basically an optimised version of the algorithm from “p-adic Heights and Log Convergence” (Mazur, Stein, Tate), and “Computing p-adic heights via point multiplication” (David Harvey, still draft form).
Running time is soft-$O(N^2\lambda^{-1} \log p)$, plus whatever time is necessary to compute $E_2$.

AUTHORS:

- David Harvey (2008-01): wrote based on previous \texttt{padic\_sigma()} function

EXAMPLES:

```python
sage: E = EllipticCurve([-1, 1/4])
sage: E.padic_sigma_truncated(5, 10)
O(5^11) + (1 + O(5^10))*t + O(5^9)*t^2 + (3 + 2*5^2 + 3*5^3 + 3*5^6 + 4*5^7 + ⋯)
    -O(5^8))*t^3 + O(5^7)*t^4 + (2 + O(5^2))*t^5 + O(t^6)
    -O(5^5)*t^6 + (2 + O(5^2))*t^7 + O(5^3)*t^8 + (1 + O(5^2))*t^9 + O(t^10) + O(t^11)
```

Note the precision of the $t^3$ coefficient depends only on $N$, not on lamb:

```python
sage: E.padic_sigma_truncated(5, 10, lamb=2)
O(5^17) + (1 + O(5^14))*t + O(5^11)*t^2 + (3 + 2*5^2 + 3*5^3 + 3*5^6 + 4*5^7 + ⋯)
    -O(5^8))*t^3 + O(5^5)*t^4 + (2 + O(5^2))*t^5 + O(t^6)
```

Compare against plain \texttt{padic\_sigma()} function over a dense range of $N$ and lamb:

```python
sage: E = EllipticCurve([1, 2, 3, 4, 7])
# long time
sage: E2 = E.padic_E2(5, 50)
# long time
sage: for N in range(2, 10):
    # long time
    for lamb in range(10):
        # long time
        correct = E.padic_sigma(5, N + 3*lamb, E2=E2)
        # long time
        compare = E.padic_sigma_truncated(5, N=N, lamb=lamb, E2=E2)
        # long time
        assert compare == correct
```

\texttt{pari\_curve()}

Return the PARI curve corresponding to this elliptic curve.

EXAMPLES:

```python
sage: E = EllipticCurve([0, 0, 1, -1, 0])
sage: e = E.pari_curve()
sage: type(e)
'<... 'cypari2.gen.Gen'>
sage: e.type()
't_VEC'
sage: e.ellan(10)
[1, -2, -3, 2, -2, 6, -1, 0, 6, 4]
```

```python
sage: E = EllipticCurve(RationalField(), ['1/3', '2/3'])
sage: e = E.pari_curve()
sage: e[:5]
[0, 0, 1/3, 2/3]
```

When doing certain computations, PARI caches the results:

```python
sage: E = EllipticCurve('37a1')
sage: _ = E.__dict__.pop('pari_curve', None)  # clear cached data
sage: Epari = E.pari_curve()
```
Elliptic curves, Release 9.7

(continued from previous page)

```
sage: Epari
[0, 0, 1, -1, 0, 0, -2, 1, -1, 48, -216, 37, 110592/37, Vecsmall([1]),
→[Vecsmall([64, 1])], [0, 0, 0, 0, 0, 0, 0, 0]]
sage: Epari.omega()
[2.99345864623196, -2.45138938198679*I]
sage: Epari
[0, 0, 1, -1, 0, 0, -2, 1, -1, 48, -216, 37, 110592/37, Vecsmall([1]),
→[Vecsmall([64, 1])], [2.99345864623196, -2.45138938198679*I], 0, [0.
→837565435283323, 0.26954436405445, -1.10715987168877, 1.37675430809421, 1.
→94472530697209, 0.56797098877878]~, 0, 0, 0, 0, 0]
```

This shows that the bug uncovered by trac ticket #4715 is fixed:

```
sage: Ep = EllipticCurve('903b3').pari_curve()
```

This still works, even when the curve coefficients are large (see trac ticket #13163):

```
sage: E = EllipticCurve([438269645756479469160344238788106497, 28, 3992, 16777216, 298])
sage: E.pari_curve()
[438269645756479469160344238788106497, 28, 3992, 16777216, 298, ...]
sage: E.minimal_model()
Elliptic Curve defined by y^2 + x*y + y = x^3 + x^2 -
→768642393408379739067598116922917190767418358326184511391146727143672423167091
→84392497987772304274754929188483919679303372
→82022804435357361483773108648734271851215988504820214784899752662100459663011709
→992446860978249728593285880891991
over Rational Field
```

`pari_mincurve()`

Return the PARI curve corresponding to a minimal model for this elliptic curve.

EXAMPLES:

```
sage: E = EllipticCurve(RationalField(), ['1/3', '2/3'])
sage: e = E.pari_mincurve()
sage: e[:5]
[0, 0, 0, 27, 486]
sage: E.conductor()
47232
sage: e.ellglobalred()
[47232, [1, 0, 0, 0], 2, [2, 7; 3, 2; 41, 1], [7, 2, 0, 1], [2, -3, 0, 2], [1, 5, 0, 1]]
```

`period_lattice(embedding=None)`

Return the period lattice of the elliptic curve with respect to the differential \(dx/(2y + a_1x + a_3)\).

INPUT:

- `embedding` – ignored (for compatibility with the `period_lattice` function for `elliptic_curve_number_field`)

OUTPUT:

(period lattice) The PeriodLattice_ell object associated to this elliptic curve (with respect to the natural embedding of \(\mathbb{Q}\) into \(\mathbb{R}\)).
EXAMPLES:

```
sage: E = EllipticCurve('37a')  
sage: E.period_lattice()  
Period lattice associated to Elliptic Curve defined by y^2 + y = x^3 - x over Rational Field
```

`point_search(\text{height} \_\text{limit}, \text{verbose} = \text{False}, \text{rank} \_\text{bound} = \text{None})`

Search for points on a curve up to an input bound on the naive logarithmic height.

**INPUT:**
- `height_limit` – float; bound on naive height
- `verbose` – boolean (default: False); if True, report on the saturation process otherwise just return the result
- `rank_bound` – boolean (optional); if provided, stop saturating once we find this many independent nontorsion points

**OUTPUT:** points (list) - list of independent points which generate the subgroup of the Mordell-Weil group generated by the points found and then saturated.

**Warning:** `height_limit` is logarithmic, so increasing by 1 will cause the running time to increase by a factor of approximately 4.5 (\text{exp}(1.5)).

**IMPLEMENTATION:** Uses Michael Stoll’s ratpoints module in PARI/GP.

**EXAMPLES:**

```
sage: E = EllipticCurve('389a1')  
sage: E.point_search(5, verbose=False)  
[(-1 : 1 : 1), (0 : 0 : 1)]
```

Increasing the `height_limit` takes longer, but finds no more points:

```
sage: E.point_search(10, verbose=False)  
[(-1 : 1 : 1), (0 : 0 : 1)]
```

In fact this curve has rank 2 so no more than 2 points will ever be output, but we are not using this fact.

```
sage: E.saturation(_)  
[(-1 : 1 : 1), (0 : 0 : 1)], 1, 0.152460177943144
```

What this shows is that if the rank is 2 then the points listed do generate the Mordell-Weil group (mod torsion). Finally,

```
sage: E.rank()  
2
```

If we only need one independent generator:

```
sage: E.point_search(5, verbose=False, rank_bound=1)  
[(-2 : 0 : 1)]
```

`pollack_stevens_modular_symbol(sign=0, implementation='eclib')`

Create the modular symbol attached to the elliptic curve, suitable for overconvergent calculations.
INPUT:

- sign – +1 or -1 or 0 (default), in which case this it is the sum of the two
- implementation – either ‘eclib’ (default) or ‘sage’. This determines classical modular symbols which implementation of the underlying classical modular symbols is used

EXAMPLES:

```python
sage: E = EllipticCurve('113a1')
sage: symb = E.pollack_stevens_modular_symbol()
sage: symb
Modular symbol of level 113 with values in Sym^0 Q^2
sage: symb.values()
[-1/2, 1, -1, 0, 1, 1, -1, 0, -1, 0, 0, 1, -1, 0, 0, 1, 0, 0, 0]
sage: E = EllipticCurve([0,1])
sage: symb = E.pollack_stevens_modular_symbol(+1)
sage: symb.values()
[-1/6, 1/12, 0, 1/6, 1/12, 1/3, -1/12, 0, -1/6, -1/12, -1/4, -1/6, 1/12]
```

`prove_BSD(E, verbosity=0, two_desc='mwrank', proof=None, secs_hi=5, return_BSD=False)`

Attempt to prove the Birch and Swinnerton-Dyer conjectural formula for $E$, returning a list of primes $p$ for which this function fails to prove $\text{BSD}(E,p)$.

Here, $\text{BSD}(E,p)$ is the statement: “the Birch and Swinnerton-Dyer formula holds up to a rational number coprime to $p$.”

INPUT:

- $E$ – an elliptic curve
- verbosity – int, how much information about the proof to print.
  - 0: print nothing
  - 1: print sketch of proof
  - 2: print information about remaining primes
- two_desc – string (default 'mwrank'), what to use for the two-descent. Options are 'mwrank', 'simon', 'sage'
- proof – bool or None (default: None, see proof.elliptic_curve or sage.structure.proof). If False, this function just immediately returns the empty list.
- secs_hi – maximum number of seconds to try to compute the Heegner index before switching over to trying to compute the Heegner index bound. (Rank 0 only!)
- return_BSD – bool (default: False) whether to return an object which contains information to reconstruct a proof

Note: When printing verbose output, phrases such as “by Mazur” are referring to the following list of papers:

REFERENCES:

- [Cha2005]
- [Jet2008]
- [Kat2004]
EXAMPLES:

```python
sage: EllipticCurve('11a').prove_BSD(verbosity=2)
p = 2: True by 2-descent
True for p not in {2, 5} by Kolyvagin.
Kolyvagin's bound for p = 5 applies by Lawson-Wuthrich
True for p = 5 by Kolyvagin bound
[]
```

```python
sage: EllipticCurve('14a').prove_BSD(verbosity=2)
p = 2: True by 2-descent
True for p not in {2, 3} by Kolyvagin.
Kolyvagin's bound for p = 3 applies by Lawson-Wuthrich
True for p = 3 by Kolyvagin bound
[]
```

```python
sage: E = EllipticCurve("20a1")
sage: E.prove_BSD(verbosity=2)
p = 2: True by 2-descent
True for p not in {2, 3} by Kolyvagin.
Kato further implies that #Sha[3] is trivial.
[]
```

```python
sage: E = EllipticCurve("50b1")
sage: E.prove_BSD(verbosity=2)
p = 2: True by 2-descent
True for p not in {2, 3, 5} by Kolyvagin.
Kolyvagin's bound for p = 3 applies by Lawson-Wuthrich
Kolyvagin's bound for p = 5 applies by Lawson-Wuthrich
True for p = 3 by Kolyvagin bound
True for p = 5 by Kolyvagin bound
[]
sage: E.prove_BSD(two_desc='simon')
[]
```

A rank two curve:

```python
sage: E = EllipticCurve('389a')
```

We know nothing with proof=True:

```python
sage: E.prove_BSD()  
Set of all prime numbers: 2, 3, 5, 7, ...
```
We (think we) know everything with proof=False:

```
sage: E.prove_BSD(proof=False)
[]
```

A curve of rank 0 and prime conductor:

```
sage: E = EllipticCurve('19a')
sage: E.prove_BSD(verbosity=2)
p = 2: True by 2-descent
True for p not in {2, 3} by Kolyvagin.
Kolyvagin's bound for p = 3 applies by Lawson-Wuthrich
True for p = 3 by Kolyvagin bound
[]
sage: E = EllipticCurve('37a')
sage: E.rank()
1
sage: E._EllipticCurve_rational_field__rank
(1, True)
sage: E.analytic_rank = lambda : 0
sage: E.prove_BSD()
Traceback (most recent call last):
... RuntimeError: It seems that the rank conjecture does not hold for this curve!
hesive contradiction to BSD, but is more likely a bug.
```

We test the consistency check for the 2-part of Sha:

```
sage: E = EllipticCurve('37a')
sage: S = E.sha(); S
Tate-Shafarevich group for the Elliptic Curve defined by y^2 + y = x^3 - x over Rational Field
sage: def foo(use_database):
....: return 4
sage: S.an = foo
sage: E.prove_BSD()
Traceback (most recent call last):
... RuntimeError: Apparent contradiction: 0 <= rank(sha[2]) <= 0, but ord_2(sha_an) = 2
```

An example with a Tamagawa number at 5:

```
sage: E = EllipticCurve('123a1')
sage: E.prove_BSD(verbosity=2)
p = 2: True by 2-descent
True for p not in {2, 5} by Kolyvagin.
Kolyvagin's bound for p = 5 applies by Lawson-Wuthrich
True for p = 5 by Kolyvagin bound
[]
```

A curve for which 3 divides the order of the Tate-Shafarevich group:
Elliptic curves, Release 9.7

```
sage: E = EllipticCurve('681b')
sage: E.prove_BSD(verbosity=2)  # long time
p = 2: True by 2-descent...
True for p not in {2, 3} by Kolyvagin....
Remaining primes:
p = 3: irreducible, surjective, non-split multiplicative
   (0 <= ord_p <= 2)
   ord_p(#Sha_an) = 2
[3]
```

A curve for which we need to use heegner_index_bound:

```
sage: E = EllipticCurve('198b')
sage: E.prove_BSD(verbosity=1, secs_hi=1)
p = 2: True by 2-descent
True for p not in {2, 3} by Kolyvagin.
[3]
```

The return_BSD option gives an object with detailed information about the proof:

```
sage: E = EllipticCurve('26b')
sage: B = E.prove_BSD(return_BSD=True)
sage: B.two_tor_rk
0
sage: B.N
26
sage: B.gens
[]
sage: B.primes
[]
sage: B.heegner_indexes
{-23: 2}
```

**q_eigenform**(prec)

Synonym for self.q_expansion(prec).

**EXAMPLES:**

```
sage: E = EllipticCurve('37a1')
sage: E.q_eigenform(10)
q - 2*q^2 - 3*q^3 + 2*q^4 - 2*q^5 + 6*q^6 - q^7 + 6*q^9 + O(q^10)
sage: E.q_eigenform(10) == E.q_expansion(10)
True
```

**q_expansion**(prec)

Return the $q$-expansion to precision prec of the newform attached to this elliptic curve.

**INPUT:**

- prec – an integer

**OUTPUT:**

a power series (in the variable ‘q’)
Note: If you want the output to be a modular form and not just a $q$-expansion, use `modular_form()`.

EXAMPLES:

```python
sage: E = EllipticCurve('37a1')
sage: E.q_expansion(20)
qu + 2q^2 - 3q^3 + 2q^4 - q^5 + 6q^6 + 6q^7 + 6q^8 + 4q^9 - q^10 - 5q^11 - 6q^12 - 2q^13 + 2q^14 + 6q^15 - 4q^16 - 12q^18 + O(q^20)
```

**quadratic_twist($D$)**

Return the global minimal model of the quadratic twist of this curve by $D$.

EXAMPLES:

```python
sage: E = EllipticCurve('37a1')
sage: E7 = E.quadratic_twist(7); E7
Elliptic Curve defined by y^2 = x^3 - 784*x + 5488 over Rational Field
sage: E7.conductor()
29008
sage: E7.quadratic_twist(7) == E
True
```

**rank**

(``use_database=True, verbose=False, only_use_mwrank=True, algorithm='mwrank_lib', proof=None``)

Return the rank of this elliptic curve, assuming no conjectures.

If we fail to provably compute the rank, raises a `RuntimeError` exception.

INPUT:

- `use_database` -- boolean (default: `True`); if `True`, try to look up the rank in the Cremona database
- `verbose` -- (default: `False`) if specified changes the verbosity of `mwrank` computations
- `algorithm` -- (default: `'mwrank_lib'`) one of:
  - `'mwrank_shell'` -- call `mwrank` shell command
  - `'mwrank_lib'` -- call `mwrank` c library
- `only_use_mwrank` -- (default: `True`) if `False` try using analytic rank methods first
- `proof` -- bool (default: `None`, see `proof.elliptic_curve` or `sage.structure.proof`); note that results obtained from databases are considered `proof=True`

OUTPUT: the rank of the elliptic curve as `Integer`

IMPLEMENTATION: Uses L-functions, `mwrank`, and databases.

EXAMPLES:

```python
sage: EllipticCurve('11a').rank()
0
sage: EllipticCurve('37a').rank()
1
sage: EllipticCurve('389a').rank()
2
sage: EllipticCurve('5077a').rank()
3
sage: EllipticCurve([[1, -1, 0, -79, 289]]).rank()  # This will use the default --proof behavior of True
(continues on next page)
```
Examples with denominators in defining equations:

```python
sage: E = EllipticCurve([0, 0, 0, 0, -675/4])
sage: E.rank()
0
sage: E = EllipticCurve([0, 0, 1/2, 0, -1/5])
sage: E.rank()
1
sage: E.minimal_model().rank()
1
```

A large example where mwrank doesn’t determine the result with certainty:

```python
sage: EllipticCurve([1,0,0,0,37455]).rank(proof=False)
0
sage: EllipticCurve([1,0,0,0,37455]).rank(proof=True)
Traceback (most recent call last):
  ...
RuntimeError: rank not provably correct (lower bound: 0)
```

**rank_bound()**

Upper bound on the rank of the curve, computed using 2-descent.

In many cases, this is the actual rank of the curve. If the curve has no 2-torsion it is the same as the 2-selmer rank.

**EXAMPLES:** The following is the curve 960D1, which has rank 0, but Sha of order 4.

```python
sage: E = EllipticCurve([0, -1, 0, -900, -10098])
sage: E.rank_bound()
0
```

It gives 0 instead of 2, because it knows Sha is nontrivial. In contrast, for the curve 571A, also with rank 0 and Sha of order 4, we get a worse bound:

```python
sage: E = EllipticCurve([0, -1, 1, -929, -10595])
sage: E.rank_bound()
2
sage: E.rank(only_use_mwrank=False)  # uses L-function
0
```

**real_components()**

Return the number of real components.

**EXAMPLES:**

14.1. **Elliptic curves over the rational numbers**
sage: E = EllipticCurve('37a')
sage: E.real_components ()
2
sage: E = EllipticCurve('37b')
sage: E.real_components ()
2
sage: E = EllipticCurve('11a')
sage: E.real_components ()
1

reduction($p$)

Return the reduction of the elliptic curve at a prime of good reduction.

**Note:** The actual reduction is done in `self.change_ring(GF(p))`; the reduction is performed after changing to a model which is minimal at $p$.

**INPUT:**

- $p$ – a (positive) prime number

**OUTPUT:** an elliptic curve over the finite field $\mathbb{F}_p$

**EXAMPLES:**

```
sage: E = EllipticCurve('389a1')
sage: E.reduction(2)
Elliptic Curve defined by y^2 + y = x^3 + x^2 over Finite Field of size 2
sage: E.reduction(3)
Elliptic Curve defined by y^2 + y = x^3 + x^2 + x over Finite Field of size 3
sage: E.reduction(5)
Elliptic Curve defined by y^2 + y = x^3 + x^2 + 3*x over Finite Field of size 5
sage: E.reduction(38)
Traceback (most recent call last):
  ...  
AttributeError: p must be prime.
sage: E.reduction(389)
Traceback (most recent call last):
  ...  
AttributeError: The curve must have good reduction at p.
sage: E = EllipticCurve([5^4,5^6])
sage: E.reduction(5)
Elliptic Curve defined by y^2 = x^3 + x + 1 over Finite Field of size 5
```

regulator($proof=None, precision=53, **kwds$)

Return the regulator of this curve, which must be defined over $\mathbb{Q}$.

**INPUT:**

- `proof` – bool or `None` (default: `None`, see `proof`, `sage.structure.proof`). Note that results from databases are considered `proof = True`
- `precision` – (int, default 53): the precision in bits of the result
- `**kwds` – passed to `gens()` method

**EXAMPLES:**

```
```
Elliptic curves, Release 9.7

```python
sage: E = EllipticCurve([0, 0, 1, -1, 0])
sage: E.regulator()
0.0511114082399688
sage: EllipticCurve('11a').regulator()
1.00000000000000
sage: EllipticCurve('37a').regulator()
0.0511114082399688
sage: EllipticCurve('389a').regulator()
0.152460177943144
sage: EllipticCurve('5077a').regulator()
0.41714355875838...
```

### root_number(p=None)

Return the root number of this elliptic curve.

This is 1 if the order of vanishing of the L-function $L(E,s)$ at 1 is even, and -1 if it is odd.

**INPUT:**

- $p$ – (optional) if given, return the local root number at $p$

**EXAMPLES:**

```python
sage: EllipticCurve('11a1').root_number()
1
sage: EllipticCurve('37a1').root_number()
-1
sage: EllipticCurve('389a1').root_number()
1
sage: type(EllipticCurve('389a1').root_number())
<...
'sage.rings.integer.Integer'>
```

The root number is cached:

```python
sage: E = EllipticCurve('100a1')
sage: E.root_number(2)
-1
sage: E.root_number(5)
1
sage: E.root_number(7)
1
```

### satisfies_heegner_hypothesis(D)

Returns True precisely when $D$ is a fundamental discriminant that satisfies the Heegner hypothesis for this elliptic curve.
**saturation**\(^{(\text{points,~verbose=False,~max\_prime=-1,~min\_prime=2})}\)

Given a list of rational points on \(E\), compute the saturation in \(E(\mathbb{Q})\) of the subgroup they generate.

**INPUT:**

- **points** (list) – list of points on \(E\)
- **verbose** (bool) – (default: False) if True, give verbose output
- **max\_prime** – int (default: -1); if -1 (the default), an upper bound is computed for the primes at which the subgroup may not be saturated, and saturation is performed for all primes up to this bound; otherwise, the bound used is the minimum of \(\text{max\_prime}\) and the computed bound
- **min\_prime** (int) – (default: 2) only do \(p\)-saturation at primes \(p\) greater than or equal to this

**Note:** To saturate at a single prime \(p\), set \(\text{max\_prime}\) and \(\text{min\_prime}\) both to \(p\). One situation where this is useful is after mapping saturated points from another elliptic curve by a \(p\)-isogeny, since the images may not be \(p\)-saturated but will be saturated at all other primes.

**OUTPUT:**

- **saturation** (list) – points that form a basis for the saturation
- **index** (int) – the index of the group generated by points in their saturation
- **regulator** (real with default precision) – regulator of saturated points.

**ALGORITHM:**

Uses Cremona’s eclib package, which computes a bound on the saturation index. To \(p\)-saturate, or prove \(p\)-saturation, we consider the reductions of the points modulo primes \(q\) of good reduction such that \(E(F_q)\) has order divisible by \(p\).

**Note:** In versions of eclib up to v20190909, division of points in eclib was done using floating point methods, without automatic handling of precision, so that \(p\)-saturation sometimes failed unless \text{mwrank\_set\_precision()} was called in advance with a suitably high bit precision. Since version v20210310 of eclib, division is done using exact methods based on division polynomials, and \(p\)-saturation cannot fail in this way.

**Note:** The computed index of saturation may be large, in which case saturation may take a long time. For example, the rank 4 curve \(\text{EllipticCurve([0,1,1,-9872,374262])}\) has a saturation index bound of 11816 and takes around 40 seconds to prove saturation.

**EXAMPLES:**

```python
sage: E = EllipticCurve('11a1')
sage: E.satisfies_heegner_hypothesis(-7)
True
sage: E.satisfies_heegner_hypothesis(-11)
False
```
**selmer_rank()**

The rank of the 2-Selmer group of the curve.

**EXAMPLES:** The following is the curve 960D1, which has rank 0, but Sha of order 4.

```
sage: E = EllipticCurve([0, -1, 0, -900, -10098])
sage: E.selmer_rank()
3
```

Here the Selmer rank is equal to the 2-torsion rank (=1) plus the 2-rank of Sha (=2), and the rank itself is zero:

```
sage: E.rank()
0
```

In contrast, for the curve 571A, also with rank 0 and Sha of order 4, we get a worse bound:

```
sage: E = EllipticCurve([0, -1, 1, -929, -10595])
sage: E.selmer_rank()
2
```

To establish that the rank is in fact 0 in this case, we would need to carry out a higher descent:

```
sage: E.three_selmer_rank()  # optional - magma
0
```

Or use the L-function to compute the analytic rank:

```
sage: E.rank(only_use_mwrank=False)
0
```

**sha()**

Return an object of class ‘sage.schemes.elliptic_curves.sha_tateSha’ attached to this elliptic curve.

This can be used in functions related to bounding the order of Sha (The Tate-Shafarevich group of the curve).

**EXAMPLES:**

```
sage: E = EllipticCurve('37a1')
sage: S=E.sha()
sage: S
Tate-Shafarevich group for the Elliptic Curve defined by y^2 + y = x^3 - x over Rational Field
```

```
sage: S.bound_kolyvagin()
([2], 1)
```

**silverman_height_bound(algorithm='default')**

Return the Silverman height bound.
This is a positive real (floating point) number $B$ such that for all points $P$ on the curve over any number field, $|h(P) - \hat{h}(P)| \leq B$, where $h(P)$ is the naive logarithmic height of $P$ and $\hat{h}(P)$ is the canonical height.

**INPUT:**

- **algorithm** – one of the following:
  - `'default'` (default) - compute using a Python implementation in Sage
  - `'mwrank'` – use a C++ implementation in the mwrank library

**Note:**

- The CPS_height_bound is often better (i.e. smaller) than the Silverman bound, but it only applies for points over the base field, whereas the Silverman bound works over all number fields.
- The Silverman bound is also fairly straightforward to compute over number fields, but isn’t implemented here.
- Silverman’s paper is ‘The Difference Between the Weil Height and the Canonical Height on Elliptic Curves’, Math. Comp., Volume 55, Number 192, pages 723-743. We use a correction by Bremner with 0.973 replaced by 0.961, as explained in the source code to mwrank (htconst.cc).

**EXAMPLES:**

```
sage: E = EllipticCurve(['37a1'])
sage: E.silverman_height_bound()
4.825400758180918
sage: E.silverman_height_bound(algorithm='mwrank')
4.825400758180918
sage: E.CPS_height_bound()
0.16397076103046915
```

**simon_two_descent** *(verbose=0, liml=5, lim3=50, limtriv=3, maxprob=20, limbigprime=30, known_points=None)*

Return lower and upper bounds on the rank of the Mordell-Weil group $E(\mathbb{Q})$ and a list of points of infinite order.

**INPUT:**

- **verbose** – 0, 1, 2, or 3 (default: 0), the verbosity level
- **liml** – (default: 5) limit on trivial points on quartics
- **lim3** – (default: 50) limit on points on ELS quartics
- **limtriv** – (default: 3) limit on trivial points on $E$
- **maxprob** – (default: 20)
- **limbigprime** – (default: 30) to distinguish between small and large prime numbers. Use probabilistic tests for large primes. If 0, don’t any probabilistic tests.
- **known_points** – (default: None) list of known points on the curve

**OUTPUT:** a triple (lower, upper, list) consisting of

- **lower** (integer) – lower bound on the rank
- **upper** (integer) – upper bound on the rank
- **list** – list of points of infinite order in $E(\mathbb{Q})$
The integer upper is in fact an upper bound on the dimension of the 2-Selmer group, hence on the dimension of $E(\mathbb{Q})/2E(\mathbb{Q})$. It is equal to the dimension of the 2-Selmer group except possibly if $E(\mathbb{Q})[2]$ has dimension 1. In that case, upper may exceed the dimension of the 2-Selmer group by an even number, due to the fact that the algorithm does not perform a second descent.

To obtain a list of generators, use E.gens().

IMPLEMENTATION:

Uses Denis Simon’s PARI/GP scripts from http://www.math.unicaen.fr/~simon/

EXAMPLES:

We compute the ranks of the curves of lowest known conductor up to rank 8. Amazingly, each of these computations finishes almost instantly!

```
sage: E = EllipticCurve('11a1')
sage: E.simon_two_descent()
(0, 0, [])
sage: E = EllipticCurve('37a1')
sage: E.simon_two_descent()
(1, 1, [(0 : 0 : 1)])
sage: E = EllipticCurve('389a1')
sage: E.simon_two_descent()
(2, 2, [(1 : 0 : 1), (-11/9 : 28/27 : 1)])
sage: E = EllipticCurve('5077a1')
sage: E.simon_two_descent()
(3, 3, [(1 : 0 : 1), (2 : 0 : 1), (0 : 2 : 1)])
```

In this example Simon’s program does not find any points, though it does correctly compute the rank of the 2-Selmer group.

```
sage: E = EllipticCurve([1, -1, 0, -751055859, -7922219731979])
sage: E.simon_two_descent()
(1, 1, [])
```

The rest of these entries were taken from Tom Womack’s page http://tom.womack.net/maths/conductors.htm

```
sage: E = EllipticCurve([1, -1, 0, -79, 289])
sage: E.simon_two_descent()
(4, 4, [(1 : 1 : 1), (3 : 1 : 1), (0 : -1 : 1), (5 : 1 : 1)])
sage: E = EllipticCurve([1, 1, 0, -10012, 48720])
sage: E = E.simon_two_descent(); r,s
(6, 6)
sage: E = EllipticCurve([0, 0, 0, -10012, 346900])
sage: E = E.simon_two_descent(); r,s
(7, 7)
sage: E = EllipticCurve([0, 0, 1, -23737, 960366])
sage: E = E.simon_two_descent(); r,s
(8, 8)
```

Example from trac ticket #10832:
Example where the lower bound is known to be 1 despite that the algorithm has not found any points of infinite order
\[
\texttt{sage: } E = \text{EllipticCurve}([1, 1, 0, -23611790086, 1396491910863060])
\]
\[
\texttt{sage: } E.\text{simon\_two\_descent}()
(1, 2, [])
\]
\[
\texttt{sage: } E.\text{rank}()
1
\]
\[
\texttt{sage: } E.\text{gens}() \quad \# \text{ uses mwrank}
[(4311692542083/48594841 : -13035144436525227/338754636611 : 1)]
\]

Example for trac ticket \#5153:
\[
\texttt{sage: } E = \text{EllipticCurve}([3,0])
\]
\[
\texttt{sage: } E.\text{simon\_two\_descent}()
(1, 2, [(1 : 2 : 1)])
\]

The upper bound on the 2-Selmer rank returned by this method need not be sharp. In following example, the upper bound equals the actual 2-Selmer rank plus 2 (see trac ticket \#10735):
\[
\texttt{sage: } E = \text{EllipticCurve('438e1')}
\]
\[
\texttt{sage: } E.\text{simon\_two\_descent}()
(0, 3, [])
\]
\[
\texttt{sage: } E.\text{selmer\_rank}() \quad \# \text{ uses mwrank}
1
\]

**supersingular\_primes(\(B\))**

Return a list of all supersingular primes for this elliptic curve up to and possibly including \(B\).

**EXAMPLES:**
\[
\texttt{sage: } e = \text{EllipticCurve('11a')}
\]
\[
\texttt{sage: } e.\text{aplist}(20)
[-2, -1, 1, -2, 1, 4, -2, 0]
\]
\[
\texttt{sage: } e.\text{supersingular\_primes(1000)}
[2, 19, 29, 199, 569, 809]
\]

\[
\texttt{sage: } e = \text{EllipticCurve('27a')}
\]
\[
\texttt{sage: } e.\text{aplist}(20)
[0, 0, -1, 0, 5, 0, -7]
\]
\[
\texttt{sage: } e.\text{supersingular\_primes(97)}
[2, 5, 11, 17, 23, 29, 41, 47, 53, 59, 71, 83, 89]
\]
\[
\texttt{sage: } e.\text{ordinary\_primes(97)}
[7, 13, 19, 31, 37, 43, 61, 67, 73, 79, 97]
\]
\[
\texttt{sage: } e.\text{supersingular\_primes(3)}
[2]
\]
tamagawa_exponent\( (p) \)
The Tamagawa index of the elliptic curve at \( p \).

This is the index of the component group \( E(\mathbb{Q}_p)/E^0(\mathbb{Q}_p) \). It equals the Tamagawa number (as the component group is cyclic) except for types \( I^*_m \) (\( m \) even) when the group can be \( C_2 \times C_2 \).

EXAMPLES:

```python
sage: E = EllipticCurve('816a1')
sage: E.tamagawa_number(2)
4
sage: E.tamagawa_exponent(2)
2
sage: E.kodaira_symbol(2)
I2*
```

```python
sage: E = EllipticCurve('200c4')
sage: E.kodaira_symbol(5)
I4*
```

See trac ticket #4715:

```python
sage: E = EllipticCurve('117a3')
sage: E.tamagawa_exponent(13)
4
```

tamagawa_number\( (p) \)
The Tamagawa number of the elliptic curve at \( p \).

This is the order of the component group \( E(\mathbb{Q}_p)/E^0(\mathbb{Q}_p) \).

EXAMPLES:

```python
sage: E = EllipticCurve('11a')
sage: E.tamagawa_number(11)
5
```

```python
sage: E = EllipticCurve('37b')
sage: E.tamagawa_number(37)
3
```

tamagawa_number_old\( (p) \)
The Tamagawa number of the elliptic curve at \( p \).

This is the order of the component group \( E(\mathbb{Q}_p)/E^0(\mathbb{Q}_p) \).

EXAMPLES:
sage: E = EllipticCurve('11a1')
sage: E.tamagawa_number_old(11)
5
sage: E = EllipticCurve('37b1')
sage: E.tamagawa_number_old(37)
3

```
tamagawa_product()
Return the product of the Tamagawa numbers.
EXAMPLES:
```
sage: E = EllipticCurve('54a1')
sage: E.tamagawa_product()
3

```
tate_curve(p)
Create the Tate curve over the $p$-adics associated to this elliptic curve.
This Tate curve is a $p$-adic curve with split multiplicative reduction of
the form $y^2 + xy = x^3 + s_4x + s_6$ which is isomorphic to the given curve
over the algebraic closure of $\mathbf{Q}_p$. Its points over $\mathbf{Q}_p$ are isomorphic
to $\mathbf{Q}_p^*/\mathbf{Q}_p^2$ for a certain parameter $q \in \mathbf{Z}_p$.

INPUT:
• $p$ – a prime where the curve has split multiplicative reduction

```
EXAMPLES:
sage: e = EllipticCurve('130a1')
sage: e.tate_curve(2)
2-adic Tate curve associated to the Elliptic Curve defined by y^2 + x*y + y = x^3 - 33*x + 68 over Rational Field
```
The input curve must have multiplicative reduction at the prime.

```
sage: e.tate_curve(3)
Traceback (most recent call last):
...
ValueError: the elliptic curve must have multiplicative reduction at 3
```

We compute with $p = 5$:

```
sage: T = e.tate_curve(5); T
5-adic Tate curve associated to the Elliptic Curve defined by y^2 + x*y + y = x^3 - 33*x + 68 over Rational Field
```
We find the Tate parameter $q$:

```
sage: T.parameter(prec=5)
3*5^3 + 3*5^4 + 2*5^5 + 2*5^6 + 3*5^7 + O(5^8)
```
We compute the $\mathcal{L}$-invariant of the curve:

```
sage: T.L_invariant(prec=10)
5^3 + 4*5^4 + 2*5^5 + 2*5^6 + 2*5^7 + 3*5^8 + 5^9 + O(5^10)
```
three_selmer_rank\((algorithm='UseSUnits')\)
Return the 3-selmer rank of this elliptic curve, computed using Magma.

INPUT:

\* algorithm -- ‘Heuristic’ (which is usually much faster in large examples), ‘FindCubeRoots’, or ‘UseSUnits’ (default)

OUTPUT: nonnegative integer

EXAMPLES: A rank 0 curve:

\begin{verbatim}
sage: EllipticCurve('11a').three_selmer_rank()       # optional - magma
0
\end{verbatim}

A rank 0 curve with rational 3-isogeny but no 3-torsion

\begin{verbatim}
sage: EllipticCurve('14a3').three_selmer_rank()      # optional - magma
0
\end{verbatim}

A rank 0 curve with rational 3-torsion:

\begin{verbatim}
sage: EllipticCurve('14a1').three_selmer_rank()      # optional - magma
1
\end{verbatim}

A rank 1 curve with rational 3-isogeny:

\begin{verbatim}
sage: EllipticCurve('91b').three_selmer_rank()       # optional - magma
2
\end{verbatim}

A rank 0 curve with nontrivial 3-Sha. The Heuristic option makes this about twice as fast as without it.

\begin{verbatim}
sage: EllipticCurve('681b').three_selmer_rank(algorithm='Heuristic')  # long...
˓→time (10 seconds); optional - magma
2
\end{verbatim}

torsion_order()
Return the order of the torsion subgroup.

EXAMPLES:

\begin{verbatim}
sage: e = EllipticCurve('11a')
sage: e.torsion_order()
5
\end{verbatim}

\begin{verbatim}
sage: type(e.torsion_order())
<... 'sage.rings.integer.Integer'>
sage: e = EllipticCurve([1,2,3,4,5])
sage: e.torsion_order()
1
\end{verbatim}

torsion_points()
Return the torsion points of this elliptic curve as a sorted list.

OUTPUT: A list of all the torsion points on this elliptic curve.

EXAMPLES:
Some curves with large torsion groups:

```
sage: E = EllipticCurve([-1386747, 368636886])
sage: T = E.torsion_subgroup(); T
Torsion Subgroup isomorphic to \( \mathbb{Z}/8 + \mathbb{Z}/2 \) associated to the
Elliptic Curve defined by \( y^2 = x^3 - 1386747x + 368636886 \) over
Rational Field
sage: E.torsion_points()
[(-1293 : 0 : 1),
 (-933 : -29160 : 1),
 (-933 : 29160 : 1),
 (-285 : -27216 : 1),
 (-285 : 27216 : 1),
 (0 : 1 : 0),
 (147 : -12960 : 1),
 (147 : 12960 : 1),
 (282 : 0 : 1),
 (1011 : 0 : 1),
 (1227 : -22680 : 1),
 (1227 : 22680 : 1),
 (2307 : -97200 : 1),
 (2307 : 97200 : 1),
 (8787 : -816480 : 1),
 (8787 : 816480 : 1)]
sage: EllipticCurve('210b5').torsion_points()
[(-41/4 : 37/8 : 1),
 (-5 : -103 : 1),
 (-5 : 107 : 1),
 (0 : 1 : 0),
 (10 : -208 : 1),
 (10 : 197 : 1),
 (37 : -397 : 1),
 (37 : 359 : 1),
 (100 : -1153 : 1),
 (100 : 1052 : 1),
 (415 : -8713 : 1),
 (415 : 8297 : 1)]
sage: EllipticCurve('210e2').torsion_points()
[(-36 : 18 : 1),
 (-26 : -122 : 1),
 (-26 : 148 : 1),
 (-8 : -122 : 1),
 (-8 : 130 : 1),
 (0 : 1 : 0),
 (4 : -62 : 1),
 (4 : 58 : 1),
 (31/4 : -31/8 : 1),
 (28 : -14 : 1),
```
(34 : -122 : 1),
(34 : 88 : 1),
(64 : -482 : 1),
(64 : 418 : 1),
(244 : -3902 : 1),
(244 : 3658 : 1)

**torsion_subgroup()**
Return the torsion subgroup of this elliptic curve.

**OUTPUT:** The EllipticCurveTorsionSubgroup instance associated to this elliptic curve.

**Note:** To see the torsion points as a list, use **torsion_points()**.

**EXAMPLES:**
```
sage: EllipticCurve('11a').torsion_subgroup()
Torsion Subgroup isomorphic to \mathbb{Z}/5 associated to the Elliptic Curve defined by \rightarrow y^2 + y = x^3 - x^2 - 10*x - 20 over Rational Field
```
```
sage: EllipticCurve('37b').torsion_subgroup()
Torsion Subgroup isomorphic to \mathbb{Z}/3 associated to the Elliptic Curve defined by \rightarrow y^2 + y = x^3 + x^2 - 23*x - 50 over Rational Field
```
```
sage: e = EllipticCurve([-1386747,368636886]);e
Elliptic Curve defined by y^2 = x^3 - 1386747*x + 368636886 over Rational Field
sage: G = e.torsion_subgroup(); G
Torsion Subgroup isomorphic to \mathbb{Z}/8 + \mathbb{Z}/2 associated to the Elliptic Curve defined by y^2 = x^3 - 1386747*x + 368636886 over Rational Field
sage: G.0*3 + G.1
(1227 : 22680 : 1)
sage: G.1
(282 : 0 : 1)
sage: list(G)
```
**two_descent**
```
(\texttt{verbose=True}, \texttt{selmer\_only=False}, \texttt{first\_limit=20}, \texttt{second\_limit=8}, \texttt{n\_aux=-1}, \texttt{second\_descent=1})
```
Compute 2-descent data for this curve.

**INPUT:**
- **verbose** – (default: True) print what mwrank is doing; if False, **no output** is printed
- **selmer_only** – (default: False) selmer_only switch
- **first_limit** – (default: 20) firstlim is bound on x+z second_limit- (default: 8) secondlim is bound on log max x,z , i.e. logarithmic
- **n_aux** – (default: -1) n_aux only relevant for general 2-descent when 2-torsion trivial; n_aux=-1 causes default to be used (depends on method)
• second_descent – (default: True) second_descent only relevant for descent via 2-isogeny

OUTPUT:
Return True if the descent succeeded, i.e. if the lower bound and the upper bound for the rank are the same. In this case, generators and the rank are cached. A return value of False indicates that either rational points were not found, or that Sha[2] is nontrivial and mwrank was unable to determine this for sure.

EXAMPLES:

```
sage: E = EllipticCurve('37a1')
sage: E.two_descent(verbos=False)
True
```

two_descent_simon(verbos=0, lim1=5, lim3=50, limtriv=3, maxprob=20, limbigprime=30, known_points=None)

Return lower and upper bounds on the rank of the Mordell-Weil group $E(\mathbb{Q})$ and a list of points of infinite order.

INPUT:
• verbose – 0, 1, 2, or 3 (default: 0), the verbosity level
• lim1 – (default: 5) limit on trivial points on quartics
• lim3 – (default: 50) limit on points on ELS quartics
• limtriv – (default: 3) limit on trivial points on $E$
• maxprob – (default: 20)
• limbigprime – (default: 30) to distinguish between small and large prime numbers. Use probabilistic tests for large primes. If 0, don’t any probabilistic tests.
• known_points – (default: None) list of known points on the curve

OUTPUT: a triple (lower, upper, list) consisting of
• lower (integer) – lower bound on the rank
• upper (integer) – upper bound on the rank
• list – list of points of infinite order in $E(\mathbb{Q})$

The integer upper is in fact an upper bound on the dimension of the 2-Selmer group, hence on the dimension of $E(\mathbb{Q})/2E(\mathbb{Q})$. It is equal to the dimension of the 2-Selmer group except possibly if $E(\mathbb{Q})[2]$ has dimension 1. In that case, upper may exceed the dimension of the 2-Selmer group by an even number, due to the fact that the algorithm does not perform a second descent.

To obtain a list of generators, use $E$.gens().

IMPLEMENTATION:
Uses Denis Simon’s PARI/GP scripts from http://www.math.unicaen.fr/~simon/

EXAMPLES:
We compute the ranks of the curves of lowest known conductor up to rank 8. Amazingly, each of these computations finishes almost instantly!

```
sage: E = EllipticCurve('11a1')
sage: E.simon_two_descent()
(0, 0, [])
sage: E = EllipticCurve('37a1')
```

(continues on next page)
Elliptic curves, Release 9.7

In this example Simon’s program does not find any points, though it does correctly compute the rank of the 2-Selmer group.

The rest of these entries were taken from Tom Womack’s page http://tom.womack.net/maths/conductors.htm

Example from trac ticket #10832:

Example where the lower bound is known to be 1 despite that the algorithm has not found any points of infinite order

(continued from previous page)
sage: E.gens()  # uses mwrank
[(4311692542083/48594841 : -13035144436525227/338754636611 : 1)]

Example for trac ticket #5153:

```python
sage: E = EllipticCurve([3,0])
sage: E.simon_two_descent()
(1, 2, [(1 : 2 : 1)])
```

The upper bound on the 2-Selmer rank returned by this method need not be sharp. In following example, the upper bound equals the actual 2-Selmer rank plus 2 (see trac ticket #10735):

```python
sage: E = EllipticCurve('438e1')
sage: E.simon_two_descent()
(0, 3, [])
sage: E.selmer_rank()  # uses mwrank
1
```

sage.schemes.elliptic_curves.ell_rational_field.
cremona_curves(conductors)
Return iterator over all known curves (in database) with conductor in the list of conductors.

EXAMPLES:

```python
sage: [(E.label(), E.rank()) for E in cremona_curves(srange(35,40))]
[('35a1', 0), ('35a2', 0), ('35a3', 0), ('36a1', 0), ('36a2', 0), ('36a3', 0), ('36a4', 0), ('37a1', 1), ('37b1', 0), ('37b2', 0), ('37b3', 0), ('38a1', 0), ('38a2', 0), ('38a3', 0), ('38b1', 0), ('38b2', 0), ('39a1', 0), ('39a2', 0), ('39a3', 0), ('39a4', 0)]
```

sage.schemes.elliptic_curves.ell_rational_field.
cremona_optimal_curves(conductors)
Return iterator over all known optimal curves (in database) with conductor in the list of conductors.

EXAMPLES:

```python
sage: [(E.label(), E.rank()) for E in cremona_optimal_curves(srange(35,40))]
[('35a1', 0), ('36a1', 0), ('38a1', 0), ('38a2', 0), ('38a3', 0), ('38b1', 0), ('38b2', 0), ('39a1', 0), ('39a2', 0), ('39a3', 0), ('39a4', 0)]
```
There is one case – 990h3 – when the optimal curve isn’t labeled with a 1:

```python
sage: [e.cremona_label() for e in cremona_optimal_curves([990])]
['990a1', '990b1', '990c1', '990d1', '990e1', '990f1', '990g1', '990h3', '990i1',
 '990j1', '990k1', '990l1']
```

sage.schemes.elliptic_curves.ell_rational_field.elliptic_curve_congruence_graph(\texttt{curves})

Return the congruence graph for this set of elliptic curves.

\textbf{INPUT:}

\begin{itemize}
\item curves – a list of elliptic curves
\end{itemize}

\textbf{OUTPUT:}

The graph with each curve as a vertex (labelled by its Cremona label) and an edge from \( E \) to \( F \) labelled \( p \) if and only if \( E \) is congruent to \( F \) mod \( p \)

\textbf{EXAMPLES:}

```python
sage: from sage.schemes.elliptic_curves.ell_rational_field import elliptic_curve_congruence_graph
sage: curves = list(cremona_optimal_curves([11..30]))
sage: G = elliptic_curve_congruence_graph(curves)
```

Graph on 12 vertices

sage.schemes.elliptic_curves.ell_rational_field.integral_points_with_bounded_mw_coeffs(\texttt{E}, \texttt{mw_base}, \texttt{N}, \texttt{x_bound})

Return the set of integers \( x \) which are \( x \)-coordinates of points on the curve \( E \) which are linear combinations of the generators (basis and torsion points) with coefficients bounded by \( N \).

\textbf{INPUT:}

\begin{itemize}
\item \( E \) – an elliptic curve
\item \texttt{mw_base} – a list of points on \( E \) (generators)
\item \( N \) – a positive integer (bound on coefficients)
\item \texttt{x_bound} – a positive real number (upper bound on size of \( x \)-coordinates)
\end{itemize}

\textbf{OUTPUT:}

(list) list of integral points on \( E \) which are linear combinations of the given points with coefficients bounded by \( N \) in absolute value.
14.2 Tables of elliptic curves of given rank

The default database of curves contains the following data:

<table>
<thead>
<tr>
<th>Rank</th>
<th>Number of curves</th>
<th>Maximal conductor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>30427</td>
<td>9999</td>
</tr>
<tr>
<td>1</td>
<td>31871</td>
<td>9999</td>
</tr>
<tr>
<td>2</td>
<td>2388</td>
<td>9999</td>
</tr>
<tr>
<td>3</td>
<td>836</td>
<td>119888</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>1175648</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>37396136</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>6663562874</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>896913586322</td>
</tr>
<tr>
<td>8</td>
<td>6</td>
<td>457532830151317</td>
</tr>
<tr>
<td>9</td>
<td>7</td>
<td>~9.612839e+21</td>
</tr>
<tr>
<td>10</td>
<td>6</td>
<td>~1.971057e+21</td>
</tr>
<tr>
<td>11</td>
<td>6</td>
<td>~1.803406e+24</td>
</tr>
<tr>
<td>12</td>
<td>1</td>
<td>~2.696017e+29</td>
</tr>
<tr>
<td>14</td>
<td>1</td>
<td>~3.627533e+37</td>
</tr>
<tr>
<td>15</td>
<td>1</td>
<td>~1.640078e+56</td>
</tr>
<tr>
<td>17</td>
<td>1</td>
<td>~2.750021e+56</td>
</tr>
<tr>
<td>19</td>
<td>1</td>
<td>~1.373776e+65</td>
</tr>
<tr>
<td>20</td>
<td>1</td>
<td>~7.381324e+73</td>
</tr>
<tr>
<td>21</td>
<td>1</td>
<td>~2.611208e+85</td>
</tr>
<tr>
<td>22</td>
<td>1</td>
<td>~2.272064e+79</td>
</tr>
<tr>
<td>23</td>
<td>1</td>
<td>~1.139647e+89</td>
</tr>
<tr>
<td>24</td>
<td>1</td>
<td>~3.257638e+95</td>
</tr>
<tr>
<td>28</td>
<td>1</td>
<td>~3.455601e+141</td>
</tr>
</tbody>
</table>

Note that lists for $r \geq 4$ are not exhaustive; there may well be curves of the given rank with conductor less than the listed maximal conductor, which are not included in the tables.


See also the functions cremona_curves() and cremona_optimal_curves() which enable easy looping through the Cremona elliptic curve database.

```python
class sage.schemes.elliptic_curves.ec_database.EllipticCurves

Bases: object

rank(rank, tors=0, n=10, labels=False)

Return a list of at most $n$ curves with given rank and torsion order.

INPUT:
- rank (int) – the desired rank
- tors (int, default 0) – the desired torsion order (ignored if 0)
- n (int, default 10) – the maximum number of curves returned.
- labels (bool, default False) – if True, return Cremona labels instead of curves.

OUTPUT:
(list) A list at most $n$ of elliptic curves of required rank.
```
EXAMPLES:

```python
sage: elliptic_curves.rank(n=5, rank=3, tors=2, labels=True)
["59450i1", "59450i2", "61376c1", "61376c2", "65481c1"]
```

```python
sage: elliptic_curves.rank(n=5, rank=0, tors=5, labels=True)
["11a1", "11a3", "38b1", "50b1", "50b2"]
```

```python
sage: elliptic_curves.rank(n=5, rank=1, tors=7, labels=True)
["574i1", "4730k1", "6378c1"]
```

```python
sage: e = elliptic_curves.rank(6)[0]; e.ainvs(), e.conductor()
((1, 1, 0, -2582, 48720), 5187563742)
```

```python
sage: e = elliptic_curves.rank(7)[0]; e.ainvs(), e.conductor()
((0, 0, 0, -10012, 346900), 382623908456)
```

```python
sage: e = elliptic_curves.rank(8)[0]; e.ainvs(), e.conductor()
((1, -1, 0, -106384, 13075804), 249649566346838)
```

For large conductors, the labels are not known:

```python
sage: L = elliptic_curves.rank(6, n=3); L
[Elliptic Curve defined by y^2 + x*y = x^3 + x^2 - 2582*x + 48720 over Rational Field,
 Elliptic Curve defined by y^2 + y = x^3 - 7077*x + 235516 over Rational Field,
 Elliptic Curve defined by y^2 + x*y = x^3 - x^2 - 2326*x + 43456 over Rational Field]
```

```python
sage: L[0].cremona_label()
Traceback (most recent call last):
...
LookupError: Cremona database does not contain entry for Elliptic Curve defined by y^2 + x*y = x^3 + x^2 - 2582*x + 48720 over Rational Field
```

```
```

14.3 Elliptic curves over number fields

An elliptic curve $E$ over a number field $K$ can be given by a Weierstrass equation whose coefficients lie in $K$ or by using `base_extend` on an elliptic curve defined over a subfield.

One major difference to elliptic curves over $\mathbb{Q}$ is that there might not exist a global minimal equation over $K$, when $K$ does not have class number one. Another difference is the lack of understanding of modularity for general elliptic curves over general number fields.

Currently Sage can obtain local information about $E/K_v$ for finite places $v$, it has an interface to Denis Simon’s script for 2-descent, it can compute the torsion subgroup of the Mordell-Weil group $E(K)$, and it can work with isogenies defined over $K$.

EXAMPLES:

```python
sage: K.<i> = NumberField(x^2+1)
sage: E = EllipticCurve([0,4+i])
sage: E.discriminant()
```

(continues on next page)
-3456*i - 6480

sage: P = E([i, 2])
sage: P + P
(-2*i + 9/16 : -9/4*i - 101/64 : 1)

sage: E.has_good_reduction(2+i)
True

sage: E.local_data(4+i)
Local data at Fractional ideal (i + 4):
Reduction type: bad additive
Local minimal model: Elliptic Curve defined by y^2 = x^3 + (i+4) over Number Field in i with defining polynomial x^2 + 1
Minimal discriminant valuation: 2
Conductor exponent: 2
Kodaira Symbol: II
Tamagawa Number: 1
sage: E.tamagawa_product_bsd()
1

sage: E.simon_two_descent()
(1, 1, [(i : 2 : 1)])

sage: E.torsion_order()
1

sage: E.isogenies_prime_degree(3)
[Isogeny of degree 3 from Elliptic Curve defined by y^2 = x^3 + (i+4) over Number Field in i with defining polynomial x^2 + 1 to Elliptic Curve defined by y^2 = x^3 + (-27*i-108) over Number Field in i with defining polynomial x^2 + 1]

AUTHORS:
• Robert Bradshaw 2007
• John Cremona
• Chris Wuthrich

REFERENCE:

class sage.schemes.elliptic_curves.ell_number_field.EllipticCurve_number_field(K, ainvs)
Bases: sage.schemes.elliptic_curves.ell_field.EllipticCurve_field

Elliptic curve over a number field.

EXAMPLES:
sage: K.<i> = NumberField(x^2+1)
sage: E = EllipticCurve([i, i - 1, i + 1, 24*i + 15, 14*i + 35])
Elliptic Curve defined by y^2 + i*x*y + (i+1)*y = x^3 + (i-1)*x^2 + (24*i+15)*x + (14*i+35) over Number Field in i with defining polynomial x^2 + 1
**base_extend(R)**

Return the base extension of `self` to `R`.

**EXAMPLES:**

```
sage: E = EllipticCurve('11a3')
sage: K = QuadraticField(-5, 'a')
sage: E.base_extend(K)
Elliptic Curve defined by y^2 + y = x^3 + (-1)*x^2 over Number Field in a with defining polynomial x^2 + 5 with a = 2.236067977499790?*I
```

Check that non-torsion points are remembered when extending the base field (see trac ticket #16034):

```
sage: E = EllipticCurve([1, 0, 1, -1751, -31352])
sage: K.<d> = QuadraticField(5)
sage: E.gens()
[(52 : 111 : 1)]
sage: EK = E.base_extend(K)
sage: EK.gens()
[(52 : 111 : 1)]
```

**cm_discriminant()**

Return the CM discriminant of the \( j \)-invariant of this curve, or 0.

**OUTPUT:**

An integer \( D \) which is either 0 if this curve \( E \) does not have Complex Multiplication) (CM), or an imaginary quadratic discriminant if \( j(E) \) is the \( j \)-invariant of the order with discriminant \( D \).

**Note:** If \( E \) has CM but the discriminant \( D \) is not a square in the base field \( K \) then the extra endomorphisms will not be defined over \( K \). See also `has_rational_cm()`.

**EXAMPLES:**

```
sage: EllipticCurve(j=0).cm_discriminant()
-3
sage: EllipticCurve(j=1).cm_discriminant()
Traceback (most recent call last):
...
ValueError: Elliptic Curve defined by y^2 + x*y = x^3 + 36*x + 3455 over Rational Field does not have CM
sage: EllipticCurve(j=1728).cm_discriminant()
-4
sage: EllipticCurve(j=8000).cm_discriminant()
-8
sage: K.<a> = QuadraticField(5)
sage: EllipticCurve(j=282880*a + 632000).cm_discriminant()
-20
sage: K.<a> = NumberField(x^3 - 2)
sage: EllipticCurve(j=31710790944000*a^2 + 39953093016000*a + 50337742902000).cm_discriminant()
-108
```
conductor()

Return the conductor of this elliptic curve as a fractional ideal of the base field.

OUTPUT:

(fractional ideal) The conductor of the curve.

EXAMPLES:

```sage
sage: K.<i> = NumberField(x^2+1)
sage: EllipticCurve([i, i - 1, i + 1, 24*i + 15, 14*i + 35]).conductor()
Fractional ideal (21*i - 3)
sage: K.<a> = NumberField(x^2-x+3)
sage: EllipticCurve([1 + a , -1 + a , 1 + a , -11 + a , 5 -9*a ]).conductor()
Fractional ideal (-6*a)
sage: K.<a> = NumberField(x^2-38)
sage: E = EllipticCurve([0,0,0, 21796814856932765568243810*a - 13436496724198567128296995, 121774567239345229314269094644186997594*a - 750668847495706904791115375024037711300])
sage: E.conductor()
Fractional ideal (1)
```

A not so well known curve with everywhere good reduction:

```sage
sage: K.<a> = NumberField(x^2-38)
sage: E = EllipticCurve([1 + a , -1 + a , 1 + a , -11 + a , 5 -9*a ]).conductor()
Fractional ideal (-6*a)
```

An example which used to fail (see trac ticket #5307):

```sage
sage: K.<w> = NumberField(x^2+x+6)
sage: E = EllipticCurve([w,-1,0,-w-6,0])
sage: E.conductor()
Fractional ideal (86304, w + 5898)
```

An example raised in trac ticket #11346:

```sage
sage: K.<g> = NumberField(x^2 - x - 1)
sage: E1 = EllipticCurve(K,[0,0,0,-1/48,-161/864])
sage: [(p.smallest_integer(),e) for p,e in E1.conductor().factor()]
[(2, 4), (3, 1), (5, 1)]
```

galois_representation()

The compatible family of the Galois representation attached to this elliptic curve.

Given an elliptic curve $E$ over a number field $K$ and a rational prime number $p$, the $p^n$-torsion $E[p^n]$ points of $E$ is a representation of the absolute Galois group of $K$. As $n$ varies we obtain the Tate module $T_pE$ which is a a representation of $G_K$ on a free $\mathbb{Z}_p$-module of rank 2. As $p$ varies the representations are compatible.

EXAMPLES:

```sage
sage: K = NumberField(x**2 + 1, 'a')
sage: E = EllipticCurve('11a1').change_ring(K)
sage: rho = E.galois_representation()
sage: rho
Compatible family of Galois representations associated to the Elliptic Curve defined by y^2 + y = x^3 + (-1)*x^2 + (-10)*x + (-20) over Number Field in a with defining polynomial x^2 + 1
sage: rho.is_surjective(3)
```

(continues on next page)
sage: rho.is_surjective(5)  # long time (4s on sage.math, 2014)
False
sage: rho.non_surjective()
[5]

gens(**kwds)
Return some points of infinite order on this elliptic curve.

Contrary to what the name of this method suggests, the points it returns do not always generate a subgroup of full rank in the Mordell-Weil group, nor are they necessarily linearly independent. Moreover, the number of points can be smaller or larger than what one could expect after calling rank() or rank_bounds().

**Note:** The optional parameters control the Simon two descent algorithm; see the documentation of simon_two_descent() for more details.

**INPUT:**
- **verbose** – 0, 1, 2, or 3 (default: 0), the verbosity level
- **lim1** – (default: 2) limit on trivial points on quartics
- **lim3** – (default: 4) limit on points on ELS quartics
- **limtriv** – (default: 2) limit on trivial points on elliptic curve
- **maxprob** – (default: 20)
- **limbigprime** – (default: 30) to distinguish between small and large prime numbers. Use probabilistic tests for large primes. If 0, do not use probabilistic tests.
- **known_points** – (default: None) list of known points on the curve

**OUTPUT:**
A set of points of infinite order given by the Simon two-descent.

**Note:** For non-quadratic number fields, this code does return, but it takes a long time.

**EXAMPLES:**

```
sage: K.<a> = NumberField(x^2 + 23, 'a')
sage: E = EllipticCurve(K,[0,0,0,101,0])
sage: E.gens()
[(23831509/8669448*a - 2867471/8669448 : 76507317707/18049790736*a -
  424166479633/18049790736 : 1),
 (-2031032029/969232392*a + 58813561/969232392 : -1557598463041/
  21336681877488*a : 1)],
```

It can happen that no points are found if the height bounds used in the search are too small (see trac ticket #10745):

```
sage: K.<y> = NumberField(x^4 + x^2 - 7)
sage: E = EllipticCurve(K, [1, 0, 5*y^2 + 16, 0, 0])
```

(continues on next page)
Here is a curve of rank 2:

```sage
K.<t> = NumberField(x^2-17)
sage: E = EllipticCurve(K,[-4,0])
sage: E.gens()
[(-1/2*t + 1/2 : -1/2*t + 1/2 : 1), (-t + 3 : -2*t + 10 : 1)]
sage: E.rank()
2
```

Test that points of finite order are not included (see trac ticket #13593):  

```sage
sage: E = EllipticCurve("17a3")
sage: K.<t> = NumberField(x^2+3)
sage: EK = E.base_extend(K)
sage: EK.rank()
0
sage: EK.gens()
[]
```

IMPLEMENTATION:  

For curves over quadratic fields which are base-changes from \( \mathbb{Q} \), we delegate the work to \texttt{gens_quadratic()} where methods over \( \mathbb{Q} \) suffice. Otherwise, we use Denis Simon's PARI/GP scripts from http://www.math.unicaen.fr/~simon/.

\texttt{gens_quadratic(**kwds)}  
Return generators for the Mordell-Weil group modulo torsion, for a curve which is a base change from \( \mathbb{Q} \) to a quadratic field.

EXAMPLES:

```sage
sage: E = EllipticCurve([1,2,3,40,50])
sage: E.conductor()
2123582
sage: E.gens()
[(5 : 17 : 1)]
sage: K.<i> = QuadraticField(-1)
sage: EK = E.change_ring(K)
sage: EK.gens_quadratic()
[(5 : 17 : 1), (-13 : 48*i + 5 : 1)]
sage: E.change_ring(QuadraticField(3, 'a')).gens_quadratic()
[(5 : 17 : 1), (-1 : 2*a - 1 : 1), (11/4 : 33/4*a - 23/8 : 1)]
```

(continues on next page)
Elliptic curves, Release 9.7

2483776

```python
sage: E.gens()
[(47995640297578081/7389879886648100 : -2503816180254048018837479/
   63526655830129794121000 : 1)]
```

```python
sage: K.<a> = QuadraticField(7)
sage: E.change_ring(K).gens_quadratic()
```

```python
[(-1209642055/59583566*a + 1639995844/29791783 : -377240626321899/
  172089253212*a + 138577803462855/245841793316 : 1),
  (1/28 : 393/392*a + 138577803462855/245841793316 : 1),
  (-61*a + 162 : 1098*a - 2916 : 1)]
```

```python
sage: E = EllipticCurve([1, a])
sage: E.gens_quadratic()
Traceback (most recent call last):
...
ValueError: gens_quadratic() requires the elliptic curve to be a base change
from Q
```

```python
global_integral_model()
```

Return a model of self which is integral at all primes.

EXAMPLES:

```python
sage: K.<i> = NumberField(x^2+1)
sage: E = EllipticCurve([i/5,i/5,i/5,i/5,i/5])
sage: P1,P2 = K.primes_above(5)
sage: E.global_integral_model()
Elliptic Curve defined by y^2 + (-i)*x*y + (-25*i)*y = x^3 + 5*i*x^2 + 125*i*x
   + 3125*i over Number Field in i with defining polynomial x^2 + 1
```

trac ticket #7935:

```python
sage: K.<a> = NumberField(x^2-38)
sage: E = EllipticCurve([a,1/2])
sage: E.global_integral_model()
Elliptic Curve defined by y^2 = x^3 + 1444*a*x + 27436 over Number Field in a
   with defining polynomial x^2 - 38
```

trac ticket #9266:

```python
sage: K.<s> = NumberField(x^2-5)
sage: w = (1+s)/2
sage: E = EllipticCurve(K,[2,w])
sage: E.global_integral_model()
Elliptic Curve defined by y^2 = x^3 + 2*x + (1/2*s+1/2) over Number Field in s
   with defining polynomial x^2 - 5
```

trac ticket #12151:

```python
sage: K.<v> = NumberField(x^2 + 161*x - 150)
sage: E = EllipticCurve([25105/216*v - 3839/36, 634768555/7776*v - 98002625/
   1296, 634768555/7776*v - 98002625/1296, 0, 0])
sage: M = E.global_integral_model(); M # choice varies, not tested
```

14.3. Elliptic curves over number fields 317

(continues on next page)
Elliptic curve defined by $y^2 + (2094779518028859*v-19404929053030351)*x*y + x^3 + y = x^3 + y$ over Number Field in v with defining polynomial $x^2 + 161*x - 150$

trac ticket #14476:

```
sage: R.<t> = QQ[]
sage: K.<g> = NumberField(t^4 - t^3 - 3*t^2 - t + 1)
sage: E = EllipticCurve([ -43/625*g^3 + 14/625*g^2 - 4/625*g + 706/625, -4862/78125*g^3 - 4074/78125*g^2 - 711/78125*g + 10304/78125, -4862/78125*g^3 - 4074/78125*g^2 - 711/78125*g + 10304/78125, 0,0])
sage: E.global_integral_model()
Elliptic Curve defined by y^2 + (15*g^3-48*g-42)*x*y + (-111510*g^3-162162*g^2-44145*g+37638)*y = x^3 + (-954*g^3-1134*g^2+81*g+576)*x^2 over Number Field in g with defining polynomial t^4 - t^3 - 3*t^2 - t + 1
```

global_minimal_model(proof=None, semi_global=False)

Return a model of self that is integral, and minimal.

**Note:** Over fields of class number greater than 1, a global minimal model may not exist. If it does not, set the parameter `semi_global` to `True` to obtain a model minimal at all but one prime.

**INPUT:**

- `proof` – whether to only use provably correct methods (default controlled by global proof module).
  
  Note that the proof module is `number_field`, not `elliptic_curves`, since the functions that actually need the flag are in number fields.

- `semi_global` (boolean, default `False`) – if there is no global minimal model, return a semi-global minimal model (minimal at all but one prime) instead, if `True`; raise an error if `False`. No effect if a global minimal model exists.

**OUTPUT:**

A global integral and minimal model, or an integral minimal model at all but one prime of there is no global minimal model and the flag `semi_global` is `True`.

**EXAMPLES:**

```
sage: K.<a> = NumberField(x^2-38)
sage: E = EllipticCurve([0,0,0, 2179681485693276568243810*a - 2179681485693276568243810, 1217745672393452293142690946441897594*a - 1217745672393452293142690946441897594, 75668847495706904791115375024037711300])
sage: E2 = E.global_minimal_model()
sage: E2
Elliptic Curve defined by y^2 + a*x*y + (a+1)*y = x^3 + (a+1)*x^2 + (4*a+15)*x over Number Field in a with defining polynomial x^2 - 38
sage: E2.local_data()
[]
```

See trac ticket #11347:
```python
sage: K.<g> = NumberField(x^2 - x - 1)
sage: E = EllipticCurve(K, [0, 0, 0, -1/48, 161/864]).integral_model().global_minimal_model(); E
Elliptic Curve defined by y^2 + x*y + y = x^3 + x^2 over Number Field in g with defining polynomial x^2 - x - 1
sage: [(p.norm(), e) for p, e in E.conductor().factor()]
[(9, 1), (5, 1)]
sage: [(p.norm(), e) for p, e in E.discriminant().factor()]
[(-5, 2), (9, 1)]
```

See trac ticket #14472, this used not to work over a relative extension:

```python
sage: K1.<w> = NumberField(x^2+x+1)
sage: m = polygen(K1)
sage: K2.<v> = K1.extension(m^2-w+1)
sage: E = EllipticCurve([0*v, -432])
sage: E.global_minimal_model()
```

See trac ticket #18662: for fields of class number greater than 1, even when global minimal models did exist, their computation was not implemented. Now it is:

```python
sage: K.<a> = NumberField(x^2-10)
sage: K.class_number()
2
sage: E = EllipticCurve([0, 0, -186408*a - 589491, 78055704*a + 246833838])
sage: E.discriminant().norm()
16375845905239507992576
sage: E.discriminant().norm().factor()
2^31 * 3^27
sage: E.has_global_minimal_model()
True
```

If there is no global minimal model, this method will raise an error unless you set the parameter `semi_global` to `True`:

```python
sage: K.<a> = NumberField(x^2-10)
sage: K.class_number()
2
sage: E = EllipticCurve([a, a, 0, 3*a+8, 4*a+3])
sage: E.has_global_minimal_model()
False
sage: E.global_minimal_model()
Traceback (most recent call last):
...
```

ValueError: Elliptic Curve defined by y^2 + a*x*y = x^3 + a*x^2 + (3*a+8)*x + (4*a+3) over Number Field in a with defining polynomial x^2 - 10 has no global minimal model! For a semi-global minimal model use semi_global=True

sage: E.global_minimal_model(semi_global=True)
Elliptic Curve defined by y^2 + a*x*y = x^3 + a*x^2 + (3*a+8)*x + (4*a+3) over Number Field in a with defining polynomial x^2 - 10

An example of a curve with everywhere good reduction but which has no model with unit discriminant:

sage: K.<a> = NumberField(x^2-x-16)
sage: K.class_number()
2
sage: E = EllipticCurve([0,0,0,-15221331*a - 53748576, -79617688290*a - 281140318368])
sage: Emin = E.global_minimal_model(semi_global=True)
sage: Emin.ainvs()
(a, a - 1, a, 605*a - 2728, 15887*a - 71972)
sage: Emin.discriminant()
-17*a - 16
sage: Emin.discriminant().norm()
-4096
sage: Emin.minimal_discriminant_ideal()
Fractional ideal (1)
sage: E.conductor()
Fractional ideal (1)

global_minimality_class()
Return the obstruction to this curve having a global minimal model.

OUTPUT:
An ideal class of the base number field, which is trivial if and only if the elliptic curve has a global minimal model, and which can be used to find global and semi-global minimal models.

EXAMPLES:
A curve defined over a field of class number 2 with no global minimal model was a nontrivial minimality class:

sage: K.<a> = NumberField(x^2-x-16)
sage: K.class_number()
2
sage: E = EllipticCurve([0,0,0,-22500, 750000*a])
sage: E.global_minimality_class()
Fractional ideal class (10, 5*a)
sage: E.global_minimality_class().order()
2

Over the same field, a curve defined by a non-minimal model has trivial class, showing that a global minimal model does exist:

sage: K.<a> = NumberField(x^2-x-16)
sage: E = EllipticCurve([0,0,0,4536*a+14148,-163728*a-474336])
sage: E.is_global_minimal_model()
False
Over a field of class number 1 the result is always the trivial class:

```python
sage: K.<a> = NumberField(x^2-5)
sage: E = EllipticCurve([0, 0, 0, K(16), K(64)])
sage: E.global_minimality_class()
Trivial principal fractional ideal class
```

### has_additive_reduction(P)

Return True if this elliptic curve has (bad) additive reduction at the prime $P$.

**INPUT:**

- $P$ – a prime ideal of the base field of self, or a field element generating such an ideal.

**OUTPUT:**

(bool) True if the curve has additive reduction at $P$, else False.

**EXAMPLES:**

```python
sage: E = EllipticCurve('27a1')
sage: [(p,E.has_additive_reduction(p)) for p in prime_range(15)]
[(2, False), (3, True), (5, False), (7, False), (11, False), (13, False)]
```

```python
sage: K.<a> = NumberField(x^3-2)
sage: P17a, P17b = [P for P,e in K.factor(17)]
sage: E = EllipticCurve([0,0,0,2*a+1])
sage: [(p,E.has_additive_reduction(p)) for p in [P17a,P17b]]
[(Fractional ideal (4*a^2 - 2*a + 1), False),
 (Fractional ideal (2*a + 1), True)]
```

### has_bad_reduction(P)

Return True if this elliptic curve has bad reduction at the prime $P$.

**INPUT:**

- $P$ – a prime ideal of the base field of self, or a field element generating such an ideal.

**OUTPUT:**

(bool) True if the curve has bad reduction at $P$, else False.

**Note:** This requires determining a local integral minimal model; we do not just check that the discriminant of the current model has valuation zero.

**EXAMPLES:**
sage: E = EllipticCurve('14a1')
sage: [(p, E.has_bad_reduction(p)) for p in prime_range(15)]
[(2, True), (3, False), (5, False), (7, True), (11, False), (13, False)]
sage: K.<a> = NumberField(x^3-2)
sage: P17a, P17b = [P for P, e in K.factor(17)]
sage: E = EllipticCurve([0,0,0,0,2*a+1])
sage: [(p,E.has_bad_reduction(p)) for p in [P17a,P17b]]
[(Fractional ideal (4*a^2 - 2*a + 1), False),
 (Fractional ideal (2*a + 1), True)]

has_cm()  
Return whether or not this curve has a CM j-invariant.

OUTPUT:
True if this curve has CM over the algebraic closure of the base field, otherwise False. See also cm_discriminant() and has_rational_cm().

Note: Even if E has CM in this sense (that its j-invariant is a CM j-invariant), if the associated negative discriminant D is not a square in the base field K, the extra endomorphisms will not be defined over K. See also the method has_rational_cm() which tests whether E has extra endomorphisms defined over K or a given extension of K.

EXAMPLES:
sage: EllipticCurve(j=0).has_cm()  
True
sage: EllipticCurve(j=1).has_cm()  
False
sage: EllipticCurve(j=1728).has_cm()  
True
sage: EllipticCurve(j=8000).has_cm()  
True
sage: K.<a> = QuadraticField(5)
sage: EllipticCurve(j=282880*a + 632000).has_cm()  
True
sage: K.<a> = NumberField(x^3 - 2)
sage: EllipticCurve(j=31710790944000*a^2 + 39953093016000*a + 50337742902000).has_cm()  
True

has_global_minimal_model()  
Return whether this elliptic curve has a global minimal model.

OUTPUT:
Boolean, True iff a global minimal model exists, i.e. an integral model which is minimal at every prime.

EXAMPLES:
sage: K.<a> = NumberField(x^2-10)
sage: E = EllipticCurve([0,0,0,4536*a+14148,-163728*a-474336])
sage: E.is_global_minimal_model()  
(continues on next page)
Elliptic curves, Release 9.7

(continued from previous page)

False
sage: E.has_global_minimal_model()
True

**has_good_reduction***(**P**)  
Return True if this elliptic curve has good reduction at the prime **P**.

**INPUT:**

- **P** – a prime ideal of the base field of self, or a field element generating such an ideal.

**OUTPUT:**

(boo) – True if the curve has good reduction at **P**, else False.

**Note:** This requires determining a local integral minimal model; we do not just check that the discriminant of the current model has valuation zero.

**EXAMPLES:**

```python
sage: E = EllipticCurve('14a1')
sage: [(p,E.has_good_reduction(p)) for p in prime_range(15)]
[(2, False), (3, True), (5, True), (7, False), (11, True), (13, True)]
sage: K.<a> = NumberField(x^3-2)
sage: P17a, P17b = [P for P,e in K.factor(17)]
sage: E = EllipticCurve([0,0,0,0,2*a+1])
sage: [(p,E.has_good_reduction(p)) for p in [P17a,P17b]]
[(Fractional ideal (4*a^2 - 2*a + 1), True),
 (Fractional ideal (2*a + 1), False)]
```

**has_multiplicative_reduction***(**P**)  
Return True if this elliptic curve has (bad) multiplicative reduction at the prime **P**.

**Note:** See also `has_split_multiplicative_reduction()` and `has_nonsplit_multiplicative_reduction()`.

**INPUT:**

- **P** – a prime ideal of the base field of self, or a field element generating such an ideal.

**OUTPUT:**

(boo) True if the curve has multiplicative reduction at **P**, else False.

**EXAMPLES:**

```python
sage: E = EllipticCurve('14a1')
sage: [(p,E.has_multiplicative_reduction(p)) for p in prime_range(15)]
[(2, True), (3, False), (5, False), (7, True), (11, False), (13, False)]
sage: K.<a> = NumberField(x^3-2)
sage: P17a, P17b = [P for P,e in K.factor(17)]
sage: E = EllipticCurve([0,0,0,0,2*a+1])
```

(continues on next page)
Elliptic curves, Release 9.7

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Elliptic curves, Release 9.7

sage: [(p,E.has_multiplicative_reduction(p)) for p in [P17a,P17b]]
[(Fractional ideal (4*a^2 - 2*a + 1), False), (Fractional ideal (2*a + 1), False)]

has_nonsplit_multiplicative_reduction(P)

Return True if this elliptic curve has (bad) non-split multiplicative reduction at the prime \( P \).

INPUT:

- \( P \) – a prime ideal of the base field of self, or a field element generating such an ideal.

OUTPUT:

(bool) True if the curve has non-split multiplicative reduction at \( P \), else False.

EXAMPLES:

sage: E = EllipticCurve('14a1')
sage: [(p,E.has_nonsplit_multiplicative_reduction(p)) for p in prime_range(15)]
[(2, True), (3, False), (5, False), (7, False), (11, False), (13, False)]

sage: K.<a> = NumberField(x^3-2)
sage: P17a, P17b = [P for P,e in K.factor(17)]
sage: E = EllipticCurve([0,0,0,0,2*a+1])
sage: [(p,E.has_nonsplit_multiplicative_reduction(p)) for p in [P17a,P17b]]
[(Fractional ideal (4*a^2 - 2*a + 1), False), (Fractional ideal (2*a + 1), False)]

has_rational_cm(field=None)

Return whether or not this curve has CM defined over its base field or a given extension.

INPUT:

- field – a field, which should be an extension of the base field of the curve. If field is None (the default), it is taken to be the base field of the curve.

OUTPUT:

True if the ring of endomorphisms of this curve over the given field is larger than \( \mathbb{Z} \); otherwise False. See also \( \text{cm\_discriminant()} \) and \( \text{has\_cm()} \).

Note: If \( E \) has CM but the discriminant \( D \) is not a square in the given field \( K \) then the extra endomorphisms will not be defined over \( K \), and this function will return False. See also \( \text{has\_cm()} \). To obtain the CM discriminant, use \( \text{cm\_discriminant()} \).

EXAMPLES:

sage: E = EllipticCurve(j=0)
sage: E.has_cm()
True
sage: E.has_rational_cm()
False
sage: D = E.cm_discriminant(); D
-3
sage: E.has_rational_cm(QuadraticField(D))
True

(continues on next page)
sage: E = EllipticCurve(j=1728)
sage: E.has_cm()
True
sage: E.has_rational_cm()
False
sage: D = E.cm_discriminant(); D
-4
sage: E.has_rational_cm(QuadraticField(D))
True

Higher degree examples:

sage: K.<a> = QuadraticField(5)
sage: E = EllipticCurve(j=282880*a + 632000)
sage: E.has_cm()
True
sage: E.has_rational_cm()
False
sage: E.cm_discriminant()
-20
sage: E.has_rational_cm(K.extension(x^2+5,'b'))
True

An error is raised if a field is given which is not an extension of the base field:

sage: E.has_rational_cm(QuadraticField(-20))
Traceback (most recent call last):
  ...  
ValueError: Error in has_rational_cm: Number Field in a with defining polynomial x^2 + 20 with a = 4.472135954999579?*I is not an extension field of Number Field in a with defining polynomial x^2 - 5 with a = 2.
  ...236067977499790?

sage: K.<a> = NumberField(x^3 - 2)
sage: E = EllipticCurve(j=31710790944000*a^2 + 3995309301600*a + ...50337742902000)
sage: E.has_cm()
True
sage: E.has_rational_cm()
False
sage: D = E.cm_discriminant(); D
-108
sage: E.has_rational_cm(K.extension(x^2+108,'b'))
True

**has_split_multiplicative_reduction**(P)

Return True if this elliptic curve has (bad) split multiplicative reduction at the prime P.

**INPUT:**

- P – a prime ideal of the base field of self, or a field element generating such an ideal.

**OUTPUT:**
(bool) True if the curve has split multiplicative reduction at \( P \), else False.

**EXAMPLES:**

```
sage: E = EllipticCurve('14a1')
sage: [(p, E.has_split_multiplicative_reduction(p)) for p in prime_range(15)]
[(2, False), (3, False), (5, False), (7, True), (11, False), (13, False)]

sage: K.<a> = NumberField(x^3-2)
sage: P17a, P17b = [P for P, e in K.factor(17)]
sage: E = EllipticCurve([0,0,0,0,2*a+1])
sage: [(p, E.has_split_multiplicative_reduction(p)) for p in [P17a, P17b]]
[(Fractional ideal (4*a^2 - 2*a + 1), False), (Fractional ideal (2*a + 1), False)]
```

`height_function()`

Return the canonical height function attached to self.

**EXAMPLES:**

```
sage: K.<a> = NumberField(x^2 - 5)
sage: E = EllipticCurve(K, '11a3')
sage: E.height_function()
EllipticCurveCanonicalHeight object associated to Elliptic Curve defined by y^2 + y = x^3 + (-1)*x^2 over Number Field in a with defining polynomial x^2 - 5
```

`height_pairing_matrix(points=None, precision=None, normalised=True)`

Return the height pairing matrix of the given points.

**INPUT:**

- **points** (list or None (default)) – a list of points on this curve, or None, in which case self.gens() will be used.
- **precision** (int or None (default)) – number of bits of precision of result, or None, for default RealField precision.
- **normalised** (bool, default True) – if True, use normalised heights which are independent of base change. Otherwise use the non-normalised Néron-Tate height, as required for the regulator in the BSD conjecture.

**EXAMPLES:**

```
sage: E = EllipticCurve([0, 0, 1, -1, 0])
sage: E.height_pairing_matrix()
[0.0511114082399688]
sage: EllipticCurve('11a').height_pairing_matrix()
[]
sage: E = EllipticCurve('5077a1')
sage: E.height_pairing_matrix([E.lift_x(x) for x in [-2,-7/4,1]], precision=100)
[ 1.3685725053539301120518194471 -1.3095767070865761992624519454 -0.
→ 63486715783715592064475542573]
[ -1.3095767070865761992624519454 2.7173593928122930896610589220 1.
→ 999818430667292139777571432]
[ -0.63486715783715592064475542573 1.099818430667292139777571432 0.
→ 66820516565192793503314205089]
```

(continues on next page)
sage: E = EllipticCurve(’389a1’)
sage: P,Q = E.point([-1,1,1]),E.point([0,-1,1])
sage: E.height_pairing_matrix([P,Q])
\[
\begin{array}{cc}
0.686667083305587 & 0.268478098806726 \\
0.268478098806726 & 0.327000773651605 \\
\end{array}
\]
Over a number field:

sage: x = polygen(QQ)
sage: K.<t> = NumberField(x^2+47)
sage: EK = E.base_extend(K)
sage: EK.height_pairing_matrix([EK(P),EK(Q)])
\[
\begin{array}{cc}
0.686667083305587 & 0.268478098806726 \\
0.268478098806726 & 0.327000773651605 \\
\end{array}
\]

When the parameter `normalised` is set to `False`, each height is multiplied by the degree `d` of the base field, and the regulator of `r` points is multiplied by `d^r`:

sage: E.height_pairing_matrix([P,Q], normalised=False)
\[
\begin{array}{cc}
4.33883868987537 & -1.74011876084301 \\
-1.74011876084301 & 0.849171674941418 \\
\end{array}
\]
sage: E.regulator_of_points([P,Q], normalised=False)
0.656405615744281

`integral_model()`

Return a model of self which is integral at all primes.

**EXAMPLES:**

sage: K.<i> = NumberField(x^2+1)
sage: E = EllipticCurve([i/5,i/5,i/5,i/5,i/5])
sage: P1,P2 = K.primes_above(5)
sage: E.global_integral_model()  
Elliptic Curve defined by y^2 + (-i)*x*y + (-25*i)*y = x^3 + 5*i*x^2 + 125*i*x + 3125*i over Number Field in i with defining polynomial x^2 + 1

trac ticket #7935:

sage: K.<a> = NumberField(x^2-38)
sage: E = EllipticCurve([a,1/2])
Elliptic curves, Release 9.7

sage: E.global_integral_model()
Elliptic Curve defined by y^2 = x^3 + 1444*a*x + 27436 over Number Field in a
˓→with defining polynomial x^2 - 38

trac ticket #9266:

sage: K.<s> = NumberField(x^2-5)
sage: w = (1+s)/2
sage: E = EllipticCurve(K,[2,w])
sage: E.global_integral_model()
Elliptic Curve defined by y^2 = x^3 + 2*x + (1/2*s+1/2) over Number Field in s
˓→with defining polynomial x^2 - 5

trac ticket #12151:

sage: K.<v> = NumberField(x^2 + 161*x - 150)
sage: E = EllipticCurve([25105/216*v - 3839/36, 634768555/7776*v - 98002625/
˓→1296, 634768555/7776*v - 98002625/1296, 0, 0])
sage: M = E.global_integral_model(); M
# choice varies, not tested
Elliptic Curve defined by y^2 + (2094779518028859*v-1940492905300351)*x*y +
˓→(47799726847254419310117823445416530471127500*v-+
˓→442791377441346852919930773849502871958097500)*y = x^3 +
˓→(26519784699047674853185542622500*v-245665253064697072225840460652500)*x^2+
˓→over Number Field in v with defining polynomial x^2 + 161*x - 150

trac ticket #14476:

sage: R.<t> = QQ[]
sage: K.<g> = NumberField(t^4 - t^3 - 3*t^2 - t + 1)
sage: E = EllipticCurve([-43/625*g^3 + 14/625*g^2 - 4/625*g + 706/625, -4862/
˓→78125*g^3 - 4074/78125*g^2 - 711/78125*g + 10304/78125, -4862/78125*g^3 -+
˓→4074/78125*g^2 - 711/78125*g + 10304/78125, 0, 0])
sage: E.global_integral_model()
Elliptic Curve defined by y^2 + (15*g^3-48*g-42)*x*y + (-111510*g^3-162162*g^2-+
˓→44145*g+37638)*y = x^3 + (-954*g^3-1134*g^2+81*g+576)*x^2 over Number Field
˓→in g with defining polynomial t^4 - t^3 - 3*t^2 - t + 1

is_Q_curve(maxp=100, certificate=False, verbose=False)

Return True if this is a Q-curve, with optional certificate.

INPUT:

• maxp (int, default 100): bound on primes used for checking necessary local conditions. The result will
not depend on this, but using a larger value may return False faster.

• certificate (bool, default False): if True then a second value is returned giving a certificate for
the Q-curve property.

OUTPUT:

If certificate is False: either True (if E is a Q-curve), or False.

If certificate is True: a tuple consisting of a boolean flag as before and a certificate, defined as follows:

• when the flag is True, so E is a Q-curve:
– either \{'CM':D\} where \(D\) is a negative discriminant, when \(E\) has potential CM with discriminant \(D\);
– otherwise \{'CM': 0, 'core_poly': f, 'rho': \(\rho\), 'r': r, 'N': N\}, when \(E\) is a non-CM \(\mathbb{Q}\)-curve, where the core polynomial \(f\) is an irreducible monic polynomial over \(\mathbb{Q}\) of degree 2\(\rho\), all of whose roots are \(j\)-invariants of curves isogenous to \(E\), the core level \(N\) is a square-free integer with \(r\) prime factors which is the LCM of the degrees of the isogenies between these conjugates.

For example, if there exists a curve \(E'\) isogenous to \(E\) with \(j(E') = j \in \mathbb{Q}\), then the certificate is \{'CM':0, 'r':0, 'rho':0, 'core_poly': x-j, 'N':1\}.

• when the flag is False, so \(E\) is not a \(\mathbb{Q}\)-curve, the certificate is a prime \(p\) such that the reductions of \(E\) at the primes dividing \(p\) are inconsistent with the property of being a \(\mathbb{Q}\)-curve. See the documentation for \texttt{sage.src.schemes.elliptic_curves.Qcurves.is_Q_curve()} for details.

\textbf{ALGORITHM:}

See the documentation for \texttt{sage.src.schemes.elliptic_curves.Qcurves.is_Q_curve()}, and [CrNa2020] for details.

\textbf{EXAMPLES:}

A non-CM curve over \(\mathbb{Q}\) and a CM curve over \(\mathbb{Q}\) are both trivially \(\mathbb{Q}\)-curves:

\begin{verbatim}
sage: E = EllipticCurve([1,2,3,4,5])
sage: flag, cert = E.is_Q_curve(certificate=True)
sage: flag
True
sage: cert
{'CM': 0, 'N': 1, 'core_poly': x, 'r': 0, 'rho': 0}

sage: E = EllipticCurve(j=8000)
sage: flag, cert = E.is_Q_curve(certificate=True)
sage: flag
True
sage: cert
{'CM': -8}
\end{verbatim}

A non-\(\mathbb{Q}\)-curve over a quartic field. The local data at bad primes above 3 is inconsistent:

\begin{verbatim}
sage: R.<x> = PolynomialRing(QQ)
sage: K.<a> = NumberField(R([3, 0, -5, 0, 1]))
sage: E = EllipticCurve(K([-3,-4,1,1]),K([4,-1,-1,0]),K([-621, -778,138,-178]),K([9509,2046,-24728,10380]))
sage: E.is_Q_curve(certificate=True, verbose=True)
Checking whether Elliptic Curve defined by y^2 + (a^3+a^2-4*a-3)*x*y + (a^2-2)*y = x^3 + (-a^2-a+4)*x^2 + (-178*a^3+138*a^2+778*a-621)*x + (10380*a^3-24728*a^2+2046*a+9509) over Number Field in a with defining polynomial x^4 -5*x^2 + 3 is a Q-curve
No: inconsistency at the 2 primes dividing 3
- potentially multiplicative: [True, False]
(False, 3)
\end{verbatim}

A non-\(\mathbb{Q}\)-curve over a quadratic field. The local data at bad primes is consistent, but the local test at good primes above 13 is not:

\begin{verbatim}
sage: K.<a> = NumberField(R([-10, 0, 1]))
sage: E = EllipticCurve(K([0,1]),K([-1,-1]),K([0,0]),K([-236,40]),K([-1840, 464]))
(continues on next page)\end{verbatim}
A quadratic Q-curve with CM discriminant $-15$ (so the $j$-invariant is not in $\mathbb{Q}$):

```
sage: R.<x> = PolynomialRing(QQ)
sage: K.<a> = NumberField(R([-1, -1, 1]))
sage: E = EllipticCurve([K([-2,-4,1,1]),K([0,1,0,0]),K([0,1,0,0]),K([-2,-16,0,4]),K([-19,-32,4,8])])
sage: flag, cert = E.is_Q_curve(certificate=True)  # long time
sage: flag  # long time
True
sage: cert  # long time
{'CM': 0, 'N': 1, 'core_degs': [1], 'core_poly': x - 85184/3, 'r': 0, 'rho': 0}
```

Over the same field, a so-called strict Q-curve which is not isogenous to one with rational $j$, but whose core field is quadratic. In fact the isogeny class over $K$ consists of 6 curves, four with conjugate quartic $j$-invariants and 2 with quadratic conjugate $j$-invariants in $\mathbb{Q}(\sqrt{3})$ (but which are not base-changes from the quadratic subfield):

```
sage: E = EllipticCurve([K([0,-3,0,1]),K([1,4,0,-1]),K([0,0,0,0]),K([-2,-16,0,4]),K([-19,-32,4,8])])
sage: flag, cert = E.is_Q_curve(certificate=True)  # long time
sage: flag  # long time
True
sage: cert  # long time
{'CM': 0, 'N': 2, 'core_degs': [1, 2], 'core_poly': x^2 - 840064*x + 1593413632, 'r': 1, 'rho': 1}
```
is_global_integral_model()

Return whether self is integral at all primes.

EXAMPLES:

sage: K.<i> = NumberField(x^2+1)
sage: E = EllipticCurve([i/5,i/5,i/5,i/5,i/5])
sage: P1,P2 = K.primes_above(5)
sage: Emin = E.global_integral_model()
sage: Emin.is_global_integral_model()
True

is_global_minimal_model()

Return whether this elliptic curve is a global minimal model.

OUTPUT:

Boolean, False if E is not integral, or if E is non-minimal at some prime, else True.

EXAMPLES:

sage: K.<a> = NumberField(x^2-10)
sage: E = EllipticCurve([0, 0, 0, -22500, 750000*a])
sage: E.is_global_minimal_model()
False
sage: E.non_minimal_primes()
[Fractional ideal (2, a), Fractional ideal (5, a)]

sage: E = EllipticCurve([0,0,0,-3024,46224])
sage: E.is_global_minimal_model()
False
sage: E.non_minimal_primes()
[2, 3]
sage: Emin = E.global_minimal_model()
sage: Emin.is_global_minimal_model()
True

A necessary condition to be a global minimal model is that the model must be globally integral:

sage: E = EllipticCurve([0,0,0,1/2,1/3])
sage: E.is_global_minimal_model()
False
sage: Emin = E.global_minimal_model()
sage: Emin.is_global_minimal_model()
True
sage: Emin.ainvs()
(0, 1, 1, -2, 0)

is_isogenous(other, proof=True, maxnorm=100)

Return whether or not self is isogenous to other.

INPUT:

• other – another elliptic curve.

• proof (default True) – If False, the function will return True whenever the two curves have the same conductor and are isogenous modulo \( p \) for all primes \( p \) of norm up to maxnorm. If True, the function returns False when the previous condition does not hold, and if it does hold we compute the complete isogeny class to see if the curves are indeed isogenous.
• **maxnorm** (integer, default 100) – The maximum norm of primes \( p \) for which isogeny modulo \( p \) will be checked.

**OUTPUT:**

(\text{bool}) True if there is an isogeny from curve \texttt{self} to curve \texttt{other}.

**EXAMPLES:**

```python
sage: x = polygen(QQ, 'x')
sage: F = NumberField(x^2 -2, 's'); F
Number Field in s with defining polynomial x^2 - 2
sage: E1 = EllipticCurve(F, [7,8])
sage: E2 = EllipticCurve(F, [0,5,0,1,0])
sage: E3 = EllipticCurve(F, [0,-10,0,21,0])
sage: E1.is_isogenous(E2)  # False
sage: E1.is_isogenous(E1)  # True
sage: E2.is_isogenous(E2)  # True
sage: E2.is_isogenous(E1)  # False
sage: E2.is_isogenous(E3)  # True
```

```python
sage: x = polygen(QQ, 'x')
sage: F = NumberField(x^2 -2, 's'); F
Number Field in s with defining polynomial x^2 - 2
sage: E = EllipticCurve('14a1')
sage: EE = EllipticCurve('14a2')
sage: E1 = E.change_ring(F)
sage: E2 = EE.change_ring(F)
sage: E1.is_isogenous(E2)  # True
```

```python
sage: x = polygen(QQ, 'x')
sage: F = NumberField(x^2 -2, 's'); F
Number Field in s with defining polynomial x^2 - 2
sage: k.<a> = NumberField(x^3 + 7)
sage: E = EllipticCurve(F, [7,8])
sage: EE = EllipticCurve(k, [2, 2])
sage: E.is_isogenous(EE)
Traceback (most recent call last):
...
ValueError: Second argument must be defined over the same number field.
```

Some examples from Cremona’s 1981 tables:

```python
sage: K.<i> = QuadraticField(-1)
sage: E1 = EllipticCurve([i + 1, 0, 1, -240*i - 400, -2869*i - 2627])
sage: E1.conductor()  # Fractional ideal (-4*i - 7)
sage: E2 = EllipticCurve([1+i,0,1,0,0])
sage: E2.conductor()  # Fractional ideal (1+i)
```

(continues on next page)
Fractional ideal \((-4\cdot i - 7)\)

\[
sage: \text{E1.is_isogenous(E2)} \quad \# \text{ long time}
\]

True

\[
sage: \text{E1.is_isogenous(E2, proof=False)} \quad \# \text{ faster (~170ms)}
\]

True

In this case \(E1\) and \(E2\) are in fact 9-isogenous, as may be deduced from the following:

\[
sage: \text{E3} = \text{EllipticCurve([i + 1, 0, 1, -5\cdot i - 5, -2\cdot i - 5])}
\]

\[
sage: \text{E3.is_isogenous(E1)}
\]

True

\[
sage: \text{E3.is_isogenous(E2)}
\]

True

\[
sage: \text{E1.isogeny_degree(E2)} \quad \# \text{ long time}
\]

9

\[\text{is_local_integral_model}(\ast P)\]
Tests if self is integral at the prime ideal \(P\), or at all the primes if \(P\) is a list or tuple.

INPUT:

- \(\ast P\) – a prime ideal, or a list or tuple of primes.

EXAMPLES:

\[
sage: K.<i> = \text{NumberField}(x^2+1)
\]

\[
sage: \text{P1,P2 = K.primes_above(5)}
\]

\[
sage: \text{E} = \text{EllipticCurve([i/5,i/5,i/5,i/5,i/5])}
\]

\[
sage: \text{E.is_local_integral_model(P1,P2)}
\]

False

\[
sage: \text{Emin} = \text{E.local_integral_model(P1,P2)}
\]

\[
sage: \text{Emin.is_local_integral_model(P1,P2)}
\]

True

\[\text{isogenies_prime_degree}(l=None, \text{algorithm}=\text{'Billerey'}, \text{minimal_models}=\text{True})\]

Return a list of \(\ell\)-isogenies from self, where \(\ell\) is a prime.

INPUT:

- \(l\) – either None or a prime or a list of primes.

- \text{algorithm} (string, default ‘Billerey’) – the algorithm to use to compute the reducible primes when \(l\) is None. Ignored for CM curves or if \(l\) is provided. Values are ‘Billerey’ (default), ‘Larson’, and ‘heuristic’.

- \text{minimal_models} (bool, default True) – if True, all curves computed will be minimal or semi-minimal models. Over fields of larger degree it can be expensive to compute these so set to False.

OUTPUT:

(list) \(\ell\)-isogenies for the given \(\ell\) or if \(\ell\) is None, all isogenies of prime degree (see below for the CM case).

\[\text{Note: }\text{Over } \mathbb{Q}, \text{ the codomains of the isogenies returned are standard minimal models. Over other number fields they are global minimal models if these exist, otherwise models which are minimal at all but one prime.}\]
Note: For curves with rational CM, isogenies of primes degree exist for infinitely many primes \( \ell \), though there are only finitely many isogenous curves up to isomorphism. The list returned only includes one isogeny of prime degree for each codomain.

EXAMPLES:

```python
sage: K.<i> = QuadraticField(-1)
sage: E = EllipticCurve(K, [0,0,0,0,1])
sage: isogs = E.isogenies_prime_degree()
sage: [phi.degree() for phi in isogs]
[2, 3]
sage: pol = PolynomialRing(QQ, 'x')([1,-3,5,-5,5,-3,1])
sage: L.<a> = NumberField(pol)
sage: js = hilbert_class_polynomial(-23).roots(L,multiplicities=False); len(js)
3
sage: E = EllipticCurve(j=js[0])
sage: len(E.isogenies_prime_degree())  # long time
3
```

Set `minimal_models` to `False` to avoid computing minimal models of the isogenous curves, since that can be time-consuming since it requires computation of the class group:

```python
sage: proof.number_field(False)
sage: K.<z> = CyclotomicField(53)
sage: E = EllipticCurve(K,[0,6,0,2,0])
sage: E.isogenies_prime_degree(2, minimal_models=False)

[Isoenary of degree 2 from Elliptic Curve defined by y^2 = x^3 + 6*x^2 + 2*x over Cyclotomic Field of order 53 and degree 52 to Elliptic Curve defined by y^2 = x^3 + 6*x^2 + (-8)*x + (-48) over Cyclotomic Field of order 53 and degree 52]
```

`isogeny_class`(`reducible_primes=None, algorithm='Billerey', minimal_models=True)`

Return the isogeny class of this elliptic curve.

**INPUT:**

- `reducible_primes` (list of ints, or None (default)) – if not None then this should be a list of primes; in computing the isogeny class, only composites isogenies of these degrees will be used.
- `algorithm` (string, default ‘Billerey’) – the algorithm to use to compute the reducible primes. Ignored for CM curves or if `reducible_primes` is provided. Values are ‘Billerey’ (default), ‘Larson’, and ‘heuristic’.
- `minimal_models` (bool, default True) – if True, all curves in the class will be minimal or semi-minimal models. Over fields of larger degree it can be expensive to compute these so set to `False`.

**OUTPUT:**

An instance of the class `sage.schemes.elliptic_curves.isogeny_class.IsogenyClass_EC_NumberField`. From this object may be obtained a list of curves in the class, a matrix of the degrees of the isogenies between them, and the isogenies themselves.
Note: If using the algorithm ‘heuristic’ for non-CM curves, the result is not guaranteed to be the complete isogeny class, since only reducible primes up to the default bound in `reducible_primes_naive()` (currently 1000) are tested. However, no examples of non-CM elliptic curves with reducible primes greater than 100 have yet been computed so the output is likely to be correct.

Note: By default, the curves in the isogeny class will all be minimal models if these exist (for example, when the class number is 1); otherwise they will be minimal at all but one prime. This behaviour can be switched off if desired, for example over fields where the computation of the class group would be too expensive.

EXAMPLES:

```
sage: K.<i> = QuadraticField(-1)
sage: E = EllipticCurve(K, [0,0,0,0,1])
sage: C = E.isogeny_class(); C
Isogeny class of Elliptic Curve defined by y^2 = x^3 + 1 over Number Field in i with defining polynomial x^2 + 1 with i = 1*I
```

The curves in the class (sorted):

```
sage: [E1.ainvs() for E1 in C]
[(0, 0, 0, 0, -27),
 (0, 0, 0, 0, 1),
 (i + 1, i, i + 1, -i + 3, 4*i),
 (i + 1, i, i + 1, -i + 33, -58*i)]
```

The matrix of degrees of cyclic isogenies between curves:

```
sage: C.matrix()
[1 3 6 2]
[3 1 2 6]
[6 2 1 3]
[2 6 3 1]
```

The array of isogenies themselves is not filled out but only contains those used to construct the class, the other entries containing the integer 0. This will be changed when the class `EllipticCurveIsogeny` allowed composition. In this case we used 2-isogenies to go from 0 to 2 and from 1 to 3, and 3-isogenies to go from 0 to 1 and from 2 to 3:

```
sage: isogs = C.isogenies()  
sage: [((i,j),isogs[i][j].degree()) for i in range(4) for j in range(4) if isogs[i][j]!=0]
```

(continues on next page)
Elliptic curves, Release 9.7

((0, 1), (1/9*x^3 - 12)/x^2),
((0, 3), (-1/2*i*x^2 + i*x - 12*i)/(x - 3)),
((1, 0), (x^3 + 4)/x^2),
((1, 2), (-1/2*i*x^2 - i*x - 2*i)/(x + 1)),
((2, 1), (1/2*i*x^2 - x)/(x + 3/2*i)),
((2, 3), (x^3 + 4*i*x^2 - 10*x - 10*i)/(x^2 + 4*i*x - 4)),
((3, 0), (1/2*i*x^2 + x + 4*i)/(x - 5/2*i)),
((3, 2), (1/9*x^3 - 4/3*i*x^2 - 34/3*x + 226/9*i)/(x^2 - 8*i*x - 16))

The isogeny class may be visualized by obtaining its graph and plotting it:

```
sage: G = C.graph()
sage: G.show(edge_labels=True)  # long time

sage: K.<i> = QuadraticField(-1)
sage: E = EllipticCurve([1+i, -i, i, 1, 0])
sage: C = E.isogeny_class(); C
Isogeny class of Elliptic Curve defined by y^2 + (i+1)*x*y + i*y = x^3 + (-i)*x^2 + x over Number Field in i with defining polynomial x^2 + 1 with i = 1*I
sage: len(C)  # long time
6
sage: C.matrix()  # long time
[ 1 3 9 18 6 2]
[ 3 1 3 6 2 6]
[ 9 3 1 2 6 18]
[18 6 2 1 3 9]
[ 6 2 6 3 1 3]
[ 2 6 18 9 3 1]
sage: [E1.ainvs() for E1 in C]  # long time
[(i + 1, i - 1, i, -i - 1, -i + 1),
 (i + 1, i - 1, i, 14*i + 4, 7*i + 14),
 (i + 1, i - 1, i, 59*i + 99, 372*i - 410),
 (i + 1, -i, i, -240*i - 399, 2869*i + 2627),
 (i + 1, -i, i, -5*i - 4, 2*i + 5),
 (i + 1, -i, i, 1, 0)]
```

An example with CM by \(\sqrt{-5}\):

```
sage: pol = PolynomialRing(QQ, 'x')([1,0,3,0,1])
sage: K.<c> = NumberField(pol)
sage: j = 1480640+565760*c^2
sage: E = EllipticCurve(j=j)
sage: E.has_cm()  # long time
True
sage: E.has_rational_cm()  # long time
True
sage: E.cm_discriminant()  # long time
-20
sage: C = E.isogeny_class()
sage: len(C)
2
sage: C.matrix()
```

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An example with CM by $\sqrt{-23}$ (class number 3):

```python
sage: pol = PolynomialRing(QQ, 'x')([1,-3,5,-5,5,-3,1])
sage: L.<a> = NumberField(pol)
sage: js = hilbert_class_polynomial(-23).roots(L,multiplicities=False); len(js)
3
sage: E = EllipticCurve(j=js[0])
sage: E.has_rational_cm()
True
sage: len(E.isogenies_prime_degree())  # long time
3
sage: C = E.isogeny_class(); len(C)  # long time
6
```

The reason for the isogeny class having size six while the class number is only 3 is that the class also contains three curves with CM by the order of discriminant $-92 = 4 \cdot (-23)$, which also has class number 3. The curves in the class are sorted first by CM discriminant (then lexicographically using a-invariants):

```python
sage: [F.cm_discriminant() for F in C]  # long time
[-23, -23, -23, -92, -92, -92]
```

2 splits in the order with discriminant $-23$, into two primes of order 3 in the class group, each of which induces a 2-isogeny to a curve with the same endomorphism ring; the third 2-isogeny is to a curve with the smaller endomorphism ring:

```python
sage: [phi.codomain().cm_discriminant() for phi in E.isogenies_prime_degree()]  # long time
[-92, -23, -23]
```

The graph of this isogeny class has a shape which does not occur over $\mathbb{Q}$: a triangular prism. Note that for curves without CM, the graph has an edge between two curves if and only if they are connected by an isogeny of prime degree, and this degree is uniquely determined by the two curves, but in the CM case this property does not hold, since for pairs of curves in the class with the same endomorphism ring $O$, the
set of degrees of isogenies between them is the set of integers represented by a primitive integral binary quadratic form of discriminant \( \text{disc}(O) \), and this form represents infinitely many primes. In the matrix we give a small prime represented by the appropriate form. In this example, the matrix is formed by four \( 3 \times 3 \) blocks. The isogenies of degree 2 indicated by the upper left \( 3 \times 3 \) block of the matrix could be replaced by isogenies of any degree represented by the quadratic form \( 2x^2 + xy + 3y^2 \) of discriminant \( -23 \). Similarly in the lower right block, the entries of 3 could be represented by any integers represented by the quadratic form \( 3x^2 + 2xy + 8y^2 \) of discriminant \( -92 \). In the top right block and lower left blocks, by contrast, the prime entries 2 are unique determined:

```
sage: G = C.graph()  # long time
sage: G.adjacency_matrix()  # long time
```

\[
\begin{bmatrix}
0 & 1 & 1 & 0 & 1 & 0 \\
1 & 0 & 1 & 0 & 0 & 0 \\
1 & 1 & 0 & 0 & 0 & 1 \\
0 & 1 & 0 & 0 & 1 & 1 \\
1 & 0 & 0 & 1 & 0 & 1 \\
0 & 0 & 1 & 1 & 1 & 0
\end{bmatrix}
\]

To display the graph without any edge labels:

```
sage: G.show()  # not tested
```

To display the graph with edge labels: by default, for curves with rational CM, the labels are the coefficients of the associated quadratic forms:

```
sage: G.show(edge_labels=True)  # not tested
```

For an alternative view, first relabel the edges using only 2 labels to distinguish between isogenies between curves with the same endomorphism ring and isogenies between curves with different endomorphism rings, then use a 3-dimensional plot which can be rotated:

```
sage: for i,j,l in G.edge_iterator():  # long time
....:     G.set_edge_label(i, j, l.count(',', '))
sage: G.show3d(color_by_label=True)  # long time
```

A class number 6 example. First we set up the fields: \( \text{pol} \) defines the same field as \( \text{pol26} \) but is simpler:

```
sage: pol26 = hilbert_class_polynomial(-4*26)
sage: pol = x^6-x^5+2*x^4+x^3-2*x^2-x-1
sage: K.<a> = NumberField(pol)
sage: L.<b> = K.extension(x^2+26)
```

Only 2 of the \( j \)-invariants with discriminant -104 are in \( K \), though all are in \( L \):

```
sage: len(pol26.roots(K))
2
sage: len(pol26.roots(L))
6
```

We create an elliptic curve defined over \( K \) with one of the \( j \)-invariants in \( K \):

```
sage: j1 = pol26.roots(K)[0][0]
sage: E = EllipticCurve(j=j1)
sage: E.has_cm()()
True
```

(continues on next page)
Elliptic curves, Release 9.7

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```python
sage: E.has_rational_cm()
False
sage: E.has_rational_cm(L)
True
```

Over $\mathbb{K}$ the isogeny class has size 4, with 2 curves for each of the 2 $\mathbb{K}$-rational $j$-invariants:

```python
sage: C = E.isogeny_class(); len(C)  # long time (~11s)
4
sage: C.matrix()  # long time
[ 1 13 2 26]
[13 1 26 2]
[ 2 26 1 13]
[26 2 13 1]
sage: len(Set([EE.j_invariant() for EE in C.curves]))  # long time
2
```

Over $\mathbb{L}$, the isogeny class grows to size 6 (the class number):

```python
sage: EL = E.change_ring(L)
sage: CL = EL.isogeny_class(minimal_models=False)  # long time
sage: len(CL)  # long time
6
sage: s1 = Set([EE.j_invariant() for EE in CL.curves])  # long time
sage: s2 = Set(pol26.roots(L,multiplicities=False))  # long time
sage: s1 == s2  # long time
True
```

In each position in the matrix of degrees, we see primes (or 1). In fact the set of degrees of cyclic isogenies from curve $i$ to curve $j$ is infinite, and is the set of all integers represented by one of the primitive binary quadratic forms of discriminant $-104$, from which we have selected a small prime:

```python
sage: CL.matrix()  # long time # random (see :trac:`19229`)  
[1 2 3 3 5 5]
[2 1 5 5 3 3]
[3 5 1 3 2 5]
[3 5 3 1 5 2]
[5 3 2 5 1 3]
[5 3 5 2 3 1]
```

To see the array of binary quadratic forms:

```python
sage: CL.qf_matrix()  # long time # random (see :trac:`19229`)  
[[[1], [2, 0, 13], [3, -2, 9], [3, -2, 9], [5, -4, 6], [5, -4, 6]],
 [2, 0, 13], [1], [5, -4, 6], [5, -4, 6], [3, -2, 9], [3, -2, 9]],
 [3, -2, 9], [5, -4, 6], [1], [3, -2, 9], [2, 0, 13], [5, -4, 6]],
 [3, -2, 9], [5, -4, 6], [3, -2, 9], [1], [5, -4, 6], [2, 0, 13]],
 [5, -4, 6], [3, -2, 9], [2, 0, 13], [5, -4, 6], [1], [3, -2, 9]],
 [5, -4, 6], [3, -2, 9], [5, -4, 6], [2, 0, 13], [3, -2, 9], [1]]]
```

As in the non-CM case, the isogeny class may be visualized by obtaining its graph and plotting it. Since there are more edges than in the non-CM case, it may be preferable to omit the edge_labels:

---

14.3. Elliptic curves over number fields 339
It is possible to display a 3-dimensional plot, with colours to represent the different edge labels, in a form which can be rotated!

```
sage: G.show3d(color_by_label=True)  # long time
```

Over larger number fields several options make computations tractable. Here we use algorithm ‘heuristic’ which avoids a rigorous computation of the reducible primes, only testing those less than 1000, and setting minimal_models to False avoid having to compute the class group of \( K \). To obtain minimal models set proof.number_field(False); the class group computation takes an additional 10s:

```
sage: K.<z> = CyclotomicField(53)
sage: E = EllipticCurve(K,[0,6,2,0])
sage: C = E.isogeny_class(algorithm='heuristic', minimal_models=False); C  # long time (10s)
Isogeny class of Elliptic Curve defined by y^2 = x^3 + 6*x^2 + 2*x over Cyclotomic Field of order 53 and degree 52
```

**isogeny_degree(other)**

Return the minimal degree of an isogeny between self and other, or 0 if no isogeny exists.

INPUT:

* other – another elliptic curve.

OUTPUT:

(int) The degree of an isogeny from self to other, or 0.

EXAMPLES:

```
sage: x = QQ['x'].0
sage: F = NumberField(x^2 - 2, 's'); F
Number Field in s with defining polynomial x^2 - 2
sage: E = EllipticCurve('14a1')
sage: EE = EllipticCurve('14a2')
sage: E1 = E.change_ring(F)
sage: E2 = EE.change_ring(F)
sage: E1.isogeny_degree(E2)  # long time
2
sage: E2.isogeny_degree(E2)
1
sage: E5 = EllipticCurve('14a5').change_ring(F)
sage: E1.isogeny_degree(E5)  # long time
6
```

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```
sage: K.<i> = QuadraticField(-1)
sage: E = EllipticCurve([1+i, -i, i, 1, 0])
sage: C = E.isogeny_class() # long time
sage: [E.isogeny_degree(F) for F in C] # long time
[2, 6, 18, 9, 3, 1]
```

**kodaira_symbol**\(\left(P, \text{proof}=\text{None}\right)\)

Return the Kodaira Symbol of this elliptic curve at the prime \(P\).

**INPUT:**

- \(P\) – either None or a prime ideal of the base field of self.
- \(\text{proof}\) – whether to only use provably correct methods (default controlled by global proof module). Note that the proof module is number_field, not elliptic_curves, since the functions that actually need the flag are in number fields.

**OUTPUT:**

The Kodaira Symbol of the curve at \(P\), represented as a string.

**EXAMPLES:**

```
sage: K.<a> = NumberField(x^2-5)
sage: E = EllipticCurve([20, 225, 750, 625*a + 6875, 31250*a + 46875])
sage: bad_primes = E.discriminant().support(); bad_primes
[Fractional ideal (-a), Fractional ideal (7/2*a - 81/2), Fractional ideal (-a - 52), Fractional ideal (2)]
sage: [E.kodaira_symbol(P) for P in bad_primes]
[I0, I1, I1, II]
sage: K.<a> = QuadraticField(-11)
sage: E = EllipticCurve('11a1').change_ring(K)
sage: [E.kodaira_symbol(P) for P in K(11).support()]
[I10]
```

**lll_reduce**\(\left(\text{points, height_matrix}=\text{None, precision}=\text{None}\right)\)

Return an LLL-reduced basis from a given basis, with transform matrix.

**INPUT:**

- \(\text{points}\) – a list of points on this elliptic curve, which should be independent.
- \(\text{height_matrix}\) – the height-pairing matrix of the points, or None. If None, it will be computed.
- \(\text{precision}\) – number of bits of precision of intermediate computations (default: None, for default RealField precision; ignored if \(\text{height_matrix}\) is supplied)

**OUTPUT:** A tuple (newpoints, U) where \(U\) is a unimodular integer matrix, new_points is the transform of points by \(U\), such that new_points has LLL-reduced height pairing matrix

**Note:** If the input points are not independent, the output depends on the undocumented behaviour of PARI’s pari:qflllgram function when applied to a Gram matrix which is not positive definite.

**EXAMPLES:**

Some examples over \(\mathbb{Q}\):
```
sage: E = EllipticCurve([0, 1, 1, -2, 42])
sage: Pi = E.gens(); Pi
sage: Q, U = E.lll_reduce(Pi)
sage: all(sum(U[i,j]*Pi[i] for i in range(4)) == Q[j] for j in range(4))
True
sage: sorted(Q)
[(-4 : 1 : 1), (-3 : 5 : 1), (-2 : 6 : 1), (0 : 6 : 1)]
sage: U.det()
1
sage: E.regulator_of_points(Pi)
4.59088036960573
sage: E.regulator_of_points(Q)
4.59088036960574
```

```
sage: E = EllipticCurve([1,0,1,-120039822036992245303534619191166796374, ...
˓→9351361230729481250627334/1366561, ...
˓→983886013344700707678587482584/141566320009, ...
˓→1124614335716851053281176544216033/152487126016]
sage: points = [E.lift_x(x) for x in xi]
sage: newpoints, U = E.lll_reduce(points)  # long time (35s on sage.math, 2011)
sage: [P[0] for P in newpoints]  # long time
[6823883569166584943, 594953987899294213, 2005024558054813068, ...
˓→5864065934033506970637/676, ...
˓→5428468206026253719/4, ...
˓→110352253665081002517811734/21353641, ...
˓→454246340850352215460183165/5424617104, ...
˓→983886013344700707678587482584/141566320009, ...
˓→1124614335716851053281176544216033/152487126016]
```

342 Chapter 14. Elliptic curves over number fields
An example to show the explicit use of the height pairing matrix:

```
E = EllipticCurve([0, 1, 1, -2, 42])
P = E.gens()
H = E.height_pairing_matrix(P, 3)
E.lll_reduce(P, height_matrix=H)
```

```
( [[1 0 0 1]
  [0 1 0 1]
  [0 0 0 1]]
  [(-4 : 1 : 1), (-3 : 5 : 1), (-2 : 6 : 1), (1 : -7 : 1)], [0 0 1 1]
)
```

Some examples over number fields (see trac ticket #9411):

```
K.<a> = QuadraticField(-23)
E = EllipticCurve(K, [0,0,1,-1,0])
P = E(-2,-(a+1)/2)
Q = E(0,-1)
E.lll_reduce([P,Q])
```

```
( [[0 1]]
  [(-a + 4 : -3*a + 7 : 1), (-17/18*a - 1/9 : -109/108*a + 277/108 : 1)], [1 0]
)
```

```
K.<a> = QuadraticField(-5)
E = EllipticCurve(K, [0,a])
points = [E.point([-211/841*a - 6044/841,-209584/24389*a + 53634/24389]),
          E.point([-17/18*a - 1/9, -109/108*a - 277/108])]
E.lll_reduce(points)
```

```
( [(-a + 4 : -3*a + 7 : 1), (-17/18*a - 1/9 : 109/108*a + 277/108 : 1)], [1 0]
)
```

`local_data(P=None, proof=None, algorithm='pari', globally=False)`

Local data for this elliptic curve at the prime $P$.

**INPUT:**

- **P** – either None, a prime ideal of the base field of self, or an element of the base field that generates a prime ideal.
- **proof** – whether to only use provably correct methods (default controlled by global proof module). Note that the proof module is number_field, not elliptic_curves, since the functions that actually need the flag are in number fields.
- **algorithm** (string, default: “pari”) – Ignored unless the base field is $\mathbb{Q}$. If “pari”, use the PARI C-library pari:ellglobalred implementation of Tate’s algorithm over $\mathbb{Q}$. If “generic”, use the general number field implementation.
- **globally** – whether the local algorithm uses global generators for the prime ideals. Default is False, which will not require any information about the class group. If True, a generator for $P$ will be used if $P$ is principal. Otherwise, or if globally is False, the minimal model returned will preserve integrality at other primes, but not minimality.
OUTPUT:

If $P$ is specified, returns the `EllipticCurveLocalData` object associated to the prime $P$ for this curve. Otherwise, returns a list of such objects, one for each prime $P$ in the support of the discriminant of this model.

Note: The model is not required to be integral on input.

EXAMPLES:

```python
sage: K.<i> = NumberField(x^2+1)
sage: E = EllipticCurve([1 + i, 0, 1, 0, 0])
sage: E.local_data()
[Local data at Fractional ideal (2*i + 1):
  Reduction type: bad non-split multiplicative
  Local minimal model: Elliptic Curve defined by y^2 + (i+1)*x*y + y = x^3 over
  Number Field in i with defining polynomial x^2 + 1
  Minimal discriminant valuation: 1
  Conductors exponent: 1
  Kodaira Symbol: I1
  Tamagawa Number: 1,
  Local data at Fractional ideal (-3*i - 2):
  Reduction type: bad split multiplicative
  Local minimal model: Elliptic Curve defined by y^2 + (i+1)*x*y + y = x^3 over
  Number Field in i with defining polynomial x^2 + 1
  Minimal discriminant valuation: 2
  Conductors exponent: 1
  Kodaira Symbol: I2
  Tamagawa Number: 2]
sage: E.local_data(K.ideal(3))
Local data at Fractional ideal (3):
  Reduction type: good
  Local minimal model: Elliptic Curve defined by y^2 + (i+1)*x*y + y = x^3 over
  Number Field in i with defining polynomial x^2 + 1
  Minimal discriminant valuation: 0
  Conductors exponent: 0
  Kodaira Symbol: I0
  Tamagawa Number: 1
sage: E.local_data(2*i + 1)
Local data at Fractional ideal (2*i + 1):
  Reduction type: bad non-split multiplicative
  Local minimal model: Elliptic Curve defined by y^2 + (i+1)*x*y + y = x^3 over
  Number Field in i with defining polynomial x^2 + 1
  Minimal discriminant valuation: 1
  Conductors exponent: 1
  Kodaira Symbol: I1
  Tamagawa Number: 1
```

An example raised in trac ticket #3897:

```python
sage: E = EllipticCurve([1,1])
sage: E.local_data(3)
```

(continues on next page)
Reduction type: good
Local minimal model: Elliptic Curve defined by $y^2 = x^3 + x + 1$ over Rational Field
Minimal discriminant valuation: 0
Conductor exponent: 0
Kodaira Symbol: I0
Tamagawa Number: 1

\textbf{local\_integral\_model}(\textit{P})

Return a model of self which is integral at the prime ideal $P$.

\textbf{Note:} The integrality at other primes is not affected, even if $P$ is non-principal.

\textbf{INPUT:}
- \textit{P} – a prime ideal, or a list or tuple of primes.

\textbf{EXAMPLES:}

\texttt{sage: K.<i> = NumberField(x^2+1)}
\texttt{sage: P1,P2 = K.primes_above(5)}
\texttt{sage: E = EllipticCurve([i/5,i/5,i/5,i/5,i/5])}
\texttt{sage: E.local_integral_model((P1,P2))}
Elliptic Curve defined by $y^2 + (-i)*x*y + (-25*i)*y = x^3 + 5*i*x^2 + 125*i*x + 3125*i$ over Number Field in i with defining polynomial $x^2 + 1$

\textbf{local\_minimal\_model}(\textit{P}, \textit{proof}=None, \textit{algorithm}=\textquote{pari})

Return a model which is integral at all primes and minimal at $P$.

\textbf{INPUT:}
- \textit{P} – either None or a prime ideal of the base field of self.
- \textit{proof} – whether to only use provably correct methods (default controlled by global proof module). Note that the proof module is number_field, not elliptic_curves, since the functions that actually need the flag are in number fields.
- \textit{algorithm} (string, default: “pari”) – Ignored unless the base field is $\mathbb{Q}$. If “pari”, use the PARI C-library \texttt{pariellglobalred} implementation of Tate’s algorithm over $\mathbb{Q}$. If “generic”, use the general number field implementation.

\textbf{OUTPUT:}
A model of the curve which is minimal (and integral) at $P$.

\textbf{Note:} The model is not required to be integral on input.

For principal $P$, a generator is used as a uniformizer, and integrality or minimality at other primes is not affected. For non-principal $P$, the minimal model returned will preserve integrality at other primes, but not minimality.

\textbf{EXAMPLES:}

\texttt{sage: K.<a> = NumberField(x^2-5)}
\texttt{sage: E = EllipticCurve([20, 225, 750, 1250*a + 6250, 62500*a + 15625])}
minimal_discriminant_ideal()

Return the minimal discriminant ideal of this elliptic curve.

OUTPUT:

The integral ideal $D$ whose valuation at every prime $P$ is that of the local minimal model for $E$ at $P$. If $E$ has a global minimal model, this will be the principal ideal generated by the discriminant of any such model, but otherwise it can be a proper divisor of the discriminant of any model.

EXAMPLES:

```python
sage: K.<a> = NumberField(x^2-x-57)
sage: K.class_number()
3
sage: E = EllipticCurve([a,-a,a,-5692-820*a,-259213-36720*a])
sage: K.ideal(E.discriminant())
Fractional ideal (90118662980*a + 636812084644)
sage: K.ideal(E.discriminant()).factor()
(Fractional ideal (2))^2 * (Fractional ideal (3, a + 2))^12
```

Here the minimal discriminant ideal is principal but there is no global minimal model since the quotient is the 12th power of a non-principal ideal:

```python
sage: E.minimal_discriminant_ideal()
Fractional ideal (4)
sage: E.minimal_discriminant_ideal().factor()
(Fractional ideal (2))^2
```

If (and only if) the curve has everywhere good reduction the result is the unit ideal:

```python
sage: K.<a> = NumberField(x^2-26)
sage: E = EllipticCurve([a,a-1,a+1,4*a+10,2*a+6])
sage: E.conductor()
Fractional ideal (1)
sage: E.discriminant()
-104030*a - 530451
sage: E.minimal_discriminant_ideal()
Fractional ideal (1)
```

Over $\mathbb{Q}$, the result returned is an ideal of $\mathbb{Z}$ rather than a fractional ideal of $\mathbb{Q}$:

```python
sage: E = EllipticCurve([1,2,3,4,5])
sage: E.minimal_discriminant_ideal()
Principal ideal (10351) of Integer Ring
```

non_minimal_primes()

Return a list of primes at which this elliptic curve is not minimal.

OUTPUT:

A list of prime ideals (or prime numbers when the base field is $\mathbb{Q}$, empty if this is a global minimal model.

EXAMPLES:
Elliptic curves, Release 9.7

sage: K.<a> = NumberField(x^2-10)
sage: E = EllipticCurve([0, 0, 0, -22500, 750000*a])
sage: E.non_minimal_primes()
[Fractional ideal (2, a), Fractional ideal (5, a)]
sage: K.ideal(E.discriminant()).factor()
(Fractional ideal (2, a))^24 * (Fractional ideal (3, a + 1))^5 * (Fractional ideal (3, a + 2))^5 * (Fractional ideal (5, a))^24 * (Fractional ideal (7))
sage: E.minimal_discriminant_ideal().factor()
(Fractional ideal (2, a))^12 * (Fractional ideal (3, a + 1))^5 * (Fractional ideal (3, a + 2))^5 * (Fractional ideal (7))

Over $\mathbb{Q}$, the primes returned are integers, not ideals:

sage: E = EllipticCurve([0,0,0,-3024,46224])
sage: E.non_minimal_primes()
[2, 3]
sage: Emin = E.global_minimal_model()
sage: Emin.non_minimal_primes()
[]

If the model is not globally integral, a ValueError is raised:

sage: E = EllipticCurve([0,0,0,1/2,1/3])
sage: E.non_minimal_primes()
Traceback (most recent call last):
... ValueError: non_minimal_primes only defined for integral models

**period_lattice**(embedding)
Return the period lattice of the elliptic curve for the given embedding of its base field with respect to the differential $dx/(2y+a_1x+a_3)$.

**INPUT:**

- embedding – an embedding of the base number field into $\mathbb{R}$ or $\mathbb{C}$.

**Note:** The precision of the embedding is ignored: we only use the given embedding to determine which embedding into $\mathbb{Q}bar$ to use. Once the lattice has been initialized, periods can be computed to arbitrary precision.

**EXAMPLES:**

First define a field with two real embeddings:

sage: K.<a> = NumberField(x^3-2)
sage: E = EllipticCurve([0,0,a,a,2])
sage: embs = K.embeddings(CC); len(embs)
3

For each embedding we have a different period lattice:

sage: E.period_lattice(embs[0])
Period lattice associated to Elliptic Curve defined by y^2 = x^3 + a*x + 2 over
Number Field in a with defining polynomial x^3 - 2 with respect to the
embedding Ring morphism:
From: Number Field in a with defining polynomial $x^3 - 2$
To: Algebraic Field
Defn: $a \mapsto -0.6299605249474365? - 1.091123635971722?i$

`sage:` E.period_lattice(embs[1])
Period lattice associated to Elliptic Curve defined by $y^2 = x^3 + a\cdot x + 2$ over
Number Field in a with defining polynomial $x^3 - 2$ with respect to the
embedding Ring morphism:
From: Number Field in a with defining polynomial $x^3 - 2$
To: Algebraic Field
Defn: $a \mapsto -0.6299605249474365? + 1.091123635971722?i$

`sage:` E.period_lattice(embs[2])
Period lattice associated to Elliptic Curve defined by $y^2 = x^3 + a\cdot x + 2$ over
Number Field in a with defining polynomial $x^3 - 2$ with respect to the
embedding Ring morphism:
From: Number Field in a with defining polynomial $x^3 - 2$
To: Algebraic Field
Defn: $a \mapsto 1.259921049894873?$

Although the original embeddings have only the default precision, we can obtain the basis with higher
precision later:

`sage:` L=E.period_lattice(embs[0])
`sage:` L.basis()
(1.86405007647981 - 0.903761485143226*I, -0.149344633143919 - 2.0661954272945*I)

`sage:` L.basis(prec=100)
(1.8640500764798108425920506200 - 0.90376148514322594749786960975*I, -0.14934463314391922099120107422 - 2.066195427294548995621225062*I)

```
rank(**kwds)
```
Return the rank of this elliptic curve, if it can be determined.

**Note:** The optional parameters control the Simon two descent algorithm; see the documentation of `simon_two_descent()` for more details.
If the upper and lower bounds given by Simon two-descent are the same, then the rank has been uniquely identified and we return this. Otherwise, we raise a `ValueError` with an error message specifying the upper and lower bounds.

**Note:** For non-quadratic number fields, this code does return, but it takes a long time.

**EXAMPLES:**

```python
sage: K.<a> = NumberField(x^2 + 23, 'a')
sage: E = EllipticCurve(K, '37')
sage: E == loads(dumps(E))
True
sage: E.rank()
2
```

Here is a curve with two-torsion in the Tate-Shafarevich group, so here the bounds given by the algorithm do not uniquely determine the rank:

```python
sage: E = EllipticCurve("15a5")
sage: K.<t> = NumberField(x^2-6)
sage: EK = E.base_extend(K)
sage: EK.rank(lim1=1, lim3=1, limtriv=1)
Traceback (most recent call last):
  ...  
ValueError: There is insufficient data to determine the rank - 2-descent gave lower bound 0 and upper bound 2
```

**IMPLEMENTATION:**


`rank_bounds(**kwds)`

Return the lower and upper bounds using `simon_two_descent()`. The results of `simon_two_descent()` are cached.

**Note:** The optional parameters control the Simon two descent algorithm; see the documentation of `simon_two_descent()` for more details.

**INPUT:**

- `verbose` – 0, 1, 2, or 3 (default: 0), the verbosity level
- `lim1` – (default: 2) limit on trivial points on quartics
- `lim3` – (default: 4) limit on points on ELS quartics
- `limtriv` – (default: 2) limit on trivial points on elliptic curve
- `maxprob` – (default: 20)
- `limbigprime` – (default: 30) to distinguish between small and large prime numbers. Use probabilistic tests for large primes. If 0, do not use probabilistic tests.
- `known_points` – (default: None) list of known points on the curve

**OUTPUT:**

lower and upper bounds for the rank of the Mordell-Weil group

14.3. Elliptic curves over number fields
Note: For non-quadratic number fields, this code does return, but it takes a long time.

EXAMPLES:

```
sage: K.<a> = NumberField(x^2 + 23, 'a')
sage: E = EllipticCurve(K, '37')
sage: E == loads(dumps(E))
True
sage: E.rank_bounds()
(2, 2)
```

Here is a curve with two-torsion, again the bounds coincide:

```
sage: Qrt5.<rt5> = NumberField(x^2-5)
sage: E = EllipticCurve([0,5-rt5,0,rt5,0])
sage: E.rank_bounds()
(1, 1)
```

Finally an example with non-trivial 2-torsion in Sha. So the 2-descent will not be able to determine the rank, but can only give bounds:

```
sage: E = EllipticCurve("15a5")
sage: K.<t> = NumberField(x^2-6)
sage: EK = E.base_extend(K)
sage: EK.rank_bounds(lim1=1,lim3=1,limtriv=1)
(0, 2)
```

IMPLEMENTATION:

```
rational_points(**kwds)
```

Find rational points on the elliptic curve, all arguments are passed on to sage.schemes.generic.algebraic_scheme.rational_points().

EXAMPLES:

```
sage: E = EllipticCurve('37a')
sage: E.rational_points(bound=8) # long time
[(-1 : -1 : 1),
 (-1 : 0 : 1),
 (0 : -1 : 1),
 (0 : 0 : 1),
 (0 : 1 : 0),
 (1/4 : -5/8 : 1),
 (1/4 : -3/8 : 1),
 (1 : -1 : 1),
 (1 : 0 : 1),
 (2 : -3 : 1),
 (2 : 2 : 1)]
```

Check that trac ticket #26677 is fixed:
```python
sage: E = EllipticCurve("11a1")
sage: E.rational_points(bound=5)
[\((0 : 1 : 0), (5 : 5 : 1)\)]
sage: E.rational_points(bound=6) # long time
[\((0 : 1 : 0), (5 : -6 : 1), (5 : 5 : 1)\)]
```

An example over a number field:

```python
sage: E = EllipticCurve([1,0])
sage: pts = E.rational_points(bound = 2, F = QuadraticField(-1))
sage: pts
[\((-a : 0 : 1), (0 : 0 : 1), (0 : 1 : 0), (a : 0 : 1)\)]
sage: pts[0] + pts[1]
(a : 0 : 1)
```

**real_components(embedding)**

Return the number of real components with respect to a real embedding of the base field.

**EXAMPLES:**

```python
sage: K.<a> = QuadraticField(5)
sage: embs = K.real_embeddings()
sage: E = EllipticCurve([0,1,1,a,a])
sage: [e(E.discriminant()) > 0 for e in embs]
[True, False]
sage: [E.real_components(e) for e in embs]
[2, 1]
```

**reducible_primes(algorithm='Billerey', max_l=None, num_l=None, verbose=False)**

Return a finite set of primes \(\ell\) for which \(E\) has a \(K\)-rational \(\ell\)-isogeny.

For curves without CM the list returned is exactly the finite set of primes \(\ell\) for which the mod-\(\ell\) Galois representation is reducible. For curves with CM this set is infinite; we return a finite list of primes \(\ell\) such that every curve isogenous to this curve can be obtained by a finite sequence of isogenies of degree one of the primes in the list.

**INPUT:**

- **algorithm** (string) – only relevant for non-CM curves. Either ‘Billerey’, to use the methods of [Bil2011], ‘Larson’ to use Larson’s implementation using Galois representations, or ‘heuristic’ (see below).
- **max_l** (int or None) – only relevant for non-CM curves and algorithms ‘Billerey’ and ‘heuristic’. Controls the maximum prime used in either algorithm. If None, use the default for that algorithm.
- **num_l** (int or None) – only relevant for non-CM curves and algorithm ‘Billerey’. Controls the maximum number of primes used in the algorithm. If None, use the default for that algorithm.

**Note:** The ‘heuristic’ algorithm only checks primes up to the bound \(\text{max}_l\). This is faster but not guaranteed to be complete. Both the Billerey and Larson algorithms are rigorous.

**EXAMPLES:**

```python
sage: K = NumberField(x**2 - 29, 'a'); a = K.gen()
sage: E = EllipticCurve([1, 0, ((5 + a)/2)**2, 0, 0])
(continues on next page)
```

14.3. Elliptic curves over number fields 351
sage: rho = E.galois_representation()
sage: rho.reducible_primes() # long time
[3, 5]
sage: E.reducible_primes() # long time
[3, 5]
sage: K = NumberField(x**2 + 1, 'a')
sage: E = EllipticCurve_from_j(K(1728)) # CM over K
sage: rho = E.galois_representation()
sage: rho.reducible_primes() # CM curves always return [0]
[0]
sage: E.reducible_primes()
[2]
sage: E = EllipticCurve_from_j(K(0)) # CM but NOT over K
sage: rho = E.galois_representation()
sage: rho.reducible_primes() # long time
[2, 3]
sage: E.reducible_primes()
[2, 3]
sage: E = EllipticCurve_from_j(K(2268945/128)).global_minimal_model() # c.f. [Sut2012]
sage: rho = E.galois_representation()
sage: rho.isogeny_bound() # .. but there is no 7-isogeny, long time
[7]
sage: rho.reducible_primes() # long time
[]
sage: E.reducible_primes() # long time
[]

reduction(place)

Return the reduction of the elliptic curve at a place of good reduction.

INPUT:

- place – a prime ideal in the base field of the curve

OUTPUT:

An elliptic curve over a finite field, the residue field of the place.

EXAMPLES:

sage: K.<i> = QuadraticField(-1)
sage: EK = EllipticCurve([0,0,0,i,i+3])
sage: v = K.fractional_ideal(2*i+3)
sage: EK.reduction(v)
Elliptic Curve defined by y^2 = x^3 + 5*x + 8 over Residue field of Fractional_ideal (2*i + 3)
sage: EK.reduction(K.ideal(1+i))
Traceback (most recent call last):
  ... ValueError: The curve must have good reduction at the place.
sage: EK.reduction(K.ideal(2))
Traceback (most recent call last):
  ... ValueError: The ideal must be prime.
sage: K=QQ.extension(x^2+x+1,"a")
sage: E = EllipticCurve([1024*K.0,1024*K.0])
sage: E.reduction(2*K)
Elliptic Curve defined by y^2 + (abar+1)*y = x^3 over Residue field in abar of Fractional ideal (2)

regulator_of_points(points=[], precision=None, normalised=True)
Return the regulator of the given points on this curve.

INPUT:

• points – (default: empty list) a list of points on this curve
• precision – int or None (default: None): the precision in bits of the result (default real precision if None)
• normalised (bool, default True) – if True, use normalised heights which are independent of base change. Otherwise use the non-normalised Néron-Tate height, as required for the regulator in the BSD conjecture

EXAMPLES:

sage: E = EllipticCurve('37a1')
sage: P = E(0,0)
sage: Q = E(1,0)
sage: E.regulator_of_points([P,Q])
0.000000000000000
sage: 2*P == Q
True

sage: E = EllipticCurve('5077a1')
sage: points = [E.lift_x(x) for x in [-2,-7/4,1]]
sage: E.regulator_of_points(points)
0.417143558758384
sage: E.regulator_of_points(points,precision=100)
0.41714355875838396981711954462

sage: E = EllipticCurve('389a1')
sage: E.regulator_of_points()
1.00000000000000
sage: points = [P,Q] = [E(-1,1),E(0,-1)]
sage: E.regulator_of_points(points)
0.152460177943144
sage: E.regulator_of_points(points, precision=100)
0.15246017794314375162432475705
sage: E.regulator_of_points(points, precision=200)
0.15246017794314375162432475704945582324372707748663081784028
sage: E.regulator_of_points(points, precision=300)
0.

Examples over number fields:
Elliptic curves, Release 9.7

\begin{verbatim}
sage: K.<a> = QuadraticField(97)
sage: E = EllipticCurve(K,[1,1])
sage: P = E(0,1)
sage: P.height()
0.476223106404866
sage: E.regulator_of_points([P])
0.476223106404866

When the parameter normalised is set to False, each height is multiplied by the degree \( d \) of the base field, and the regulator of \( r \) points is multiplied by \( d^r \):

\begin{verbatim}
sage: P.height(normalised=False)
0.952446212809731
sage: E.regulator_of_points([P], normalised=False)
0.952446212809731
\end{verbatim}

\begin{verbatim}
sage: E = EllipticCurve('11a1')
sage: x = polygen(QQ)
sage: K.<t> = NumberField(x^2+47)
sage: EK = E.base_extend(K)
sage: T = EK(5,5)
sage: T.order()
5
sage: P = EK(-2, -1/2*t - 1/2)
sage: P.order() +Infinity
sage: EK.regulator_of_points([P,T]) # random very small output
-1.23259516440783e-32
sage: EK.regulator_of_points([P,T]).abs() < 1e-30
True
\end{verbatim}

\begin{verbatim}
sage: E = EllipticCurve('389a1')
sage: P,Q = E.gens()
sage: E.regulator_of_points([P,Q])
0.152460177943144
sage: K.<t> = NumberField(x^2+47)
sage: EK = E.base_extend(K)
sage: EK.regulator_of_points([EK(P),EK(Q)])
0.152460177943144
\end{verbatim}

\begin{verbatim}
sage: K.<i> = QuadraticField(-1)
sage: E = EllipticCurve([0,0,0,i,i])
sage: P = E(-9+4*i,-18-25*i)
sage: Q = E(i,-i)
sage: E.height_pairing_matrix([P,Q])
\begin{bmatrix}
2.16941934493768 & -0.870059380421505 \\
-0.870059380421505 & 0.424585837470709
\end{bmatrix}
sage: E.regulator_of_points([P,Q])
0.164101403936070
\end{verbatim}

\texttt{saturation(points, \texttt{verbose}=False, \texttt{max_prime}=0, \texttt{one_prime}=0, \texttt{odd_primes_only}=False, \\
\texttt{lower_ht_bound}=None, \texttt{reg}=None, \texttt{debug}=False)}

Given a list of rational points on \( E \) over \( K \), compute the saturation in \( E(K) \) of the subgroup they generate.
\end{verbatim}
INPUT:

- **points** (list) – list of points on E. Points of finite order are ignored; the remaining points should be independent, or an error is raised.
- **verbose** (bool) – (default: False), if True, give verbose output.
- **max_prime** (int, default 0) – saturation is performed for all primes up to max_prime. If max_prime is 0, perform saturation at all primes, i.e., compute the true saturation.
- **odd_primes_only** (bool, default False) – only do saturation at odd primes.
- **one_prime** (int, default 0) – if nonzero, only do saturation at this prime.

The following two inputs are optional, and may be provided to speed up the computation.

- **lower_ht_bound** (real, default None) – lower bound of the regulator $E(K)$, if known.
- **reg** (real, default None) – regulator of the span of points, if known.
- **debug** (int, default 0) – used for debugging and testing.

OUTPUT:

- **saturation** (list) – points that form a basis for the saturation.
- **index** (int) – the index of the group generated by the input points in their saturation.
- **regulator** (real with default precision, or None) – regulator of saturated points.

EXAMPLES:

```python
sage: K.<i> = QuadraticField(-1)
sage: E = EllipticCurve('389a1')
sage: EK = E.change_ring(K)
sage: P = EK(-1,1); Q = EK(0,-1)

sage: EK.saturation([2*P], max_prime=2)
([(-1 : 1 : 1)], 2, 0.686667083305587)
sage: EK.saturation([12*P], max_prime=2)
([26/361 : -5720/6859 : 1], 4, 6.18000374975028)
sage: EK.saturation([12*P], lower_ht_bound=0.1)
([(-1 : 1 : 1)], 12, 0.686667083305587)
sage: EK.saturation([2*P, Q], max_prime=2)
([(-1 : 1 : 1), (0 : -1 : 1)], 2, 0.152460177943144)
sage: EK.saturation([P+Q, P-Q], lower_ht_bound=.1, debug=2)
([(-1 : 1 : 1), (1 : 0 : 1)], 2, 0.152460177943144)
sage: EK.saturation([P+Q, 17*Q], lower_ht_bound=0.1)  # long time
([(4 : 8 : 1), (0 : -1 : 1)], 17, 0.152460177943143)

sage: R = EK(i-2,-i-3)
sage: EK.saturation([P+R, P+Q, Q+R], lower_ht_bound=0.1)
([(841/1369*i - 171/1369 : 41334/50653*i - 74525/50653 : 1),
(4 : 8 : 1),
(-1/25*i + 18/25 : -69/125*i - 58/125 : 1)], 2,
0.183174443217351)
sage: EK.saturation([26*Q], lower_ht_bound=0.1)
([(0 : -1 : 1)], 26, 0.327000773651605)
```

Another number field:
Elliptic curves, Release 9.7

```
sage: E = EllipticCurve('389a1')
sage: K.<a> = NumberField(x^3-x+1)
sage: EK = E.change_ring(K)
sage: P = EK(-1,1); Q = EK(0,-1)
sage: EK.saturation([P+Q, P-Q], lower_ht_bound=0.1)
([(-1 : 1 : 1), (1 : 0 : 1)], 2, 0.152460177943144)
sage: EK.saturation([3*P, P+5*Q], lower_ht_bound=0.1)
([(-185/2209 : -119510/103823 : 1), (80041/34225 : -26714961/6331625 : 1)],
  15,
  0.152460177943144)
```

A different curve:

```
sage: K.<a> = QuadraticField(3)
sage: E = EllipticCurve('37a1')
sage: EK = E.change_ring(K)
sage: P = EK(0,0); Q = EK(2-a,2*a-4)
sage: EK.saturation([3*P-Q, 3*P+Q], lower_ht_bound=.01)
([0 : 0 : 1), (1/2*a : -1/4*a - 1/4 : 1)], 6, 0.0317814530725985)
```

The points must be linearly independent:

```
sage: EK.saturation([[2*P, 3*Q, P-Q]])
Traceback (most recent call last):
  ...
ValueError: points not linearly independent in saturation()
```

Degenerate case:

```
sage: EK.saturation([])
([], 1, 1.00000000000000)
```

ALGORITHM:

For rank 1 subgroups, simply do trial division up to the maximal prime divisor. For higher rank sub-
groups, perform trial division on all linear combinations for small primes, and look for projections
\(E(K) \to \oplus E(k) \otimes F_p\) which are either full rank or provide \(p\)-divisible linear combinations, where the \(k\)
here are residue fields of \(K\).

```
simon_two_descent(Verbose=0, lim1=2, lim3=4, limtriv=2, maxprob=20, limbigprime=30,
  known_points=None)
```

Return lower and upper bounds on the rank of the Mordell-Weil group \(E(K)\) and a list of points.

This method is used internally by the \(rank()\), \(rank_bounds()\) and \(gens()\) methods.

INPUT:

- `self` – an elliptic curve \(E\) over a number field \(K\)
- `verbose` – 0, 1, 2, or 3 (default: 0), the verbosity level
- `lim1` – (default: 2) limit on trivial points on quartics
- `lim3` – (default: 4) limit on points on ELS quartics
- `limtriv` – (default: 2) limit on trivial points on \(E\)
- `maxprob` – (default: 20)
• limbigprime – (default: 30) to distinguish between small and large prime numbers. Use probabilistic tests for large primes. If 0, do not use probabilistic tests.

• known_points – (default: None) list of known points on the curve

OUTPUT: a triple (lower, upper, list) consisting of

• lower (integer) – lower bound on the rank

• upper (integer) – upper bound on the rank

• list – list of points in $E(K)$

The integer upper is in fact an upper bound on the dimension of the 2-Selmer group, hence on the dimension of $E(K)/2E(K)$. It is equal to the dimension of the 2-Selmer group except possibly if $E(K)[2]$ has dimension 1. In that case, upper may exceed the dimension of the 2-Selmer group by an even number, due to the fact that the algorithm does not perform a second descent.

**Note:** For non-quadratic number fields, this code does return, but it takes a long time.

**ALGORITHM:**

Uses Denis Simon’s PARI/GP scripts from https://simond.users.lmno.cnrs.fr/.

**EXAMPLES:**

```python
sage: K.<a> = NumberField(x^2 + 23, 'a')
sage: E = EllipticCurve(K, '37')
sage: E == loads(dumps(E))
True
sage: E.simon_two_descent()
(2, 2, [(0 : 0 : 1)])
sage: E.simon_two_descent(lim1=5, lim3=5, limtriv=10, maxprob=7, limbigprime=10)
(2, 2, [(-1 : 0 : 1), (-2 : -1/2*a - 1/2 : 1)])
```

```python
sage: K.<a> = NumberField(x^2 + 7, 'a')
sage: E = EllipticCurve(K, [0,0,0,1,a]); E
Elliptic Curve defined by y^2 = x^3 + x + a over Number Field in a with defining polynomial x^2 + 7

sage: v = E.simon_two_descent(verbose=1); v
elliptic curve: Y^2 = x^3 + Mod(1, y^2 + 7)*x + Mod(y, y^2 + 7)
Trivial points on the curve = [[1, 1, 0], [Mod(1/2*y + 3/2, y^2 + 7), Mod(-y - 2, y^2 + 7), 1]]
#S(E/K)[2] = 2
#E(K)/2E(K) = 2
#III(E/K)[2] = 1
rank(E/K) = 1
listpoints = [[Mod(1/2*y + 3/2, y^2 + 7), Mod(-y - 2, y^2 + 7), 1]]
(1, 1, [(1/2*a + 3/2 : -a - 2 : 1)])

sage: v = E.simon_two_descent(verbose=2)
K = bnfinit(y^2 + 7);
a = Mod(y,K.pol);
bnfellrank(K, [0, 0, 0, 1, a], [[Mod(1/2*y + 3/2, y^2 + 7), Mod(-y - 2, y^2 + 7), 1]]);
```

(continues on next page)
A curve with 2-torsion:

```
sage: K.<a> = NumberField(x^2 + 7)
sage: E = EllipticCurve(K, [15*a])
sage: E.simon_two_descent()
# long time (3s on sage.math, 2013), points can vary
(1, 3, [...])
```

Check that the bug reported in trac ticket #15483 is fixed:

```
sage: K.<s> = QuadraticField(229)
sage: c4 = 2173 - 235*(1 - s)/2
sage: c6 = -124369 + 15988*(1 - s)/2
sage: E = EllipticCurve([-c4/48, -c6/864])
sage: E.simon_two_descent()
(0, 0, [])
sage: R.<t> = QQ[]
sage: L.<g> = NumberField(t^3 - 9*t^2 + 13*t - 4)
sage: E1 = EllipticCurve(L,[1-g*(g-1),-g^2*(g-1),-g^2*(g-1),0,0])
sage: E1.rank()
# long time (about 5 s)
0
sage: K = CyclotomicField(43).subfields(3)[0][0]
sage: E = EllipticCurve(K, [37])
sage: E.simon_two_descent()
# long time (4s on sage.math, 2013)
(3, 3, [(5/8*zeta43_0^2 + 17/8*zeta43_0 - 9/4 : -27/16*zeta43_0^2 - 103/16*zeta43_0 +...
  ˓→ 39/8 : 1),
  (0 : 0 : 1)])
```

```
tamagawa_exponent(P, proof=None)
Return the Tamagawa index of this elliptic curve at the prime P.

INPUT:

• P – either None or a prime ideal of the base field of self.

• proof – whether to only use provably correct methods (default controlled by global proof module).
  Note that the proof module is number_field, not elliptic_curves, since the functions that actually need the flag are in number fields.

OUTPUT:

(positive integer) The Tamagawa index of the curve at P.

EXAMPLES:

```
sage: K.<a> = NumberField(x^2-5)
sage: E = EllipticCurve([20, 225, 750, 625*a + 6875, 31250*a + 46875])
```

(continues on next page)
tamagawa_number\((P, proof=None)\)

Return the Tamagawa number of this elliptic curve at the prime \(P\).

**INPUT:**

- \(P\) – either None or a prime ideal of the base field of self.
- \(proof\) – whether to only use provably correct methods (default controlled by global proof module).

Note that the proof module is number_field, not elliptic_curves, since the functions that actually need the flag are in number fields.

**OUTPUT:**

(positive integer) The Tamagawa number of the curve at \(P\).

**EXAMPLES:**

```
sage: K.<a> = NumberField(x^2-5)
sage: E = EllipticCurve([20, 225, 750, 625*a + 6875, 31250*a + 46875])
sage: [E.tamagawa_number(P) for P in E.discriminant().support()]
[1, 1, 1, 1]
sage: K.<a> = QuadraticField(-11)
sage: E = EllipticCurve('11a1').change_ring(K)
sage: [E.tamagawa_number(P) for P in K(11).support()]
[10]
```

tamagawa_numbers()

Return a list of all Tamagawa numbers for all prime divisors of the conductor (in order).

**EXAMPLES:**

```
sage: e = EllipticCurve('30a1')
sage: e.tamagawa_numbers()
[2, 3, 1]
sage: vector(e.tamagawa_numbers())
(2, 3, 1)
sage: K.<a> = NumberField(x^2+3)
sage: eK = e.base_extend(K)
sage: eK.tamagawa_numbers()
[4, 6, 1]
```

tamagawa_product()

Return the product of the Tamagawa numbers \(c_v\) where \(v\) runs over all prime ideals of \(K\).

**Note:** See also tamagawa_product_bsd(), which includes an additional factor when the model is not globally minimal, as required by the BSD formula.

**OUTPUT:**
A positive integer.

EXAMPLES:

```
sage: K.<i> = NumberField(x^2+1)
sage: E = EllipticCurve([0,2+i])
sage: E.tamagawa_product()
1

sage: E = EllipticCurve([(2*i+1)^2,i*(2*i+1)^7])
sage: E.tamagawa_product()
4
```

An example over \( \mathbb{Q} \):

```
sage: E = EllipticCurve('30a')
sage: E.tamagawa_product()
6
```

An example with everywhere good reduction, where the product is empty:

```
sage: x = polygen(QQ)
sage: K.<a> = NumberField(x^2 - 38)
sage: E = EllipticCurve([a, -a + 1, a + 1, -5*a + 15, -5*a + 21])
sage: E.tamagawa_numbers()
[]
sage: E.tamagawa_product()
1
```

tamagawa_product_bsd()

Given an elliptic curve \( E \) over a number field \( K \), this function returns the integer \( C(E/K) \) that appears in the Birch and Swinnerton-Dyer conjecture accounting for the local information at finite places. If the model is a global minimal model then \( C(E/K) \) is simply the product of the Tamagawa numbers \( c_v \) where \( v \) runs over all prime ideals of \( K \). Otherwise, if the model has to be changed at a place \( v \) a correction factor appears. The definition is such that \( C(E/K) \) times the periods at the infinite places is invariant under change of the Weierstrass model. See [Tate1966] and [DD2010] for details.

**Note:** This definition differs from the definition of tamagawa_product for curves defined over \( \mathbb{Q} \). Over the rational number it is always defined to be the product of the Tamagawa numbers, so the two definitions only agree when the model is global minimal.
An example where the Neron model changes over $K$:

```python
sage: K.<t> = NumberField(x^5-10*x^3+5*x^2+10*x+1)
sage: E = EllipticCurve(K, '75a1')
sage: E.tamagawa_product_bsd()
5
sage: da = E.local_data()
sage: [dav.tamagawa_number() for dav in da]
[1, 1]
```

An example over $\mathbb{Q}$ (trac ticket #9413):

```python
sage: E = EllipticCurve('30a')
sage: E.tamagawa_product_bsd()
6
```

torsion_order()

Return the order of the torsion subgroup of this elliptic curve.

OUTPUT:

(integer) the order of the torsion subgroup of this elliptic curve.

EXAMPLES:

```python
sage: E = EllipticCurve('11a1')
sage: K.<t> = NumberField(x^4 + x^3 + 11*x^2 + 41*x + 101)
sage: EK = E.base_extend(K)
sage: EK.torsion_order()   # long time (2s on sage.math, 2014)
25

sage: E = EllipticCurve('15a1')
sage: K.<t> = NumberField(x^2 + 2*x + 10)
sage: EK = E.base_extend(K)
sage: EK.torsion_order()
16

sage: E = EllipticCurve('19a1')
sage: K.<t> = NumberField(x^9-3*x^8-4*x^7+16*x^6-3*x^5-21*x^4+5*x^3+7*x^2-7*x+1)
sage: EK = E.base_extend(K)
sage: EK.torsion_order()
9
```

torsion_points()

Return a list of the torsion points of this elliptic curve.

OUTPUT:

(list) A sorted list of the torsion points.

EXAMPLES:
sage: E = EllipticCurve('11a1')
sage: E.torsion_points()
[(0 : 1 : 0), (5 : -6 : 1), (5 : 5 : 1), (16 : -61 : 1), (16 : 60 : 1)]
sage: K.<t> = NumberField(x^4 + x^3 + 11*x^2 + 41*x + 101)
sage: EK = E.base_extend(K)
sage: EK.torsion_points()  # long time (1s on sage.math, 2014)
[(0 : 1 : 0),
 (t : 1/11*t^3 + 6/11*t^2 + 19/11*t + 48/11 : 1),
 (1/11*t^3 - 5/11*t^2 + 19/11*t - 40/11 : 6/11*t^3 - 3/11*t^2 - 26/11*t - 321/
 11 : 1),
 (1/11*t^3 - 5/11*t^2 + 19/11*t - 40/11 : 6/11*t^3 + 3/11*t^2 + 26/11*t + 310/
 11 : 1),
 (t : -1/11*t^3 - 6/11*t^2 - 19/11*t - 59/11 : 1),
 (16 : 60 : 1),
 (-3/55*t^3 - 7/55*t^2 - 2/55*t - 133/55 : 6/55*t^3 + 3/55*t^2 + 25/11*t + 156/
 55 : 1),
 (14/121*t^3 - 15/121*t^2 + 90/121*t + 232/121 : 16/121*t^3 - 69/121*t^2 + 293/
 121*t - 46/121 : 1),
 (-26/121*t^3 + 20/121*t^2 - 219/121*t - 995/121 : -15/121*t^3 - 156/121*t^2 +
 232/121*t - 2887/121 : 1),
 (10/121*t^3 + 49/121*t^2 + 168/121*t + 73/121 : -32/121*t^3 - 60/121*t^2 + 261/
 121*t + 686/121 : 1),
 (5 : 5 : 1),
 (-9/121*t^3 - 21/121*t^2 - 127/121*t - 377/121 : -7/121*t^3 + 24/121*t^2 + 197/
 121*t + 16/121 : 1),
 (3/55*t^3 + 7/55*t^2 + 2/55*t + 78/55 : 7/55*t^3 - 24/55*t^2 + 9/11*t + 17/55,
 1 : 1),
 (-5/121*t^3 + 36/121*t^2 - 84/121*t + 24/121 : -34/121*t^3 + 27/121*t^2 - 305/
 121*t - 829/121 : 1),
 (5/121*t^3 - 14/121*t^2 - 158/121*t - 453/121 : 49/121*t^3 + 129/121*t^2 + 315/
 121*t + 86/121 : 1),
 (5 : -6 : 1),
 (5/121*t^3 - 14/121*t^2 - 158/121*t - 453/121 : -49/121*t^3 + 129/121*t^2 -
 315/121*t - 207/121 : 1),
 (-5/121*t^3 + 36/121*t^2 - 84/121*t + 24/121 : 34/121*t^3 - 27/121*t^2 + 305/
 121*t + 708/121 : 1),
 (3/55*t^3 + 7/55*t^2 + 2/55*t + 78/55 : -7/55*t^3 + 24/55*t^2 - 9/11*t - 72/55,
 1 : 1),
 (-9/121*t^3 - 21/121*t^2 - 127/121*t - 377/121 : 17/121*t^3 - 24/121*t^2 + 197/
 121*t - 137/121 : 1),
 (16 : -61 : 1),
 (10/121*t^3 + 49/121*t^2 + 168/121*t + 73/121 : 32/121*t^3 + 60/121*t^2 - 261/
 121*t - 807/121 : 1),
 (-26/121*t^3 + 20/121*t^2 - 219/121*t - 995/121 : 15/121*t^3 + 156/121*t^2 -
 232/121*t + 2766/121 : 1),
 (14/121*t^3 - 15/121*t^2 + 90/121*t + 232/121 : -16/121*t^3 + 69/121*t^2 - 293/
 121*t - 75/121 : 1),
 (-3/55*t^3 - 7/55*t^2 - 2/55*t - 133/55 : -6/55*t^3 - 3/55*t^2 - 26/11*t - 211/
 55 : 1)]

sage: E = EllipticCurve('15a1')
sage: K.<t> = NumberField(x^2 + 2*x + 10)

(continues on next page)
Elliptic curves, Release 9.7

sage: EK = E.base_extend(K)
sage: EK.torsion_points()
[(-7 : -5*t - 2 : 1),
 (-7 : 5*t + 8 : 1),
 (-13/4 : 9/8 : 1),
 (-2 : -2 : 1),
 (-2 : 3 : 1),
 (-t - 2 : -t - 7 : 1),
 (-t - 2 : 2*t + 8 : 1),
 (-1 : 0 : 1),
 (t : -5 : 1),
 (t : -2*t + 4 : 1),
 (0 : 1 : 0),
 (1/2 : -5/4*t - 2 : 1),
 (1/2 : 5/4*t + 1/2 : 1),
 (3 : -2 : 1),
 (8 : -27 : 1),
 (8 : 18 : 1)]

sage: K.<i> = QuadraticField(-1)
sage: EK = EllipticCurve(K,[0,0,0,0,-1])
sage: EK.torsion_points ()
[(-2 : -3*i : 1), (-2 : 3*i : 1), (0 : -i : 1), (0 : i : 1), (0 : 1 : 0), (1 : 0 : 1)]

torsion_subgroup()

Return the torsion subgroup of this elliptic curve.

OUTPUT:

(EllipticCurveTorsionSubgroup) The EllipticCurveTorsionSubgroup associated to this elliptic curve.

EXAMPLES:

sage: E = EllipticCurve('11a1')
sage: K.<t> = NumberField(x^4 + x^3 + 11*x^2 + 41*x + 101)
sage: EK = E.base_extend(K)
sage: tor = EK.torsion_subgroup()  # long time (2s on sage.math, 2014)
sage: tor  # long time
Torsion Subgroup isomorphic to Z/5 + Z/5 associated to the Elliptic Curve
defined by y^2 + y = x^3 + (-1)*x^2 + (-10)*x + (-20) over Number Field in t
with defining polynomial x^4 + x^3 + 11*x^2 + 41*x + 101
sage: tor gens()  # long time
((16 : 60 : 1), (t : 1/11*t^3 + 6/11*t^2 + 19/11*t + 48/11 : 1))

sage: E = EllipticCurve('15a1')
sage: K.<t> = NumberField(x^2 + 2*x + 10)
sage: EK = E.base_extend(K)
sage: EK.torsion_subgroup()
Torsion Subgroup isomorphic to Z/4 + Z/4 associated to the Elliptic Curve
defined by y^2 + x*y + y = x^3 + x^2 + (-10)*x + (-10) over Number Field in t
with defining polynomial x^2 + 2*x + 10
Elliptic curves, Release 9.7

\begin{verbatim}
sage: E = EllipticCurve('19a1')
sage: K.<t> = NumberField(x^9-3*x^8-4*x^7+16*x^6-3*x^5-21*x^4+5*x^3+7*x^2-7*x+1)
sage: EK = E.base_extend(K)
sage: EK.torsion_subgroup() Torsion Subgroup isomorphic to Z/9 associated to the Elliptic Curve defined by \[ \rightarrow y^2 + y = x^3 + x^2 + (-9)*x + (-15) \] over Number Field in t with defining polynomial \[ \rightarrow x^9 - 3*x^8 - 4*x^7 + 16*x^6 - 3*x^5 - 21*x^4 + 5*x^3 + 7*x^2 - 7*x + 1 \]

sage: K.<i> = QuadraticField(-1)
sage: EK = EllipticCurve([0,0,0,i,i+3])
sage: EK.torsion_subgroup () Torsion Subgroup isomorphic to Trivial group associated to the Elliptic Curve defined by \[ \rightarrow y^2 = x^3 + i*x + (i+3) \] over Number Field in i with defining polynomial \[ \rightarrow x^2 + 1 \] with \[ i = 1*I \]
\end{verbatim}

### 14.4 Canonical heights for elliptic curves over number fields

Also, rigorous lower bounds for the canonical height of non-torsion points, implementing the algorithms in [CS2006] (over \( \mathbb{Q} \)) and [Tho2010], which also refer to [CPS2006].

**AUTHORS:**
- Robert Bradshaw (2010): initial version
- John Cremona (2014): added many docstrings and doctests

**Class** `sage.schemes.elliptic_curves.height.EllipticCurveCanonicalHeight(E)`

**Bases:** object

Class for computing canonical heights of points on elliptic curves defined over number fields, including rigorous lower bounds for the canonical height of non-torsion points.

**EXAMPLES:**

\begin{verbatim}
sage: from sage.schemes.elliptic_curves.height import EllipticCurveCanonicalHeight
sage: E = EllipticCurve([0,0,0,1])
sage: E.height_function() EllipticCurveCanonicalHeight(E) object associated to Elliptic Curve defined by \[ y^2 = x^3 + 1 \] over Rational Field

Normally this object would be created like this:

\begin{verbatim}
sage: E.height_function()
EllipticCurveCanonicalHeight(E) object associated to Elliptic Curve defined by \[ y^2 = x^3 + 1 \] over Rational Field
\end{verbatim}

**B(n, mu)**

Return the value \( B_n(\mu) \).

**INPUT:**
- \( n \) (int) – a positive integer
- \( mu \) (real) – a positive real number

364 Chapter 14. Elliptic curves over number fields
OUTPUT:

The real value $B_n(\mu)$ as defined in [Tho2010], section 5.

EXAMPLES:

Example 10.2 from [Tho2010]:

```
sage: K.<i>=QuadraticField(-1)
sage: E = EllipticCurve([0,1-i,i,-i,0])
sage: H = E.height_function()
```

In [Tho2010] the value is given as 0.772:

```
sage: RealField(12)( H.B(5, 0.01) )
0.777
```

DE$(n)$

Return the value $D_E(n)$.

**INPUT:**

- n (int) – a positive integer

**OUTPUT:**

The value $D_E(n)$ as defined in [Tho2010], section 4.

**EXAMPLES:**

```
sage: K.<i>=QuadraticField(-1)
sage: E = EllipticCurve([0,0,0,1+5*i,3+i])
sage: H = E.height_function()
sage: [H.DE(n) for n in srange(1,6)]
[0, 2*log(5) + 2*log(2), 0, 2*log(13) + 4*log(2), 0]
```

ME($E$)

Return the norm of the ideal $M_E$.

**OUTPUT:**

The norm of the ideal $M_E$ as defined in [Tho2010], section 3.1. This is 1 if $E$ is a global minimal model, and in general measures the non-minimality of $E$.

**EXAMPLES:**

```
sage: K.<i>=QuadraticField(-1)
sage: E = EllipticCurve([0,0,0,1+5*i,3+i])
sage: H = E.height_function()
sage: H.ME()
1
sage: E = EllipticCurve([0,0,0,1])
sage: E.height_function().ME()
1
sage: E = EllipticCurve([0,0,0,64])
sage: E.height_function().ME()
4096
sage: E.discriminant()/E.minimal_model().discriminant()
4096
```
\( S(x_1, x_2, v) \)

Return the union of intervals \( S^{(v)}(\xi_1, \xi_2) \).

**INPUT:**

- \( x_1, x_2 \) (real) – real numbers with \( \xi_1 \leq \xi_2 \).
- \( v \) (embedding) – a real embedding of the field.

**OUTPUT:**

The union of intervals \( S^{(v)}(\xi_1, \xi_2) \) defined in [Tho2010] section 6.1.

**EXAMPLES:**

An example over \( \mathbb{Q} \):

```sage
sage: E = EllipticCurve('389a')
sage: v = QQ.places()[0]
sage: H = E.height_function()
sage: H.S(2,3,v)
([0.224512677391895, 0.274544821597130] U [0.725455178402870, 0.775487322608105])
```

An example over a number field:

```sage
sage: K.<a> = NumberField(x^3-2)
sage: E = EllipticCurve([0,0,0,0,a])
sage: v = K.real_places()[0]
sage: H = E.height_function()
sage: H.S(9,10,v)
([0.0781194447253472, 0.0823423732016403] U [0.917657626798360, 0.92188955274653])
```

\( Sn(x_1, x_2, n, v) \)

Return the union of intervals \( S_n^{(v)}(\xi_1, \xi_2) \).

**INPUT:**

- \( x_1, x_2 \) (real) – real numbers with \( \xi_1 \leq \xi_2 \).
- \( n \) (integer) – a positive integer.
- \( v \) (embedding) – a real embedding of the field.

**OUTPUT:**

The union of intervals \( S_n^{(v)}(\xi_1, \xi_2) \) defined in [Tho2010] (Lemma 6.1).

**EXAMPLES:**

An example over \( \mathbb{Q} \):

```sage
sage: E = EllipticCurve('389a')
sage: v = QQ.places()[0]
sage: H = E.height_function()
sage: H.S(2,3,v), H.Sn(2,3,1,v)
(([0.224512677391895, 0.274544821597130] U [0.725455178402870, 0.775487322608105]),
([0.224512677391895, 0.274544821597130] U [0.725455178402870, 0.775487322608105]))
```
An example over a number field:

```
sage: K.<a> = NumberField(x^3-2)
sage: E = EllipticCurve([0,0,0,0,a])
sage: v = K.real_places()[0]
sage: H = E.height_function()
sage: H.Sn(2,3,1,v) , H.Sn(2,3,6,v)
(([0.142172065860075, 0.172845716928584] U [0.827154283071416, 0.857827934139925]),
 ([0.142172065860075, 0.172845716928584] U [0.827154283071416, 0.857827934139925]))
sage: H.Sn(2,3,6,v)
([0.0236953443100124, 0.0288076194880974] U [0.137859047178569, 0.142971322356654] U [0.190362010976679, 0.195474286154764] U [0.30452713845236, 0.3096376989023321] U [0.357028677643346, 0.362140952821431] U [0.471192380511903, 0.476304655689988] U [0.523695344310012, 0.528807619488097] U [0.637859047178569, 0.642971322356654] U [0.690362010976679, 0.695474286154764] U [0.80452713845236, 0.8096376989023321] U [0.857028677643346, 0.862140952821431] U [0.971192380511903, 0.976304655689988]))
```

**alpha(v, tol=0.01)**

Return the constant $\alpha_v$ associated to the embedding $v$.

**INPUT:**

- $v$ – an embedding of the base field into $\mathbb{R}$ or $\mathbb{C}$

**OUTPUT:**

The constant $\alpha_v$. In the notation of [CPS2006] and [Tho2010] (section 3.2), $\alpha_v^3 = \epsilon_v$. The result is cached since it only depends on the curve.

**EXAMPLES:**

Example 1 from [CPS2006]:

```
sage: K.<i>=QuadraticField(-1)
sage: E = EllipticCurve([0,0,0,1+5*i,3+i])
sage: H = E.height_function()
sage: alpha = H.alpha(K.places()[0])
sage: alpha
1.12272013439355
```

Compare with $\log(\epsilon_v) = 0.344562...$ in [CPS2006]:

14.4. Canonical heights for elliptic curves over number fields 367
Elliptic curves, Release 9.7

```python
sage: 3*alpha.log()
0.347263296676126
```

**base_field()**

Return the base field.

**EXAMPLES:**

```python
sage: E = EllipticCurve([0,0,0,0,1])
sage: H = E.height_function()
sage: H.base_field()
Rational Field
```

**complex_intersection_is_empty**(Bk, v, verbose=False, use_half=True)

Returns True iff an intersection of $T_n^{(v)}$ sets is empty.

**INPUT:**

- Bk (list) – a list of reals.
- v (embedding) – a complex embedding of the number field.
- verbose (boolean, default False) – verbosity flag.
- use_half (boolean, default False) – if True, use only half the fundamental region.

**OUTPUT:**

True or False, according as the intersection of the unions of intervals $T_n^{(v)}(-b,b)$ for $b$ in the list Bk (see [Tho2010], section 7) is empty or not. When Bk is the list of $b = \sqrt{B_n(\mu)}$ for $n = 1, 2, 3, \ldots$ for some $\mu > 0$ this means that all non-torsion points on $E$ with everywhere good reduction have canonical height strictly greater than $\mu$, by [Tho2010], Proposition 7.8.

**EXAMPLES:**

```python
sage: K.<a> = NumberField(x^3-2)
sage: E = EllipticCurve([0,0,0,0,a])
sage: v = K.complex_embeddings()[0]
sage: H = E.height_function()
```

The following two lines prove that the heights of non-torsion points on $E$ with everywhere good reduction have canonical height strictly greater than 0.02, but fail to prove the same for 0.03. For the first proof, using only $n = 1, 2, 3$ is not sufficient:

```python
sage: H.complex_intersection_is_empty([H.B(n,0.02) for n in [1,2,3]],v) # long...
time (~6s)
False
sage: H.complex_intersection_is_empty([H.B(n,0.02) for n in [1,2,3,4]],v)
True
sage: H.complex_intersection_is_empty([H.B(n,0.03) for n in [1,2,3,4]],v) # long time (4s)
False
```

Using $n \leq 6$ enables us to prove the lower bound 0.03. Note that it takes longer when the result is False than when it is True:

```python
sage: H.complex_intersection_is_empty([H.B(n,0.03) for n in [1..6]],v)
True
```
curve()

Return the elliptic curve.

EXAMPLES:

```
sage: E = EllipticCurve([0,0,0,0,1])
sage: H = E.height_function()
sage: H.curve()
Elliptic Curve defined by y^2 = x^3 + 1 over Rational Field
```

e_p(p)

Return the exponent of the group over the residue field at p.

INPUT:

* p – a prime ideal of K (or a prime number if K = Q).

OUTPUT:

A positive integer e_p, the exponent of the group of nonsingular points on the reduction of the elliptic curve modulo p. The result is cached.

EXAMPLES:

```
sage: K.<i>=QuadraticField(-1)
sage: E = EllipticCurve([0,0,0,1+5*i,3+i])
sage: H = E.height_function()
sage: H.e_p(K.prime_above(2))
2
sage: H.e_p(K.prime_above(3))
10
sage: H.e_p(K.prime_above(5))
9
sage: E.conductor().norm().factor()
2^10 * 20921
sage: p1, p2 = K.primes_above(20921)
sage: E.local_data(p1)
Local data at Fractional ideal (-40*i + 139):
Reduction type: bad split multiplicative
...
sage: H.e_p(p1)
20920
sage: E.local_data(p2)
Local data at Fractional ideal (40*i + 139):
Reduction type: good
...
sage: H.e_p(p2)
20815
```

fk_intervals(v=None, N=20, domain=Complex Interval Field with 53 bits of precision)

Return a function approximating the Weierstrass function, with error.

INPUT:

* v (embedding) – an embedding of the number field. If None (default) use the real embedding if the field is Q and raise an error for other fields.
* N (int) – The number of terms to use in the q-expansion of \( \wp \).
• domain (complex field) – the model of $\mathbb{C}$ to use, for example CDF of CIF (default).

**OUTPUT:**

A pair of functions $f_k, \text{err}$ which can be evaluated at complex numbers $z$ (in the correct domain) to give an approximation to $\wp(z)$ and an upper bound on the error, respectively. The Weierstrass function returned is with respect to the normalised lattice $[1, \tau]$ associated to the given embedding.

**EXAMPLES:**

```python
sage: E = EllipticCurve('37a')
sage: L = E.period_lattice()
sage: w1, w2 = L.normalised_basis()
sage: z = CDF(0.3, 0.4)
```

Compare the value give by the standard elliptic exponential (scaled since $f_k$ is with respect to the normalised lattice):

```python
sage: L.elliptic_exponential(z*w2, to_curve=False)[0] * w2 ** 2
-1.82543539306049 - 2.49336319992847*I
```

to the value given by this function, and see the error:

```python
sage: fk, err = E.height_function().fk_intervals(N=10)
sage: fk(CIF(z))
-1.8254353930604... - 2.493363199928...*I
```

The same, but in the domain CDF instead of CIF:

```python
sage: fk, err = E.height_function().fk_intervals(N=10, domain=CDF)
sage: fk(z)
-1.8254353930604... - 2.493363199928...*I
```

```
min(tol, n_max, verbose=False)
Returns a lower bound for all points of infinite order.
```

**INPUT:**

• tol – tolerance in output (see below).

• n_max – how many multiples to use in iteration.

• verbose (boolean, default False) – verbosity flag.

**OUTPUT:**

A positive real $\mu$ for which it has been established rigorously that every point of infinite order on the elliptic curve (defined over its ground field) has canonical height greater than $\mu$, and such that it is not possible (at least without increasing $n_max$) to prove the same for $\mu \cdot \text{tol}$.

**EXAMPLES:**

Example 1 from [CS2006] (where the same lower bound of 0.1126 was given):

```python
sage: E = EllipticCurve([1, 0, 1, 421152067, 105484554028056])
# 60490d1
sage: E.height_function().min(.0001, 5)
```

```
0.0011263287309893311
```
Example 10.1 from [Tho2010] (where a lower bound of 0.18 was given):

```python
sage: K.<i> = QuadraticField(-1)
sage: E = EllipticCurve([0,0,0,91-26*i,-144-323*i])
sage: H = E.height_function()
sage: H.min(0.1,4)  # long time (8.1s)
0.1621049443313762
```

Example 10.2 from [Tho2010]:

```python
sage: K.<i> = QuadraticField(-1)
sage: E = EllipticCurve([0,1-i,i,-i,0])
sage: H = E.height_function()
sage: H.min(0.01,5)  # long time (4s)
0.020153685521979152
```

In this example the point $P = (0, 0)$ has height 0.023 so our lower bound is quite good:

```python
sage: P = E((0,0))
sage: P.height()
0.0230242154471211
```

Example 10.3 from [Tho2010] (where the same bound of 0.0625 is given):

```python
sage: K.<a> = NumberField(x^3-2)
sage: E = EllipticCurve([0,0,0,-3*a-a^2,a^2])
sage: H = E.height_function()
sage: H.min(.01, 5)  # long time (7s)
0.0625
```

More examples over $\mathbb{Q}$:

```python
sage: E = EllipticCurve('37a')
sage: h = E.height_function()
sage: h.min(.01, 5)
0.03987318057488725
sage: E.gen(0).height()
0.0511114082399688
```

After base change the lower bound can decrease:

```python
sage: K.<a> = QuadraticField(-5)
sage: E.change_ring(K).height_function().min(0.5,10)  # long time (8s)
0.04419417382415922
sage: E = EllipticCurve('389a')
sage: h = E.height_function()
sage: h.min(0.1, 5)
0.05731275270029196
sage: [P.height() for P in E.gens()]
[0.686667083305587, 0.327000773651605]
```

\texttt{\texttt{min_gr}}(tol, n\_max, verbose=False)

Returns a lower bound for points of infinite order with good reduction.

INPUT:
• tol – tolerance in output (see below).
• n_max – how many multiples to use in iteration.
• verbose (boolean, default False) – verbosity flag.

OUTPUT:
A positive real \( \mu \) for which it has been established rigorously that every point of infinite order on the elliptic curve (defined over its ground field), which has good reduction at all primes, has canonical height greater than \( \mu \), and such that it is not possible (at least without increasing n_max) to prove the same for \( \mu \cdot \text{tol} \).

EXAMPLES:
Example 1 from [CS2006] (where a lower bound of 1.9865 was given):

```sage
E = EllipticCurve([1, 0, 1, 421152067, 105484554028056])
E.height_function().min_gr(.0001, 5)
```

1.98684388146518

Example 10.1 from [Tho2010] (where a lower bound of 0.18 was given):

```sage
K.<i> = QuadraticField(-1)
E = EllipticCurve([0,0,0,91-26*i,-144-323*i])
H = E.height_function()
H.min_gr(0.1,4)
```

# long time (8.1s)

0.1621049443313762

Example 10.2 from [Tho2010]:

```sage
K.<i> = QuadraticField(-1)
E = EllipticCurve([0,1-i,i,-i,0])
H = E.height_function()
H.min_gr(0.01, 5)
```

# long time

0.020153685521979152

In this example the point \( P = (0, 0) \) has height 0.023 so our lower bound is quite good:

```sage
P = E((0,0))
P.has_good_reduction()
True
P.height()
0.0230242154471211
```

Example 10.3 from [Tho2010] (where the same bound of 0.25 is given):

```sage
K.<a> = NumberField(x^3-2)
E = EllipticCurve([0,0,0,-3*a-a^2,a^2])
H = E.height_function()
H.min_gr(0.1,5)
```

# long time (7.2s)

0.25

\( \psi(x, v) \)
Return the normalised elliptic log of a point with this x-coordinate.

INPUT:

• xi (real) – the real x-coordinate of a point on the curve in the connected component with respect to a real embedding.
• \(v\) (embedding) – a real embedding of the number field.

OUTPUT:

A real number in the interval \([0.5, 1]\) giving the elliptic logarithm of a point on \(E\) with \(x\)-coordinate \(x_i\), on the connected component with respect to the embedding \(v\), scaled by the real period.

EXAMPLES:

An example over \(\mathbb{Q}\):

```python
sage: E = EllipticCurve('389a')
sage: v = QQ.places()[0]
sage: L = E.period_lattice(v)
sage: P = E.lift_x(10/9)
sage: L(P)
1.53151606047462
sage: L(P) / L.real_period()
0.615014189772115
sage: H = E.height_function()
sage: H.psi(10/9,v)
0.615014189772115
```

An example over a number field:

```python
sage: K.<a> = NumberField(x^3-2)
sage: E = EllipticCurve([0,0,0,0,a])
sage: P = E.lift_x(1/3*a^2 + a + 5/3)
sage: v = K.real_places()[0]
sage: L = E.period_lattice(v)
sage: L(P)
3.51086196882538
sage: L(P) / L.real_period()
0.867385122699931
sage: xP = v(P.xy()[0])
sage: H = E.height_function()
sage: H.psi(xP,v)
0.867385122699931
sage: H.psi(1.23,v)
0.785854718241495
```

\(\text{real_intersection_is_empty}(B_k, v)\)

Returns True iff an intersection of \(S_n^{(v)}\) sets is empty.

INPUT:

• \(B_k\) (list) – a list of reals.
• \(v\) (embedding) – a real embedding of the number field.

OUTPUT:

True or False, according as the intersection of the unions of intervals \(S_n^{(v)}(−b, b)\) for \(b\) in the list \(B_k\) is empty or not. When \(B_k\) is the list of \(b = B_n(\mu)\) for \(n = 1, 2, 3, \ldots\) for some \(\mu > 0\) this means that all non-torsion points on \(E\) with everywhere good reduction have canonical height strictly greater than \(\mu\), by [Tho2010], Proposition 6.2.

EXAMPLES:

An example over \(\mathbb{Q}\):
The following two lines prove that the heights of non-torsion points on $E$ with everywhere good reduction have canonical height strictly greater than 0.2, but fail to prove the same for 0.3:

```
sage: H.real_intersection_is_empty([H.B(n,0.2) for n in srange(1,10)],v)
True
sage: H.real_intersection_is_empty([H.B(n,0.3) for n in srange(1,10)],v)
False
```

An example over a number field:

```
sage: K.<a> = NumberField(x^3-2)
sage: E = EllipticCurve([0,0,0,0,a])
sage: v = K.real_places()[0]
sage: H = E.height_function()
```

The following two lines prove that the heights of non-torsion points on $E$ with everywhere good reduction have canonical height strictly greater than 0.07, but fail to prove the same for 0.08:

```
sage: H.real_intersection_is_empty([H.B(n,0.07) for n in srange(1,5)],v) # long...
˓→time (3.3s)
True
sage: H.real_intersection_is_empty([H.B(n,0.08) for n in srange(1,5)],v)
False
```

tau($v$)

Return the normalised upper half-plane parameter $\tau$ for the period lattice with respect to the embedding $v$.

**INPUT:**

- $v$ (embedding) – a real or complex embedding of the number field.

**OUTPUT:**

(Complex) $\tau = \omega_1/\omega_2$ in the fundamental region of the upper half-plane.

**EXAMPLES:**

```
sage: H.tau(QQ.places()[0])
1.22112736076463*I
```

test_mu($mu$, $N$, $verbose=True$)

Return True if we can prove that $\mu$ is a lower bound.

**INPUT:**

- $mu$ (real) – a positive real number
- $N$ (integer) – upper bound on the multiples to be used.
- $verbose$ (boolean, default True) – verbosity flag.

**OUTPUT:**
True or False, according to whether we succeed in proving that $\mu$ is a lower bound for the canonical heights of points of infinite order with everywhere good reduction.

**Note:** A True result is rigorous; False only means that the attempt failed: trying again with larger $N$ may yield True.

**EXAMPLES:**

```python
sage: K.<a> = NumberField(x^3-2)
sage: E = EllipticCurve([0,0,0,0,a])
sage: H = E.height_function()
```

This curve does have a point of good reduction whose canonical point is approximately 1.68:

```python
sage: P = E.gens(lim3=5)[0]; P
(1/3*a^2 + a + 5/3 : -2*a^2 - 4/3*a - 5/3 : 1)
sage: P.height()
1.68038085233673
sage: P.has_good_reduction()
True
```

Using $N = 5$ we can prove that 0.1 is a lower bound (in fact we only need $N = 2$), but not that 0.2 is:

```python
sage: H.test_mu(0.1, 5)
B_1(0.100000000000000) = 1.51580969677387
B_2(0.100000000000000) = 0.932072561526720
True
sage: H.test_mu(0.2, 5)
B_1(0.200000000000000) = 2.04612906979932
B_2(0.200000000000000) = 3.09458988474327
B_3(0.200000000000000) = 27.6251108409484
B_4(0.200000000000000) = 1036.24722370223
B_5(0.200000000000000) = 3.67090854562318e6
False
```

Since 0.1 is a lower bound we can deduce that the point $P$ is either primitive or divisible by either 2 or 3. In fact it is primitive:

```python
sage: (P.height()/0.1).sqrt()
4.0992487233530
sage: P.division_points(2)
[]
sage: P.division_points(3)
[]
```

$\wp_c(v)$

Return a bound for the Weierstrass $\wp$-function.

**INPUT:**

- $v$ (embedding) – a real or complex embedding of the number field.

**OUTPUT:**
(Real) \( c > 0 \) such that
\[
|\wp(z) - z^{-2}| \leq \frac{c^2|z|^2}{1 - c|z|^2}
\]
whenever \( c|z|^2 < 1 \). Given the recurrence relations for the Laurent series expansion of \( \wp \), it is easy to see that there is such a constant \( c \). [Reference?]

**EXAMPLES:**

```python
sage: E = EllipticCurve('37a')
sage: H = E.height_function()
sage: H.wp_c(QQ.places()[0])
2.68744508779950

sage: K.<i>=QuadraticField(-1)
sage: E = EllipticCurve([0,0,0,1+5*i,3+i])
sage: H = E.height_function()
sage: H.wp_c(K.places()[0])
2.66213425640096
```

**wp_intervals** \((v=None, N=20, abs_only=False)\)

Return a function approximating the Weierstrass function.

**INPUT:**

- \( v \) (embedding) – an embedding of the number field. If None (default) use the real embedding if the field is \( \mathbb{Q} \) and raise an error for other fields.
- \( N \) (int, default 20) – The number of terms to use in the \( q \)-expansion of \( \wp \).
- \( \text{abs\_only} \) (boolean, default False) – flag to determine whether (if True) the error adjustment should use the absolute value or (if False) the real and imaginary parts.

**OUTPUT:**

A function \( \wp \) which can be evaluated at complex numbers \( z \) to give an approximation to \( \wp(z) \). The Weierstrass function returned is with respect to the normalised lattice \([1, \tau]\) associated to the given embedding. For \( z \) which are not near a lattice point the function \( f_k \) is used, otherwise a better approximation is used.

**EXAMPLES:**

```python
sage: E = EllipticCurve('37a')
sage: wp = E.height_function().wp_intervals()
sage: z = CDF(0.3, 0.4)
sage: wp(CIF(z))
-1.82543539306049 - 2.4933631999285*I

sage: L = E.period_lattice()
sage: w1, w2 = L.normalised_basis()
sage: L.elliptic_exponential(z*w2, to_curve=False)[0] * w2^2
-1.82543539306049 - 2.49336319992847*I

sage: z = CDF(0.3, 0.1)
sage: wp(CIF(z))
8.5918243572165 - 5.4751982004351*I

sage: L.elliptic_exponential(z*w2, to_curve=False)[0] * w2^2
8.59182435721650 - 5.47519820043503*I
```
**wp_on_grid**($v, N, half=False$)

Return an array of the values of $\wp$ on an $N \times N$ grid.

**INPUT:**
- $v$ (embedding) – an embedding of the number field.
- $N$ (int) – The number of terms to use in the $q$-expansion of $\wp$.
- $half$ (boolean, default False) – if True, use an array of size $N \times N/2$ instead of $N \times N$.

**OUTPUT:**
An array of size either $N \times N/2$ or $N \times N$ whose $(i, j)$ entry is the value of the Weierstrass $\wp$-function at $(i + .5)/N + (j + .5) * \tau/N$, a grid of points in the fundamental region for the lattice $[1, \tau]$.

**EXAMPLES:**

```python
sage: E = EllipticCurve('37a')
sage: H = E.height_function()
sage: v = QQ.places()[0]
```

The array of values on the grid shows symmetry, since $\wp$ is even:

```python
sage: H.wp_on_grid(v, 4)
array([[25.43920182, 5.28760943, 5.28760943, 25.43920182],
       [ 6.05099485, 1.83757786, 1.83757786,  6.05099485],
       [ 6.05099485, 1.83757786, 1.83757786,  6.05099485],
       [25.43920182, 5.28760943, 5.28760943, 25.43920182]])
```

The array of values on the half-grid:

```python
sage: H.wp_on_grid(v, 4, True)
array([[25.43920182, 5.28760943],
       [ 6.05099485, 1.83757786],
       [ 6.05099485, 1.83757786],
       [25.43920182, 5.28760943]])
```

**class** `sage.schemes.elliptic_curves.height.UnionOfIntervals(endpoints)`

Bases: object

A class representing a finite union of closed intervals in $\mathbb{R}$ which can be scaled, shifted, intersected, etc.

The intervals are represented as an ordered list of their endpoints, which may include $-\infty$ and $+\infty$.

**EXAMPLES:**

```python
sage: from sage.schemes.elliptic_curves.height import UnionOfIntervals
sage: R = UnionOfIntervals([1, 2, 3, infinity]); R
([1, 2] U [3, +Infinity])
sage: R + 5
([6, 7] U [8, +Infinity])
sage: ~R
([-Infinity, 1] U [2, 3])
sage: ~R | (10*R + 100)
([-Infinity, 1] U [2, 3] U [110, 120] U [130, +Infinity])
```
Todo: Unify *UnionOfIntervals* with the class *RealSet* introduced by trac ticket #13125; see trac ticket #16063.

**finite_endpoints()**

Returns the finite endpoints of this union of intervals.

**EXAMPLES:**

```python
sage: from sage.schemes.elliptic_curves.height import UnionOfIntervals
sage: UnionOfIntervals([0,1]).finite_endpoints()
[0, 1]
sage: UnionOfIntervals([-infinity, 0, 1, infinity]).finite_endpoints()
[0, 1]
```

**classmethod intersection(L)**

Return the intersection of a list of *UnionOfIntervals*.

**INPUT:**

- L (list) – a list of *UnionOfIntervals* instances

**OUTPUT:**

A new *UnionOfIntervals* instance representing the intersection of the *UnionOfIntervals* in the list.

**Note:** This is a class method.

**EXAMPLES:**

```python
sage: from sage.schemes.elliptic_curves.height import UnionOfIntervals
sage: A = UnionOfIntervals([1,3,5,7]); A
([1, 3] U [5, 7])
sage: B = A+1; B
([2, 4] U [6, 8])
sage: A.intersection([A,B])
([2, 3] U [6, 7])
```

**intervals()**

Returns the intervals in self, as a list of 2-tuples.

**EXAMPLES:**

```python
sage: from sage.schemes.elliptic_curves.height import UnionOfIntervals
sage: UnionOfIntervals(list(range(10))).intervals()
[(0, 1), (2, 3), (4, 5), (6, 7), (8, 9)]
sage: UnionOfIntervals([-infinity, pi, 17, infinity]).intervals()
[(-Infinity, pi), (17, +Infinity)]
```

**is_empty()**

Returns whether self is empty.

**EXAMPLES:**

```python
sage: from sage.schemes.elliptic_curves.height import UnionOfIntervals
sage: UnionOfIntervals([3,4]).is_empty()
```

(continues on next page)
sage: all = UnionOfIntervals([-infinity, infinity])
sage: all.is_empty()
False
sage: (~all).is_empty()
True
sage: A = UnionOfIntervals([0,1]) & UnionOfIntervals([2,3])
sage: A.is_empty()
True

\textbf{static \textit{join}(L, condition)}

Utility function to form the union or intersection of a list of \texttt{UnionOfIntervals}.

INPUT:

\begin{itemize}
  \item \textit{L} (list) – a list of \texttt{UnionOfIntervals} instances
  \item \textit{condition} (function) – either \texttt{any} or \texttt{all}, or some other boolean function of a list of boolean values.
\end{itemize}

OUTPUT:

A new \texttt{UnionOfIntervals} instance representing the subset of ‘RR’ equal to those reals in any/all/condition of the \texttt{UnionOfIntervals} in the list.

\textbf{Note:} This is a static method for the class.

\textbf{EXAMPLES:}

sage: from sage.schemes.elliptic_curves.height import UnionOfIntervals
sage: A = UnionOfIntervals([1,3,5,7]); A
([1, 3] U [5, 7])
sage: B = A+1; B
([2, 4] U [6, 8])
sage: A.join([A,B],any) # union
([1, 4] U [5, 8])
sage: A.join([A,B],all) # intersection
([2, 3] U [6, 7])
sage: A.join([A,B],sum) # symmetric difference
([1, 2] U [3, 4] U [5, 6] U [7, 8])

\textbf{classmethod \textit{union}(L)}

Return the union of a list of \texttt{UnionOfIntervals}.

INPUT:

\begin{itemize}
  \item \textit{L} (list) – a list of \texttt{UnionOfIntervals} instances
\end{itemize}

OUTPUT:

A new \texttt{UnionOfIntervals} instance representing the union of the \texttt{UnionOfIntervals} in the list.

\textbf{Note:} This is a class method.

\textbf{EXAMPLES:}
```python
sage: from sage.schemes.elliptic_curves.height import UnionOfIntervals
sage: A = UnionOfIntervals([1,3,5,7]); A
([1, 3] U [5, 7])
sage: B = A+1; B
([2, 4] U [6, 8])
sage: A.union([A,B])
([1, 4] U [5, 8])
```

`sage.schemes.elliptic_curves.height.\texttt{eps}(err, is\_real)`

Return a Real or Complex interval centered on 0 with radius `err`.

**INPUT:**
- `err` (real) – a positive real number, the radius of the interval
- `is_real` (boolean) – if True, returns a real interval in RIF, else a complex interval in CIF

**OUTPUT:**
An element of RIF or CIF (as specified), centered on 0, with given radius.

**EXAMPLES:**
```python
sage: from sage.schemes.elliptic_curves.height import eps
sage: eps(0.01, True)
0.0?
sage: eps(0.01, False)
0.0? + 0.0?*I
```

`sage.schemes.elliptic_curves.height.\texttt{inf\_max\_abs}(f, g, D)`

Returns $\inf_D\left(\max(|f|, |g|)\right)$.

**INPUT:**
- `f, g` (polynomials) – real univariate polynomials
- `D` (UnionOfIntervals) – a subset of $\mathbb{R}$

**OUTPUT:**
A real number approximating the value of $\inf_D(\max(|f|, |g|))$.

**ALGORITHM:**
The extreme values must occur at an endpoint of a subinterval of $D$ or at a point where one of $f, f', g, g', f \pm g$ is zero.

**EXAMPLES:**
```python
sage: from sage.schemes.elliptic_curves.height import inf_max_abs, UnionOfIntervals
sage: x = polygen(RR)
sage: f = (x-10)^4+1
sage: g = 2*x^3+100
sage: D = UnionOfIntervals([1,2,3,4,5,6])
sage: inf_max_abs(f,g,D)
425.638201706391
sage: r0 = (f-g).roots()[0][0]
sage: r0
5.46053402234697
sage: max(abs(f(r0)),abs(g(r0)))
425.638201706391
```
sage.schemes.elliptic_curves.height.min_on_disk(f, tol, max_iter=10000)

Returns the minimum of a real-valued complex function on a square.

INPUT:

- \( f \) – a function from CIF to RIF
- \( \text{tol} \) (real) – a positive real number
- \( \text{max_iter} \) (integer, default 10000) – a positive integer bounding the number of iterations to be used

OUTPUT:

A 2-tuple \((s, t)\), where \( t = f(s) \) and \( s \) is a CIF element contained in the disk \(|z| \leq 1\), at which \( f \) takes its minimum value.

EXAMPLES:

```python
sage: from sage.schemes.elliptic_curves.height import min_on_disk
sage: f = lambda x: (x^2+100).abs()

sage: s, t = min_on_disk(f, 0.0001)
sage: s, f(s), t
(0.01? + 1.00?*I, 99.01?, 99.0000000000000)
```

sage.schemes.elliptic_curves.height.nonneg_region(f)

Returns the UnionOfIntervals representing the region where \( f \) is non-negative.

INPUT:

- \( f \) (polynomial) – a univariate polynomial over \( \mathbb{R} \).

OUTPUT:

A UnionOfIntervals representing the set \( \{ x \in \mathbb{R} \mid f(x) \geq 0 \} \).

EXAMPLES:

```python
sage: from sage.schemes.elliptic_curves.height import nonneg_region
sage: x = polygen(RR)
sage: nonneg_region(x^2-1)
([-Infinity, -1.00000000000000] U [1.00000000000000, +Infinity])

sage: nonneg_region(1-x^2)
([-1.00000000000000, 1.00000000000000])

sage: nonneg_region(x^3-1)
([1.00000000000000, +Infinity])

sage: nonneg_region((x-1)*(x-2))
([-Infinity, 1.00000000000000] U [2.00000000000000, +Infinity])

sage: nonneg_region(-(x-1)*(x-2))
([-Infinity, 1.00000000000000] U [2.00000000000000, 3.00000000000000])

sage: nonneg_region(x^4+1)
([-Infinity, +Infinity])

sage: nonneg_region(-x^4-1)
()
sage.schemes.elliptic_curves.height.rat_term_CIF(z, try_strict=True)

Compute the value of \( \frac{u}{(1-u)^2} \) in CIF, where \( u = \exp(2\pi i z) \).

INPUT:
- \( z \) (complex) – a CIF element
- \( \text{try\_strict} \) (bool) – flag

EXAMPLES:

```python
sage: from sage.schemes.elliptic_curves.height import rat_term_CIF
sage: z = CIF(0.5,0.2)
sage: rat_term_CIF(z)
-0.172467461182437? + 0.?e-16*I
sage: rat_term_CIF(z, False)
-0.172467461182437? + 0.?e-16*I
```

### 14.5 Saturation of Mordell-Weil groups of elliptic curves over number fields

Points \( P_1, \ldots, P_r \) in \( E(K) \), where \( E \) is an elliptic curve over a number field \( K \), are said to be \( p \)-saturated if no linear combination \( \sum n_i P_i \) is divisible by \( p \) in \( E(K) \) except trivially when all \( n_i \) are multiples of \( p \). The points are said to be saturated if they are \( p \)-saturated at all primes; this is always true for all but finitely many primes since \( E(K) \) is a finitely-generated Abelian group.

The process of \( p \)-saturating a given set of points is implemented here. The naive algorithm simply checks all \( (p^r - 1)/(p - 1) \) projective combinations of the points, testing each to see if it can be divided by \( p \). If this occurs then we replace one of the points and continue. The function \( \text{p\_saturation()} \) does one step of this, while \( \text{full\_p\_saturation()} \) repeats until the points are \( p \)-saturated. A more sophisticated algorithm for \( p \)-saturation is implemented which is much more efficient for large \( p \) and \( r \), and involves computing the reduction of the points modulo auxiliary primes to obtain linear conditions modulo \( p \) which must be satisfied by the coefficients \( a_i \) of any nontrivial relation. When the points are already \( p \)-saturated this sieving technique can prove their saturation quickly.

The method \( \text{saturation()} \) of the class \text{EllipticCurve\_number\_field} applies full \( p \)-saturation at any given set of primes, or can compute a bound on the primes \( p \) at which the given points may not be \( p \)-saturated. This involves computing a lower bound for the canonical height of points of infinite order, together with estimates from the geometry of numbers.

AUTHORS:
- Robert Bradshaw
- John Cremona

```python
class sage.schemes.elliptic_curves.saturation.EllipticCurveSaturator(E, verbose=False)
    Bases: sage.structure.sage_object.SageObject

Class for saturating points on an elliptic curve over a number field.

INPUT:
- \( E \) – an elliptic curve defined over a number field, or \( \mathbb{Q} \).
- \( \text{verbose} \) (boolean, default \( \text{False} \)) – verbosity flag.
```

\[ \text{Note:} \quad \text{This function is not normally called directly by users, who may access the data via methods of the EllipticCurve classes.} \]
add_reductions(q)
Add reduction data at primes above q if not already there.

INPUT:

• q – a prime number not dividing the defining polynomial of self.__field.

OUTPUT:

Returns nothing, but updates self._reductions dictionary for key q to a dict whose keys are the roots of the defining polynomial mod q and values tuples (nq, Eq) where Eq is an elliptic curve over $GF(q)$ and nq its cardinality. If q divides the conductor norm or order discriminant nothing is added.

EXAMPLES:

Over Q:

```
sage: from sage.schemes.elliptic_curves.saturation import EllipticCurveSaturator
sage: E = EllipticCurve('11a1')
sage: saturator = EllipticCurveSaturator(E)
sage: saturator._reductions
{}
sage: saturator.add_reductions(19)
sage: saturator._reductions
{19: {0: (20, Elliptic Curve defined by y^2 + y = x^3 + 18*x^2 + 9*x + 18 over Finite Field of size 19)}}
```

Over a number field:

```
sage: x = polygen(QQ); K.<a> = NumberField(x^2 + 2)
sage: E = EllipticCurve(K, [0,1,0,a,a])
sage: from sage.schemes.elliptic_curves.saturation import EllipticCurveSaturator
sage: saturator = EllipticCurveSaturator(E)
```

(continues on next page)
13: (12, Elliptic Curve defined by $y^2 = x^3 + x^2 + 13x + 13$ over Finite Field of size 19)}

**full_p_saturation**(*Plist, p*)

Full $p$-saturation of *Plist*.

**INPUT:**
- *Plist* (list) – a list of independent points on one elliptic curve.
- *p* (integer) – a prime number.

**OUTPUT:**

(*newPlist, exponent*) where *newPlist* has the same length as *Plist* and spans the $p$-saturation of the span of *Plist*, which contains that span with index $p^{**exponent}**$.

**EXAMPLES:**

```python
sage: from sage.schemes.elliptic_curves.saturation import EllipticCurveSaturator
glob: E = EllipticCurve('389a')
glob: K.<i> = QuadraticField(-1)
glob: EK = E.change_ring(K)
glob: P = EK(1+i,-1-2*i)
glob: saturator = EllipticCurveSaturator(EK, verbose=True)
glob: saturator.full_p_saturation([8*P],2)  
--starting full 2-saturation
Points were not 2-saturated, exponent was 3
([(i + 1 : -2*i - 1 : 1)], 3)

sage: Q = EK(0,0)
sage: R = EK(-1,1)
sage: saturator = EllipticCurveSaturator(EK, verbose=False)
sage: saturator.full_p_saturation([P,Q,R],3)  
([(i + 1 : -2*i - 1 : 1), (0 : 0 : 1), (-1 : 1 : 1)], 0)
```

An example where the points are not 7-saturated and we gain index exponent 1. Running this example with verbose=True would show that it uses the code for when the reduction has $p$-rank 2 (which occurs for the reduction modulo $16 - 5i$), which uses the Weil pairing:

```python
sage: saturator.full_p_saturation([P, Q+3*R, Q-4*R], 7)  
([(i + 1 : -2*i - 1 : 1),
  (2869/676 : 154413/17576 : 1),
  (-7095/502681 : -366258864/356400829 : 1)], 1)
```

**p_saturation**(*Plist, p, sieve=True*)

Checks whether the list of points is $p$-saturated.

**INPUT:**
- *Plist* (list) – a list of independent points on one elliptic curve.
- *p* (integer) – a prime number.
- *sieve* (boolean) – if True, use a sieve (when there are at least 2 points); otherwise test all combinations.
Note: The sieve is much more efficient when the points are saturated and the number of points or the prime are large.

OUTPUT:

Either False if the points are \(p\)-saturated, or \((i, \text{new}P)\) if they are not \(p\)-saturated, in which case after replacing the \(i\)'th point with \(\text{new}P\), the subgroup generated contains that generated by \(\text{Plist}\) with index \(p\).

EXAMPLES:

```python
sage: from sage.schemes.elliptic_curves.saturation import EllipticCurveSaturator
dl
sage: E = EllipticCurve('389a')
dl
sage: K.<i> = QuadraticField(-1)
dl
sage: EK = E.change_ring(K)
dl
sage: P = EK(1+i,-1-2*i)
dl
sage: saturator = EllipticCurveSaturator(EK)
dl
sage: saturator.p_saturation([P],2)
False
sage: saturator.p_saturation([2*P],2)
(0, (i + 1 : -2*i - 1 : 1))
dl
sage: Q = EK(0,0)
dl
sage: R = EK(-1,1)
dl
sage: saturator.p_saturation([P,Q,R],3)
False
```

Here we see an example where \(19\)-saturation is proved, with the verbose flag set to True so that we can see what is going on:

```python
sage: saturator = EllipticCurveSaturator(EK, verbose=True)
dl
sage: saturator.p_saturation([P,Q,R],19)
Using sieve method to saturate...
E has 19-torsion over Finite Field of size 197, projecting points
--> [(15 : 168 : 1), (0 : 0 : 1), (196 : 1 : 1)]
--rank is now 1
E has 19-torsion over Finite Field of size 197, projecting points
--> [(184 : 27 : 1), (0 : 0 : 1), (196 : 1 : 1)]
--rank is now 2
E has 19-torsion over Finite Field of size 293, projecting points
--> [(139 : 16 : 1), (0 : 0 : 1), (292 : 1 : 1)]
--rank is now 3
Reached full rank: points were 19-saturated
False
```

An example where the points are not \(11\)-saturated:

```python
sage: saturator = EllipticCurveSaturator(EK, verbose=False)
dl
sage: res = saturator.p_saturation([P+5*Q,P-6*Q,R],11); res
(0, (-5783311/14600041*i + 1396143/14600041 : 37679338314/55786756661*i +
˓→ 3813624227/55786756661 : 1))
dl
```

That means that the 0'th point may be replaced by the displayed point to achieve an index gain of 11:
sage: saturator.p_saturation([res[1], P-6*Q, R], 11)
False

sage.schemes.elliptic_curves.saturation.p_projections(Eq, Plist, p, debug=False)

INPUT:

- Eq – An elliptic curve over a finite field.
- Plist – a list of points on Eq.
- p – a prime number.

OUTPUT:

A list of \( r \leq 2 \) vectors in \( \mathbb{F}_p^n \), the images of the points in \( G \otimes \mathbb{F}_p \), where \( r \) is the number of vectors is the \( p \)-rank of Eq.

ALGORITHM:

First project onto the \( p \)-primary part of Eq. If that has \( p \)-rank 1 (i.e. is cyclic), use discrete logs there to define a map to \( \mathbb{F}_p \), otherwise use the Weil pairing to define two independent maps to \( \mathbb{F}_p \).

EXAMPLES:

This curve has three independent rational points:

```
sage: E = EllipticCurve([0, 0, 1, -7, 6])
```

We reduce modulo 409 where its order is \( 3^2 \cdot 7^2 \); the 3-primary part is non-cyclic while the 7-primary part is cyclic of order 49:

```
sage: F = GF(409)
sage: EF = E.change_ring(F)
sage: G = EF.abelian_group()
sage: G
Additive abelian group isomorphic to \( \mathbb{Z}/147 + \mathbb{Z}/3 \) embedded in Abelian group of points on Elliptic Curve defined by \( y^2 + y = x^3 + 402*x + 6 \) over Finite Field of size 409
```

```
sage: G.order().factor()
3^2 * 7^2
```

We construct three points and project them to the \( p \)-primary parts for \( p = 2, 3, 5, 7 \), yielding 0,2,0,1 vectors of length 3 modulo \( p \) respectively. The exact vectors output depend on the computed generators of \( G \):

```
sage: Plist = [EF([-2, 3]), EF([0, 2]), EF([1, 0])]
sage: from sage.schemes.elliptic_curves.saturation import p_projections
sage: [(p, len(p_projections(EF, Plist, p))) for p in primes(11)]
([(2, 0), (3, 2), (5, 0), (7, 1)]
```

```
sage: [(p, p_projections(EF, Plist, p)) for p in primes(11)]
([(2, []), (3, [[(0, 2, 2), (2, 2, 1)]], (5, []), (7, [[(1, 1, 1)]])]
```

sage.schemes.elliptic_curves.saturation.reduce_mod_q(x, amodq)

The reduction of \( x \) modulo the prime ideal defined by \( \text{amodq} \).

INPUT:

- \( x \) – an element of a number field \( K \).
- \( \text{amodq} \) – an element of \( GF(q) \) which is a root mod \( q \) of the defining polynomial of \( K \). This defines a degree 1 prime ideal \( Q = (q, \alpha - a) \) of \( K = Q(\alpha) \), where \( a \mod q =. \)
OUTPUT:

The image of \(x\) in the residue field of \(K\) at the prime \(Q\).

EXAMPLES:

```sage
sage: from sage.schemes.elliptic_curves.saturation import reduce_mod_q
sage: x = polygen(QQ)
sage: pol = x^3 -x^2 -3*x + 1
sage: K.<a> = NumberField(pol)
sage: [(q,[(amodq,reduce_mod_q(1-a+a^4,amodq))
.....: for amodq in sorted(pol.roots(GF(q), multiplicities=False))])
.....: for q in primes(50,70)]
[[53, []],
 (59, [(36, 28)]),
 (61, [(40, 35)]),
 (67, [(10, 8), (62, 28), (63, 60)])]
```

14.6 Torsion subgroups of elliptic curves over number fields (including \(Q\))

AUTHORS:

- Nick Alexander: original implementation over \(Q\)
- Chris Wuthrich: original implementation over number fields
- John Cremona: rewrote p-primary part to use division polynomials, added some features, unified Number Field and \(Q\) code.

class sage.schemes.elliptic_curves.ell_torsion.EllipticCurveTorsionSubgroup(E)
Bases: sage.groups.additive_abelian.additive_abelian_wrapper.AdditiveAbelianGroupWrapper

The torsion subgroup of an elliptic curve over a number field.

EXAMPLES:

Examples over \(Q\):

```sage
sage: E = EllipticCurve([-4, 0]); E
Elliptic Curve defined by y^2 = x^3 - 4*x over Rational Field
sage: G = E.torsion_subgroup(); G
Torsion Subgroup isomorphic to Z/2 + Z/2 associated to the Elliptic Curve defined by y^2 = x^3 - 4*x over Rational Field
sage: G.order()
4
sage: G.gen(0)
(-2 : 0 : 1)
sage: G.gen(1)
(0 : 0 : 1)
sage: G.ngens()
2
```
sage: E = EllipticCurve([17, -120, -60, 0, 0]); E
Elliptic Curve defined by y^2 + 17*x*y - 60*y = x^3 - 120*x^2 over Rational Field
sage: G = E.torsion_subgroup(); G
Torsion Subgroup isomorphic to Trivial group associated to the Elliptic Curve defined by y^2 + 17*x*y - 60*y = x^3 - 120*x^2 over Rational Field
sage: G.gens()
()
sage: e = EllipticCurve([0, 33076156654533652066609946884, 0,
347897536144342179642128321790729023127716119338758604800,
114112815436927429551902393280684247788154621049857648870032370285851781352816640000])
sage: e.torsion_order()
16

Constructing points from the torsion subgroup:

sage: E = EllipticCurve('14a1')
sage: T = E.torsion_subgroup()
sage: [E(t) for t in T]
[(0 : 1 : 0),
 (9 : 23 : 1),
 (2 : 2 : 1),
 (1 : -1 : 1),
 (2 : -5 : 1),
 (9 : -33 : 1)]

An example where the torsion subgroup is not cyclic:

sage: E = EllipticCurve([0,0,0,-49,0])
sage: T = E.torsion_subgroup()
sage: [E(t) for t in T]
[(0 : 1 : 0), (0 : 0 : 1), (-7 : 0 : 1), (7 : 0 : 1)]

An example where the torsion subgroup is trivial:

sage: E = EllipticCurve('37a1')
sage: T = E.torsion_subgroup()
sage: T
Torsion Subgroup isomorphic to Trivial group associated to the Elliptic Curve defined by y^2 + y = x^3 - x over Rational Field
sage: [E(t) for t in T]
[(0 : 1 : 0)]

Examples over other Number Fields:

sage: E = EllipticCurve('11a1')
sage: K.<i> = NumberField(x^2+1)
sage: EK = E.change_ring(K)
sage: from sage.schemes.elliptic_curves.ell_torsion import EllipticCurveTorsionSubgroup
sage: EllipticCurveTorsionSubgroup(EK)
Torsion Subgroup isomorphic to Z/5 associated to the Elliptic Curve defined by y^2 + y = x^3 + (-1)*x^2 + (-10)*x + (-20) over Number Field in i with defining polynomial x^2 + 1

(continues on next page)
Elliptic curves, Release 9.7

sage: E = EllipticCurve('11a1')
sage: K.<i> = NumberField(x^2+1)
sage: EK = E.change_ring(K)
sage: T = EK.torsion_subgroup()
sage: T.ngens()
1
sage: T.gen(0)
(5 : -6 : 1)

Note: this class is normally constructed indirectly as follows:

sage: T = EK.torsion_subgroup(); T
Torsion Subgroup isomorphic to Z/5 associated to the Elliptic Curve defined by y^2 + y = x^3 + (-1)*x^2 + (-10)*x + (-20) over Number Field in i with defining polynomial x^2 + 1
sage: type(T)
<class 'sage.schemes.elliptic_curves.ell_torsion.EllipticCurveTorsionSubgroup_with_category'>

AUTHORS:

• Nick Alexander: initial implementation over \( \mathbb{Q} \).
• Chris Wuthrich: initial implementation over number fields.
• John Cremona: additional features and unification.

curve()
Return the curve of this torsion subgroup.

EXAMPLES:

sage: E = EllipticCurve('11a1')
sage: K.<i> = NumberField(x^2+1)
sage: EK = E.change_ring(K)
sage: T = EK.torsion_subgroup()
sage: T.curve() is EK
True

points()
Return a list of all the points in this torsion subgroup.

The list is cached.

EXAMPLES:

sage: K.<i> = NumberField(x^2+1)
sage: E = EllipticCurve(K,[0,0,0,1,0])
sage: tor = E.torsion_subgroup()
sage: tor.points()
[(0 : 1 : 0), (0 : 0 : 1), (-i : 0 : 1), (i : 0 : 1)]

sage.schemes.elliptic_curves.ell_torsion.torsion_bound(E, number_of_places=20)
Return an upper bound on the order of the torsion subgroup.

INPUT:

• E – an elliptic curve over \( \mathbb{Q} \) or a number field
• **number_of_places** (positive integer, default = 20) – the number of places that will be used to find the bound

**OUTPUT:**

(integer) An upper bound on the torsion order.

**ALGORITHM:**

An upper bound on the order of the torsion group of the elliptic curve is obtained by counting points modulo several primes of good reduction. Note that the upper bound returned by this function is a multiple of the order of the torsion group, and in general will be greater than the order.

To avoid nontrivial arithmetic in the base field (in particular, to avoid having to compute the maximal order) we only use prime $P$ above rational primes $p$ which do not divide the discriminant of the equation order.

**EXAMPLES:**

```python
sage: CDB = CremonaDatabase()
sage: from sage.schemes.elliptic_curves.ell_torsion import torsion_bound
sage: [torsion_bound(E) for E in CDB.iter([14])]
[6, 6, 6, 6, 6, 6]
sage: [E.torsion_order() for E in CDB.iter([14])]
[6, 6, 2, 6, 2, 6]
```

An example over a relative number field (see trac ticket #16011):

```python
sage: R.<x> = QQ[]
sage: F.<a> = QuadraticField(5)
sage: K.<b> = F.extension(x^2-3)
sage: E = EllipticCurve(K,[0,0,0,b,1])
sage: E.torsion_subgroup().order()
1
```

An example of a base-change curve from $\mathbb{Q}$ to a degree 16 field:

```python
sage: from sage.schemes.elliptic_curves.ell_torsion import torsion_bound
sage: f = PolynomialRing(QQ, 'x')([5643417737593488384,0,...: -11114515801179776,0,-455989850911004,0,379781901872,...: 0,14339154953,0,-1564048,0,-194542,0,-32,0,1])
sage: K = NumberField(f,'a')
sage: E = EllipticCurve(K, [1, -1, 1, 824579, 245512517])
sage: torsion_bound(K)
16
sage: E.torsion_subgroup().invariants()
(4, 4)
```
14.7 Galois representations attached to elliptic curves

Given an elliptic curve $E$ over $\mathbb{Q}$ and a rational prime number $p$, the $p^n$-torsion $E[p^n]$ points of $E$ is a representation of the absolute Galois group $G_\mathbb{Q}$ of $\mathbb{Q}$. As $n$ varies we obtain the Tate module $T_p E$ which is a representation of $G_\mathbb{Q}$ on a free $\mathbb{Z}_p$-module of rank 2. As $p$ varies the representations are compatible.

Currently sage can decide whether the Galois module $E[p]$ is reducible, i.e., if $E$ admits an isogeny of degree $p$, and whether the image of the representation on $E[p]$ is surjective onto $\text{Aut}(E[p]) = GL_2(\mathbb{F}_p)$.

The following are the most useful functions for the class `GaloisRepresentation`.

For the reducibility:
- `is_reducible(p)`
- `is_irreducible(p)`
- `reducible_primes()`

For the image:
- `is_surjective(p)`
- `non_surjective()`
- `image_type(p)`

For the classification of the representation
- `is_semistable(p)`
- `is_unramified(p, ell)`
- `is_crystalline(p)`

**EXAMPLES:**

```sage
sage: E = EllipticCurve('196a1')
sage: rho = E.galois_representation()
sage: rho.is_irreducible(7)
True
sage: rho.is_reducible(3)
True
sage: rho.is_irreducible(2)
True
sage: rho.is_surjective(2)
False
sage: rho.is_surjective(3)
False
sage: rho.is_surjective(5)
True
sage: rho.reducible_primes()
[3]
sage: rho.non_surjective()
[2, 3]
sage: rho.image_type(2)
'The image is cyclic of order 3.'
sage: rho.image_type(3)
'The image is contained in a Borel subgroup as there is a 3-isogeny.'
```

(continues on next page)
sage: rho.image_type(5)
'The image is all of GL_2(F_5).'

For semi-stable curve it is known that the representation is surjective if and only if it is irreducible:

sage: E = EllipticCurve('11a1')
sage: rho = E.galois_representation()
sage: rho.non_surjective()
[5]
sage: rho.reducible_primes()
[5]

For cm curves it is not true that there are only finitely many primes for which the Galois representation mod p is surjective onto $GL_2(F_p)$:

sage: E = EllipticCurve('27a1')
sage: rho = E.galois_representation()
sage: rho.non_surjective()
[0]
sage: rho.reducible_primes()
[3]
sage: E.has_cm()
True
sage: rho.image_type(11)
'The image is contained in the normalizer of a non-split Cartan group. (cm)'

REFERENCES:

• [Ser1972]
• [Ser1987]
• [Coj2005]

AUTHORS:

• chris wuthrich (02/10): moved from ell_rational_field.py.

class sage.schemes.elliptic_curves.gal_reps.GaloisRepresentation(E)
Bases: sage.structure.sage_object.SageObject

The compatible family of Galois representation attached to an elliptic curve over the rational numbers.

Given an elliptic curve $E$ over $\mathbb{Q}$ and a rational prime number $p$, the $p^n$-torsion $E[p^n]$ points of $E$ is a representation of the absolute Galois group. As $n$ varies we obtain the Tate module $T_pE$ which is a representation of the absolute Galois group on a free $\mathbb{Z}_p$-module of rank 2. As $p$ varies the representations are compatible.

EXAMPLES:

sage: rho = EllipticCurve('11a1').galois_representation()
sage: rho
Compatible family of Galois representations associated to the Elliptic Curve $y^2 + y = x^3 - x^2 - 10 x - 20$ over Rational Field

elliptic_curve()

The elliptic curve associated to this representation.

EXAMPLES:
image_classes \( (p, \text{bound}=10000) \)

This function returns, given the representation \( \rho \), a list of \( p \) values that add up to 1, representing the frequency of the conjugacy classes of the projective image of \( \rho \) in \( PGL_2(\mathbb{F}_p) \).

Let \( M \) be a matrix in \( GL_2(\mathbb{F}_p) \), then define \( u(M) = \frac{\text{tr}(M)^2}{\det(M)} \), which only depends on the conjugacy class of \( M \) in \( PGL_2(\mathbb{F}_p) \). Hence this defines a map \( u : PGL_2(\mathbb{F}_p) \rightarrow \mathbb{F}_p \), which is almost a bijection between conjugacy classes of the source and \( \mathbb{F}_p \) (the elements of order \( p \) and the identity map to 4 and both classes of elements of order 2 map to 0).

This function returns the frequency with which the values of \( u \) appeared among the images of the Frobenius elements \( \alpha_\ell \) for good primes \( \ell \neq p \) below a given \( \text{bound} \).

**INPUT:**

- a prime \( p \)
- a natural number \( \text{bound} \) (optional, default=10000)

**OUTPUT:**

- a list of \( p \) real numbers in the interval \([0, 1]\) adding up to 1

**EXAMPLES:**

```python
sage: E = EllipticCurve('11a1')
sage: rho = E.galois_representation()
sage: rho.image_classes(5)
[0.2095, 0.1516, 0.2445, 0.1728, 0.2217]
sage: E = EllipticCurve('11a1')
sage: rho = E.galois_representation()
sage: rho.image_classes(5)
[0.2467, 0.0000, 0.5049, 0.0000, 0.2484]
sage: EllipticCurve('27a1').galois_representation().image_classes(5)
[0.5839, 0.1645, 0.0000, 0.1702, 0.08143]
sage: EllipticCurve('30a1').galois_representation().image_classes(5)
[0.1956, 0.1801, 0.2543, 0.1728, 0.1972]
sage: EllipticCurve('32a1').galois_representation().image_classes(5)
[0.6319, 0.0000, 0.2492, 0.0000, 0.1189]
sage: EllipticCurve('900a1').galois_representation().image_classes(5)
[0.5852, 0.1679, 0.0000, 0.1687, 0.07824]
sage: EllipticCurve('441a1').galois_representation().image_classes(5)
[0.5860, 0.1646, 0.0000, 0.1679, 0.08150]
sage: EllipticCurve('648a1').galois_representation().image_classes(5)
[0.3945, 0.3293, 0.2388, 0.0000, 0.03749]
sage: EllipticCurve('784h1').galois_representation().image_classes(7)
[0.5049, 0.0000, 0.0000, 0.0000, 0.4951, 0.0000, 0.0000]
sage: EllipticCurve('49a1').galois_representation().image_classes(7)
[0.5045, 0.0000, 0.0000, 0.0000, 0.4955, 0.0000, 0.0000]
```
**REMARKS:**

Conjugacy classes of subgroups of $PGL_2(F_5)$

For the case $p = 5$, the order of an element determines almost the value of $u$: 

<table>
<thead>
<tr>
<th>$u$</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>orders</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>6</td>
<td>1 or 5</td>
</tr>
</tbody>
</table>

Here we give here the full table of all conjugacy classes of subgroups with the values that `image_classes` should give (as bound tends to $\infty$). Comparing with the output of the above examples, it is now easy to guess what the image is.

<table>
<thead>
<tr>
<th>subgroup</th>
<th>order</th>
<th>frequencies of values of $u$</th>
</tr>
</thead>
<tbody>
<tr>
<td>trivial</td>
<td>1</td>
<td>[0.0000, 0.0000, 0.0000, 0.0000, 1.0000]</td>
</tr>
<tr>
<td>cyclic</td>
<td>2</td>
<td>[0.5000, 0.0000, 0.0000, 0.0000, 0.5000]</td>
</tr>
<tr>
<td>cyclic</td>
<td>2</td>
<td>[0.5000, 0.0000, 0.0000, 0.0000, 0.5000]</td>
</tr>
<tr>
<td>cyclic</td>
<td>3</td>
<td>[0.0000, 0.6667, 0.0000, 0.0000, 0.3333]</td>
</tr>
<tr>
<td>Klein</td>
<td>4</td>
<td>[0.7500, 0.0000, 0.0000, 0.0000, 0.2500]</td>
</tr>
<tr>
<td>Klein</td>
<td>4</td>
<td>[0.7500, 0.0000, 0.0000, 0.0000, 0.2500]</td>
</tr>
<tr>
<td>cyclic</td>
<td>5</td>
<td>[0.0000, 0.0000, 0.0000, 0.0000, 1.0000]</td>
</tr>
<tr>
<td>cyclic</td>
<td>6</td>
<td>[0.1667, 0.3333, 0.0000, 0.3333, 0.1667]</td>
</tr>
<tr>
<td>$S_3$</td>
<td>6</td>
<td>[0.5000, 0.3333, 0.0000, 0.0000, 0.1667]</td>
</tr>
<tr>
<td>$S_3$</td>
<td>6</td>
<td>[0.5000, 0.3333, 0.0000, 0.0000, 0.1667]</td>
</tr>
<tr>
<td>$D_4$</td>
<td>8</td>
<td>[0.6250, 0.0000, 0.2500, 0.0000, 0.1250]</td>
</tr>
<tr>
<td>$D_5$</td>
<td>10</td>
<td>[0.5000, 0.0000, 0.0000, 0.0000, 0.5000]</td>
</tr>
<tr>
<td>$A_4$</td>
<td>12</td>
<td>[0.2500, 0.6667, 0.0000, 0.0000, 0.08333]</td>
</tr>
<tr>
<td>$D_6$</td>
<td>12</td>
<td>[0.5833, 0.1667, 0.0000, 0.1667, 0.08333]</td>
</tr>
<tr>
<td>Borel</td>
<td>20</td>
<td>[0.2500, 0.0000, 0.5000, 0.0000, 0.2500]</td>
</tr>
<tr>
<td>$S_4$</td>
<td>24</td>
<td>[0.3750, 0.3333, 0.2500, 0.0000, 0.04167]</td>
</tr>
<tr>
<td>$PSL_2$</td>
<td>60</td>
<td>[0.2500, 0.3333, 0.0000, 0.0000, 0.4167]</td>
</tr>
<tr>
<td>$PGL_2$</td>
<td>120</td>
<td>[0.2083, 0.1667, 0.2500, 0.1667, 0.2083]</td>
</tr>
</tbody>
</table>

**image_type($p$)**

Return a string describing the image of the mod-$p$ representation. The result is provably correct, but only indicates what sort of an image we have. If one wishes to determine the exact group one needs to work a bit harder. The probabilistic method of `image_classes` or Sutherland’s `galrepp` package can give a very good guess what the image should be.

**INPUT:**
• p a prime number

OUTPUT:

• a string.

EXAMPLES:

```
sage: E = EllipticCurve('14a1')
sage: rho = E.galois_representation()
sage: rho.image_type(5)
'The image is all of GL_2(F_5).''

sage: E = EllipticCurve('11a1')
sage: rho = E.galois_representation()
sage: rho.image_type(5)
'The image is meta-cyclic inside a Borel subgroup as there is a 5-torsion point on the curve.'

sage: EllipticCurve('27a1').galois_representation().image_type(5)
'The image is contained in the normalizer of a non-split Cartan group. (cm)'

sage: EllipticCurve('30a1').galois_representation().image_type(5)
'The image is all of GL_2(F_5).''

sage: EllipticCurve('324b1').galois_representation().image_type(5)
'The image in PGL_2(F_5) is the exceptional group S_4.'

sage: E = EllipticCurve([0,0,0,-56,4848])
sage: rho = E.galois_representation()
sage: rho.image_type(5)
'The image is contained in the normalizer of a split Cartan group.'

sage: EllipticCurve('49a1').galois_representation().image_type(7)
'The image is contained in a Borel subgroup as there is a 7-isogeny.'

sage: EllipticCurve('121c1').galois_representation().image_type(11)
'The image is contained in a Borel subgroup as there is a 11-isogeny.'

sage: EllipticCurve('121d1').galois_representation().image_type(11)
'The image is all of GL_2(F_11).''

sage: EllipticCurve('441f1').galois_representation().image_type(13)
'The image is contained in a Borel subgroup as there is a 13-isogeny.'

```

(continues on next page)
Elliptic curves, Release 9.7

sage: EllipticCurve([0,0,1,2580,549326]).galois_representation().image_type(7)
'The image is contained in the normalizer of a split Cartan group.'

Test trac ticket #14577:

sage: EllipticCurve([0, 1, 0, -4788, 109188]).galois_representation().image_type(13)
'The image in PGL_2(F_13) is the exceptional group S_4.'

Test trac ticket #14752:

sage: EllipticCurve([0, 0, 0, -1129345880,-86028258620304]).galois_representation().image_type(11)
'The image is contained in the normalizer of a non-split Cartan group.'

For $p = 2$:

sage: E = EllipticCurve('11a1')
sage: rho = E.galois_representation()
sage: rho.image_type(2)
'The image is all of GL_2(F_2), i.e. a symmetric group of order 6.'

sage: rho = EllipticCurve('14a1').galois_representation()
sage: rho.image_type(2)
'The image is cyclic of order 2 as there is exactly one rational 2-torsion point.'

sage: rho = EllipticCurve('15a1').galois_representation()
sage: rho.image_type(2)
'The image is trivial as all 2-torsion points are rational.'

sage: rho = EllipticCurve('196a1').galois_representation()
sage: rho.image_type(2)
'The image is cyclic of order 3.'

$p = 3$:

sage: rho = EllipticCurve('33a1').galois_representation()
sage: rho.image_type(3)
'The image is all of GL_2(F_3).' 

sage: rho = EllipticCurve('30a1').galois_representation()
sage: rho.image_type(3)
'The image is meta-cyclic inside a Borel subgroup as there is a 3-torsion point on the curve.'

sage: rho = EllipticCurve('50b1').galois_representation()
sage: rho.image_type(3)
'The image is contained in a Borel subgroup as there is a 3-isogeny.'

sage: rho = EllipticCurve('3840h1').galois_representation()
sage: rho.image_type(3)
'The image is contained in a dihedral group of order 8.'

(continues on next page)
sage: rho = EllipticCurve('32a1').galois_representation()
sage: rho.image_type(3)
'The image is a semi-dihedral group of order 16, gap.SmallGroup([16,8]).'

ALGORITHM: Mainly based on Serre's paper.

is_crystalline($p$)
Return true if the $p$-adic Galois representation to $GL_2(\mathbb{Z}_p)$ is crystalline.
For an elliptic curve $E$, this is to ask whether $E$ has good reduction at $p$.

INPUT:
• $p$ a prime

OUTPUT:
• a Boolean

EXAMPLES:

sage: rho = EllipticCurve('64a1').galois_representation()
sage: rho.is_crystalline(5)
True
sage: rho.is_crystalline(2)
False

is_irreducible($p$)
Return True if the mod $p$ representation is irreducible.

INPUT:
• $p$ – a prime number

OUTPUT:
• a boolean

EXAMPLES:

sage: rho = EllipticCurve('37b').galois_representation()
sage: rho.is_irreducible(2)
True
sage: rho.is_irreducible(3)
False
sage: rho.is_reducible(2)
False
sage: rho.is_reducible(3)
True

is_ordinary($p$)
Return true if the $p$-adic Galois representation to $GL_2(\mathbb{Z}_p)$ is ordinary, i.e. if the image of the decomposition group in $\text{Gal}(\overline{\mathbb{Q}}/\mathbb{Q})$ above the prime $p$ maps into a Borel subgroup.
For an elliptic curve $E$, this is to ask whether $E$ is ordinary at $p$, i.e. good ordinary or multiplicative.

INPUT:
• $p$ a prime
Elliptic curves, Release 9.7

OUTPUT:

• a Boolean

EXAMPLES:

```
sage: rho = EllipticCurve('11a3').galois_representation()
sage: rho.is_ordinary(11)
True
sage: rho.is_ordinary(5)
True
sage: rho.is_ordinary(19)
False
```

**is_potentially_crystalline** *(p)*

Return true if the $p$-adic Galois representation to $GL_2(\mathbb{Z}_p)$ is potentially crystalline, i.e. if there is a finite extension $K/\mathbb{Q}_p$ such that the $p$-adic representation becomes crystalline.

For an elliptic curve $E$, this is to ask whether $E$ has potentially good reduction at $p$.

INPUT:

• $p$ a prime

OUTPUT:

• a Boolean

EXAMPLES:

```
sage: rho = EllipticCurve('37b1').galois_representation()
sage: rho.is_potentially_crystalline(37)
False
sage: rho.is_potentially_crystalline(7)
True
```

**is_potentially_semistable** *(p)*

Return true if the $p$-adic Galois representation to $GL_2(\mathbb{Z}_p)$ is potentially semistable.

For an elliptic curve $E$, this returns True always.

INPUT:

• $p$ a prime

OUTPUT:

• a Boolean

EXAMPLES:

```
sage: rho = EllipticCurve('27a2').galois_representation()
sage: rho.is_potentially_semistable(3)
True
```

**is_quasi_unipotent** *(p, ell)*

Return true if the Galois representation to $GL_2(\mathbb{Z}_p)$ is quasi-unipotent at $\ell \neq p$, i.e. if there is a finite extension $K/\mathbb{Q}$ such that the inertia group at a place above $\ell$ in $\text{Gal}(\overline{\mathbb{Q}}/K)$ maps into a Borel subgroup.

For a Galois representation attached to an elliptic curve $E$, this returns always True.

INPUT:
is_reducible($p$)
Return True if the mod-$p$ representation is reducible. This is equivalent to the existence of an isogeny defined over $\mathbb{Q}$ of degree $p$ from the elliptic curve.

INPUT:
• $p$ – a prime number

OUTPUT:
• a boolean

The answer is cached.

EXAMPLES:
```
sage: rho = EllipticCurve('121a').galois_representation()
sage: rho.is_reducible(7)
False
sage: rho.is_reducible(11)
True
sage: EllipticCurve('11a').galois_representation().is_reducible(5)
True
sage: rho = EllipticCurve('11a2').galois_representation()
sage: rho.is_reducible(5)
True
sage: EllipticCurve('11a2').torsion_order()
1
```
is_surjective \( p, A=1000 \)  
Return True if the mod-p representation is surjective onto \( Aut(E[p]) = GL_2(\mathbb{F}_p) \).
False if it is not, or None if we were unable to determine whether it is or not.

INPUT:

- \( p \) (integer) – a prime number
- \( A \) (integer) – a bound on the number of \( a_p \) to use

OUTPUT:

- (boolean) – True if the mod-p representation is surjective and False if not.

The answer is cached.

EXAMPLES:

```
sage: rho = EllipticCurve('37b').galois_representation()
sage: rho.is_surjective(2)
True
sage: rho.is_surjective(3)
False
```

```
sage: rho = EllipticCurve('121a1').galois_representation()
sage: rho.non_surjective()  
[11]
sage: rho.is_surjective(5)
True
sage: rho.is_surjective(11)
False
```

```
sage: rho = EllipticCurve('121d1').galois_representation()
sage: rho.is_surjective(5)
False
sage: rho.is_surjective(11)
True
```

Here is a case, in which the algorithm does not return an answer:

```
sage: rho = EllipticCurve([0,0,1,2580,549326]).galois_representation()
sage: rho.is_surjective(7)
```

In these cases, one can use image_type to get more information about the image:

```
sage: rho.image_type(7)
'The image is contained in the normalizer of a split Cartan group.'
```

REMARKS:

1. If \( p \geq 5 \) then the mod-p representation is surjective if and only if the p-adic representation is surjective. When \( p = 2, 3 \) there are counterexamples. See papers of Dokchitser and Elkies for more details.
2. For the primes \( p = 2 \) and \( 3 \), this will always answer either True or False. For larger primes it might give None.

**is_unipotent(\( p, ell \))**

Return true if the Galois representation to \( GL_2(\mathbb{Z}_p) \) is unipotent at \( \ell \neq p \), i.e. if the inertia group at a place above \( \ell \) in \( \text{Gal}(\bar{\mathbb{Q}}/\mathbb{Q}) \) maps into a Borel subgroup.

For a Galois representation attached to an elliptic curve \( E \), this returns True if \( E \) has semi-stable reduction at \( \ell \).

**INPUT:**

- \( p \) a prime
- \( ell \) a different prime

**OUTPUT:**

- Boolean

**EXAMPLES:**

```python
sage: rho = EllipticCurve('120a1').galois_representation()
sage: rho.is_unipotent(2,5)  # True
sage: rho.is_unipotent(5,2)  # False
sage: rho.is_unipotent(5,7)  # True
sage: rho.is_unipotent(5,3)  # True
sage: rho.is_unipotent(5,5)  # Traceback (most recent call last):
...  
 ValueError: unipotent is not defined for \( l = p \), use semistable instead.
```

**is_unramified(\( p, ell \))**

Return true if the Galois representation to \( GL_2(\mathbb{Z}_p) \) is unramified at \( \ell \), i.e. if the inertia group at a place above \( \ell \) in \( \text{Gal}(\bar{\mathbb{Q}}/\mathbb{Q}) \) has trivial image in \( GL_2(\mathbb{Z}_p) \).

For a Galois representation attached to an elliptic curve \( E \), this returns True if \( \ell \neq p \) and \( E \) has good reduction at \( \ell \).

**INPUT:**

- \( p \) a prime
- \( ell \) another prime

**OUTPUT:**

- Boolean

**EXAMPLES:**

```python
sage: rho = EllipticCurve('20a3').galois_representation()
sage: rho.is_unramified(5,7)  # True
sage: rho.is_unramified(5,5)  # False
```

(continues on next page)
This says that the 5-adic representation is unramified at 7, but the 7-adic representation is ramified at 5.

**non_surjective**(\(A=1000\))

Return a list of primes \(p\) such that the mod-\(p\) representation might not be surjective. If \(p\) is not in the returned list, then the mod-\(p\) representation is provably surjective.

By a theorem of Serre, there are only finitely many primes in this list, except when the curve has complex multiplication.

If the curve has CM, we simply return the sequence [0] and do no further computation.

**INPUT:**
- \(A\) – an integer (default 1000). By increasing this parameter the resulting set might get smaller.

**OUTPUT:**
- list – if the curve has CM, returns [0]. Otherwise, returns a list of primes where mod-\(p\) representation is very likely not surjective. At any prime not in this list, the representation is definitely surjective.

**EXAMPLES:**

```python
sage: E = EllipticCurve([0, 0, 1, -38, 90]) # 361A
sage: E.galois_representation().non_surjective() # CM curve
[0]
```

```python
sage: E = EllipticCurve([0, -1, 1, 0, 0]) # X_1(11)
sage: E.galois_representation().non_surjective()
[5]
```

```python
sage: E = EllipticCurve([0, 0, 1, -1, 0]) # 37A
sage: E.galois_representation().non_surjective()
[]
```

```python
sage: E = EllipticCurve([0, -1, 1, -2, -1]) # 141C
sage: E.galois_representation().non_surjective()
[13]
```

```python
sage: E = EllipticCurve([1, -1, 1, -9965, 385220]) # 9999a1
sage: rho = E.galois_representation()
sage: rho.non_surjective()
[2]
```

```python
sage: E = EllipticCurve(’324b1’)
sage: rho = E.galois_representation()
sage: rho.non_surjective()
[3, 5]
```

**ALGORITHM:** We first find an upper bound \(B\) on the possible primes. If \(E\) is semi-stable, we can take \(B = 11\) by a result of Mazur. There is a bound by Serre in the case that the \(j\)-invariant is not integral in terms of the smallest prime of good reduction. Finally there is an unconditional bound by Cojocaru, but which depends on the conductor of \(E\). For the prime below that bound we call **is_surjective**.
reducible_primes()

Return a list of the primes $p$ such that the mod-$p$ representation is reducible. For all other primes the representation is irreducible.

EXAMPLES:

```python
sage: rho = EllipticCurve('225a').galois_representation()
sage: rho.reducible_primes()
[3]
```

## 14.8 Galois representations for elliptic curves over number fields

This file contains the code to compute for which primes the Galois representation attached to an elliptic curve (over an arbitrary number field) is surjective. The functions in this file are called by the is_surjective and non_surjective methods of an elliptic curve over a number field.

EXAMPLES:

```python
sage: K = NumberField(x**2 - 29, 'a'); a = K.gen()
sage: E = EllipticCurve([1, 0, ((5 + a)/2)**2, 0, 0])
sage: rho = E.galois_representation()
sage: rho.is_surjective(29)  # Cyclotomic character not surjective.
False
sage: rho.is_surjective(31)  # See Section 5.10 of [Ser1972].
True
sage: rho.non_surjective()  # long time (4s on sage.math, 2014)
[3, 5, 29]
```

AUTHORS:

- John Cremona (2017): implementation of Billerey’s algorithm to find all reducible primes

REFERENCES:

- [Ser1972]
- [Sun2012]

```
sage.schemes.elliptic_curves.gal_reps_number_field.Billerey_B_bound(E, max_l=200, num_l=8,
small_prime_bound=0,
default=False)
```

We compute $B_l$ for $l$ up to max_l (at most) until num_l nonzero values are found (at most). Return the list of primes dividing all $B_l$ computed, excluding those dividing 6 or ramified or of bad reduction or less than small_prime_bound. If no non-zero values are found return [0].

INPUT:
• E – an elliptic curve over a number field \( K \), given by a global integral model.
• \( \text{max}_l \) (int, default 200) – maximum size of primes \( l \) to check.
• \( \text{num}_l \) (int, default 8) – maximum number of primes \( l \) to check.
• \( \text{small}_\text{prime}_\text{bound} \) (int, default 0) – remove primes less than this from the output.
• debug (bool, default False) – if True prints details.

**Note:** The purpose of the small\(_{\text{prime}}\)_\text{bound} is that it is faster to deal with these using the local test; by ignoring them here, we enable the algorithm to terminate sooner when there are no large reducible primes, which is always the case in practice.

**EXAMPLES:**

```python
sage: K = NumberField(x**2 - 29, 'a'); a = K.gen()
sage: E = EllipticCurve([1, 0, ((5 + a)/2)**2, 0, 0])
sage: from sage.schemes.elliptic_curves.gal_reps_number_field import Billerey_B_bound
sage: Billerey_B_bound(E)
[5]
```

If we do not use enough primes \( l \), extraneous primes will be included which are not reducible primes:

```python
sage: Billerey_B_bound(E, num_l=6)
[5, 7]
```

Similarly if we do not use large enough primes \( l \):

```python
sage: Billerey_B_bound(E, max_l=50, num_l=8)
[5, 7]
sage: Billerey_B_bound(E, max_l=100, num_l=8)
[5]
```

This curve does have a rational 5-isogeny:

```python
sage: len(E.isogenies_prime_degree(5))
1
```

```
sage.schemes.elliptic_curves.gal_reps_number_field.Billerey_B_l(E, l, B=0)

Return Billerey's \( B_l \), adapted from the definition in [Bil2011], after (9).

**INPUT:**

• E – an elliptic curve over a number field \( K \), given by a global integral model.
• l (int) – a rational prime
• B (int) – 0 or LCM of previous \( B_l \): the prime-to-B part of this \( B_l \) is ignored.

**EXAMPLES:**

```python
sage: K = NumberField(x**2 - 29, 'a'); a = K.gen()
sage: E = EllipticCurve([1, 0, ((5 + a)/2)**2, 0, 0])
sage: from sage.schemes.elliptic_curves.gal_reps_number_field import Billerey_B_l
sage: [Billerey_B_l(E, l) for l in primes(15)]
[112307752537600, ...
```

(continues on next page)
sage.schemes.elliptic_curves.gal_reps_number_field.Billerey_P_l(E, l)

Return Billerey’s $P_l^*$ as defined in [Bil2011], equation (9).

INPUT:

- $E$ – an elliptic curve over a number field $K$, given by a global integral model.
- $l$ – a rational prime

EXAMPLES:

```python
sage: K = NumberField(x**2 - 29, 'a'); a = K.gen()
sage: E = EllipticCurve([1, 0, ((5 + a)/2)**2, 0, 0])
sage: [Billerey_P_l(E, l) for l in primes(10)]
[x^2 + 8143*x + 16777216,
 x^2 + 451358*x + 282429536481,
 x^4 - 664299076*x^3 + 295155493652343750*x^2 - 39595310449600219726562500*x ~ 3552713678800500929355621337890625,
 x^4 - 207302404*x^3 - 377423798538689366394*x^2 - 39715249826471656586987520004*x ~ 36703368217294125441230211032033660188801]
```

sage.schemes.elliptic_curves.gal_reps_number_field.Billerey_R_bound(E, max_l=200, num_l=8, small_prime_bound=None, debug=False)

Compute Billerey’s bound $R$.

We compute $R_q$ for $q$ dividing primes $l$ up to $\text{max}_l$ (at most) until $\text{num}_l$ nonzero values are found (at most). Return the list of primes dividing all $R_q$ computed, excluding those dividing 6 or ramified or of bad reduction or less than $\text{small}_l\text{prime}_l\text{bound}$. If no non-zero values are found return [0].

INPUT:

- $E$ – an elliptic curve over a number field $K$, given by a global integral model.
- $\text{max}_l$ (int, default 200) – maximum size of rational primes l for which the primes $q$ above l are checked.
- $\text{num}_l$ (int, default 8) – maximum number of rational primes l for which the primes $q$ above l are checked.
- $\text{small}_l\text{prime}_l\text{bound}$ (int, default 0) – remove primes less than this from the output.
- $\text{debug}$ (bool, default False) – if True prints details.

Note: The purpose of the small_prime_bound is that it is faster to deal with these using the local test; by ignoring them here, we enable the algorithm to terminate sooner when there are no large reducible primes, which is always the case in practice.

EXAMPLES:

```python
sage: K = NumberField(x**2 - 29, 'a'); a = K.gen()
sage: E = EllipticCurve([1, 0, ((5 + a)/2)**2, 0, 0])
```
We may get no bound at all if we do not use enough primes:

```python
sage: Billerey_R_bound(E, max_l=2, debug=False)
[0]
```

Or we may get a bound but not a good one if we do not use enough primes:

```python
sage: Billerey_R_bound(E, num_l=1, debug=False)
[5, 17, 67, 157]
```

In this case two primes is enough to restrict the set of possible reducible primes to just \{5\}. This curve does have a rational 5-isogeny:

```python
sage: Billerey_R_bound(E, num_l=2, debug=False)
[5]
```

```python
sage: len(E.isogenies_prime_degree(5))
1
```

---

sage.schemes.elliptic_curves.gal_reps_number_field.Billerey_R_q(E, q, B=0)
Return Billerey’s $R_q$, adapted from the definition in [Bil2011], Theorem 2.8.

**INPUT:**
- $E$ – an elliptic curve over a number field $K$, given by a global integral model.
- $q$ – a prime ideal of $K$
- $B$ (int) – 0 or LCM of previous $R_q$: the prime-to-B part of this $R_q$ is ignored.

**EXAMPLES:**

```python
sage: K = NumberField(x**2 - 29, 'a'); a = K.gen()
sage: E = EllipticCurve([1, 0, ((5 + a)/2)**2, 0, 0])
sage: from sage.schemes.elliptic_curves.gal_reps_number_field import Billerey_R_q
sage: [Billerey_R_q(E,K.prime_above(l)) for l in primes(10)]
[1123077552537600, 227279663773903886745600, 519569195621169600000000000000000, 252485933820556361829926400000000]
```

---

sage.schemes.elliptic_curves.gal_reps_number_field.Frobenius_filter($E$, $L$, patience=100)
Determine which primes in $L$ might have an image contained in a Borel subgroup, by checking of traces of Frobenius.

**Note:** This function will sometimes return primes for which the image is not contained in a Borel subgroup. This issue cannot always be fixed by increasing patience as it may be a result of a failure of a local-global principle for isogenies.

**INPUT:**
- $E$ – EllipticCurve over a number field.
- L – a list of prime numbers.
- patience (int), default 100 – a positive integer bounding the number of traces of Frobenius to use while trying to prove irreducibility.

**OUTPUT:**
- list – The list of all primes \( \ell \) in L for which the mod \( \ell \) image might be contained in a Borel subgroup of \( GL_2(\mathbb{F}_\ell) \).

**EXAMPLES:**

```
sage: E = EllipticCurve('11a1') # has a 5-isogeny
sage: sage.schemes.elliptic_curves.gal_reps_number_field.Frobenius_filter(E, →primes(40))
[5]
```

Example to show that the output may contain primes where the representation is in fact reducible. Over \( \mathbb{Q} \) the following is essentially the unique such example by [Sut2012]:

```
sage: E = EllipticCurve_from_j(2268945/128)
sage: sage.schemes.elliptic_curves.gal_reps_number_field.Frobenius_filter(E, [7, →11])
[7]
```

This curve does possess a 7-isogeny modulo every prime of good reduction, but has no rational 7-isogeny:

```
sage: E.isogenies_prime_degree(7)
[]
```

A number field example:

```
sage: K.<i> = QuadraticField(-1)
sage: E = EllipticCurve([i+1, -i, -399-240*i, 2627+2869*i])
sage: sage.schemes.elliptic_curves.gal_reps_number_field.Frobenius_filter(E, →primes(20))
[2, 3]
```

Here the curve really does possess isogenies of degrees 2 and 3:

```
sage: [len(E.isogenies_prime_degree(l)) for l in [2,3]]
[1, 1]
```

**class** `sage.schemes.elliptic_curves.gal_reps_number_field.GaloisRepresentation(E)`

Bases: `sage.structure.sage_object.SageObject`

The compatible family of Galois representation attached to an elliptic curve over a number field.

Given an elliptic curve \( E \) over a number field \( K \) and a rational prime number \( p \), the \( p^n \)-torsion \( E[p^n] \) points of \( E \) is a representation of the absolute Galois group \( G_K \) of \( K \). As \( n \) varies we obtain the Tate module \( T_{p^n}E \) which is a representation of \( G_K \) on a free \( \mathbb{Z}_p \)-module of rank 2. As \( p \) varies the representations are compatible.

**EXAMPLES:**

```
sage: K = NumberField(x**2 + 1, 'a')
sage: E = EllipticCurve('11a1').change_ring(K)
sage: rho = E.galois_representation()
```

(continues on next page)
Elliptic curves, Release 9.7

sage: rho
Compatible family of Galois representations associated to the Elliptic Curve,
...defined by y^2 + y = x^3 + (-1)*x^2 + (-10)*x + (-20) over Number Field in a with...
...defining polynomial x^2 + 1

elliptic_curve()

Return the elliptic curve associated to this representation.

EXAMPLES:

sage: K = NumberField(x^2 + 1, 'a'); a = K.gen()
sage: E = EllipticCurve_from_j(a)
sage: rho = E.galois_representation()
sage: rho.elliptic_curve() == E
True

is_surjective(p, A=100)

Return True if the mod-p representation is (provably) surjective onto \( Aut(E[p]) = GL_2(F_p) \). Return False if it is (probably) not.

INPUT:

• p - int - a prime number.
• A - int - a bound on the number of traces of Frobenius to use  while trying to prove surjectivity.

EXAMPLES:

sage: K = NumberField(x**2 - 29, 'a'); a = K.gen()
sage: E = EllipticCurve([1, 0, ((5 + a)/2)**2, 0, 0])
sage: rho = E.galois_representation()
sage: rho.is_surjective(29)  # Cyclotomic character not surjective.
False
sage: rho.is_surjective(7)  # See Section 5.10 of [Ser1972].
True

If \( E \) is defined over \( \mathbb{Q} \), then the exceptional primes for \( E/K \) are the same as the exceptional primes for \( E \), except for those primes that are ramified in \( K/\mathbb{Q} \) or are less than \([K : \mathbb{Q}]\):

sage: K = NumberField(x**2 + 11, 'a')
sage: E = EllipticCurve([2, 14])
sage: rhoQQ = E.galois_representation()
sage: rhoK = E.change_ring(K).galois_representation()
sage: rhoQQ.is_surjective(2) == rhoK.is_surjective(2)
False
sage: rhoQQ.is_surjective(3) == rhoK.is_surjective(3)
True
sage: rhoQQ.is_surjective(5) == rhoK.is_surjective(5)
True

For CM curves, the mod-p representation is never surjective:

sage: K.<a> = NumberField(x^2-x+1)
sage: E = EllipticCurve([0,0,0,0,a])
sage: E.has_cm()
Elliptic curves, Release 9.7

(continued from previous page)

```sage
sage: rho = E.galois_representation()
sage: any(rho.is_surjective(p) for p in [2,3,5,7])
False
```

**isogeny_bound**(A=100)

Return a list of primes \( p \) including all primes for which the image of the mod-\( p \) representation is contained in a Borel.

**Note:** For the actual list of primes \( p \) at which the representation is reducible see `reducible_primes()`.

**INPUT:**

- \( A \) – int (a bound on the number of traces of Frobenius to use while trying to prove the mod-\( p \) representation is not contained in a Borel).

**OUTPUT:**

- list – A list of primes which contains (but may not be equal to) all \( p \) for which the image of the mod-\( p \) representation is contained in a Borel subgroup. At any prime not in this list, the image is definitely not contained in a Borel. If \( E \) has \( CM \) defined over \( K \), the list [0] is returned.

**EXAMPLES:**

```sage
sage: K = NumberField(x**2 - 29, 'a'); a = K.gen()
sage: E = EllipticCurve([1, 0, ((5 + a)/2)**2, 0, 0])
sage: rho = E.galois_representation()
sage: rho.isogeny_bound() # See Section 5.10 of [Ser1972].
[3, 5]
sage: E = EllipticCurve_from_j(K(1728)).galois_representation().isogeny_bound() # CM over K
[0]
sage: E = EllipticCurve_from_j(K(0)).galois_representation().isogeny_bound() # NOT over K
[2, 3]
sage: E = EllipticCurve_from_j(K(2268945/128)) # c.f. [Sut2012] # No 7-isogeny, but...
[7]
```

For curves with rational CM, there are infinitely many primes \( p \) for which the mod-\( p \) representation is reducible, and [0] is returned:

```sage
sage: K.<a> = NumberField(x^2-x+1)
sage: E = EllipticCurve([0,0,0,0,a])
sage: E.has_rational_cm()
True
sage: rho = E.galois_representation()
sage: rho.isogeny_bound()
[0]
```

An example (an elliptic curve with everywhere good reduction over an imaginary quadratic field with quite large discriminant), which failed until fixed at trac ticket #21776:

3. 14.8. Galois representations for elliptic curves over number fields  409
sage: K.<a> = NumberField(x^2 - x + 112941801)
sage: E = EllipticCurve([a+1,a-1,a,-23163076*a + 266044005933275,
    → 57560769602038*a - 836483958630700313803])
sage: E.conductor().norm()
1
sage: GR = E.galois_representation()
sage: GR.isogeny_bound()
[]

non_surjective(A=100)
Return a list of primes \( p \) including all primes for which the mod-\( p \) representation might not be surjective.

INPUT:
• \( A \) – int (a bound on the number of traces of Frobenius to use while trying to prove surjectivity).

OUTPUT:
• list – A list of primes where mod-\( p \) representation is very likely not surjective. At any prime not in this list, the representation is definitely surjective. If \( E \) has CM, the list [0] is returned.

EXAMPLES:

sage: K = NumberField(x**2 - 29, 'a'); a = K.gen()
sage: E = EllipticCurve([1, 0, ((5 + a)/2)**2, 0, 0])
sage: rho = E.galois_representation()
sage: rho.non_surjective() # See Section 5.10 of [Ser1972].
[3, 5, 29]
sage: K = NumberField(x**2 + 3, 'a'); a = K.gen()
sage: E = EllipticCurve([0, -1, 1, -10, -20]).change_ring(K) # X_0(11)
sage: rho = E.galois_representation()
sage: rho.non_surjective() # long time (4s on sage.math, 2014)
[3, 5]
sage: K = NumberField(x**2 + 1, 'a'); a = K.gen()
sage: E = EllipticCurve_from_j(1728).change_ring(K) # CM
sage: rho = E.galois_representation()
sage: rho.non_surjective()
[0]
sage: K = NumberField(x**2 - 5, 'a'); a = K.gen()
sage: E = EllipticCurve_from_j(146329141248*a - 327201914880) # CM
sage: rho = E.galois_representation()
sage: rho.non_surjective() # long time (3s on sage.math, 2014)
[0]

reducible_primes()
Return a list of primes \( p \) for which the mod-\( p \) representation is reducible, or [0] for CM curves.

OUTPUT:
• list – A list of those primes \( p \) for which the mod-\( p \) representation is contained in a Borel subgroup, i.e. is reducible. If \( E \) has CM defined over \( K \), the list [0] is returned (in this case the representation is reducible for infinitely many primes).

EXAMPLES:

sage: K = NumberField(x**2 - 29, 'a'); a = K.gen()
sage: E = EllipticCurve([1, 0, ((5 + a)/2)**2, 0, 0])

(continues on next page)
sage: rho = E.galois_representation()

sage: rho.isogeny_bound() # See Section 5.10 of [Ser1972].
[3, 5]

sage: rho.reducible_primes()
[3, 5]

sage: K = NumberField(x**2 + 1, 'a')

sage: EllipticCurve_from_j(K(1728)).galois_representation().isogeny_bound() # CM over K
[0]

sage: EllipticCurve_from_j(K(0)).galois_representation().reducible_primes() # CM but NOT over K
[2, 3]

sage: E = EllipticCurve_from_j(K(2268945/128)) # c.f. [Sut2012]

sage: rho = E.galois_representation()

sage: rho.isogeny_bound() # ... but there is no 7-isogeny ...
[7]

sage: rho.reducible_primes()
[]

For curves with rational CM, there are infinitely many primes $p$ for which the mod-$p$ representation is reducible, and [0] is returned:

sage: K.<a> = NumberField(x^2-x+1)

sage: E = EllipticCurve([0,0,0,0,a])

sage: E.has_rational_cm()
True

sage: rho = E.galois_representation()

sage: rho.reducible_primes()
[0]

.. _deg_one_primes_iter:

sage.schemes.elliptic_curves.gal_reps_number_field.deg_one_primes_iter(K, principal_only=False)

Return an iterator over degree 1 primes of $K$.

INPUT:

- $K$ – a number field
- principal_only – bool; if True, only yield principal primes

OUTPUT:

An iterator over degree 1 primes of $K$ up to the given norm, optionally yielding only principal primes.

EXAMPLES:

sage: K.<a> = QuadraticField(-5)

sage: from sage.schemes.elliptic_curves.gal_reps_number_field import deg_one_primes_iter

sage: it = deg_one_primes_iter(K)

sage: [next(it) for _ in range(6)]
[(Fractional ideal (2, a + 1),)
 Fractional ideal (3, a + 1),
 Fractional ideal (3, a + 2),
 Fractional ideal (3, a + 3),
 Fractional ideal (3, a + 4),
 Fractional ideal (3, a + 5),]
Fractional ideal (-a),
Fractional ideal (7, a + 3),
Fractional ideal (7, a + 4)]

sage: it = deg_one_primes_iter(K, True)
sage: [next(it) for _ in range(6)]
[Fractional ideal (-a),
 Fractional ideal (-2*a + 3),
 Fractional ideal (2*a + 3),
 Fractional ideal (a + 6),
 Fractional ideal (a - 6),
 Fractional ideal (-3*a + 4)]

sage.schemes.elliptic_curves.gal_reps_number_field.reducible_primes_Billerey(E, num_l=None, max_l=None, verbose=False)

Return a finite set of primes ℓ containing all those for which E has a K-rational ell-isogeny, where K is the base field of E: i.e., the mod-ℓ representation is irreducible for all ℓ outside the set returned.

INPUT:

• E – an elliptic curve defined over a number field K.
• max_l (int or None (default)) – the maximum prime ℓ to use for the B-bound and R-bound. If None, a default value will be used.
• num_l (int or None (default)) – the number of primes ℓ to use for the B-bound and R-bound. If None, a default value will be used.

Note: If E has CM then [0] is returned. In this case use the function sage.schemes.elliptic_curves.isogeny_class.possible_isogeny_degrees

We first compute Billeray’s B_bound using at most num_l primes of size up to max_l. If that fails we compute Billeray’s R_bound using at most num_q primes of size up to max_q.

Provided that one of these methods succeeds in producing a finite list of primes we check these using a local condition, and finally test that the primes returned actually are reducible. Otherwise we return [0].

EXAMPLES:

    sage: from sage.schemes.elliptic_curves.gal_reps_number_field import reducible_primes_Billerey
    sage: K = NumberField(x**2 - 29, 'a'); a = K.gen()
    sage: E = EllipticCurve([1, 0, ((5 + a)/2)**2, 0, 0])
    sage: reducible_primes_Billerey(E)
    [3, 5]
    sage: K = NumberField(x**2 + 1, 'a')
    sage: E = EllipticCurve_from_j(K(1728)) # CM over K
    sage: reducible_primes_Billerey(E)
    [0]
    sage: E = EllipticCurve_from_j(K(0)) # CM but NOT over K
    sage: reducible_primes_Billerey(E)
    [2, 3]

An example where a prime is not reducible but passes the test:
Elliptic curves, Release 9.7

```python
sage: E = EllipticCurve_from_j(K(2268945/128)).global_minimal_model()  # c.f. [Sut2012]
sage: reducible_primes_Billerey(E)[7]
```

`sage.schemes.elliptic_curves.gal_reps_number_field.reducible_primes_naive(E, max_l=None, num_P=None, verbose=False)`

Return locally reducible primes ℓ up to max_l.

The list of primes ℓ returned consists of all those up to max_l such that E mod P has an ℓ-isogeny, where K is the base field of E, for num_P primes P of K. In most cases E then has a K-rational ℓ-isogeny, but there are rare exceptions.

INPUT:
- E – an elliptic curve defined over a number field K
- max_l (int or None (default)) – the maximum prime ℓ to test.
- num_P (int or None (default)) – the number of primes P of K to use in testing each ℓ.

EXAMPLES:
```
sage: from sage.schemes.elliptic_curves.gal_reps_number_field import reducible_primes_naive
sage: K.<a> = NumberField(x^4 - 5*x^2 + 3)
sage: E = EllipticCurve(K, [a^2 - 2, -a^2 + 3, a^2 - 2, -50*a^2 + 35, 95*a^2 - 67])
sage: reducible_primes_naive(E, num_P=10)
sage: reducible_primes_naive(E, num_P=15)
[2, 5, 197, 557, 653, 769]
sage: reducible_primes_naive(E, num_P=20)
[2, 5]
sage: reducible_primes_naive(E)
[2, 5]
sage: [phi.degree() for phi in E.isogenies_prime_degree()]
[2, 2, 2, 5]
```

### 14.9 Isogeny class of elliptic curves over number fields

**AUTHORS:**
- David Roe (2012-03-29) – initial version.
- John Cremona (2014-08) – extend to number fields.

```python
class sage.schemes.elliptic_curves.isogeny_class.IsogenyClass_EC(E, label=None, empty=False)
Bases: sage.structure.sage_object.SageObject
Isogeny class of an elliptic curve.
```

**Note:** The current implementation chooses a curve from each isomorphism class in the isogeny class. Over \( \mathbb{Q} \) this is a unique reduced minimal model in each isomorphism class. Over number fields the model chosen may change in future.
graph()

Return a graph whose vertices correspond to curves in this class, and whose edges correspond to prime degree isogenies.

**Note:** There are only finitely many possible isogeny graphs for curves over \( \mathbb{Q} \) [Maz1978b]. This function tries to lay out the graph nicely by special casing each isogeny graph. This could also be done over other number fields, such as quadratic fields.

**Note:** The vertices are labeled 1 to \( n \) rather than 0 to \( n-1 \) to match LMFDB and Cremona labels for curves over \( \mathbb{Q} \).

**Examples:**

```python
sage: isocls = EllipticCurve('15a3').isogeny_class()
sage: G = isocls.graph()
sage: sorted(G._pos.items())
([(1, [-0.8660254, 0.5]), (2, [-0.8660254, 1.5]), (3, [-1.7320508, 0]), (4, [0, -0.8660254, 1.5]), (5, [0, -1]), (6, [0.8660254, 0.5]), (7, [0.8660254, 1.5]), (8, [1.7320508, 0])]
```

index(\( C \))

Return the index of a curve in this class.

**Input:**
- \( C \) – an elliptic curve in this isogeny class.

**Output:**
- \( i \) – an integer so that the \( i \) th curve in the class is isomorphic to \( C \)

**Examples:**

```python
sage: E = EllipticCurve('990j1')
sage: iso = E.isogeny_class(order="lmfdb") # orders lexicographically on a-invariants
sage: iso.index(E.short_weierstrass_model())
2
```

isogenies(\( fill=False \))

Return a list of lists of isogenies and 0s, corresponding to the entries of \( \text{matrix()} \)

**Input:**
- \( fill \) – boolean (default False). Whether to only return prime degree isogenies. Currently only implemented for \( fill=False \).

**Output:**
- a list of lists, where the \( j \) th entry of the \( i \) th list is either zero or a prime degree isogeny from the \( i \) th curve in this class to the \( j \) th curve.

**Warning:** The domains and codomains of the isogenies will have the same Weierstrass equation as the curves in this class, but they may not be identical python objects in the current implementation.
EXAMPLES:

```
sage: isocls = EllipticCurve('15a3').isogeny_class()
sage: f = isocls.isogenies()[0][1]; f
Isogeny of degree 2 from Elliptic Curve defined by y^2 + x*y + y = x^3 + x^2 - 5*x + 2 over Rational Field to Elliptic Curve defined by y^2 + x*y + y = x^3 + x^2 - 80*x + 242 over Rational Field
sage: f.domain() == isocls.curves[0] and f.codomain() == isocls.curves[1]
True
```

`matrix(fill=True)`

Return the matrix whose entries give the minimal degrees of isogenies between curves in this class.

INPUT:

- `fill` – boolean (default True). If False then the matrix will contain only zeros and prime entries; if True it will fill in the other degrees.

EXAMPLES:

```
sage: isocls = EllipticCurve('15a3').isogeny_class()
sage: isocls.matrix()
[ 1 2 2 2 4 4 8 8]
[ 2 1 4 4 8 16 16 16]
[ 2 4 1 4 8 8 16 16]
[ 2 4 4 1 2 2 4 4]
[ 4 8 8 2 1 4 8 8]
[ 4 8 8 2 4 1 2 2]
[ 8 16 16 4 8 2 1 4]
[ 8 16 16 4 8 2 4 1]
sage: isocls.matrix(fill=False)
[0 2 2 2 0 0 0 0]
[2 0 0 0 0 0 0 0]
[2 0 0 0 0 0 0 0]
[2 0 0 2 2 0 0 0]
[0 0 0 2 0 0 0 0]
[0 0 0 2 0 0 2 2]
[0 0 0 0 0 2 0 0]
[0 0 0 0 0 2 0 0]
```

`qf_matrix()`

Return the array whose entries are quadratic forms representing the degrees of isogenies between curves in this class (CM case only).

OUTPUT:

a 2x2 array (list of lists) of list, each of the form [2] or [2,1,3] representing the coefficients of an integral quadratic form in 1 or 2 variables whose values are the possible isogeny degrees between the i'th and j'th curve in the class.

EXAMPLES:

```
sage: pol = PolynomialRing(QQ,'x')([1,0,3,0,1])
sage: K.<c> = NumberField(pol)
sage: j = 1480640+565760*c^2
sage: E = EllipticCurve(j=j)
sage: C = E.isogeny_class()
```
Elliptic curves, Release 9.7

\texttt{sage}: \texttt{C.qf_matrix()}
[[[1], [2, 2, 3]], [[2, 2, 3], [1]]]

\texttt{reorder(order)}

Return a new isogeny class with the curves reordered.

INPUT:

\begin{itemize}
  \item \texttt{order} – None, a string or an iterable over all curves in this class. See \texttt{sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field.isogeny_class()} for more details.
\end{itemize}

OUTPUT:

\begin{itemize}
  \item Another \texttt{IsogenyClass_EC} with the curves reordered (and matrices and maps changed as appropriate)
\end{itemize}

EXAMPLES:

\begin{verbatim}
\texttt{sage}: \texttt{isocls = EllipticCurve('15a1').isogeny_class()}
\texttt{sage}: \texttt{print("\n\n".join(repr(C) for C in isocls.curves))}
Elliptic Curve defined by y^2 + x*y + y = x^3 + x^2 - 10*x - 10 over Rational Field
Elliptic Curve defined by y^2 + x*y + y = x^3 + x^2 - 5*x + 2 over Rational Field
Elliptic Curve defined by y^2 + x*y + y = x^3 + x^2 + 35*x - 28 over Rational Field
Elliptic Curve defined by y^2 + x*y + y = x^3 + x^2 - 135*x - 660 over Rational Field
Elliptic Curve defined by y^2 + x*y + y = x^3 + x^2 - 80*x + 242 over Rational Field
Elliptic Curve defined by y^2 + x*y + y = x^3 + x^2 - 110*x - 880 over Rational Field
Elliptic Curve defined by y^2 + x*y + y = x^3 + x^2 over Rational Field
Elliptic Curve defined by y^2 + x*y + y = x^3 + x^2 + 35*x - 28 over Rational Field
\texttt{sage}: \texttt{isocls2 = isocls.reorder('lmfdb')}
\texttt{sage}: \texttt{print("\n\n".join(repr(C) for C in isocls2.curves))}
Elliptic Curve defined by y^2 + x*y + y = x^3 + x^2 - 2160*x - 39540 over Rational Field
Elliptic Curve defined by y^2 + x*y + y = x^3 + x^2 - 135*x - 660 over Rational Field
Elliptic Curve defined by y^2 + x*y + y = x^3 + x^2 - 110*x - 880 over Rational Field
Elliptic Curve defined by y^2 + x*y + y = x^3 + x^2 - 80*x + 242 over Rational Field
Elliptic Curve defined by y^2 + x*y + y = x^3 + x^2 - 5*x + 2 over Rational Field
Elliptic Curve defined by y^2 + x*y + y = x^3 + x^2 over Rational Field
\end{verbatim}
class sage.schemes.elliptic_curves.isogeny_class.IsogenyClass_EC_NumberField(E, reducible_primes=None, algorithm='Billerey', minimal_models=True)

Bases: sage.schemes.elliptic_curves.isogeny_class.IsogenyClass_EC

Isogeny classes for elliptic curves over number fields.

copy()

Return a copy (mostly used in reordering).

EXAMPLES:

```sage
sage: K.<i> = QuadraticField(-1)
sage: E = EllipticCurve(K, [0,0,0,0,1])
sage: C = E.isogeny_class()
sage: C2 = C.copy()
sage: C is C2
False
sage: C == C2
True
```

class sage.schemes.elliptic_curves.isogeny_class.IsogenyClass_EC_Rational(E, algorithm='sage', label=None, empty=False)

Bases: sage.schemes.elliptic_curves.isogeny_class.IsogenyClass_EC_NumberField

Isogeny classes for elliptic curves over \( \mathbb{Q} \).

copy()

Return a copy (mostly used in reordering).

EXAMPLES:

```sage
sage: E = EllipticCurve('11a1')
sage: C = E.isogeny_class()
sage: C2 = C.copy()
sage: C is C2
False
sage: C == C2
True
```

sage.schemes.elliptic_curves.isogeny_class.isogeny_degrees_cm(E, verbose=False)

Return a list of primes \( \ell \) sufficient to generate the isogeny class of \( E \), where \( E \) has CM.

INPUT:

- \( E \) – An elliptic curve defined over a number field.

OUTPUT:

A finite list of primes \( \ell \) such that every curve isogenous to this curve can be obtained by a finite sequence of isogenies of degree one of the primes in the list.

ALGORITHM:
For curves with CM by the order $O$ of discriminant $d$, the Galois representation is always non-surjective and the curve will admit $\ell$-isogenies for infinitely many primes $\ell$, but there are only finitely many codomains $E'$. The primes can be divided according to the discriminant $d'$ of the CM order $O'$ associated to $E$: either $O = O'$, or one contains the other with index $\ell$, since $\ell O \subset O'$ and vice versa.

Case (1): $O = O'$. The degrees of all isogenies between $E$ and $E'$ are precisely the integers represented by one of the classes of binary quadratic forms $Q$ of discriminant $d$. Hence to obtain all possible isomorphism classes of codomain $E'$, we need only use one prime $\ell$ represented by each such class $Q$. It would in fact suffice to use primes represented by forms which generate the class group. Here we simply omit the principal class and one from each pair of inverse classes, and include a prime represented by each of the remaining forms.

Case (2): $[O : O'] = \ell$: so $d = \ell^2d'$. We include all prime divisors of $d$.

Case (3): $[O : O'] = \ell$: we may assume that $\ell$ does not divide $d$ as we have already included these, so $\ell$ either splits or is inert in $O$; the class numbers satisfy $h(O') = (\ell \pm 1)h(O)$ accordingly. We include all primes $\ell$ such that $\ell \pm 1$ divides the degree $[K : Q]$.

For curves with only potential CM we proceed as in the CM case, using $2[K : Q]$ instead of $[K : Q]$.

EXAMPLES:

For curves with CM by a quadratic order of class number greater than 1, we use the structure of the class group to only give one prime in each ideal class:

```python
sage: pol = PolynomialRing(QQ, 'x')([1,-3,5,-5,5,-3,1])
sage: L.<a> = NumberField(pol)
sage: j = hilbert_class_polynomial(-23).roots(L,multiplicities=False)[0]
sage: E = EllipticCurve(j=j)
sage: from sage.schemes.elliptic_curves.isogeny_class import isogeny_degrees_cm
sage: isogeny_degrees_cm(E, verbose=True)
CM case, discriminant = -23
initial primes: {2}
upward primes: {}
downward ramified primes: {}
downward split primes: {2, 3}
downward inert primes: {5}
primes generating the class group: [2]
Complete set of primes: {2, 3, 5}
[2, 3, 5]
```

Return a list of primes $\ell$ sufficient to generate the isogeny class of $E$.

**INPUT:**

- $E$ – An elliptic curve defined over a number field.
- `algorithm` (string, default ‘Billerey’) – Algorithm to be used for non-CM curves: either ‘Billerey’, ‘Larson’, or ‘heuristic’. Only relevant for non-CM curves and base fields other than $\mathbb{Q}$.
- `max_l` (int or None) – only relevant for non-CM curves and algorithms ‘Billerey’ and ‘heuristic’. Controls the maximum prime used in either algorithm. If None, use the default for that algorithm.
- `num_l` (int or None) – only relevant for non-CM curves and algorithm ‘Billerey’. Controls the maximum number of primes used in the algorithm. If None, use the default for that algorithm.
• exact (bool, default True) – if True, perform an additional check that the primes returned are all reducible. If False, skip this step, in which case some of the primes returned may be irreducible.

OUTPUT:
A finite list of primes \( \ell \) such that every curve isogenous to this curve can be obtained by a finite sequence of isogenies of degree one of the primes in the list.

ALGORITHM:
For curves without CM, the set may be taken to be the finite set of primes at which the Galois representation is not surjective, since the existence of an \( \ell \)-isogeny is equivalent to the image of the mod-\( \ell \) Galois representation being contained in a Borel subgroup. Two rigorous algorithms have been implemented to determine this set, due to Larson and Billeray respectively. We also provide a non-rigorous ‘heuristic’ algorithm which only tests reducible primes up to a bound depending on the degree of the base field.

For curves with CM see the documentation for isogeny_degrees_cm().

EXAMPLES:
For curves without CM we determine the primes at which the mod \( p \) Galois representation is reducible, i.e. contained in a Borel subgroup:

```python
sage: from sage.schemes.elliptic_curves.isogeny_class import possible_isogeny_degrees
sage: E = EllipticCurve('11a1')
sage: possible_isogeny_degrees(E)
[5]
sage: possible_isogeny_degrees(E, algorithm='Larson')
[5]
sage: possible_isogeny_degrees(E, algorithm='Billerey')
[5]
sage: possible_isogeny_degrees(E, algorithm='heuristic')
[5]
```

We check that in this case \( E \) really does have rational 5-isogenies:

```python
sage: [phi.degree() for phi in E.isogenies_prime_degree()]
[5, 5]
```

Over an extension field:

```python
sage: E3 = E.change_ring(CyclotomicField(3))
sage: possible_isogeny_degrees(E3)
[5]
sage: [phi.degree() for phi in E3.isogenies_prime_degree()]
[5, 5]
```

A higher degree example (LMFDB curve 5.5.170701.1-4.1-b1):

```python
sage: K.<a> = NumberField(x^5 - x^4 - 6*x^3 + 4*x + 1)
sage: E = EllipticCurve(K, [a^3 - a^2 - 5*a + 1, a^4 - a^3 - 5*a^2 - a + 1, -a^4 + 2*a^3 + 5*a^2 - 5*a - 3, a^4 - a^3 - 5*a^2 - a, -3*a^4 + 4*a^3 + 17*a^2 - 6*a - 12])
sage: possible_isogeny_degrees(E, algorithm='heuristic')
[2]
sage: possible_isogeny_degrees(E, algorithm='Billerey')
```

(continues on next page)
Elliptic curves, Release 9.7

[2] sage: possible_isogeny_degrees(E, algorithm='Larson')

LMFDB curve 4.4.8112.1-108.1-a5:

sage: K.<a> = NumberField(x^4 - 5*x^2 + 3)
sage: E = EllipticCurve(K, [a^2 - 2, -a^2 + 3, a^2 - 2, -50*a^2 + 35, 95*a^2 - 67])
sage: possible_isogeny_degrees(E, exact=False, algorithm='Billerey')

[2, 5]
sage: possible_isogeny_degrees(E, exact=False, algorithm='Larson')

[2, 5]
sage: possible_isogeny_degrees(E, exact=False, algorithm='heuristic')

[2, 5]
sage: possible_isogeny_degrees(E)

[2, 5]

This function only returns the primes which are isogeny degrees:

sage: Set(E.isogeny_class().matrix().list())
{1, 2, 4, 5, 20, 10}

For curves with CM by a quadratic order of class number greater than 1, we use the structure of the class group to only give one prime in each ideal class:

sage: pol = PolynomialRing(QQ, 'x')( [1,-3,5,-5,5,-3,1])
sage: L.<a> = NumberField(pol)
sage: j = hilbert_class_polynomial(-23).roots(L,multiplicities=False)[0]
sage: E = EllipticCurve(j=j)
sage: from sage.schemes.elliptic_curves.isogeny_class import possible_isogeny_degrees

sage: possible_isogeny_degrees(E, verbose=True)
CM case, discriminant = -23
initial primes: {2}
upward primes: {}
downward ramified primes: {}
downward split primes: {2, 3}
downward inert primes: {5}
primes generating the class group: [2]
Complete set of primes: {2, 3, 5}
[2, 3, 5]

14.10 Tate-Shafarevich group

If $E$ is an elliptic curve over a global field $K$, the Tate-Shafarevich group is the subgroup of elements in $H^1(K, E)$ which map to zero under every global-to-local restriction map $H^1(K, E) \to H^1(K_v, E)$, one for each place $v$ of $K$.

The group is usually denoted by the Russian letter Sha (cyrillic Sha), in this document it will be denoted by $Sha$.

$Sha$ is known to be an abelian torsion group. It is conjectured that the Tate-Shafarevich group is finite for any elliptic curve over a global field. But it is not known in general.
A theorem of Kolyvagin and Gross-Zagier using Heegner points shows that if the L-series of an elliptic curve $E/Q$ does not vanish at 1 or has a simple zero there, then $Sha$ is finite.

A theorem of Kato, together with theorems from Iwasawa theory, allows for certain primes $p$ to show that the $p$-primary part of $Sha$ is finite and gives an effective upper bound for it.

The ($p$-adic) conjecture of Birch and Swinnerton-Dyer predicts the order of $Sha$ from the leading term of the ($p$-adic) L-series of the elliptic curve.

Sage can compute a few things about $Sha$. The commands $an$, $an_numerical$ and $an_padic$ compute the conjectural order of $Sha$ as a real or $p$-adic number. With $p$-primary_bound one can find an upper bound of the size of the $p$-primary part of $Sha$. Finally, if the analytic rank is at most 1, then bound_kato and bound_kolyvagin find all primes for which the theorems of Kato and Kolyvagin respectively do not prove the triviality the $p$-primary part of $Sha$.

**EXAMPLES:**

```python
sage: E = EllipticCurve('11a1')
sage: S = E.sha()
sage: S.bound_kato()
[2]
sage: S.bound_kolyvagin()
([2, 5], 1)
sage: S.an_padic(7,3)
1 + O(7^5)
sage: S.an()
1
sage: S.an_numerical()
1.00000000000000
sage: E = EllipticCurve('389a')
sage: S = E.sha(); S
Tate-Shafarevich group for the Elliptic Curve defined by y^2 + y = x^3 + x^2 - 2*x over Rational Field
sage: S.an_numerical()
1.00000000000000
sage: S.p_primary_bound(5)
\$
\$
0
sage: S.an_padic(5)
1 + 0(5)
sage: S.an_padic(5, prec=4)  # long time (2s on sage.math, 2011)
1 + 0(5^3)
```

**AUTHORS:**

- William Stein (2007) – initial version
- Chris Wuthrich (April 2009) – reformat docstrings

**class** `sage.schemes.elliptic_curves.sha_tateSha(E)`

Bases: `sage.structure.sage_object.SageObject`

The Tate-Shafarevich group associated to an elliptic curve.

If $E$ is an elliptic curve over a global field $K$, the Tate-Shafarevich group is the subgroup of elements in $H^1(K, E)$ which map to zero under every global-to-local restriction map $H^1(K, E) \to H^1(K_v, E)$, one for each place $v$ of $K$. 

14.10. Tate-Shafarevich group 421
EXAMPLES:

```python
sage: E = EllipticCurve('571a1')
sage: E._set_gens([])  # curve has rank 0, but non-trivial Sha[2]
sage: S = E.sha()  
[2]
sage: S.bound_kato()  
[[2], 1]
sage: S.bound_kolyvagin()  
([2], 1)
sage: S.an_padic(7,3)
4 + O(7^5)
sage: S.an()  
4
sage: S.an_numerical()  
4.00000000000000
sage: E = EllipticCurve('389a')
sage: S = E.sha(); S
Tate-Shafarevich group for the Elliptic Curve defined by y^2 + y = x^3 + x^2 - 2*x  
→ over Rational Field
sage: S.an_numerical()  
1.00000000000000
sage: S.p_primary_bound(5)  # long time
0
sage: S.an_padic(5)  # long time
1 + O(5)
sage: S.an_padic(5,prec=4)  # very long time
1 + O(5^3)
an(use_database=False, descent_second_limit=12)

Returns the Birch and Swinnerton-Dyer conjectural order of Sha as a provably correct integer, unless the analytic rank is > 1, in which case this function returns a numerical value.

INPUT:

- use_database – bool (default: False): if True, try to use any databases installed to lookup the analytic order of Sha, if possible. The order of Sha is computed if it cannot be looked up.

- descent_second_limit – int (default: 12); limit to use on point searching for the quartic twist in the hard case

This result is proved correct if the order of vanishing is 0 and the Manin constant is <= 2.

If the optional parameter use_database is True (default: False), this function returns the analytic order of Sha as listed in Cremona’s tables, if this curve appears in Cremona’s tables.

NOTE:

If you come across the following error:

```python
sage: E = EllipticCurve([0, 0, 1, -34874, -2506691])
sage: E.sha().an()
Traceback (most recent call last):
...  
RuntimeError: Unable to compute the rank, hence generators, with certainty  
→(lower bound=0, generators found=[]). This could be because Sha(E/Q)[2] is  
→nontrivial.
```
Try increasing `descent_second_limit` then trying this command again.

You can increase the `descent_second_limit` (in the above example, set to the default, 12) option to try again:

```
sage: E.sha().an(descent_second_limit=16)  # long time (2s on sage.math, 2011)
1
```

EXAMPLES:

```
sage: E = EllipticCurve([0, -1, 1, -10, -20])  # 11A = X_0(11)
sage: E.sha().an()
1
```

```
sage: E = EllipticCurve([0, -1, 1, 0, 0])  # X_1(11)
sage: E.sha().an()
1
```

```
sage: EllipticCurve('14a4').sha().an()
1
```

```
sage: EllipticCurve('14a4').sha().an(use_database=True)  # will be faster if you have large Cremona database installed
1
```

The smallest conductor curve with nontrivial $Sha$:

```
sage: E = EllipticCurve([1,1,1,-352,-2689])  # 66b3
sage: E.sha().an()
4
```

The four optimal quotients with nontrivial $Sha$ and conductor <= 1000:

```
sage: E = EllipticCurve([0, -1, 1, -929, -10595])  # 571A
sage: E.sha().an()
4
```

```
sage: E = EllipticCurve([1, 1, 0, -900, -10098])  # 960D
sage: E.sha().an()
4
```

```
sage: E = EllipticCurve([0, 1, 0, -20, -42])  # 960N
sage: E.sha().an()
4
```

The smallest conductor curve of rank > 1:

```
sage: E = EllipticCurve([0, 1, 1, -2, 0])  # 389A (rank 2)
sage: E.sha().an()
1.00000000000000
```

The following are examples that require computation of the Mordell-Weil group and regulator:
Elliptic curves, Release 9.7

```python
sage: E = EllipticCurve([0, 0, 1, -1, 0])  # 37A (rank 1)
sage: E.sha().an()
1

sage: E = EllipticCurve("1610f3")
sage: E.sha().an()
4
```

In this case the input curve is not minimal, and if this function did not transform it to be minimal, it would give nonsense:

```python
sage: E = EllipticCurve([0,-432*6^2])
sage: E.sha().an()
1
```

See trac ticket #10096: this used to give the wrong result 6.0000 before since the minimal model was not used:

```python
sage: E = EllipticCurve([1215*1216,0])  # non-minimal model
sage: E.sha().an()  # long time (2s on sage.math, 2011)
1.00000000000000
sage: E.minimal_model().sha().an()  # long time (1s on sage.math, 2011)
1.00000000000000
```

`an_numerical(prec=None, use_database=True, proof=None)`

Return the numerical analytic order of $Sha$, which is a floating point number in all cases.

**INPUT:**

- `prec` – integer (default: 53) bits precision – used for the L-series computation, period, regulator, etc.
- `use_database` – whether the rank and generators should be looked up in the database if possible. Default is `True`
- `proof` – bool or `None` (default: `None`, see `proof.[tab]` or `sage.structure.proof`) proof option passed onto regulator and rank computation.

**Note:** See also the `an()` command, which will return a provably correct integer when the rank is 0 or 1.

**Warning:** If the curve's generators are not known, computing them may be very time-consuming. Also, computation of the L-series derivative will be time-consuming for large rank and large conductor, and the computation time for this may increase substantially at greater precision. However, use of very low precision less than about 10 can cause the underlying PARI library functions to fail.

**EXAMPLES:**

```python
sage: EllipticCurve('11a').sha().an_numerical()
1.00000000000000
sage: EllipticCurve('37a').sha().an_numerical()
1.00000000000000
sage: EllipticCurve('389a').sha().an_numerical()
1.00000000000000
```

(continues on next page)
sage: EllipticCurve('66b3').sha().an_numerical()
4.00000000000000
sage: EllipticCurve('5077a').sha().an_numerical()
1.00000000000000

A rank 4 curve:

sage: EllipticCurve([1, -1, 0, -79, 289]).sha().an_numerical()  # long time (3s on sage.math, 2011)
1.00000000000000

A rank 5 curve:

sage: EllipticCurve([0, 0, 1, -79, 342]).sha().an_numerical(prec=10, proof=False)  # long time (22s on sage.math, 2011)
1.0

See trac ticket #1115:

sage: sha = EllipticCurve('37a1').sha()
sage: [sha.an_numerical(prec) for prec in range(40,100,10)]  # long time (3s on sage.math, 2013)
[1.0, 1.0000000000, 1.00000000000, 1.00000000000000, 1.0000000000000000, 1.000000000000000000]

an_padic(p, prec=0, use_twists=True)
Returns the conjectural order of \(\text{Sha}(E/Q)\), according to the \(p\)-adic analogue of the Birch and Swinnerton-Dyer conjecture as formulated in [MTT1986] and [BP1993].

INPUT:

- \(p\) – a prime > 3
- \(\text{prec}\) (optional) – the precision used in the computation of the \(p\)-adic L-Series
- \(\text{use_twists}\) (default: True) – If True the algorithm may change to a quadratic twist with minimal conductor to do the modular symbol computations rather than using the modular symbols of the curve itself. If False it forces the computation using the modular symbols of the curve itself.

OUTPUT: \(p\)-adic number - that conjecturally equals \(\#\text{Sha}(E/Q)\).

If \(\text{prec}\) is set to zero (default) then the precision is set so that at least the first \(p\)-adic digit of conjectural \(\#\text{Sha}(E/Q)\) is determined.

EXAMPLES:

Good ordinary examples:

sage: EllipticCurve('11a1').sha().an_padic(5)  # rank 0
1 + O(5^22)
sage: EllipticCurve('43a1').sha().an_padic(5)  # rank 1
1 + O(5)
sage: EllipticCurve('389a1').sha().an_padic(5,4)  # rank 2, long time (2s on sage.math, 2011)
Elliptic curves, Release 9.7

(continued from previous page)

```
1 + O(5^3)
```

```
sage: EllipticCurve('858k2').sha().an_padic(7)  # rank 0, non trivial sha,
   ˓→ long time (10s on sage.math, 2011)
7^2 + O(7^24)
```

```
sage: EllipticCurve('300b2').sha().an_padic(3)  # 9 elements in sha, long time,
    → (2s on sage.math, 2011)
3^2 + O(3^24)
```

```
sage: EllipticCurve('300b2').sha().an_padic(7, prec=6)  # long time
2 + 7 + O(7^8)
```

`Exceptional cases:`

```
sage: EllipticCurve('11a1').sha().an_padic(11)  # rank 0
    → 1 + O(11^22)
```

```
sage: EllipticCurve('130a1').sha().an_padic(5)  # rank 1
    → 1 + O(5)
```

`Non-split, but rank 0 case (trac ticket #7331):`

```
sage: EllipticCurve('270b1').sha().an_padic(5)  # rank 0, long time (2s on sage.
    → math, 2011)
1 + O(5^22)
```

```
The output has the correct sign:
```

```
sage: EllipticCurve('123a1').sha().an_padic(41)  # rank 1, long time (3s on sage.
    → math, 2011)
1 + O(41)
```

`Supersingular cases:`

```
sage: EllipticCurve('34a1').sha().an_padic(5)  # rank 0
    → 1 + O(5^22)
```

```
sage: EllipticCurve('53a1').sha().an_padic(5)  # rank 1, long time (11s on sage.
    → math, 2011)
1 + O(5)
```

`Cases that use a twist to a lower conductor:`

```
sage: EllipticCurve('99a1').sha().an_padic(5)
    → 1 + O(5)
```

```
sage: EllipticCurve('240d3').sha().an_padic(5)  # sha has 4 elements here
    → 4 + O(5)
```

```
sage: EllipticCurve('448c5').sha().an_padic(7, prec=4, use_twists=False)  # long,
    → time (2s on sage.math, 2011)
2 + 7 + O(7^6)
```

```
sage: EllipticCurve([-19,34]).sha().an_padic(5)  # see trac #6455, long time,
    → (4s on sage.math, 2011)
1 + O(5)
```

`Test for trac ticket #15737:`
bound()  
Compute a provably correct bound on the order of the Tate-Shafarevich group of this curve. The bound is either False (no bound) or a list B of primes such that any prime divisor of the order of \Sha is in this list.

EXAMPLES:

```sage
E = EllipticCurve([-100,0])
s = E.sha()
s.an_padic(13)
1 + 0(13^20)
```

bound_kato()  
Returns a list of primes \( p \) such that the theorems of Kato’s [Kat2004] and others (e.g., as explained in a thesis of Grigor Grigorov [Gri2005]) imply that if \( p \) divides the order of \( \Sha(E/\Q) \) then \( p \) is in the list.

If \( L(E, 1) = 0 \), then this function gives no information, so it returns False.

THEOREM: Suppose \( L(E, 1) \neq 0 \) and \( p \neq 2 \) is a prime such that

- \( E \) does not have additive reduction at \( p \),
- either the \( p \)-adic representation is surjective or has its image contained in a Borel subgroup.

Then \( \text{ord}_p(\#\Sha(E)) \) is bounded from above by the \( p \)-adic valuation of \( L(E, 1) \cdot \#E(\Q)_{\text{tor}}/(\Omega_E \cdot \prod c_v) \).

If the L-series vanishes, the method \texttt{p_primary_bound} can be used instead.

EXAMPLES:

```sage
E = EllipticCurve([0, -1, 1, -10, -20])  # 11A = X_0(11)
s = E.sha().bound_kato()
[2]
sage: E = EllipticCurve([0, -1, 1, 0, 0])  # X_1(11)
s = E.sha().bound_kato()
[2]
sage: E = EllipticCurve([1,1,1,-352,-2689])  # 66B3
s = E.sha().bound_kato()
[2]
sage: E = EllipticCurve([1, -1, 0, -332311, -73733731])  # 1058D1
s = E.sha().bound_kato()
[2, 5, 23]
sage: E.galois_representation().non_surjective()  # long time (about 1 second)
\[ \rightarrow (\text{about 1 second}) \]
[
]
```

For the following curve one really has that 25 divides the order of \( \Sha \) (by [GJPST2009]):

```sage
E = EllipticCurve([1, -1, 0, -332311, -73733731])  # 1058D1
s = E.sha().bound_kato()
[2, 5, 23]
sage: E.galois_representation().non_surjective()  # long time (about 1 second)
\[ \rightarrow (\text{about 1 second}) \]
[
]
```

For this one, \( \Sha \) is divisible by 7:

```sage
E = EllipticCurve([0, 0, 0, -4062871, -3152083138])  # 3364C1
s = E.sha().bound_kato()
[2, 7, 29]
```

No information about curves of rank > 0:
bound_kolyvagin\((D=0, \text{regulator}=\text{None}, \text{ignore\_nonsurj\_hypothesis}=\text{False})\)

Given a fundamental discriminant \(D \neq -3, -4\) that satisfies the Heegner hypothesis for \(E\), return a list of primes so that Kolyvagin’s theorem (as in Gross’s paper) implies that any prime divisor of \(Sha\) is in this list.

**INPUT:**

- \(D\) – (optional) a fundamental discriminant \(< -4\) that satisfies the Heegner hypothesis for \(E\); if not given, use the first such \(D\)
- \(\text{regulator}\) – (optional) regulator of \(E(K)\); if not given, will be computed (which could take a long time)
- \(\text{ignore\_nonsurj\_hypothesis}\) (optional: default False) – If True, then gives the bound coming from Heegner point index, but without any hypothesis on surjectivity of the mod-\(p\) representation.

**OUTPUT:**

- list – a list of primes such that if \(p\) divides \(Sha(E/K)\), then \(p\) is in this list, unless \(E/K\) has complex multiplication or analytic rank greater than 2 (in which case we return 0).
- index – the odd part of the index of the Heegner point in the full group of \(K\)-rational points on \(E\). (If \(E\) has CM, returns 0.)

**REMARKS:**

1) We do not have to assume that the Manin constant is 1 (or a power of 2). If the Manin constant were divisible by a prime, that prime would get included in the list of bad primes.

2) We assume the Gross-Zagier theorem is true under the hypothesis that \(gcd(N, D) = 1\), instead of the stronger hypothesis \(gcd(2 \cdot N, D) = 1\) that is in the original Gross-Zagier paper. That Gross-Zagier is true when \(gcd(N, D) = 1\) is “well-known” to the experts, but does not seem to written up well in the literature.

3) Correctness of the computation is guaranteed using interval arithmetic, under the assumption that the regulator, square root, and period lattice are computed to precision at least \(10^{-10}\), i.e., they are correct up to addition or a real number with absolute value less than \(10^{-10}\).

**EXAMPLES:**

We get no information when the curve has rank 2.

<table>
<thead>
<tr>
<th>sage: E = EllipticCurve('389a')</th>
<th>sage: E.sha().bound_kolyvagin()</th>
</tr>
</thead>
<tbody>
<tr>
<td>([2], 1)</td>
<td></td>
</tr>
<tr>
<td>sage: E = EllipticCurve('681b')</td>
<td></td>
</tr>
<tr>
<td>sage: E.sha().bound_kolyvagin()</td>
<td>(0, 0)</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
p_primary_bound($p$)
Return a provable upper bound for the order of the $p$-primary part $Sha(E)(p)$ of the Tate-Shafarevich group.

**INPUT:**
- $p$ – a prime > 2

**OUTPUT:**
- $e$ – a non-negative integer such that $p^e$ is an upper bound for the order of $Sha(E)(p)$

In particular, if this algorithm does not fail, then it proves that the $p$-primary part of $Sha$ is finite. This works also for curves of rank > 1.

Note also that this bound is sharp if one assumes the main conjecture of Iwasawa theory of elliptic curves. One may use the method p_primary_order for checking if the extra conditions hold under which the main conjecture is known by the work of Skinner and Urban. This then returns the provable $p$-primary part of the Tate-Shafarevich group.

Currently the algorithm is only implemented when the following conditions are verified:
- The $p$-adic Galois representation must be surjective or must have its image contained in a Borel subgroup.
- The reduction at $p$ is not allowed to be additive.
- If the reduction at $p$ is non-split multiplicative, then the rank must be 0.
- If $p = 3$, then the reduction at 3 must be good ordinary or split multiplicative, and the rank must be 0.

**ALGORITHM:**
The algorithm is described in [SW2013]. The results for the reducible case can be found in [Wu2004]. The main ingredient is Kato’s result on the main conjecture in Iwasawa theory.

**EXAMPLES:**
```python
sage: e = EllipticCurve('11a3')
sage: e.sha().p_primary_bound(3)
0
sage: e.sha().p_primary_bound(5)
0
sage: e.sha().p_primary_bound(7)
0
sage: e.sha().p_primary_bound(11)
0
sage: e.sha().p_primary_bound(13)
0
sage: e = EllipticCurve('389a1')
sage: e.sha().p_primary_bound(5)
0
sage: e.sha().p_primary_bound(7)
```
(continues on next page)
Elliptic curves, Release 9.7

(continued from previous page)

```python
sage: e.sha().p_primary_bound(11)
0
sage: e.sha().p_primary_bound(13)
0
sage: e = EllipticCurve('858k2')
sage: e.sha().p_primary_bound(3)  # long time (10s on sage.math, 2011)
0
```

Some checks for trac ticket #6406 and trac ticket #16959:

```python
sage: e.sha().p_primary_bound(7)  # long time
2
sage: E = EllipticCurve('608b1')
sage: E.sha().p_primary_bound(5)
Traceback (most recent call last):
...  
ValueError: The p-adic Galois representation is not surjective or reducible. Current knowledge about Euler systems does not provide an upper bound in this case. Try an_padic for a conjectural bound.

sage: E.sha().an_padic(5)  # long time
1 + O(5^22)
sage: E = EllipticCurve('5040bi1')
sage: E.sha().p_primary_bound(5)  # long time
0
```

**p_primary_order**\(^{(p)}\)

Return the order of the \(p\)-primary part of the Tate-Shafarevich group.

This uses the result of Skinner and Urban [SU2014] on the main conjecture in Iwasawa theory. In particular the elliptic curve must have good ordinary reduction at \(p\), the residual Galois representation must be surjective. Furthermore there must be an auxiliary prime \(\ell\) dividing the conductor of the curve exactly once such that the residual representation is ramified at \(p\).

**INPUT:**

- \(p\) – an odd prime

**OUTPUT:**

- \(e\) – a non-negative integer such that \(p^e\) is the order of the \(p\)-primary order if the conditions are satisfied and raises a \texttt{ValueError} otherwise.

**EXAMPLES:**

```python
sage: E = EllipticCurve('389a1')  # rank 2
sage: E.sha().p_primary_order(5)
0
sage: E = EllipticCurve('11a1')
sage: E.sha().p_primary_order(7)
0
```

(continues on next page)
sage: E.sha().p_primary_order(5)
Traceback (most recent call last):
...
ValueError: The order is not provably known using Skinner-Urban.
Try running p_primary_bound to get a bound.

two_selmer_bound()
This returns the 2-rank, i.e. the $F_2$-dimension of the 2-torsion part of $Sha$, provided we can determine the rank of $E$.

EXAMPLES:

sage: sh = EllipticCurve('571a1').sha()
sage: sh.two_selmer_bound()
2
sage: sh.an()
4

sage: sh = EllipticCurve('66a1').sha()
sage: sh.two_selmer_bound()
0
sage: sh.an()
1

sage: sh = EllipticCurve('960d1').sha()
sage: sh.two_selmer_bound()
2
sage: sh.an()
4

14.11 Complex multiplication for elliptic curves

This module implements the functions

- hilbert_class_polynomial
- cm_j_invariants
- cm_orders
- discriminants_with_bounded_class_number
- cm_j_invariants_and_orders
- largest_fundamental_disc_with_class_number

AUTHORS:

- Robert Bradshaw
- John Cremona
- William Stein

sage.schemes.elliptic_curves.cm.cm_j_invariants(K, proof=None)
Return a list of all CM $j$-invariants in the field $K$.  

14.11. Complex multiplication for elliptic curves 431
INPUT:

• \( \mathbb{K} \) – a number field
• \( \text{proof} \) – (default: \( \text{proof.number_field()} \))

OUTPUT:

(list) – A list of CM \( j \)-invariants in the field \( \mathbb{K} \).

EXAMPLES:

```python
sage: cm_j_invariants(QQ)
[-262537412640768000, -147197952000, -884736000, -12288000, -884736, -32768, -3375, 0, 1728, 8000, 54000, 287496, 16581375]
```

Over imaginary quadratic fields there are no more than over \( \mathbb{Q} \):

```python
sage: cm_j_invariants(QuadraticField(-1, 'i'))
[-262537412640768000, -147197952000, -884736000, -12288000, -884736, -32768, -3375, 0, 1728, 8000, 54000, 287496, 16581375]
```

Over real quadratic fields there may be more, for example:

```python
sage: len(cm_j_invariants(QuadraticField(5, 'a'))) 31
```

Over number fields \( \mathbb{K} \) of many higher degrees this also works:

```python
sage: K.<a> = NumberField(x^3 - 2)
sage: cm_j_invariants(K)
[-262537412640768000, -147197952000, -884736000, -12288000, -884736, -32768, -3375, 0, 1728, 8000, 54000, 287496, 16581375, 1728, 8000, 54000, 287496, 16581375]
sage: K.<a> = NumberField(x^4 - 2)
sage: len(cm_j_invariants(K))
23
```

\text{Return a list of all CM} \( j \)-\text{invariants in the field} \( \mathbb{K} \), together with the associated orders.}

\text{INPUT:}

• \( \mathbb{K} \) – a number field
• \( \text{proof} \) – (default: \( \text{proof.number_field()} \))

\text{OUTPUT:}

(list) A list of 3-tuples \((D, f, j)\) where \( j \) is a CM \( j \)-invariant in \( \mathbb{K} \) with quadratic fundamental discriminant \( D \) and conductor \( f \).

EXAMPLES:

```python
sage: cm_j_invariants_and_orders(QQ)
[(-3, -12288000, -3, 2, 54000, -3, 3, 0, -4, 2, 287496, -4, 1, 1728, -
\rightarrow 7, 2, 16581375, -7, 1, -3375, -8, 1, 8000, -11, 1, -32768, -19, 1, -
\rightarrow 884736, -43, 1, -884736000, -67, 1, -147197952000, -163, 1, -
\rightarrow 262537412640768000)]
```
Over an imaginary quadratic field there are no more than over $\mathbb{Q}Q$:

```
sage: cm_j_invariants_and_orders(QuadraticField(-1, 'i'))
[(-163, 1, -262537412640768000), (-67, 1, -147197952000), (-43, 1, -8847360000), (-19, 1, -884736), (-11, 1, -32768), (-8, 1, 8000), (-7, 1, -3375), (-7, 2, 16581375), (-4, 1, 1728), (-4, 2, 287496), (-3, 1, 0), (-3, 2, 54000), (-3, 3, -12288000)]
```

Over real quadratic fields there may be more:

```
sage: v = cm_j_invariants_and_orders(QuadraticField(5, 'a')); len(v)
31
sage: [(D, f) for D, f, j in v if j not in QQ]
[(-235, 1), (-235, 1), (-115, 1), (-115, 1), (-40, 1), (-40, 1), (-35, 1), (-35, 1), (-20, 1), (-20, 1), (-15, 1), (-15, 1), (-15, 2), (-15, 2), (-4, 5), (-4, 5), (-3, 5), (-3, 5)]
```

Over number fields $K$ of many higher degrees this also works:

```
sage: K.<a> = NumberField(x^3 - 2)
sage: cm_j_invariants_and_orders(K)
[(-163, 1, -262537412640768000), (-67, 1, -147197952000), (-43, 1, -8847360000), (-19, 1, -884736), (-11, 1, -32768), (-8, 1, 8000), (-7, 1, -3375), (-7, 2, 16581375), (-4, 1, 1728), (-4, 2, 287496), (-3, 1, 0), (-3, 2, 54000), (-3, 3, -12288000), (-3, 6, 31710790944000*a^2 + 39953093016000*a + 5033774292000)]
```

```
sage.schemes.elliptic_curves.cm.cms_orders(h, proof=None)
Return a list of all pairs $(D, f)$ where there is a CM order of discriminant $Df^2$ with class number $h$, with $D$ a fundamental discriminant.

INPUT:

• $h$ – positive integer
• $proof$ – (default: proof.number_field())

OUTPUT:

• list of 2-tuples $(D, f)$

EXAMPLES:

```
sage: cm_orders(0)
[]
sage: v = cm_orders(1);
v
[(-3, 3), (-3, 2), (-3, 1), (-4, 2), (-4, 1), (-7, 2), (-7, 1), (-8, 1), (-11, 1), (-19, 1), (-43, 1), (-67, 1), (-163, 1)]
sage: type(v[0][0]), type(v[0][1])
(<... 'sage.rings.integer.Integer'>, <... 'sage.rings.integer.Integer'>)
sage: v = cm_orders(2);
v
[(-3, 7), (-3, 5), (-3, 4), (-4, 5), (-4, 4), (-4, 3), (-7, 4), (-8, 3), (-8, 2), (-11, 3), (-15, 2), (-20, 1), (-24, 1), (-35, 1), (-40, 1), (-51, 1), (-52, 1), (-88, 1), (-91, 1), (-115, 1), (-123, 1), (-148, 1), (-187, 1), (-232, 1), (-235, 1), (-267, 1), (-403, 1), (-427, 1)]
sage: len(v)
29
```

(continues on next page)
sage: set([hilbert_class_polynomial(D*f^2).degree() for D,f in v])
{2}

Any degree up to 100 is implemented, but may be prohibitively slow:

sage: cm_orders(3)
[(-3, 9), (-3, 6), (-11, 2), (-19, 2), (-23, 2), (-23, 1), (-31, 2), (-31, 1), (-43, 2), (-59, 1), (-67, 2), (-83, 1), (-107, 1), (-139, 1), (-163, 2), (-211, 1), (-283, 1), (-307, 1), (-331, 1), (-379, 1), (-499, 1), (-547, 1), (-643, 1), (-883, -1), (-907, 1)]
sage: len(cm_orders(4))
84

sage.schemes.elliptic_curves.cm.discriminants_with_bounded_class_number(hmax, B=None, proof=None)

Return dictionary with keys class numbers ℎ ≤ ℎmax and values the list of all pairs (𝐷, 𝑓), with 𝐷 < 0 a fundamental discriminant such that 𝐷𝑓² has class number ℎ. If the optional bound 𝐵 is given, return only those pairs with fundamental |𝐷| ≤ 𝐵, though 𝑓 can still be arbitrarily large.

INPUT:

• hmax – integer
• 𝐵 – integer or None; if None returns all pairs
• proof – this code calls the PARI function pari:qfbclassno, so it could give wrong answers when proof`==`False. The default is whatever proof.number_field() is. If proof==False and 𝐵 is None, at least the number of discriminants is correct, since it is double checked with Watkins’s table.

OUTPUT:

• dictionary

In case 𝐵 is not given, we use Mark Watkins’s: “Class numbers of imaginary quadratic fields” to compute a 𝐵 that captures all ℎ up to ℎmax (only available for ℎmax ≤ 100).

EXAMPLES:

sage: v = sage.schemes.elliptic_curves.cm.discriminants_with_bounded_class_number(3)
sage: sorted(v)
[1, 2, 3]
sage: v[1]
[(-3, 3), (-3, 2), (-3, 1), (-4, 2), (-4, 1), (-7, 2), (-7, 1), (-8, 1), (-11, 1), (-19, 1), (-43, 1), (-67, 1), (-163, 1)]
sage: v[2]
[(-3, 7), (-3, 5), (-3, 4), (-4, 5), (-4, 4), (-4, 3), (-7, 4), (-8, 3), (-8, 2), (-11, 3), (-15, 2), (-15, 1), (-20, 1), (-24, 1), (-35, 1), (-40, 1), (-51, 1), (-52, 1), (-88, 1), (-91, 1), (-115, 1), (-123, 1), (-148, 1), (-187, 1), (-232, 1), (-235, 1), (-267, 1), (-403, 1), (-427, 1)]
sage: v[3]
[(-3, 9), (-3, 6), (-11, 2), (-19, 2), (-23, 2), (-23, 1), (-31, 2), (-31, 1), (-43, 2), (-59, 1), (-67, 2), (-83, 1), (-107, 1), (-139, 1), (-163, 2), (-211, 1), (-283, 1), (-307, 1), (-331, 1), (-379, 1), (-499, 1), (-547, 1), (-643, 1), (-883, -1), (-907, 1)]
Find all class numbers for discriminant up to 50:

```python
sage: [(-3, 3), (-3, 2), (-3, 1), (-4, 2), (-4, 1), (-7, 2), (-7, 1), (-8, 1), (-11, 1), (-19, 1), (-43, 1), (-3, 7), (-3, 5), (-3, 4), (-4, 5), (-4, 4), (-4, 3), (-7, 4), (-8, 3), (-11, 3), (-15, 2), (-15, 1), (-20, 1), (-24, 1), (-35, 1), (-40, 1), (-3, 9), (-3, 6), (-11, 2), (-19, 2), (-23, 2), (-23, 1), (-31, 2), (-31, 1), (-43, 2), (-3, 13), (-3, 11), (-3, 8), (-4, 10), (-4, 8), (-4, 7), (-4, 6), (-7, 8), (-7, 6), (-7, 3), (-8, 6), (-8, 4), (-11, 5), (-15, 4), (-19, 5), (-19, 3), (-20, 3), (-24, 2), (-35, 3), (-39, 2), (-39, 1), (-40, 2), (-43, 3), (-47, 2), (-47, 1)]
```
sage: hilbert_class_polynomial(-163, algorithm="sage")
x + 262537412640768000
sage: hilbert_class_polynomial(-163, algorithm="magma") # optional - magma
x + 262537412640768000

sage.schemes.elliptic_curves.cm.is_cm_j_invariant(j, method='new')
Return whether or not this is a CM \(j\)-invariant.

INPUT:

• \(j\) – an element of a number field \(K\)

OUTPUT:

A pair \((\text{bool}, (d,f))\) which is either \((\text{False, None})\) if \(j\) is not a CM \(j\)-invariant or \((\text{True, (d,f)})\) if \(j\) is the \(j\)-invariant of the imaginary quadratic order of discriminant \(D = df^2\) where \(d\) is the associated fundamental discriminant and \(f\) the index.

**Note:** The current implementation makes use of the classification of all orders of class number up to 100, and hence will raise an error if \(j\) is an algebraic integer of degree greater than this. It would be possible to implement a more general version, using the fact that \(d\) must be supported on the primes dividing the discriminant of the minimal polynomial of \(j\).

**EXAMPLES:**

```python
sage: from sage.schemes.elliptic_curves.cm import is_cm_j_invariant
sage: is_cm_j_invariant(0)
(True, (-3, 1))
sage: is_cm_j_invariant(8000)
(True, (-8, 1))
sage: K.<a> = QuadraticField(5)
sage: is_cm_j_invariant(282880*a + 632000)
(True, (-20, 1))
sage: K.<a> = NumberField(x^3 - 2)
sage: is_cm_j_invariant(31710790944000*a^2 + 39953093016000*a + 50337742902000)
(True, (-3, 6))
```

sage.schemes.elliptic_curves.cm.largest_fundamental_disc_with_class_number(h)
Return largest absolute value of any fundamental discriminant with class number \(h\), and the number of fundamental discriminants with that class number. This is known for \(h\) up to 100, by work of Mark Watkins.

INPUT:

• \(h\) – integer

**EXAMPLES:**

```python
sage: sage.schemes.elliptic_curves.cm.largest_fundamental_disc_with_class_number(0)
(0, 0)
sage: sage.schemes.elliptic_curves.cm.largest_fundamental_disc_with_class_number(1)
(163, 9)
sage: sage.schemes.elliptic_curves.cm.largest_fundamental_disc_with_class_number(2)
(427, 18)
sage: sage.schemes.elliptic_curves.cm.largest_fundamental_disc_with_class_number(10)
```

(continues on next page)
(13843, 87)
sage: sage.schemes.elliptic_curves.cm.largest_fundamental_disc_with_class_number(100)
(1856563, 1736)
sage: sage.schemes.elliptic_curves.cm.largest_fundamental_disc_with_class_number(101)
Traceback (most recent call last):
  ... NotImplementedError: largest discriminant not known for class number 101

## 14.12 Testing whether elliptic curves over number fields are Q-curves

**AUTHORS:**
- John Cremona (February 2021)

The code here implements the algorithm of Cremona and Najman presented in [CrNa2020].

`sage.schemes.elliptic_curves.Qcurves.Step4Test(E, B, oldB=0, verbose=False)`

Apply local Q-curve test to E at all primes up to B.

**INPUT:**
- `E` (elliptic curve): an elliptic curve defined over a number field
- `B` (integer): upper bound on primes to test
- `oldB` (integer, default 0): lower bound on primes to test
- `verbose` (boolean, default `False`): verbosity flag

**OUTPUT:**
Either `(False, p)`, if the local test at `p` proves that `E` is not a Q-curve, or `(True, 0)` if all local tests at primes between `oldB` and `B` fail to prove that `E` is not a Q-curve.

**ALGORITHM** (see [CrNa2020] for details):
This local test at `p` only applies if `E` has good reduction at all of the primes lying above `p` in the base field `K` of `E`. It tests whether (1) `E` is either ordinary at all `P | p`, or supersingular at all; (2) if ordinary at all, it tests that the squarefree part of `a_2^2 - 4N(P)` is the same for all `P | p`.

**EXAMPLES:**
A non-Q-curve over a quartic field (with LMFDB label ‘4.4.8112.1-12.1-a1’) fails this test at `p = 13`:

```
sage: from sage.schemes.elliptic_curves.Qcurves import Step4Test
sage: R.<x> = PolynomialRing(QQ)
sage: K.<a> = NumberField(R([3, 0, -5, 0, 1]))
sage: E = EllipticCurve([K([-3,-4,1,1]),K([4,-1,-1,0]),K([-2,0,1,0]),K([-621,778, -138,-178]),K([9509,2046,-24728,10380])])
sage: Step4Test(E, 100, verbose=True)
No: inconsistency at the 2 ordinary primes dividing 13
  - Frobenius discriminants mod squares: [-3, -1]
(False, 13)
```

A Q-curve over a sextic field (with LMFDB label ‘6.6.1259712.1-64.1-a6’) passes this test for all `p < 100`:

```
sage: from sage.schemes.elliptic_curves.Qcurves import Step4Test
sage: R.<x> = PolynomialRing(QQ)
sage: K.<a> = NumberField(R([3, 0, -5, 0, 1]))
sage: E = EllipticCurve([K([-3,-4,1,1]),K([4,-1,-1,0]),K([-2,0,1,0]),K([-621,778, -138,-178]),K([9509,2046,-24728,10380])])
sage: Step4Test(E, 100, verbose=True)
No: inconsistency at the 2 ordinary primes dividing 13
  - Frobenius discriminants mod squares: [-3, -1]
(False, 13)
```
sage: from sage.schemes.elliptic_curves.Qcurves import Step4Test
sage: R.<x> = PolynomialRing(QQ)
sage: K.<a> = NumberField(R([-3, 0, 9, 0, -6, 0, 1]))
sage: E = EllipticCurve([K([1,-3,0,1,0,0]),K([5,-3,-6,1,1,0]),K([1,-3,0,1,0,0]),K([-139,-129,331,277,-76,-63]),K([2466,1898,-5916,-4582,1361,1055])])
sage: Step4Test(E, 100, verbose=True)
(True, 0)
sage.schemes.elliptic_curves.Qcurves.conjugacy_test(jlist, verbose=False)
Test whether a list of algebraic numbers contains a complete conjugacy class of 2-power degree.

INPUT:

• *jlist* (list): a list of algebraic numbers in the same field
• *verbose* (boolean, default False): verbosity flag

OUTPUT:

A possibly empty list of irreducible polynomials over \( \mathbb{Q} \) of 2-power degree all of whose roots are in the list.

EXAMPLES:

sage: from sage.schemes.elliptic_curves.Qcurves import conjugacy_test
sage: conjugacy_test([3])
[x - 3]
sage: K.<a> = QuadraticField(2)
sage: conjugacy_test([K(3), a])
[x - 3]
sage: conjugacy_test([K(3), 3*a])
[x - 3]
sage: conjugacy_test([3*a])
[]
sage: conjugacy_test([3*a, 3-a])
[x^2 - 6*x + 7]
sage: x = polygen(QQ)
sage: f = x^3-3
sage: K.<a> = f.splitting_field()
sage: js = f.roots(K, multiplicities=False)
sage: conjugacy_test(js)
[]
sage: f = x^4-3
sage: K.<a> = NumberField(f)
sage: js = f.roots(K, multiplicities=False)
sage: conjugacy_test(js)
[]
sage: K.<a> = f.splitting_field()
sage: js = f.roots(K, multiplicities=False)
sage: conjugacy_test(js)
[x^4 - 3]
sage.schemes.elliptic_curves.Qcurves.is_Q_curve(E, maxp=100, certificate=False, verbose=False)
Return whether \( E \) is a \( \mathbb{Q} \)-curve, with optional certificate.

INPUT:

• \( E \) (elliptic curve) – an elliptic curve over a number field.
• \texttt{maxp} (int, default 100): bound on primes used for checking necessary local conditions. The result will not depend on this, but using a larger value may return \texttt{False} faster.

• \texttt{certificate} (bool, default \texttt{False}): if \texttt{True} then a second value is returned giving a certificate for the \( \mathbb{Q} \)-curve property.

OUTPUT:

If \texttt{certificate} is \texttt{False}: either \texttt{True} (if \( \mathcal{E} \) is a \( \mathbb{Q} \)-curve), or \texttt{False}.

If \texttt{certificate} is \texttt{True}: a tuple consisting of a boolean flag as before and a certificate, defined as follows:

• when the flag is \texttt{True}, so \( \mathcal{E} \) is a \( \mathbb{Q} \)-curve:
  
  – either \{\'CM\':\( D \)\} where \( D \) is a negative discriminant, when \( \mathcal{E} \) has potential CM with discriminant \( D \);
  
  – otherwise \{\'CM\': 0, \'core_poly\': \( f \), \'r\': \( r \), \'N\': \( N \)\}, when \( \mathcal{E} \) is a non-CM \( \mathbb{Q} \)-curve, where the core polynomial \( f \) is an irreducible monic polynomial over \( \mathbb{Q} \mathbb{Q} \) of degree \( 2^r \), all of whose roots are \( j \)-invariants of curves isogenous to \( \mathcal{E} \), the core level \( N \) is a square-free integer with \( r \) prime factors which is the LCM of the degrees of the isogenies between these conjugates. For example, if there exists a curve \( \mathcal{E}' \) isogenous to \( \mathcal{E} \) with \( j(\mathcal{E}') = j \in \mathbb{Q} \), then the certificate is \{\'CM\':0, \'r\':0, \'rho\':0, \'core_poly\': \( x-j \), \'N\':1\}.

• when the flag is \texttt{False}, so \( \mathcal{E} \) is not a \( \mathbb{Q} \)-curve, the certificate is a prime \( p \) such that the reductions of \( \mathcal{E} \) at the primes dividing \( p \) are inconsistent with the property of being a \( \mathbb{Q} \)-curve. See the ALGORITHM section for details.

ALGORITHM:

See [CrNa2020] for details.

1. If \( \mathcal{E} \) has rational \( j \)-invariant, or has CM, then return \texttt{True}.

2. Replace \( \mathcal{E} \) by a curve defined over \( K = \mathbb{Q}(j(\mathcal{E})) \). Let \( N \) be the conductor norm.

3. For all primes \( p \mid N \) check that the valuations of \( j \) at all \( P \mid p \) are either all negative or all non-negative; if not, return \texttt{False}.

4. For \( p \leq \text{maxp} \), \( p \nmid N \), check that either \( \mathcal{E} \) is ordinary mod \( P \) for all \( P \mid p \), or \( \mathcal{E} \) is supersingular mod \( P \) for all \( P \mid p \); if neither, return \texttt{False}. If all are ordinary, check that the integers \( a_P(\mathcal{E})^2 - 4N(P) \) have the same square-free part; if not, return \texttt{False}.

5. Compute the \( K \)-isogeny class of \( \mathcal{E} \) using the “heuristic” option (which is faster, but not guaranteed to be complete). Check whether the set of \( j \)-invariants of curves in the class of \( 2 \)-power degree contains a complete Galois orbit. If so, return \texttt{True}.

6. Otherwise repeat step 4 for more primes, and if still undecided, repeat Step 5 without the “heuristic” option, to get the complete \( K \)-isogeny class (which will probably be no bigger than before). Now return \texttt{True} if the set of \( j \)-invariants of curves in the class contains a complete Galois orbit, otherwise return \texttt{False}.

EXAMPLES:

A non-CM curve over \( \mathbb{Q} \) and a CM curve over \( \mathbb{Q} \) are both trivially \( \mathbb{Q} \)-curves:

```
sage: from sage.schemes.elliptic_curves.Qcurves import is_Q_curve
sage: E = EllipticCurve([1,2,3,4,5])
sage: flag, cert = is_Q_curve(E, certificate=True)
sage: flag
True
sage: cert
{'CM': 0, 'N': 1, 'core_poly': x, 'r': 0, 'rho': 0}
```
A non-Q-curve over a quartic field. The local data at bad primes above 3 is inconsistent:

```python
sage: from sage.schemes.elliptic_curves.Qcurves import is_Q_curve
sage: R.<x> = PolynomialRing(QQ)
sage: K.<a> = NumberField(R([3, 0, -5, 0, 1]))
sage: E = EllipticCurve([K([-3,-4,1,1]),K([-178,138,-2046,9509])])
sage: is_Q_curve(E, certificate=True, verbose=True)
Checking whether Elliptic Curve defined by y^2 + (a^3+a^2-4*a-3)*x*y + (a^2-2)*y = x^3 + (-a^2-a+4)*x^2 + (10380*a^3-24728*a^2+2046*a+9509) over Number Field in a with defining polynomial x^4 - 5*x^2 + 3 is a Q-curve
No: inconsistency at the 2 primes dividing 3 - potentially multiplicative: [True, False] (False, 3)
```

A quadratic Q-curve with CM discriminant \(-15\) (j-invariant not in \(Q\)):

```python
sage: from sage.schemes.elliptic_curves.Qcurves import is_Q_curve
sage: R.<x> = PolynomialRing(QQ)
sage: K.<a> = NumberField(R([-1, 0, 1]))
sage: E = EllipticCurve(K([-1,0]),K([-236,40]),K([-1840,464])))
sage: is_Q_curve(E, certificate=True, verbose=True)
Checking whether Elliptic Curve defined by y^2 + x*y + a*y = x^3 + (-1)*x^2 + (-2*a)*x + a over Number Field in a with defining polynomial x^2 - 1 is a Q-curve
Yes: E is CM (discriminant -15) (True, {'CM': -15})
```

An example over \(Q(\sqrt{2}, \sqrt{3})\). The j-invariant is in \(Q(\sqrt{6})\), so computations will be done over that field, and in fact there is an isogenous curve with rational j, so we have a so-called rational Q-curve:
sage: K.<a> = NumberField(R([1, 0, -4, 0, 1]))
sage: E = EllipticCurve([K([-2,-4,1,1]),K([0,1,0,0]),K([0,1,0,0]),K([-4780,9170,-1265,-2463]),K([163923,-316598,-43876,84852])])
sage: flag, cert = is_Q_curve(E, certificate=True)
sage: flag
True
sage: cert
{'CM': 0, 'N': 1, 'core_degs': [1], 'core_poly': x - 85184/3, 'r': 0, 'rho': 0}

Over the same field, a so-called strict Q-curve which is not isogenous to one with rational $j$, but whose core field is quadratic. In fact the isogeny class over $K$ consists of 6 curves, four with conjugate quartic $j$-invariants and 2 with quadratic conjugate $j$-invariants in $\mathbb{Q}(\sqrt{3})$ (but which are not base-changes from the quadratic subfield):

\begin{verbatim}
sage: E = EllipticCurve([K([0,-3,0,1]),K([1,4,0,-1]),K([0,0,0,0]),K([-2,-16,0,4]),
                     K([-19,-32,4,8])])
sage: flag, cert = is_Q_curve(E, certificate=True)
sage: flag
True
sage: cert
{'CM': 0, 'N': 2, 'core_degs': [1, 2], 'core_poly': x^2 - 840064*x + 1593413632, 'r': 1, 'rho': 1}
\end{verbatim}

The following relate to elliptic curves over local nonarchimedean fields.

### 14.13 Local data for elliptic curves over number fields

Let $E$ be an elliptic curve over a number field $K$ (including $\mathbb{Q}$). There are several local invariants at a finite place $v$ that can be computed via Tate’s algorithm (see [Sil1994] IV.9.4 or [Tate1975]).

These include the type of reduction (good, additive, multiplicative), a minimal equation of $E$ over $K_v$, the Tamagawa number $c_v$, defined to be the index $[E(K_v) : E^0(K_v)]$ of the points with good reduction among the local points, and the exponent of the conductor $f_v$.

The functions in this file will typically be called by using `local_data`.

**EXAMPLES:**

\begin{verbatim}
sage: K.<i> = NumberField(x^2+1)
sage: E = EllipticCurve([(2+i)^2,(2+i)^7])
sage: pp = K.fractional_ideal(2+i)
sage: da = E.local_data(pp)
sage: da.has_bad_reduction()
True
sage: da.has_multiplicative_reduction()
False
sage: da.kodaira_symbol()
I0^*
sage: da.tamagawa_number()
4
\end{verbatim}

(continues on next page)
Elliptic curves, Release 9.7

An example to show how the Neron model can change as one extends the field:

```
sage: E = EllipticCurve([0,-1])
sage: E.local_data(2)
Local data at Principal ideal (2) of Integer Ring:
  Reduction type: bad additive
  Local minimal model: Elliptic Curve defined by y^2 = x^3 - 1 over Rational Field
  Minimal discriminant valuation: 4
  Conductor exponent: 4
  Kodaira Symbol: II
  Tamagawa Number: 1

sage: EK = E.base_extend(K)
sage: EK.local_data(1+i)
Local data at Fractional ideal (i + 1):
  Reduction type: bad additive
  Local minimal model: Elliptic Curve defined by y^2 = x^3 + (-1) over Number Field in i with defining polynomial x^2 + 1
  Minimal discriminant valuation: 8
  Conductor exponent: 2
  Kodaira Symbol: IV*
  Tamagawa Number: 3
```

Or how the minimal equation changes:

```
sage: E = EllipticCurve([0,8])
sage: E.is_minimal()
True
sage: EK = E.base_extend(K)
sage: da = EK.local_data(1+i)
sage: da.minimal_model()
Elliptic Curve defined by y^2 = x^3 + (-i) over Number Field in i with defining polynomial x^2 + 1
```

AUTHORS:

- John Cremona: First version 2008-09-21 (refactoring code from ell_number_field.py and ell_rational_field.py)
- Chris Wuthrich: more documentation 2010-01

```
class sage.schemes.elliptic_curves.ell_local_data.EllipticCurveLocalData(E, P, proof=None, algorithm='pari', globally=False)

    Bases: sage.structure.sage_object.SageObject

    The class for the local reduction data of an elliptic curve.

    Currently supported are elliptic curves defined over Q, and elliptic curves defined over a number field, at an arbitary prime or prime ideal.

    INPUT:
```
• $E$ – an elliptic curve defined over a number field, or $\mathbb{Q}$.

• $P$ – a prime ideal of the field, or a prime integer if the field is $\mathbb{Q}$.

• `proof` (bool) – if True, only use provably correct methods (default controlled by global proof module). Note that the proof module is `number_field`, not `elliptic_curves`, since the functions that actually need the flag are in number fields.

• `algorithm` (string, default: “pari”) – Ignored unless the base field is $\mathbb{Q}$. If “pari”, use the PARI C-library `ellglobalred` implementation of Tate’s algorithm over $\mathbb{Q}$. If “generic”, use the general number field implementation.

Note: This function is not normally called directly by users, who may access the data via methods of the `EllipticCurve` classes.

**EXAMPLES:**

```python
sage: from sage.schemes.elliptic_curves.ell_local_data import EllipticCurveLocalData
sage: E = EllipticCurve('14a1')
sage: EllipticCurveLocalData(E,2)
Local data at Principal ideal (2) of Integer Ring:
Reduction type: bad non-split multiplicative
Local minimal model: Elliptic Curve defined by $y^2 + x*y + y = x^3 + 4*x - 6$ over $\mathbb{Q}$
Minimal discriminant valuation: 6
Conductor exponent: 1
Kodaira Symbol: I6
Tamagawa Number: 2
```

`bad_reduction_type()`

Return the type of bad reduction of this reduction data.

**OUTPUT:**

(int or `None`):

• +1 for split multiplicative reduction

• -1 for non-split multiplicative reduction

• 0 for additive reduction

• `None` for good reduction

**EXAMPLES:**

```python
sage: E = EllipticCurve('14a1')
sage: [(p,E.local_data(p).bad_reduction_type()) for p in prime_range(15)]
[(2, -1), (3, None), (5, None), (7, 1), (11, None), (13, None)]
sage: K.<a> = NumberField(x^3-2)
sage: P17a, P17b = [P for P,e in K.factor(17)]
sage: E = EllipticCurve([0,0,0,2*a+1])
sage: [(p,E.local_data(p).bad_reduction_type()) for p in [P17a,P17b]]
[(Fractional ideal (4*a^2 - 2*a + 1), None), (Fractional ideal (2*a + 1), 0)]
```

`conductor_valuation()`

Return the valuation of the conductor from this local reduction data.
EXAMPLES:

```python
sage: from sage.schemes.elliptic_curves.ell_local_data import EllipticCurveLocalData
sage: E = EllipticCurve([0,0,0,0,64]); E
Elliptic Curve defined by y^2 = x^3 + 64 over Rational Field
sage: data = EllipticCurveLocalData(E,2)
sage: data.conductor_valuation()
2
discriminant_valuation()
Return the valuation of the minimal discriminant from this local reduction data.

EXAMPLES:

```python
sage: from sage.schemes.elliptic_curves.ell_local_data import EllipticCurveLocalData
sage: E = EllipticCurve([0,0,0,0,64]); E
Elliptic Curve defined by y^2 = x^3 + 64 over Rational Field
sage: data = EllipticCurveLocalData(E,2)
sage: data.discriminant_valuation()
4
```

has_additive_reduction()
Return True if there is additive reduction.

EXAMPLES:

```python
sage: E = EllipticCurve('27a1')
sage: [(p,E.local_data(p).has_additive_reduction()) for p in prime_range(15)]
[(2, False), (3, True), (5, False), (7, False), (11, False), (13, False)]
```

K.<a> = NumberField(x^3-2)
sage: P17a, P17b = [P for P,e in K.factor(17)]
sage: E = EllipticCurve([0,0,0,2*a+1])
sage: [(p,E.local_data(p).has_additive_reduction()) for p in [P17a,P17b]]
[(Fractional ideal (4*a^2 - 2*a + 1), False),
 (Fractional ideal (2*a + 1), True)]

has_bad_reduction()
Return True if there is bad reduction.

EXAMPLES:

```python
sage: E = EllipticCurve('14a1')
sage: [(p,E.local_data(p).has_bad_reduction()) for p in prime_range(15)]
[(2, True), (3, False), (5, False), (7, True), (11, False), (13, False)]
```

K.<a> = NumberField(x^3-2)
sage: P17a, P17b = [P for P,e in K.factor(17)]
sage: E = EllipticCurve([0,0,0,2*a+1])
sage: [(p,E.local_data(p).has_bad_reduction()) for p in [P17a,P17b]]
[(Fractional ideal (4*a^2 - 2*a + 1), False),
 (Fractional ideal (2*a + 1), True)]

Chapter 14. Elliptic curves over number fields
**has_good_reduction()**

Return True if there is good reduction.

**EXAMPLES:**

```python
sage: E = EllipticCurve('14a1')
sage: [(p,E.local_data(p).has_good_reduction()) for p in prime_range(15)]
[(2, False), (3, True), (5, True), (7, False), (11, True), (13, True)]
```

```python
sage: K.<a> = NumberField(x^3-2)
sage: P17a, P17b = [P for P,e in K.factor(17)]
sage: E = EllipticCurve([0,0,0,2*a+1])
sage: [(p,E.local_data(p).has_good_reduction()) for p in [P17a,P17b]]
[(Fractional ideal (4*a^2 - 2*a + 1), True), (Fractional ideal (2*a + 1), False)]
```

**has_multiplicative_reduction()**

Return True if there is multiplicative reduction.

**Note:** See also `has_split_multiplicative_reduction()` and `has_nonsplit_multiplicative_reduction()`.

**EXAMPLES:**

```python
sage: E = EllipticCurve('14a1')
sage: [(p,E.local_data(p).has_multiplicative_reduction()) for p in prime_range(15)]
[(2, True), (3, False), (5, False), (7, True), (11, False), (13, False)]
```

```python
sage: K.<a> = NumberField(x^3-2)
sage: P17a, P17b = [P for P,e in K.factor(17)]
sage: E = EllipticCurve([0,0,0,2*a+1])
sage: [(p,E.local_data(p).has_multiplicative_reduction()) for p in [P17a,P17b]]
[(Fractional ideal (4*a^2 - 2*a + 1), False), (Fractional ideal (2*a + 1), False)]
```

**has_nonsplit_multiplicative_reduction()**

Return True if there is non-split multiplicative reduction.

**EXAMPLES:**

```python
sage: E = EllipticCurve('14a1')
sage: [(p,E.local_data(p).has_nonsplit_multiplicative_reduction()) for p in prime_range(15)]
[(2, True), (3, False), (5, False), (7, False), (11, False), (13, False)]
```

```python
sage: K.<a> = NumberField(x^3-2)
sage: P17a, P17b = [P for P,e in K.factor(17)]
sage: E = EllipticCurve([0,0,0,2*a+1])
sage: [(p,E.local_data(p).has_nonsplit_multiplicative_reduction()) for p in [P17a,P17b]]
[(Fractional ideal (4*a^2 - 2*a + 1), False), (Fractional ideal (2*a + 1), False)]
```
**has_split_multiplicative_reduction()**

Return True if there is split multiplicative reduction.

**EXAMPLES:**

```python
sage: E = EllipticCurve('14a1')
sage: [(p, E.local_data(p).has_split_multiplicative_reduction()) for p in prime_range(15)]
[(2, False), (3, False), (5, False), (7, True), (11, False), (13, False)]
```

**kodaira_symbol()**

Return the Kodaira symbol from this local reduction data.

**EXAMPLES:**

```python
sage: from sage.schemes.elliptic_curves.ell_local_data import EllipticCurveLocalData
sage: E = EllipticCurve([0,0,0,0,64]); E
Elliptic Curve defined by y^2 = x^3 + 64 over Rational Field
sage: data = EllipticCurveLocalData(E,2)
sage: data.kodaira_symbol()
IV
```

**minimal_model**(reduce=True)

Return the (local) minimal model from this local reduction data.

**INPUT:**

- **reduce** – (default: True) if set to True and if the initial elliptic curve had globally integral coefficients, then the elliptic curve returned by Tate’s algorithm will be “reduced” as specified in _reduce_model() for curves over number fields.

**EXAMPLES:**

```python
sage: from sage.schemes.elliptic_curves.ell_local_data import EllipticCurveLocalData
sage: E = EllipticCurve([0,0,0,0,64]); E
Elliptic Curve defined by y^2 = x^3 + 64 over Rational Field
sage: data = EllipticCurveLocalData(E,2)
sage: data.minimal_model() == E.local_minimal_model(2)
True
```

To demonstrate the behaviour of the parameter reduce:

```python
sage: K.<a> = NumberField(x^3+x+1)
sage: E = EllipticCurve(K, [0, 0, a, 0, 1])
(continues on next page)```
Elliptic curves, Release 9.7

sage: E.local_data(K.ideal(a-1)).minimal_model()
Elliptic Curve defined by y^2 + a*y = x^3 + 1 over Number Field in a with defining polynomial x^3 + x + 1

sage: E.local_data(K.ideal(a-1)).minimal_model(reduce=False)
Elliptic Curve defined by y^2 + (a+2)*y = x^3 + 3*x^2 + 3*x + (-a+1) over Number Field in a with defining polynomial x^3 + x + 1

sage: E = EllipticCurve([2, 1, 0, -2, -1])
sage: E.local_data(ZZ.ideal(2), algorithm="generic").minimal_model(reduce=False)
Elliptic Curve defined by y^2 + 2*x*y + 2*y = x^3 + x^2 - 4*x - 2 over Rational Field

sage: E.local_data(ZZ.ideal(2), algorithm="pari").minimal_model(reduce=False)
Traceback (most recent call last):
  ... ValueError: the argument reduce must not be False if algorithm=pari is used

sage: E.local_data(ZZ.ideal(2), algorithm="generic").minimal_model()
Elliptic Curve defined by y^2 = x^3 - x^2 - 3*x + 2 over Rational Field

sage: E.local_data(ZZ.ideal(2), algorithm="pari").minimal_model()
Elliptic Curve defined by y^2 = x^3 - x^2 - 3*x + 2 over Rational Field

trac ticket #14476:

sage: t = QQ['t'].0
sage: K.<g> = NumberField(t^4 - t^3 - 3*t^2 - t + 1)
sage: E = EllipticCurve([-2*g^3 + 10/3*g^2 + 3*g - 2/3, -11/9*g^3 + 34/9*g^2 - 7/3*g + 4/9, 0, 0])
sage: vv = K.fractional_ideal(g^2 - g - 2)
sage: E.local_data(vv).minimal_model()
Elliptic Curve defined by y^2 + (-2*g^3+10/3*g^2+3*g-2/3)*x*y + (-11/9*g^3+34/9*g^2-7/3*g+4/9)*y = x^3 + (-11/9*g^3+34/9*g^2-7/3*g+4/9)*x^2 over Number Field in g with defining polynomial t^4 - t^3 - 3*t^2 - t + 1

prime()

Return the prime ideal associated with this local reduction data.

EXAMPLES:

sage: from sage.schemes.elliptic_curves.ell_local_data import EllipticCurveLocalData
sage: E = EllipticCurve([0,0,0,0,64]); E
Elliptic Curve defined by y^2 = x^3 + 64 over Rational Field
sage: data = EllipticCurveLocalData(E,2)
sage: data.prime()
Principal ideal (2) of Integer Ring

tamagawa_exponent()

Return the Tamagawa index from this local reduction data.

This is the exponent of $E(K_v)/E^0(K_v)$; in most cases it is the same as the Tamagawa index.

EXAMPLES:

sage: from sage.schemes.elliptic_curves.ell_local_data import EllipticCurveLocalData
sage: E = EllipticCurve([0,0,0,0,64]); E
Elliptic Curve defined by y^2 = x^3 + 64 over Rational Field
sage: data = EllipticCurveLocalData(E,2)
sage: data.tamagawa_exponent()
1

(continues on next page)
sage: E = EllipticCurve('816a1')

sage: data = EllipticCurveLocalData(E,2)

sage: data.kodaira_symbol()
I2*

sage: data.tamagawa_number()
4

sage: data.tamagawa_exponent()
2

sage: E = EllipticCurve('200c4')

sage: data = EllipticCurveLocalData(E,5)

sage: data.kodaira_symbol()
I4*

sage: data.tamagawa_number()
4

sage: data.tamagawa_exponent()
2

```text
tamagawa_number()
```

Return the Tamagawa number from this local reduction data.

This is the index \([E(K_v) : E^0(K_v)]\).

**EXAMPLES:**

```text
sage: from sage.schemes.elliptic_curves.ell_local_data import EllipticCurveLocalData

sage: E = EllipticCurve([0,0,0,0,64]); E
Elliptic Curve defined by y^2 = x^3 + 64 over Rational Field

sage: data = EllipticCurveLocalData(E,2)

sage: data.tamagawa_number()
3
```

sage.schemes.elliptic_curves.ell_local_data.check_prime(K, P)

Function to check that \(P\) determines a prime of \(K\), and return that ideal.

**INPUT:**

- \(K\) – a number field (including \(\mathbb{Q}\)).
- \(P\) – an element of \(K\) or a (fractional) ideal of \(K\).

**OUTPUT:**

- If \(K\) is \(\mathbb{Q}\): the prime integer equal to or which generates \(P\).
- If \(K\) is not \(\mathbb{Q}\): the prime ideal equal to or generated by \(P\).

---

**Note:** If \(P\) is not a prime and does not generate a prime, a `TypeError` is raised.

**EXAMPLES:**

```text
sage: from sage.schemes.elliptic_curves.ell_local_data import check_prime

sage: check_prime(QQ,3)
3
```

(continues on next page)
\begin{verbatim}
sage: check_prime(QQ,QQ(3))
3
sage: check_prime(QQ,ZZ.ideal(31))
31
sage: K.<a> = NumberField(x^2-5)
sage: check_prime(K,a)
Fractional ideal (a)
sage: check_prime(K,a+1)
Fractional ideal (a + 1)
sage: [check_prime(K,P) for P in K.primes_above(31)]
[Fractional ideal (5/2*a + 1/2), Fractional ideal (5/2*a - 1/2)]
sage: L.<b> = NumberField(x^2+3)
sage: check_prime(K, L.ideal(5))
Traceback (most recent call last):
...TypeError: The ideal Fractional ideal (5) is not a prime ideal of Number Field in a
˓→with defining polynomial x^2 - 5
sage: check_prime(K, L.ideal(b))
Traceback (most recent call last):
...TypeError: No compatible natural embeddings found for Number Field in a with
˓→defining polynomial x^2 - 5 and Number Field in b with defining polynomial x^2 + 3
\end{verbatim}

### 14.14 Kodaira symbols

Kodaira symbols encode the type of reduction of an elliptic curve at a (finite) place.

The standard notation for Kodaira Symbols is as a string which is one of \( I_m, \ \Pi, \ \Pi^*, \ \Pi^\ast, \ \III, \ \III^*, \ \IV^* \), where \( m \) denotes a non-negative integer. These have been encoded by single integers by different people. For convenience we give here the conversion table between strings, the eclib coding and the PARI encoding.

<table>
<thead>
<tr>
<th>Kodaira Symbol</th>
<th>Eclib coding</th>
<th>PARI Coding</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_0 )</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>( I_0^* )</td>
<td>1</td>
<td>-1</td>
</tr>
<tr>
<td>( I_m )</td>
<td>10m</td>
<td>( m + 4 )</td>
</tr>
<tr>
<td>( I_m^* )</td>
<td>10m + 1</td>
<td>(- (m + 4))</td>
</tr>
<tr>
<td>( \Pi )</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>( \III )</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>( \IV )</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>( \Pi^* )</td>
<td>7</td>
<td>-2</td>
</tr>
<tr>
<td>( \III^* )</td>
<td>6</td>
<td>-3</td>
</tr>
<tr>
<td>( \IV^* )</td>
<td>5</td>
<td>-4</td>
</tr>
</tbody>
</table>

**AUTHORS:**

- David Roe <roed@math.harvard.edu>
- John Cremona

\( \text{sage.schemes.elliptic_curves.kodaira_symbol.KodairaSymbol} \)\( \text{(symbol)} \)

Return the specified Kodaira symbol.
INPUT:

- symbol (string or integer) – Either a string of the form “I0”, “I1”, ..., “In”, “II”, “III”, IV, “I0*”, “I1*”, ..., “In*”, “II*”, “III*”, or “IV*”, or an integer encoding a Kodaira symbol using PARI’s conventions.

OUTPUT:

(KodairaSymbol) The corresponding Kodaira symbol.

EXAMPLES:

```
sage: KS = KodairaSymbol
sage: [KS(n) for n in range(1,10)]
[I0, II, III, IV, I1, I2, I3, I4, I5]
sage: [KS(-n) for n in range(1,10)]
[I0*, II*, III*, IV*, I1*, I2*, I3*, I4*, I5*]
sage: all(KS(str(KS(n))) == KS(n) for n in range(-10,10) if n != 0)
True
```

**class** `sage.schemes.elliptic_curves.kodaira_symbol.KodairaSymbol_class(symbol)`

Bases: `sage.structure.sage_object.SageObject`

Class to hold a Kodaira symbol of an elliptic curve over a \( p \)-adic local field.

Users should use the `KodairaSymbol()` function to construct Kodaira Symbols rather than use the class constructor directly.

### 14.15 Tate’s parametrisation of \( p \)-adic curves with multiplicative reduction

Let \( E \) be an elliptic curve defined over the \( p \)-adic numbers \( \mathbb{Q}_p \). Suppose that \( E \) has multiplicative reduction, i.e. that the \( j \)-invariant of \( E \) has negative valuation, say \( n \). Then there exists a parameter \( q \) in \( \mathbb{Z}_p \) of valuation \( n \) such that the points of \( E \) defined over the algebraic closure \( \overline{\mathbb{Q}}_p \) are in bijection with \( \overline{\mathbb{Q}}_p \times / q^{\mathbb{Z}} \). More precisely there exists the series \( s_4(q) \) and \( s_6(q) \) such that the \( y^2 + xy = x^3 + s_4(q)x + s_6(q) \) curve is isomorphic to \( E \) over \( \mathbb{Q}_p \) (or over \( \mathbb{Q}_p \) if the reduction is split multiplicative). There is a \( p \)-adic analytic map from \( \mathbb{Q}_p^\times \) to this curve with kernel \( q^{\mathbb{Z}} \). Points of good reduction correspond to points of valuation 0 in \( \mathbb{Q}_p^\times \).

See chapter V of [Sil1994] for more details.

**AUTHORS:**

- Chris Wuthrich (23/05/2007): first version
- Chris Wuthrich (04/09): reformatted docstrings.

**class** `sage.schemes.elliptic_curves.ell_tate_curve.TateCurve(E, p)`

Bases: `sage.structure.sage_object.SageObject`

Tate’s \( p \)-adic uniformisation of an elliptic curve with multiplicative reduction.

**Note:** Some of the methods of this Tate curve only work when the reduction is split multiplicative over \( \mathbb{Q}_p \).

**EXAMPLES:**
sage: e = EllipticCurve('130a1')
sage: eq = e.tate_curve(5); eq
5-adic Tate curve associated to the Elliptic Curve defined by y^2 + x*y + y = x^3 - 33*x + 68 over Rational Field
sage: eq == loads(dumps(eq))
True

REFERENCES: [Sil1994]

E2 (prec=20)
Return the value of the p-adic Eisenstein series of weight 2 evaluated on the elliptic curve having split multiplicative reduction.

INPUT:
• prec – the p-adic precision, default is 20.

EXAMPLES:

sage: eq = EllipticCurve('130a1').tate_curve(5)
sage: eq.E2(prec=10)
4 + 2*5^2 + 2*5^3 + 5^4 + 2*5^5 + 5^7 + 5^8 + 2*5^9 + O(5^10)

sage: T = EllipticCurve('14').tate_curve(7)
sage: T.E2(30)
2 + 4*7 + 7^2 + 3*7^3 + 6*7^4 + 5*7^5 + 2*7^6 + 7^7 + 5*7^8 + 6*7^9 + 5*7^10 + \ldots
   + 2*7^11 + 6*7^12 + 4*7^13 + 3*7^15 + 5*7^16 + 4*7^17 + 4*7^18 + 2*7^20 + 7^21 + \ldots
   + 5*7^22 + 4*7^23 + 4*7^24 + 3*7^25 + 6*7^26 + 3*7^27 + 6*7^28 + O(7^30)

L_invariant (prec=20)
Return the mysterious \(\mathcal{L}\)-invariant associated to an elliptic curve with split multiplicative reduction.

One instance where this constant appears is in the exceptional case of the p-adic Birch and Swinnerton-Dyer conjecture as formulated in [MTT1986]. See [Col2004] for a detailed discussion.

INPUT:
• prec – the p-adic precision, default is 20.

EXAMPLES:

sage: eq = EllipticCurve('130a1').tate_curve(5)
sage: eq.L_invariant(prec=10)
5^3 + 4*5^4 + 2*5^5 + 2*5^6 + 2*5^7 + 3*5^8 + 5^9 + O(5^10)

curve (prec=20)
Return the p-adic elliptic curve of the form \(y^2 + xy = x^3 + s_4x + s_6\).

This curve with split multiplicative reduction is isomorphic to the given curve over the algebraic closure of \(\mathbb{Q}_p\).

INPUT:
• prec – the p-adic precision, default is 20.

EXAMPLES:

sage: eq = EllipticCurve('130a1').tate_curve(5)
sage: eq.curve(prec=5)

(continues on next page)
Elliptic Curve defined by $y^2 + (1+O(5^5))*x*y = x^3 + (2^5*5^4+5^6+5^7+3^5*5^8+O(5^9))*x + (2^5*3+5^4+2*5^5+5^7+O(5^8))$ over 5-adic Field with capped relative precision 5

**is_split()**

Return True if the given elliptic curve has split multiplicative reduction.

**EXAMPLES:**

```python
sage: eq = EllipticCurve('130a1').tate_curve(5)
sage: eq.is_split()
True

sage: eq = EllipticCurve('37a1').tate_curve(37)
sage: eq.is_split()
False
```

**lift($P$, prec=20)**

Given a point $P$ in the formal group of the elliptic curve $E$ with split multiplicative reduction, this produces an element $u$ in $\mathbb{Q}_p^\times$ mapped to the point $P$ by the Tate parametrisation. The algorithm return the unique such element in $1 + p\mathbb{Z}_p$.

**INPUT:**

- $P$ – a point on the elliptic curve.
- $prec$ – the $p$-adic precision, default is 20.

**EXAMPLES:**

```python
sage: e = EllipticCurve('130a1')
sage: eq = e.tate_curve(5)
sage: P = e([-6,10])
sage: l = eq.lift(12*P, prec=10); l
1 + 4*5 + 5^3 + 5^4 + 4*5^5 + 5^6 + 5^7 + 4*5^8 + 5^9 + O(5^10)
```

Now we map the lift $l$ back and check that it is indeed right.: 

```python
sage: eq.parametrisation_onto_original_curve(l)
(4*5^-2 + 2*5^-1 + 4*5 + 3*5^3 + 5^4 + 2*5^5 + 4*5^6 + O(5^7) : 2*5^-3 + 5^-1 + 4 + 4*5 + 5^2 + 3*5^3 + 4*5^4 + O(5^6) : 1 + O(5^9))
```

**original_curve()**

Return the elliptic curve the Tate curve was constructed from.

**EXAMPLES:**

```python
sage: eq = EllipticCurve('130a1').tate_curve(5)
sage: eq.original_curve()
Elliptic Curve defined by $y^2 + x*y + y = x^3 - 33*x + 68$ over Rational Field
padic_height \((\text{prec}=20)\)

Return the canonical \(p\)-adic height function on the original curve.

INPUT:

- \(\text{prec}\) – the \(p\)-adic precision, default is 20.

OUTPUT:

- A function that can be evaluated on rational points of \(E\).

EXAMPLES:

```
sage: e = EllipticCurve('130a1')
sage: eq = e.tate_curve(5)
sage: h = eq.padic_height(prec=10)
sage: P = e.gens()[0]
sage: h(P)
2*5^-1 + 1 + 2*5 + 2*5^2 + 3*5^3 + 3*5^6 + 5^7 + O(5^9)
```

Check that it is a quadratic function:

```
sage: h(3*P)-3^2*h(P)
O(5^9)
```

padic_regulator \((\text{prec}=20)\)

Compute the canonical \(p\)-adic regulator on the extended Mordell-Weil group as in [MTT1986] (with the correction of [Wer1998] and sign convention in [SW2013].)

The \(p\)-adic Birch and Swinnerton-Dyer conjecture predicts that this value appears in the formula for the leading term of the \(p\)-adic L-function.

INPUT:

- \(\text{prec}\) – the \(p\)-adic precision, default is 20.

EXAMPLES:

```
sage: eq = EllipticCurve('130a1').tate_curve(5)
sage: eq.padic_regulator()
2*5^-1 + 1 + 2*5 + 2*5^2 + 3*5^3 + 3*5^6 + 5^7 + 3*5^9 + 3*5^10 + 3*5^12 + 4*5^˓
˓\rightarrow 13 + 3*5^15 + 2*5^16 + 3*5^18 + 4*5^19 + 4*5^20 + 3*5^21 + 4*5^22 + O(5^23)
```

parameter \((\text{prec}=20)\)

Return the Tate parameter \(q\) such that the curve is isomorphic over the algebraic closure of \(\mathbb{Q}_p\) to the curve \(\mathbb{Q}_p^\times /\mathbb{Z}\).

INPUT:

- \(\text{prec}\) – the \(p\)-adic precision, default is 20.

EXAMPLES:

```
sage: eq = EllipticCurve('130a1').tate_curve(5)
sage: eq.parameter(prec=5)
3*5^3 + 3*5^4 + 2*5^5 + 2*5^6 + 3*5^7 + O(5^8)
```

parametrisation_onto_original_curve \((u, \text{prec}=\text{None})\)

Given an element \(u\) in \(\mathbb{Q}_p^\times\), this computes its image on the original curve under the \(p\)-adic uniformisation of \(E\).
Elliptic curves, Release 9.7

INPUT:

- $u$ – a non-zero $p$-adic number.
- $\text{prec}$ – the $p$-adic precision, default is the relative precision of $u$ otherwise 20.

EXAMPLES:

```python
sage: eq = EllipticCurve('130a1').tate_curve(5)
sage: eq,parametrisation_onto_original_curve(1+5+5^2+O(5^10))
(4*5^2 - 2 + 4*5^4 - 1 + 4 + 2*5^3 + 3*5^6 + 0(5^7) : 3*5^4 - 3 + 5^2 - 2 + 4*5^1 - 1 + 1 + 4*5 + 5^2 + 3*5^1 + 0(5^6) : 1 + 0(5^10))
sage: eq.parametrisation_onto_original_curve(1+5+5^2+O(5^10), prec=20)
Traceback (most recent call last):
  ... ValueError: requested more precision than the precision of u
```

Here is how one gets a 4-torsion point on $E$ over $\mathbb{Q}_5$:

```python
sage: R = Qp(5,30)
sage: i = R(-1).sqrt()
sage: T = eq.parametrisation_onto_original_curve(i, prec=30); T
(2 + 3*5 + 4*5^2 + 2*5^3 + 5^4 + 4*5^5 + 2*5^7 + 5^8 + 5^9 + 5^12 + 3*5^13 + ˓→ 3*5^14 + 5^15 + 4*5^17 + 5^18 + 3*5^19 + 2*5^20 + 4*5^21 + 5^22 + 3*5^23 + ˓→ 3*5^24 + 4*5^25 + 3*5^26 + 3*5^27 + 3*5^28 + 3*5^29 + 0(5^30) : 3*5 + 5^2 + 5^ ˓→ 4 + 3*5^5 + 3*5^7 + 2*5^8 + 4*5^9 + 5^10 + 2*5^11 + 4*5^13 + 2*5^14 + 4*5^15 ˓→ + 4*5^16 + 3*5^17 + 2*5^18 + 4*5^20 + 2*5^21 + 2*5^22 + 4*5^23 + 4*5^24 + 4*5^ ˓→ 25 + 5^26 + 3*5^27 + 2*5^28 + 0(5^30) : 1 + 0(5^30))
sage: 4*T
(0 : 1 + 0(5^30) : 0)
```

\texttt{parametrisation}_\texttt{onto}_\texttt{tate}_\texttt{curve}(u, \text{prec}=\text{None})

Given an element $u$ in $\mathbb{Q}_p^\times$, this computes its image on the Tate curve under the $p$-adic uniformisation of $E$.

INPUT:

- $u$ – a non-zero $p$-adic number.
- $\text{prec}$ – the $p$-adic precision, default is the relative precision of $u$ otherwise 20.

EXAMPLES:

```python
sage: eq = EllipticCurve('130a1').tate_curve(5)
```

\texttt{prime}()

Return the residual characteristic $p$. 454
EXAMPLES:

```python
sage: eq = EllipticCurve('130a1').tate_curve(5)
sage: eq.original_curve()
Elliptic Curve defined by y^2 + x*y + y = x^3 - 33*x + 68
over Rational Field
sage: eq.prime()
5
```

Analytic properties over $\mathbb{C}$.

## 14.16 Weierstrass $\wp$-function for elliptic curves

The Weierstrass $\wp$ function associated to an elliptic curve over a field $k$ is a Laurent series of the form

$$
\wp(z) = \frac{1}{z^2} + c_2 \cdot z^2 + c_4 \cdot z^4 + \cdots.
$$

If the field is contained in $\mathbb{C}$, then this is the series expansion of the map from $\mathbb{C}$ to $E(\mathbb{C})$ whose kernel is the period lattice of $E$.

Over other fields, like finite fields, this still makes sense as a formal power series with coefficients in $k$ - at least its first $p - 2$ coefficients where $p$ is the characteristic of $k$. It can be defined via the formal group as $x + c$ in the variable $z = \log_E(t)$ for a constant $c$ such that the constant term $c_0$ in $\wp(z)$ is zero.

EXAMPLES:

```python
sage: E = EllipticCurve([0,1])
sage: E.weierstrass_p()
z^-2 - 1/7*z^4 + 1/637*z^10 - 1/84721*z^16 + O(z^20)
```

REFERENCES:

- [BMSS2006]

AUTHORS:

- Dan Shumov 04/09: original implementation
- Chris Wuthrich 11/09: major restructuring
- Jeroen Demeyer (2014-03-06): code clean up, fix characteristic bound for quadratic algorithm (see trac ticket #15855)

```python
sage.schemes.elliptic_curves.ell_wp.compute_wp_fast(k, A, B, m)
```

Computes the Weierstrass function of an elliptic curve defined by short Weierstrass model: $y^2 = x^3 + Ax + B$. It does this with as fast as polynomial of degree $m$ can be multiplied together in the base ring, i.e. $O(M(n))$ in the notation of [BMSS2006].

Let $p$ be the characteristic of the underlying field: Then we must have either $p = 0$, or $p > m + 3$.

INPUT:

- $k$ – the base field of the curve
- $A$ – and
- $B$ – as the coefficients of the short Weierstrass model $y^2 = x^3 + Ax + B$, and
- $m$ – the precision to which the function is computed to.
the Weierstrass $\wp$ function as a Laurent series to precision $m$.

**ALGORITHM:**

This function uses the algorithm described in section 3.3 of [BMSS2006].

**EXAMPLES:**

```
sage: from sage.schemes.elliptic_curves.ell_wp import compute_wp_fast
sage: compute_wp_fast(QQ, 1, 8, 7)
z^-2 - 1/5*z^2 - 8/7*z^4 + 1/75*z^6 + O(z^7)
sage: k = GF(37)
sage: compute_wp_fast(k, k(1), k(8), 5)
z^-2 + 22*z^2 + 20*z^4 + O(z^5)
```

sage.schemes.elliptic_curves.ell_wp.compute_wp_pari(E, prec)

Computes the Weierstrass $\wp$-function with the ellwp function from PARI.

**EXAMPLES:**

```
sage: E = EllipticCurve([0,1])
sage: from sage.schemes.elliptic_curves.ell_wp import compute_wp_pari
sage: compute_wp_pari(E, prec=20)
z^-2 - 1/7*z^4 + 1/637*z^10 - 1/84721*z^16 + O(z^20)
sage: compute_wp_pari(E, prec=30)
z^-2 - 1/7*z^4 + 1/637*z^10 - 1/84721*z^16 + 3/38548055*z^22 - 4/8364927935*z^28 + O(z^30)
```

sage.schemes.elliptic_curves.ell_wp.compute_wp_quadratic(k, A, B, prec)

Compute the truncated Weierstrass function of an elliptic curve defined by short Weierstrass model: $y^2 = x^3 + Ax + B$. Uses an algorithm that is of complexity $O(prec^2)$. Let $p$ be the characteristic of the underlying field. Then we must have either $p = 0$, or $p > prec + 2$.

**INPUT:**

- $k$ – the field of definition of the curve
- $A$ – and
- $B$ – the coefficients of the elliptic curve
- $prec$ – the precision to which we compute the series.

**OUTPUT:**

A Laurent series approximating the Weierstrass $\wp$-function to precision $prec$.

**ALGORITHM:**

This function uses the algorithm described in section 3.2 of [BMSS2006].

**EXAMPLES:**

```
sage: E = EllipticCurve([7,0])
sage: E.weierstrass_p(prec=10, algorithm='quadratic')
z^-2 - 7/5*z^2 + 49/75*z^6 + O(z^10)
sage: E = EllipticCurve(GF(103),[1,2])
```
sage: E.weierstrass_p(algorithm='quadratic')
z^-2 + 41*z^2 + 88*z^4 + 11*z^6 + 57*z^8 + 55*z^10 + 73*z^12 + 11*z^14 + 17*z^16 + → 50*z^18 + 0(z^20)

sage: from sage.schemes.elliptic_curves.ell_wp import compute_wp_quadratic
sage: compute_wp_quadratic(E.base_ring(), E.a4(), E.a6(), prec=10)
z^-2 + 41*z^2 + 88*z^4 + 11*z^6 + 57*z^8 + O(z^10)

sage.schemes.elliptic_curves.ell_wp.solve_linear_differential_system(a, b, c, alpha)
Solves a system of linear differential equations: \(a f' + b f = c\) and \(f'(0) = \alpha\) where \(a, b,\) and \(c\) are power series in one variable and \(\alpha\) is a constant in the coefficient ring.

**ALGORITHM:**
due to Brent and Kung '78.

**EXAMPLES:**

```python
sage: from sage.schemes.elliptic_curves.ell_wp import solve_linear_differential_system
sage: k = GF(17)
sage: R.<x> = PowerSeriesRing(k)
sage: a = 1+x+O(x^7); b = x+O(x^7); c = 1+x^3+O(x^7); alpha = k(3)
sage: f = solve_linear_differential_system(a,b,c,alpha)
sage: f
3 + x + 15*x^2 + x^3 + 10*x^5 + 3*x^6 + 13*x^7 + O(x^8)
sage: a*f.derivative()+b*f - c
O(x^7)
sage: f(0) == alpha
True
```

sage.schemes.elliptic_curves.ell_wp.weierstrass_p(E, prec=20, algorithm=None)
Compute the Weierstrass \(\wp\)-function on an elliptic curve.

**INPUT:**

- \(E\) – an elliptic curve
- \(\text{prec}\) – precision
- \(\text{algorithm}\) – string or None (default: None): a choice of algorithm among "pari", "fast", "quadratic"; or None to let this function determine the best algorithm to use.

**OUTPUT:**
a a Laurent series in one variable \(z\) with coefficients in the base field \(k\) of \(E\).

**EXAMPLES:**

```python
sage: E = EllipticCurve('11a1')
sage: E.weierstrass_p(prec=10)
z^-2 + 31/15*z^2 + 2501/756*z^4 + 961/675*z^6 + 77531/41580*z^8 + O(z^10)
sage: E.weierstrass_p(prec=8)
z^-2 + 31/15*z^2 + 2501/756*z^4 + 961/675*z^6 + O(z^8)
sage: Esh = E.short_weierstrass_model()
sage: Esh.weierstrass_p(prec=8)
z^-2 + 13392/5*z^2 + 1080432/7*z^4 + 59781888/25*z^6 + O(z^8)
```

(continues on next page)
sage: E.weierstrass_p(prec=8, algorithm='pari')
z^-2 + 31/15*z^2 + 2501/756*z^4 + 961/675*z^6 + O(z^8)
sage: E.weierstrass_p(prec=8, algorithm='quadratic')
z^-2 + 31/15*z^2 + 2501/756*z^4 + 961/675*z^6 + O(z^8)

sage: k = GF(11)
sage: E = EllipticCurve(k, [1,1])
sage: E.weierstrass_p(prec=6, algorithm='fast')
z^-2 + 2*z^2 + 3*z^4 + O(z^6)
sage: E.weierstrass_p(prec=7, algorithm='fast')
Traceback (most recent call last):
  ... ValueError: for computing the Weierstrass p-function via the fast algorithm, the characteristic (11) of the underlying field must be greater than prec + 4 = 11

sage: E.weierstrass_p(prec=8)
z^-2 + 2*z^2 + 3*z^4 + 5*z^6 + O(z^8)
sage: E.weierstrass_p(prec=8, algorithm='quadratic')
z^-2 + 2*z^2 + 3*z^4 + 5*z^6 + O(z^8)
sage: E.weierstrass_p(prec=8, algorithm='pari')
z^-2 + 2*z^2 + 3*z^4 + 5*z^6 + O(z^8)
sage: E.weierstrass_p(prec=9)
Traceback (most recent call last):
  ... NotImplementedError: currently no algorithms for computing the Weierstrass p-function for that characteristic / precision pair is implemented. Lower the precision below char(k) - 2

sage: E.weierstrass_p(prec=9, algorithm="quadratic")
Traceback (most recent call last):
  ... ValueError: for computing the Weierstrass p-function via the quadratic algorithm, the characteristic (11) of the underlying field must be greater than prec + 2 = 11

sage: E.weierstrass_p(prec=9, algorithm='pari')
Traceback (most recent call last):
  ... ValueError: for computing the Weierstrass p-function via pari, the characteristic (11) of the underlying field must be greater than prec + 2 = 11

14.17 Period lattices of elliptic curves and related functions

Let $E$ be an elliptic curve defined over a number field $K$ (including $\mathbb{Q}$). We attach a period lattice (a discrete rank 2 subgroup of $\mathbb{C}$) to each embedding of $K$ into $\mathbb{C}$.

In the case of real embeddings, the lattice is stable under complex conjugation and is called a real lattice. These have two types: rectangular, (the real curve has two connected components and positive discriminant) or non-rectangular (one connected component, negative discriminant).

The periods are computed to arbitrary precision using the AGM (Gauss’s Arithmetic-Geometric Mean).

EXAMPLES:
Elliptic curves, Release 9.7

```
sage: K.<a> = NumberField(x^3-2)
sage: E = EllipticCurve([0,1,0,a,a])
```

First we try a real embedding:

```
sage: emb = K.embeddings(RealField())[0]
sage: L = E.period_lattice(emb); L
Period lattice associated to Elliptic Curve defined by y^2 = x^3 + x^2 + a*x + a over
→ Number Field in a with defining polynomial x^3 - 2 with respect to the embedding Ring
→ morphism:
From: Number Field in a with defining polynomial x^3 - 2
To: Algebraic Real Field
Defn: a |--> 1.259921049894873?
```

The first basis period is real:

```
sage: L.basis()
(3.81452977217855, 1.90726488608927 + 1.34047785962440*I)
sage: L.is_real()
True
```

For a basis \( \omega_1, \omega_2 \) normalised so that \( \omega_1/\omega_2 \) is in the fundamental region of the upper half-plane, use the function `normalised_basis()` instead:

```
sage: L.normalised_basis()
(1.90726488608927 - 1.34047785962440*I, -1.90726488608927 - 1.34047785962440*I)
```

Next a complex embedding:

```
sage: emb = K.embeddings(ComplexField())[0]
sage: L = E.period_lattice(emb); L
Period lattice associated to Elliptic Curve defined by y^2 = x^3 + x^2 + a*x + a over
→ Number Field in a with defining polynomial x^3 - 2 with respect to the embedding Ring
→ morphism:
From: Number Field in a with defining polynomial x^3 - 2
To: Algebraic Field
Defn: a |--> -0.6299605249474365? - 1.091123635971722?*I
```

In this case, the basis \( \omega_1, \omega_2 \) is always normalised so that \( \tau = \omega_1/\omega_2 \) is in the fundamental region in the upper half plane:

```
sage: w1,w2 = L.basis(); w1,w2
(-1.37588604166076 - 2.58560946624443*I, -2.10339907847356 + 0.428378776460622*I)
sage: L.is_real()
False
sage: tau = w1/w2; tau
0.387694505032876 + 1.30821088214407*I
sage: L.normalised_basis()
(-1.37588604166076 - 2.58560946624443*I, -2.10339907847356 + 0.428378776460622*I)
```

We test that bug trac ticket #8415 (caused by a PARI bug fixed in v2.3.5) is OK:

```
sage: E = EllipticCurve('37a')
sage: K.<a> = QuadraticField(-7)
```

(continues on next page)
Elliptic curves, Release 9.7

sage: EK = E.change_ring(K)
sage: EK.period_lattice(K.complex_embeddings()[0])
Period lattice associated to Elliptic Curve defined by y^2 + y = x^3 + (-1)*x over Number Field in a with defining polynomial x^2 + 7 with a = 2.645751311064591?*I with respect to the embedding Ring morphism:
  From: Number Field in a with defining polynomial x^2 + 7 with a = 2.645751311064591?*I
  To:  Algebraic Field
  Defn: a |--> -2.645751311064591?*I

REFERENCES:
• [CT2013]

AUTHORS:
• ?: initial version.
• John Cremona:
  – Adapted to handle real embeddings of number fields, September 2008.
  – Added basis_matrix function, November 2008
  – Added support for complex embeddings, May 2009.
  – Added complex elliptic logs, March 2010; enhanced, October 2010.

class sage.schemes.elliptic_curves.period_lattice.PeriodLattice(base_ring, rank, degree, sparse=False, coordinate_ring=None)

Bases: sage.modules.free_module.FreeModule_generic_pid

The class for the period lattice of an algebraic variety.

class sage.schemes.elliptic_curves.period_lattice.PeriodLattice_ell(E, embedding=None)

Bases: sage.schemes.elliptic_curves.period_lattice.PeriodLattice

The class for the period lattice of an elliptic curve.

Currently supported are elliptic curves defined over \( \mathbb{Q} \), and elliptic curves defined over a number field with a real or complex embedding, where the lattice constructed depends on that embedding.

basis(prec=None, algorithm='sage')

Return a basis for this period lattice as a 2-tuple.

INPUT:

• prec (default: None) – precision in bits (default precision if None).

• algorithm (string, default ‘sage’) – choice of implementation (for real embeddings only) between ‘sage’ (native Sage implementation) or ‘pari’ (use the PARI library: only available for real embeddings).

OUTPUT:

(tuple of Complex) \( (\omega_1, \omega_2) \) where the lattice is \( \mathbb{Z}\omega_1 + \mathbb{Z}\omega_2 \). If the lattice is real then \( \omega_1 \) is real and positive, \( \Im(\omega_2) > 0 \) and \( \Re(\omega_1/\omega_2) \) is either 0 (for rectangular lattices) or \( 1 \) (for non-rectangular lattices). Otherwise, \( \omega_1/\omega_2 \) is in the fundamental region of the upper half-plane. If the latter normalisation is required for real lattices, use the function normalised_basis() instead.

EXAMPLES:
This shows that the issue reported at trac ticket #3954 is fixed:

```python
sage: E = EllipticCurve('37a')
sage: E.period_lattice().basis()
(2.99345864623196, 2.45138938198679*I)
```

This shows that the issue reported at trac ticket #4064 is fixed:

```python
sage: E = EllipticCurve('37a')
sage: b1 = E.period_lattice().basis(prec=30)
sage: b2 = E.period_lattice().basis(prec=30)
sage: b1 == b2
True
```

```python
sage: K.<a> = NumberField(x^3-2)
sage: emb = K.embeddings(RealField())[0]
sage: E = EllipticCurve([0,1,0,a,a])
sage: L = E.period_lattice(emb)
sage: L.basis(64)
(3.81452977217854509, 1.90726488608927255 + 1.34047785962440202*I)
```

```python
sage: emb = K.embeddings(ComplexField())[0]
sage: L = E.period_lattice(emb)
sage: w1, w2 = L.basis(); w1, w2
(-1.37588604166076 - 2.58560946624443*I, -2.10339907847356 + 0.˓→42837877640622*I)
sage: L.is_real()
False
sage: tau = w1/w2; tau
0.387694505032876 + 1.30821088214407*I
```

```python
basis_matrix(prec=None, normalised=False)
```

Return the basis matrix of this period lattice.

**INPUT:**

- `prec` (int or None `(default)`) -- real precision in bits (default real precision if `'None`).

- `normalised` (bool, default False) – if True and the embedding is real, use the normalised basis (see `normalised_basis()`) instead of the default.

**OUTPUT:**

A 2x2 real matrix whose rows are the lattice basis vectors, after identifying \( \mathbb{C} \) with \( \mathbb{R}^2 \).

**EXAMPLES:**

```python
sage: E = EllipticCurve('37a')
sage: E.period_lattice().basis_matrix()
```
Elliptic curves, Release 9.7

[ 2.99345864623196 0.000000000000000]
[0.000000000000000 2.45138938198679]

sage: K.<a> = NumberField(x^3-2)
sage: emb = K.embeddings(RealField())[0]
sage: E = EllipticCurve([0,1,0,a,a])
sage: L = E.period_lattice(emb)
sage: L.basis_matrix(64)
[ 3.81452977217854509 0.000000000000000000
 [ 1.90726488608927255 1.34047785962440202]

See trac ticket #4388:

sage: L = EllipticCurve('11a1').period_lattice()
sage: L.basis_matrix()
[ 1.26920930427955 0.000000000000000000
 [0.634604652139777 1.45881661693850]
 sage: L.basis_matrix(normalised=True)
[ 0.634604652139777 -1.45881661693850]
[ -1.26920930427955 0.000000000000000000]

sage: L = EllipticCurve('389a1').period_lattice()
sage: L.basis_matrix()
[ 2.49021256085505 0.000000000000000000
 [0.000000000000000 1.97173770155165]
 sage: L.basis_matrix(normalised=True)
[ 2.49021256085505 0.000000000000000000
 [0.000000000000000 -1.97173770155165]

complex_area(prec=None)

Return the area of a fundamental domain for the period lattice of the elliptic curve.

INPUT:

* prec (int or None ``(default)) -- real precision in bits (default real precision if ``None).

EXAMPLES:

sage: E = EllipticCurve('37a')
sage: E.period_lattice().complex_area()
7.33813274078958

coordinates(z, rounding=None)

Return the coordinates of a complex number w.r.t. the lattice basis
INPUT:

- `z` (complex) – A complex number.
- `rounding` (default `None`) – whether and how to round the output (see below).

OUTPUT:

When `rounding` is `None` (the default), returns a tuple of reals `x, y` such that `z = x w_1 + y w_2` where `w_1, w_2` are a basis for the lattice (normalised in the case of complex embeddings).

When `rounding` is ‘round’, returns a tuple of integers `n_1, n_2` which are the closest integers to the `x, y` defined above. If `z` is in the lattice these are the coordinates of `z` with respect to the lattice basis.

When `rounding` is ‘floor’, returns a tuple of integers `n_1, n_2` which are the integer parts to the `x, y` defined above. These are used in `reduce()`

EXAMPLES:

```
sage: E = EllipticCurve('389a')
sage: L = E.period_lattice()
sage: w1, w2 = L.basis(prec=100)
sage: P = E([-1,1])
sage: zP = P.elliptic_logarithm(precision=100); zP
0.47934825019021931612953301006 + 0.98586885077582410221120384908*I
sage: L.coordinates(zP)
(0.1924929051139422735263996419, 0.5)
```

```
sage: L.coordinates(12*w1+23*w2)
(12.000000000000000000000000000, 23.000000000000000000000000000)
```

```
sage: L.coordinates(12*w1+23*w2, rounding='floor')
(11, 22)
```

```
sage: L.coordinates(12*w1+23*w2, rounding='round')
(12, 23)
```

curve()

Return the elliptic curve associated with this period lattice.

EXAMPLES:

```
sage: E = EllipticCurve('37a')
sage: L = E.period_lattice()
sage: L.curve() is E
True
```

```
sage: K.<a> = NumberField(x^3-2)
sage: E = EllipticCurve([0,1,0,a,a])
sage: L = E.period_lattice(K.embeddings(RealField())[0])
sage: L.curve() is E
True
```

```
sage: L = E.period_lattice(K.embeddings(ComplexField())[0])
sage: L.curve() is E
True
```
e_log_RC(xP, yP, prec=None, reduce=True)

Return the elliptic logarithm of a real or complex point.

- **xP, yP** (real or complex) – Coordinates of a point on the embedded elliptic curve associated with this period lattice.
- **prec** (default: None) – real precision in bits (default real precision if None).
- **reduce** (default: True) – if True, the result is reduced with respect to the period lattice basis.

**OUTPUT:**

(complex number) The elliptic logarithm of the point \((xP, yP)\) with respect to this period lattice. If \(E\) is the elliptic curve and \(\sigma : K \to \mathbb{C}\) the embedding, the returned value \(z\) is such that \(z \pmod{L}\) maps to \((xP, yP) = \sigma(P)\) under the standard Weierstrass isomorphism from \(\mathbb{C}/L\) to \(\sigma(E)\). If **reduce** is True, the output is reduced so that it is in the fundamental period parallelogram with respect to the normalised lattice basis.

**ALGORITHM:**

Uses the complex AGM. See [CT2013] for details.

**EXAMPLES:**

```sage
sage: E = EllipticCurve('389a')
sage: L = E.period_lattice()
sage: P = E([-1,1])
sage: xP, yP = [RR(c) for c in P.xy()]
sage: L.e_log_RC(xP, yP)
0.479348250190219 + 0.985868850775824*I
```

The elliptic log from the real coordinates:

```sage
sage: L.e_log_RC(xP, yP)
0.479348250190219 + 0.985868850775824*I
```

The same elliptic log from the algebraic point:

```sage
sage: L(P)
0.479348250190219 + 0.985868850775824*I
```

A number field example:

```sage
sage: K.<a> = NumberField(x^3-2)
sage: E = EllipticCurve([0,0,0,0,a])
sage: v = K.real_places()[0]
sage: L = E.period_lattice(v)
sage: P = E.lift_x(1/3*a^2 + a + 5/3)
sage: L(P)
3.51086196882538
sage: xP, yP = [v(c) for c in P.xy()]
sage: L.e_log_RC(xP, yP)
3.51086196882538
```

Elliptic logs of real points which do not come from algebraic points:

```sage
sage: ER = EllipticCurve([v(ai) for ai in E.a_invariants()])
sage: P = ER.lift_x(12.34)
sage: xP, yP = P.xy()
sage: xP, yP
(continues on next page)
```
Elliptic curves, Release 9.7

Elliptic curves, Release 9.7

(continued from previous page)

Elliptic logs of complex points:

```sage
v = K.complex_embeddings()[0]
L = E.period_lattice(v)
P = E.lift_x(1/3*a^2 + a + 5/3)
L(P)
1.68207104397706 - 1.87873661686704*I
sage: xP, yP = [v(c) for c in P.xy()]
sage: L.e_log_RC(xP, yP)
1.68207104397706 - 1.87873661686704*I
sage: EC = EllipticCurve([v(ai) for ai in E.a_invariants()])
sage: xP, yP = EC.lift_x(0).xy()
sage: L.e_log_RC(xP, yP)
1.03355715602040 - 0.867257428417356*I
```

**ei()**

Return the x-coordinates of the 2-division points of the elliptic curve associated with this period lattice, as elements of QQbar.

**EXAMPLES:**

```sage
E = EllipticCurve('37a')
L = E.period_lattice()
L.ei()
[-1.107159871688768?, 0.2695944364054446?, 0.8375654352833230?]
```

In the following example, we should have one purely real 2-division point coordinate, and two conjugate purely imaginary coordinates.

```sage
K.<a> = NumberField(x^3-2)
E = EllipticCurve([0,1,0,a,a])
L = E.period_lattice(K.embeddings(RealField())[0])
x1,x2,x3 = L.ei()
sage: abs(x1.real())+abs(x2.real())<1e-14
True
sage: x1.imag(),x2.imag(),x3
(-1.122462048309373?, 1.122462048309373?, -1.000000000000000?)
```

```sage
E = EllipticCurve(K.embeddings(ComplexField())[0])
L.ei()
[-1.000000000000000? + 0.?e-1...*I,
-0.9720806486198328? - 0.561231024154687?*I,
0.9720806486198328? + 0.561231024154687?*I]
```

**elliptic_exponential(z, to_curve=True)**

Return the elliptic exponential of a complex number.
INPUT:

- \( z \) (complex) – A complex number (viewed modulo this period lattice).
- \( \text{to\_curve} \) (bool, default True): see below.

OUTPUT:

- If \( \text{to\_curve} \) is False, a 2-tuple of real or complex numbers representing the point \((x, y) = (\wp(z), \wp'(z))\) where \( \wp \) denotes the Weierstrass \( \wp \)-function with respect to this lattice.
- If \( \text{to\_curve} \) is True, the point \((X, Y) = (x - b_2/12, y - (a_1(x - b_2/12) - a_3)/2)\) as a point in \( E(\mathbb{R}) \) or \( E(\mathbb{C}) \), with \((x, y) = (\wp(z), \wp'(z))\) as above, where \( E \) is the elliptic curve over \( \mathbb{R} \) or \( \mathbb{C} \) whose period lattice this is.
- If the lattice is real and \( z \) is also real then the output is a pair of real numbers if \( \text{to\_curve} \) is True, or a point in \( E(\mathbb{R}) \) if \( \text{to\_curve} \) is False.

Note: The precision is taken from that of the input \( z \).

EXAMPLES:

```python
sage: E = EllipticCurve([1,1,1,-8,6])
sage: P = E(1,-2)
sage: L = E.period_lattice()
sage: z = L(P); z
1.17044757240090
sage: L.elliptic_exponential(z)
(0.999999999999999 : -2.00000000000000)
sage: _.curve()
Elliptic Curve defined by y^2 + 1.00000000000000*x*y + 1.00000000000000*y = x^3 + 1.00000000000000*x^2 - 8.00000000000000*x + 6.00000000000000 over Real Field with 53 bits of precision
sage: L.elliptic_exponential(z,to_curve=False)
(1.41666666666667, -2.00000000000000)
sage: z = L(P,prec=201); z
1.17044757240089592298992188482371493504472561677451007994189
sage: L.elliptic_exponential(z)
(1.00000000000000000000000000000000000000000000000000000000000 : -2.00000000000000000000000000000000000000000000000000000000000 : 1.00000000000000000000000000000000000000000000000000000000000)
(continues on next page)
```

Examples over number fields:

```python
sage: x = polygen(QQ)
sage: K.<a> = NumberField(x^3-2)
sage: embs = K.embeddings(CC)
sage: E = EllipticCurve('37a')
sage: EK = E.change_ring(K)
sage: Li = [EK.period_lattice(e) for e in embs]
sage: P = EK(-1,-1)
sage: Q = EK(a-1,1-a^2)
sage: zi = [L.elliptic_logarithm(P) for L in Li]
sage: [c.real() for c in Li[0].elliptic_exponential(zi[0])]
[-1.00000000000000, -1.00000000000000, 1.00000000000000]
sage: [c.real() for c in Li[0].elliptic_exponential(zi[1])]
```

(continues on next page)
[-1.00000000000000, -1.00000000000000, 1.00000000000000]
sage: [c.real() for c in Li[0].elliptic_exponential(zi[2])]
[-1.00000000000000, -1.00000000000000, 1.00000000000000]
sage: zi = [L.elliptic_logarithm(Q) for L in Li]
sage: Li[0].elliptic_exponential(zi[0])
(-1.62996052494744 + 1.09112363597172*I : 1.00000000000000)
sage: [embs[0](c) for c in Q]
[-1.62996052494744, 1.79370052598410, --> 1.00000000000000]
sage: Li[1].elliptic_exponential(zi[1])
(-1.62996052494744 + 1.09112363597172*I : 1.00000000000000)
sage: [embs[1](c) for c in Q]
[-1.62996052494744, 1.79370052598410, --> 1.00000000000000]
sage: [c.real() for c in Li[2].elliptic_exponential(zi[2])]
[0.259921049894873, -0.587401051968200, 1.00000000000000]
sage: [embs[2](c) for c in Q]
[0.259921049894873, -0.587401051968200, 1.00000000000000]

Test to show that trac ticket #8820 is fixed:

sage: E = EllipticCurve('37a')
sage: K.<a> = QuadraticField(-5)
sage: L = E.change_ring(K).period_lattice(K.places()[0])
sage: L.elliptic_exponential(CDF(.1,.1))
(0.0000142854026029... - 49.9960001066650*I : 249.520141250950 + 250.039711098263*I)
sage: L.elliptic_exponential(0, to_curve=False)
(+infinity, +infinity)

z = 0 is treated as a special case:

sage: E = EllipticCurve([1,1,1,-8,6])
sage: L = E.period_lattice()
sage: L.elliptic_exponential(0, to_curve=False)
(+infinity, +infinity)

Very small z are handled properly (see trac ticket #8820):
sage: K.<a> = QuadraticField(-1)
sage: E = EllipticCurve([0,0,a,0])
sage: L = E.period_lattice(K.complex_embeddings()[0])
sage: L.elliptic_exponential(1e-100)
(0.000000000000000 : 1.000000000000000 : 0.000000000000000)

The elliptic exponential of \( z \) is returned as \((0:1:0)\) if the coordinates of \( z \) with respect to the period lattice are approximately integral:

sage: (100/log(2.0,10))/0.8
415.241011860920
sage: L.elliptic_exponential((RealField(415)(1e-100))).is_zero()
True
sage: L.elliptic_exponential((RealField(420)(1e-100))).is_zero()
False

elliptic_logarithm\((P, \text{prec}=None, \text{reduce}=\text{True})\)

Return the elliptic logarithm of a point.

INPUT:

\begin{itemize}
\item \( P \) (point) – A point on the elliptic curve associated with this period lattice.
\item \text{prec} (default: None) – real precision in bits (default real precision if None).
\item \text{reduce} (default: True) – if True, the result is reduced with respect to the period lattice basis.
\end{itemize}

OUTPUT:

(complex number) The elliptic logarithm of the point \( P \) with respect to this period lattice. If \( E \) is the elliptic curve and \( \sigma : K \to \mathbb{C} \) the embedding, the returned value \( z \) is such that \( z \pmod{L} \) maps to \( \sigma(P) \) under the standard Weierstrass isomorphism from \( \mathbb{C}/L \) to \( \sigma(E) \). If \text{reduce} is True, the output is reduced so that it is in the fundamental period parallelogram with respect to the normalised lattice basis.

ALGORITHM:

Uses the complex AGM. See [CT2013] for details.

EXAMPLES:

sage: E = EllipticCurve('389a')
sage: L = E.period_lattice()
sage: E.discriminant() > 0
True
sage: L.real_flag
1
sage: P = E([-1,1])
sage: P.is_on_identity_component ()
False
sage: L.elliptic_logarithm(P, prec=96)
0.4793482501902193161295330101 + 0.9858688507758241022112038491*I
sage: Q=E([-3,5])
sage: Q.is_on_identity_component()
True
sage: L.elliptic_logarithm(Q, prec=96)
1.931128271542559442488585220

Note that this is actually the inverse of the Weierstrass isomorphism:
An example with negative discriminant, and a torsion point:

```python
sage: E = EllipticCurve('11a1')
sage: L = E.period_lattice()
sage: E.discriminant() < 0
True
sage: L.real_flag
-1
sage: P = E([16,-61])
sage: L.elliptic_logarithm(P)
0.253841860855911
sage: L.real_period() / L.elliptic_logarithm(P)
5.00000000000000
```

An example where precision is problematic:

```python
sage: E = EllipticCurve([1, 0, 1, -85357462, 303528987048])
sage: P = E([4458713781401/835903744, -64466909836503771/24167649046528, 1])
sage: L = E.period_lattice()
sage: L.ei()
sage: L.elliptic_logarithm(P,prec=100)
0.27656204014107061464076203097
```

Some complex examples, taken from the paper by Cremona and Thongjunthug:

```python
sage: K.<i> = QuadraticField(-1)
sage: a4 = 9*i-10
sage: a6 = 21-i
sage: E = EllipticCurve([0,0,0,a4,a6])
sage: e1 = 3-2*i; e2 = 1+i; e3 = -4+i
sage: emb = K.embeddings(CC)[1]
sage: L = E.period_lattice(emb)
sage: P = E(2-i,4+2*i)
```

By default, the output is reduced with respect to the normalised lattice basis, so that its coordinates with respect to that basis lie in the interval [0,1):

```python
sage: z = L.elliptic_logarithm(P,prec=100); z
0.7044837553778220846049649302 - 0.79246725643650979858266018068*I
sage: L.coordinates(z)
(0.46247636364807931766105460692, 0.7949758872680870420076039829)
```

Using `reduce=False` this step can be omitted. In this case the coordinates are usually in the interval [-0.5,0.5), but this is not guaranteed. This option is mainly for testing purposes:

```python
sage: z = L.elliptic_logarithm(P,prec=100, reduce=False); z
0.57002153834710752778063503023 + 0.46476340520469798857457031393*I
```

(continues on next page)
The elliptic logs of the 2-torsion points are half-periods:

<table>
<thead>
<tr>
<th>sage:</th>
<th>L.elliptic_logarithm(E(e1,0),prec=100)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.646075758745356528476867052 + 0.22379609053909448304176885364*I</td>
</tr>
<tr>
<td>sage:</td>
<td>L.elliptic_logarithm(E(e2,0),prec=100)</td>
</tr>
<tr>
<td></td>
<td>0.7133068672589225379705940192 - 0.40481924028150941053684639367*I</td>
</tr>
<tr>
<td>sage:</td>
<td>L.elliptic_logarithm(E(e3,0),prec=100)</td>
</tr>
<tr>
<td></td>
<td>0.067231108515357278412180731396 - 0.628615330820603893758761524731*I</td>
</tr>
</tbody>
</table>

We check this by doubling and seeing that the resulting coordinates are integers:

| sage: | L.coordinates(2*L.elliptic_logarithm(E(e1,0),prec=100)) |
|      | (1.0000000000000000000000000000, 0.00000000000000000000000000000) |
| sage: | L.coordinates(2*L.elliptic_logarithm(E(e2,0),prec=100)) |
|      | (1.0000000000000000000000000000, 1.0000000000000000000000000000) |
| sage: | L.coordinates(2*L.elliptic_logarithm(E(e3,0),prec=100)) |
|      | (0.00000000000000000000000000000, 1.0000000000000000000000000000) |

```python
gens(prec=None, algorithm='sage')
```
Return a basis for this period lattice as a 2-tuple.

This is an alias for `basis()`. See the docstring there for a more in-depth explanation and further examples.

**INPUT:**

- `prec` (default: `None`) – precision in bits (default precision if `None`).
- `algorithm` (string, default 'sage') – choice of implementation (for real embeddings only) between 'sage' (native Sage implementation) or 'pari' (use the PARI library: only available for real embeddings).

**OUTPUT:**

(tuple of Complex) \((\omega_1, \omega_2)\) where the lattice is \(\mathbb{Z}\omega_1 + \mathbb{Z}\omega_2\). If the lattice is real then \(\omega_1\) is real and positive, \(\Im(\omega_2) > 0\) and \(\Re(\omega_1/\omega_2)\) is either 0 (for rectangular lattices) or \(\frac{1}{2}\) (for non-rectangular lattices). Otherwise,
\omega_1/\omega_2 is in the fundamental region of the upper half-plane. If the latter normalisation is required for real lattices, use the function \texttt{normalised_basis()} instead.

**EXAMPLES:**

```
sage: E = EllipticCurve('37a')
sage: E.period_lattice().gens()
(2.99345864623196, 2.45138938198679*I)
```

```
sage: E.period_lattice().gens(prec = 100)
(2.9934586462319596298320099794, 2.4513893819867900608542248319*I)
```

**is_real()**

Return True if this period lattice is real.

**EXAMPLES:**

```
sage: f = EllipticCurve('11a')
sage: f.period_lattice().is_real()
True
```

```
sage: K.<i> = QuadraticField(-1)
sage: E = EllipticCurve(K,[0,0,0,i,2*i])
sage: emb = K.embeddings(ComplexField())[0]
sage: L = E.period_lattice(emb)
sage: L.is_real()
False
```

```
sage: K.<a> = NumberField(x^3-2)
sage: E = EllipticCurve([0,1,0,a,a])
sage: [E.period_lattice(emb).is_real() for emb in K.embeddings(CC)]
[False, False, True]
```

**ALGORITHM:**
The lattice is real if it is associated to a real embedding; such lattices are stable under conjugation.

**is_rectangular()**

Return True if this period lattice is rectangular.

**Note:** Only defined for real lattices; a RuntimeError is raised for non-real lattices.

**EXAMPLES:**

```
sage: f = EllipticCurve('11a')
sage: f.period_lattice().basis()
(1.26920930427955, 0.634604652139777 + 1.45881661693850*I)
sage: f.period_lattice().is_rectangular()
False
```

```
sage: f = EllipticCurve('37b')
sage: f.period_lattice().basis()
(1.08852159290423, 1.76761067023379*I)
```

sage: f.period_lattice().is_rectangular()
True

ALGORITHM:
The period lattice is rectangular precisely if the discriminant of the Weierstrass equation is positive, or equivalently if the number of real components is 2.

**normalised_basis** *(prec=None, algorithm='sage')*

Return a normalised basis for this period lattice as a 2-tuple.

**INPUT:**
- **prec** (default: None) – precision in bits (default precision if None).
- **algorithm** (string, default 'sage') – choice of implementation (for real embeddings only) between 'sage' (native Sage implementation) or 'pari' (use the PARI library: only available for real embeddings).

**OUTPUT:**
(tuple of Complex) \((\omega_1, \omega_2)\) where the lattice has the form \(\mathbb{Z}\omega_1 + \mathbb{Z}\omega_2\). The basis is normalised so that \(\omega_1/\omega_2\) is in the fundamental region of the upper half-plane. For an alternative normalisation for real lattices (with the first period real), use the function basis() instead.

**EXAMPLES:**

```sage
e = EllipticCurve('37a')
e.period_lattice().normalised_basis()
(2.99345864623196, -2.45138938198679*I)
```

```sage
K.<a> = NumberField(x^3-2)
emb = K.embeddings(RealField())[0]
e = EllipticCurve([0,1,0,a,a])
L = e.period_lattice(emb)
L.normalised_basis(64)
(1.9872648860892755 - 1.3404778596244020*I, -1.9072648860892755 - 1.3404778596244020*I)
```

```sage
emb = K.embeddings(ComplexField())[0]
L = e.period_lattice(emb)
w1,w2 = L.normalised_basis(); w1,w2
(-1.37588604166076 - 2.58560946624443*I, -2.10339907847356 + 0.428378776460622*I)
```

```sage
L.is_real()
False
tau = w1/w2; tau
0.387694505032876 + 1.3082108814407*I
```

**omega** *(prec=None, bsd_normalise=False)*

Return the real or complex volume of this period lattice.

**INPUT:**
- **prec** (int or None) – real precision in bits (default real precision if None)
- **bsd_normalise** (bool, default False) – flag to use BSD normalisation in the complex case.
OUTPUT:

(real) For real lattices, this is the real period times the number of connected components. For non-real lattices it is the complex area, or double the area if bsd_normalise is True.

Note: If the curve is given by a global minimal Weierstrass equation, then with bsd_normalise = True, this gives the correct period in the BSD conjecture: the product of this quantity over all embeddings appears in the BSD formula. In general a correction factor is required to make allowance for the model.

EXAMPLES:

```python
sage: E = EllipticCurve('37a')
sage: E.period_lattice().omega()
5.98691729246392
```

This is not a minimal model:

```python
sage: E = EllipticCurve([0,-432*6^2])
sage: E.period_lattice().omega()
0.486109385710056
```

If you were to plug the above omega into the BSD conjecture, you would get an incorrect value, out by a factor of 2. The following works though:

```python
sage: F = E.minimal_model()
sage: F.period_lattice().omega()
0.97221877120113
```

A complex example (taken from J.E.Cremona and E.Whitley, Periods of cusp forms and elliptic curves over imaginary quadratic fields, Mathematics of Computation 62 No. 205 (1994), 407-429). See trac ticket #29645 and trac ticket #29782:

```python
sage: K.<i> = QuadraticField(-1)
sage: E = EllipticCurve([0,1-i,i,-i,0])
sage: L = E.period_lattice(K.embeddings(CC)[0])
sage: L.omega()
8.80694160502647
```

`real_period(prec=None, algorithm='sage')`

Return the real period of this period lattice.

INPUT:

- prec (int or None (default)) – real precision in bits (default real precision if None)
• **algorithm** (string, default ‘sage’) – choice of implementation (for real embeddings only) between ‘sage’ (native Sage implementation) or ‘pari’ (use the PARI library: only available for real embeddings).

**Note:** Only defined for real lattices; a RuntimeError is raised for non-real lattices.

**EXAMPLES:**

```sage
E = EllipticCurve('37a')
E.period_lattice().real_period()
2.9934584623196
```

```sage
K.<a> = NumberField(x^3-2)
emb = K.embeddings(RealField())[0]
E = EllipticCurve([0,1,0,a,a])
L = E.period_lattice(emb)
L.real_period(64)
3.81452977217854509
```

**reduce**

Reduce a complex number modulo the lattice

**INPUT:**

- z (complex) – A complex number.

**OUTPUT:**

(complex) the reduction of z modulo the lattice, lying in the fundamental period parallelogram with respect to the lattice basis. For curves defined over the reals (i.e. real embeddings) the output will be real when possible.

**EXAMPLES:**

```sage
E = EllipticCurve('389a')
L = E.period_lattice()
w1, w2 = L.basis(prec=100)
P = E([-1,1])
L.reduce(zP = P.elliptic_logarithm(precision=100); zP
0.47934825019021931612953301006 + 0.98586885077582410221120384908*I
z = zP+10*w1-20*w2; 25.381473858740770069343110929 - 38.448885180257139986236950114*I
L.reduce(z)
0.47934825019021931612953301006 + 0.98586885077582410221120384908*I
L.elliptic_logarithm(2*P)
0.958696500380439
L.reduce(L.elliptic_logarithm(2*P))
0.958696500380439
L.reduce(L.elliptic_logarithm(2*P)+10*w1-20*w2)
0.958696500380444
```

**sigma**

Return the value of the Weierstrass sigma function for this elliptic curve period lattice.

**INPUT:**

- z – a complex number
• **prec** *(default: None)* – **real precision in bits** *(default real precision if None).*

• **flag** –

  0: (default) ???

  1: computes an arbitrary determination of \( \log(\sigma(z)) \)

  2, 3: same using the product expansion instead of theta series. ???

**Note:** The reason for the ???’s above, is that the PARI documentation for ellsigma is very vague. Also this is only implemented for curves defined over \( \mathbb{Q} \).

**Todo:** This function does not use any of the PeriodLattice functions and so should be moved to ell_rational_field.

**EXAMPLES:**

```python
sage: EllipticCurve('389a1').period_lattice().sigma(CC(2,1))
2.60912163570108 - 0.200865080824587*I
```

```python
tau(prec=None, algorithm='sage')
```

Return the upper half-plane parameter in the fundamental region.

**INPUT:**

• **prec** *(default: None)* – precision in bits (default precision if None).

• **algorithm** *(string, default ‘sage’)* – choice of implementation (for real embeddings only) between ‘sage’ (native Sage implementation) or ‘pari’ (use the PARI library: only available for real embeddings).

**OUTPUT:**

*(Complex)* \( \tau = \omega_1/\omega_2 \) where the lattice has the form \( \mathbb{Z}\omega_1 + \mathbb{Z}\omega_2 \), normalised so that \( \tau = \omega_1/\omega_2 \) is in the fundamental region of the upper half-plane.

**EXAMPLES:**

```python
sage: E = EllipticCurve('37a1')
sage: L = E.period_lattice()
sage: L.tau()
1.22112736076463*I
```

```python
sage: K.<a> = NumberField(x^3-2)
sage: emb = K.embeddings(RealField())[0]
sage: E = EllipticCurve([0,1,0,a,a])
sage: L = E.period_lattice(emb)
sage: tau = L.tau(); tau
-0.338718341018919 + 0.940887817679340*I
sage: tau.abs()
1.00000000000000
sage: -0.5 <= tau.real() <= 0.5
True
```

(continues on next page)
sage: L = E.period_lattice(emb)
sage: tau = L.tau(); tau
0.387694505032876 + 1.30821088214407*I
sage: tau.abs()
1.36444961115933
sage: -0.5 <= tau.real() <= 0.5
True

sage.schemes.elliptic_curves.period_lattice.
extended_agm_iteration(a, b, c)
Internal function for the extended AGM used in elliptic logarithm computation. INPUT:
• a, b, c (real or complex) – three real or complex numbers.
OUTPUT:
(3-tuple) \((a_0, b_0, c_0)\), the limit of the iteration \((a, b, c) \mapsto ((a + b)/2, \sqrt{ab}, (c + \sqrt{c^2 + b^2 - a^2}))/2\).
EXAMPLES:

sage: from sage.schemes.elliptic_curves.period_lattice import extended_agm_iteration
sage: extended_agm_iteration(RR(1), RR(2), RR(3))
(1.45679103104691, 1.45679103104691, 3.21245294970054)
sage: extended_agm_iteration(CC(1,2), CC(2,3), CC(3,4))
(1.46242448156430 + 2.47791311676267*I, 1.46242448156430 + 2.47791311676267*I, 3.22202144343535 + 4.28383734262540*I)

sage.schemes.elliptic_curves.period_lattice.
normalise_periods(w1, w2)
Normalise the period basis \((w_1, w_2)\) so that \(w_1/w_2\) is in the fundamental region.
INPUT:
• w1, w2 (complex) – two complex numbers with non-real ratio
OUTPUT:
(tuple) \(((\omega_1', \omega_2'), [a, b, c, d])\) where \(a, b, c, d\) are integers such that
• \(ad - bc = \pm 1\);
• \((\omega_1', \omega_2') = (a\omega_1 + b\omega_2, c\omega_1 + d\omega_2)\);
• \(\tau = \omega_1'/\omega_2'\) is in the upper half plane;
• \(|\tau| \geq 1\) and \(|\Re(\tau)| \leq 1/2\).
EXAMPLES:

sage: from sage.schemes.elliptic_curves.period_lattice import reduce_tau, normalise_periods
sage: w1 = CC(1.234, 3.456)
sage: w2 = CC(1.234, 3.4560000000000001)
# in lower half plane!
0.999999999743367 - 9.16334785827644e-11*I
sage: w1/w2, abcd = normalise_periods(w1, w2)
sage: a,b,c,d = abcd
sage: w1w2 == (a*w1+b*w2, c*w1+d*w2)
True
sage: w1w2[0]/w1w2[1]
Elliptic curves, Release 9.7

sage: a*d-b*c # note change of orientation
-1

sage.schemes.elliptic_curves.period_lattice.reduce_tau(tau)

Transform a point in the upper half plane to the fundamental region.

INPUT:

• tau (complex) – a complex number with positive imaginary part

OUTPUT:

(tuple) \((\tau', [a, b, c, d])\) where \(a, b, c, d\) are integers such that

• \(ad - bc = 1\);
• \(\tau\);
• \(|\tau'| \geq 1\);
• \(|\Re(\tau')| \leq \frac{1}{2}\).

EXAMPLES:

sage: from sage.schemes.elliptic_curves.period_lattice import reduce_tau
sage: reduce_tau(CC(1.23, 3.45))
(0.230000000000000 + 3.45000000000000*I, [1, -1, 0, 1])

sage: reduce_tau(CC(1.23, 0.0345))
(-0.463960069171512 + 1.35591888067914*I, [-5, 6, 4, -5])

14.18 Regions in fundamental domains of period lattices

This module is used to represent sub-regions of a fundamental parallelogram of the period lattice of an elliptic curve, used in computing minimum height bounds.

In particular, these are the approximating sets \(S^{(v)}\) in section 3.2 of Thotsaphon Thongjunthug’s Ph.D. Thesis and paper [Tho2010].

AUTHORS:

• Robert Bradshaw (2010): initial version
• John Cremona (2014): added some docstrings and doctests

class sage.schemes.elliptic_curves.period_lattice_region.PeriodicRegion

Bases: object

EXAMPLES:

sage: import numpy as np
sage: from sage.schemes.elliptic_curves.period_lattice_region import PeriodicRegion
sage: S = PeriodicRegion(CDF(2), CDF(2*I), np.zeros((4, 4)))
sage: S.plot()
Graphics object consisting of 1 graphics primitive

sage: data = np.zeros((4, 4))
sage: data[1,1] = True
sage: S = PeriodicRegion(CDF(2), CDF(2*I+1), data)

sage: S.plot()
Graphics object consisting of 5 graphics primitives

**border**(raw=True)

Returns the boundary of this region as set of tile boundaries.

If raw is true, returns a list with respect to the internal bitmap, otherwise returns complex intervals covering the border.

**EXAMPLES:**

```python
sage: import numpy as np
sage: from sage.schemes.elliptic_curves.period_lattice_region import PeriodicRegion
sage: data = np.zeros((4, 4))
sage: data[1, 1] = True
sage: PeriodicRegion(CDF(1), CDF(I), data).border()
[(1, 1, 0), (2, 1, 0), (1, 1, 1), (1, 2, 1)]

sage: PeriodicRegion(CDF(2), CDF(I-1/2), data).border()
[(1, 1, 0), (2, 1, 0), (1, 1, 1), (1, 2, 1)]

sage: PeriodicRegion(CDF(1), CDF(I), data).border(raw=False)
[0.25000000000000000 + 1.0000000000000000*I,
 0.62500000000000000 + 1.0000000000000000*I,
 0.87500000000000000 + 1.0000000000000000*I,
 1.0000000000000000 + 0.00000000000000000*I]

sage: PeriodicRegion(CDF(2), CDF(I-1/2), data).border(raw=False)
[0.37500000000000000 + 1.0000000000000000*I,
 0.87500000000000000 + 1.0000000000000000*I,
 0.87500000000000000 + 0.00000000000000000*I,
 1.0000000000000000 + 0.00000000000000000*I]

sage: data[1:3, 2] = True
sage: PeriodicRegion(CDF(1), CDF(I), data).border()
[(1, 1, 0), (2, 1, 0), (1, 1, 1), (1, 2, 0), (1, 3, 1), (3, 2, 0), (2, 2, 1), (2, 3, 1)]
```

**contract**(corners=True)

Opposite (but not inverse) of expand; removes neighbors of complement.

**EXAMPLES:**

```python
sage: import numpy as np
sage: from sage.schemes.elliptic_curves.period_lattice_region import PeriodicRegion
sage: data = np.zeros((10, 10))
sage: S = PeriodicRegion(CDF(1), CDF(I + 1/2), data)
```

(continues on next page)
Elliptic curves, Release 9.7

sage: S.contract().data.sum()
1
sage: S.contract().contract().is_empty()
True

data
ds()
Returns the sides of each parallelogram tile.

EXAMPLES:

sage: import numpy as np
sage: from sage.schemes.elliptic_curves.period_lattice_region import PeriodicRegion
sage: data = np.zeros((4, 4))
sage: S = PeriodicRegion(CDF(2), CDF(2*I), data, full=False)
sage: S.ds()
(0.5, 0.25*I)
sage: _ = S._ensure_full()
sage: S.ds()
(0.5, 0.25*I)
sage: data = np.zeros((8, 8))
sage: S = PeriodicRegion(CDF(1), CDF(I + 1/2), data)
sage: S.ds()
(0.125, 0.0625 + 0.125*I)

expand(corners=True)
Returns a region containing this region by adding all neighbors of internal tiles.

EXAMPLES:

sage: import numpy as np
sage: from sage.schemes.elliptic_curves.period_lattice_region import PeriodicRegion
sage: data = np.zeros((4, 4))
sage: data[1,1] = True
sage: S = PeriodicRegion(CDF(1), CDF(I + 1/2), data)
sage: S.plot()
Graphics object consisting of 5 graphics primitives
sage: S.expand().plot()
Graphics object consisting of 13 graphics primitives
sage: S.expand().data
array([[1, 1, 1, 0],
       [1, 1, 1, 0],
       [1, 1, 1, 0],
       [0, 0, 0, 0]], dtype=int8)
sage: S.expand(corners=False).plot()
Graphics object consisting of 13 graphics primitives
sage: S.expand(corners=False).data
array([[0, 1, 0, 0],
       [1, 1, 1, 0],
       [0, 1, 0, 0],
       [0, 0, 0, 0]], dtype=int8)
full

innermost_point()
Returns a point well inside the region, specifically the center of (one of) the last tile(s) to be removed on contraction.

EXAMPLES:

```
sage: import numpy as np
sage: from sage.schemes.elliptic_curves.period_lattice_region import PeriodicRegion
sage: data = np.zeros((10, 10))
sage: data[1, 0:8] = True
sage: S = PeriodicRegion(CDF(1), CDF(I+1/2), data)
sage: S.innermost_point()
0.375 + 0.25*I
```

is_empty()
Returns whether this region is empty.

EXAMPLES:

```
sage: import numpy as np
sage: from sage.schemes.elliptic_curves.period_lattice_region import PeriodicRegion
sage: data = np.zeros((4, 4))
sage: PeriodicRegion(CDF(2), CDF(2*I), data).is_empty()
True
sage: data[1,1] = True
sage: PeriodicRegion(CDF(2), CDF(2*I), data).is_empty()
False
```

plot(**kwds)
Plots this region in the fundamental lattice. If full is False plots only the lower half. Note that the true nature of this region is periodic.

EXAMPLES:

```
sage: import numpy as np
sage: from sage.schemes.elliptic_curves.period_lattice_region import PeriodicRegion
sage: data = np.zeros((10, 10))
sage: data[2, 2:8] = True
sage: data[2:5, 2] = True
sage: data[3, 3] = True
sage: S = PeriodicRegion(CDF(1), CDF(I + 1/2), data)
sage: plot(S) + plot(S.expand(), rgbcolor=(1, 0, 1), thickness=2)
```

Graphics object consisting of 24 graphics primitives
**refine** *(condition=None, times=1)*

Recursive function to refine the current tiling.

**INPUT:**

- `condition` (function, default None) – if not None, only keep tiles in the refinement which satisfy the condition.
- `times` (int, default 1) – the number of times to refine; each refinement step halves the mesh size.

**OUTPUT:**

The refined PeriodicRegion.

**EXAMPLES:**

```python
sage: import numpy as np
sage: from sage.schemes.elliptic_curves.period_lattice_region import PeriodicRegion
sage: data = np.zeros((4, 4))
sage: S = PeriodicRegion(CDF(2), CDF(2*I), data, full=False)
sage: S.ds()
(0.5, 0.25*I)
```

```python
sage: S = S.refine()
```

```python
sage: S.ds()
(0.25, 0.125*I)
```

```python
sage: S = S.refine(2)
```

```python
sage: S.ds()
(0.125, 0.0625*I)
```

**verify** *(condition)*

Given a condition that should hold for every line segment on the boundary, verify that it actually does so.

**INPUT:**

- `condition` (function) – a boolean-valued function on $\mathbb{C}$.

**OUTPUT:**

True or False according to whether the condition holds for all lines on the boundary.

**EXAMPLES:**

```python
sage: import numpy as np
sage: from sage.schemes.elliptic_curves.period_lattice_region import PeriodicRegion
sage: data = np.zeros((4, 4))
```

```python
sage: data[1, 1] = True
```

```python
sage: S = PeriodicRegion(CDF(1), CDF(I), data)
```

```python
sage: S.border()
[(1, 1, 0), (2, 1, 0), (1, 1, 1), (1, 2, 1)]
```

```python
sage: condition = lambda z: z.real().abs()<1/2
```

```python
sage: S.verify(condition)
False
```

```python
sage: condition = lambda z: z.real().abs()<1
```

```python
sage: S.verify(condition)
True
```
14.19 Modular parametrization of elliptic curves over \( \mathbb{Q} \)

By the work of Taylor–Wiles et al. it is known that there is a surjective morphism

\[
\phi_E : X_0(N) \to E.
\]

from the modular curve \( X_0(N) \), where \( N \) is the conductor of \( E \). The map sends the cusp \( \infty \) to the origin of \( E \).

**EXAMPLES:**

```
sage: phi = EllipticCurve('11a1').modular_parametrization()
sage: phi
Modular parameterization from the upper half plane to Elliptic Curve defined by y^2 + y = x^3 - x^2 - 10*x - 20 over Rational Field
sage: phi(0.5+CDF(I))
(285684.320516... + 7.0...e-11*I : 1.526964169...e8 + 5.6...e-8*I : 1.00000000000000)
sage: phi.power_series(prec = 7)
(q^-2 + 2*q^-1 + 4 + 5*q + 8*q^2 + q^3 + 7*q^4 + O(q^5), -q^-3 - 3*q^-2 - 7*q^-1 - 13 - 17*q - 26*q^2 - 19*q^3 + O(q^4))
```

**AUTHORS:**

- Chris Wuthrich (02/10): moved from ell_rational_field.py.

**class** `sage.schemes.elliptic_curves.modular_parametrization.ModularParameterization(E)`

Bases: `object`

This class represents the modular parametrization of an elliptic curve

\[
\phi_E : X_0(N) \to E.
\]

Evaluation is done by passing through the lattice representation of \( E \).

**EXAMPLES:**

```
sage: phi = EllipticCurve('11a1').modular_parametrization()
sage: phi
Modular parameterization from the upper half plane to Elliptic Curve defined by y^2 + y = x^3 - x^2 - 10*x - 20 over Rational Field
```

**curve()**

Return the curve associated to this modular parametrization.

**EXAMPLES:**

```
sage: E = EllipticCurve('15a')
sage: phi = E.modular_parametrization()
sage: phi.curve() is E
True
```

**map_to_complex_numbers(z, prec=None)**

Evaluate `self` at a point \( z \in X_0(N) \) where \( z \) is given by a representative in the upper half plane, returning a point in the complex numbers.
All computations are done with \texttt{prec} bits of precision. If \texttt{prec} is not given, use the precision of \texttt{z}. Use \texttt{self(z)} to compute the image of \texttt{z} on the Weierstrass equation of the curve.

**EXAMPLES:**

\begin{verbatim}
sage: E = EllipticCurve('37a'); phi = E.modular_parametrization()
sage: tau = (sqrt(7)*I - 17)/74
sage: z = phi.map_to_complex_numbers(tau); z
0.929592715285395 - 1.22569469099340*I
sage: E.elliptic_exponential(z)
(...e-16 - ...e-16*I : ...e-16 + ...e-16*I : 1.00000000000000)
sage: phi(tau)
(...e-16 - ...e-16*I : ...e-16 + ...e-16*I : 1.00000000000000)
\end{verbatim}

\textbf{power_series}(\texttt{prec=20})

Return the power series of this modular parametrization.

The curve must be a minimal model. The \texttt{prec} parameter determines the number of significant terms. This means that \texttt{X} will be given up to \text{O}(q^{\texttt{prec}-2}) and \texttt{Y} will be given up to \text{O}(q^{\texttt{prec}-3}).

**OUTPUT:** A list of two Laurent series \((X(x), Y(x))\) of degrees -2, -3 respectively, which satisfy the equation of the elliptic curve. There are modular functions on \(\Gamma_0(N)\) where \(N\) is the conductor.

The series should satisfy the differential equation

\[
\frac{dX}{2Y + a_1 X + a_3} = \frac{f(q) dq}{q}
\]

where \(f\) is \texttt{self.curve().q_expansion()}.

**EXAMPLES:**

\begin{verbatim}
sage: E = EllipticCurve('389a1')
sage: phi = E.modular_parametrization()
sage: X,Y = phi.power_series(prec=10)
sage: X
q^-2 + 2*q^-1 + 4 + 7*q + 13*q^2 + 18*q^3 + 31*q^4 + 49*q^5 + 74*q^6 + 111*q^7 + \cdots + O(q^8)
sage: Y
-q^-3 - 3*q^-2 - 8*q^-1 - 17 - 33*q - 61*q^2 - 110*q^3 - 186*q^4 - 320*q^5 - \cdots - 528*q^6 + O(q^7)
sage: X,Y = phi.power_series()
sage: X
q^-2 + 2*q^-1 + 4 + 7*q + 13*q^2 + 18*q^3 + 31*q^4 + 49*q^5 + 74*q^6 + 111*q^7 + \cdots + 2548*q^15 + 3722*q^16 + 5374*q^17 + O(q^18)
sage: Y
-q^-3 - 3*q^-2 - 8*q^-1 - 17 - 33*q - 61*q^2 - 110*q^3 - 186*q^4 - 320*q^5 + \cdots + 528*q^6 - 861*q^7 - 1383*q^8 - 2218*q^9 - 3472*q^10 - 5451*q^11 - 8447*q^12 - \cdots - 13020*q^13 + 19923*q^14 + 30403*q^15 + 46003*q^16 + O(q^17)
\end{verbatim}

The following should give 0, but only approximately:

\begin{verbatim}
sage: q = X.parent().gen()
sage: E.defining_polynomial()(X,Y,1) + O(q^11) == 0
True
\end{verbatim}

Note that below we have to change variable from \(x\) to \(q\):
Elliptic curves, Release 9.7

```
sage: a1,_,a3,_,_ = E.a_invariants()
sage: f = E.q_expansion(17)
sage: q = f.parent().gen()
sage: f/q == (X.derivative()/(2*Y+a1*X+a3))
True
```

14.20 Modular symbols attached to elliptic curves over $\mathbb{Q}$

To an elliptic curve $E$ over the rational numbers with conductor $N$, one can associate a space of modular symbols of level $N$, because $E$ is known to be modular. The space is two-dimensional and contains a subspace on which complex conjugation acts as multiplication by $+1$ and one on which it acts by $-1$.

There are three implementations of modular symbols, two within Sage and one in Cremona’s eclib library. One can choose here which one is used.

Associated to $E$ there is a canonical generator in each space. They are maps $[.]^+$ and $[.]^-$, both $\mathbb{Q} \to \mathbb{Q}$. They are normalized such that

$$[r]^+\Omega^+ + [r]^\Omega^- = \int_\infty^r 2\pi i f(z) \, dz$$

where $f$ is the newform associated to the isogeny class of $E$ and $\Omega^+$ is the smallest positive period of the Néron differential of $E$ and $\Omega^-$ is the smallest positive purely imaginary period. Note that it depends on $E$ rather than on its isogeny class.

From eclib version v20161230, both plus and minus symbols are available and are correctly normalized. In the Sage implementation, the computation of the space provides initial generators which are not necessarily correctly normalized; here we implement two methods that try to find the correct scaling factor.

Modular symbols are used to compute $p$-adic $L$-functions.

EXAMPLES:

```
sage: E = EllipticCurve("19a1")
sage: m = E.modular_symbol()
sage: m(0)
1/3
sage: m(1/17)
-2/3
sage: m2 = E.modular_symbol(-1, implementation="sage")
sage: m2(0)
0
sage: m2(1/5)
1/2
sage: V = E.modular_symbol_space()
sage: V
Modular Symbols subspace of dimension 1 of Modular Symbols space of dimension 2 for \Gamma_0(19) of weight 2 with sign 1 over Rational Field
sage: V.q_eigenform(30)
q - 2*q^3 - 2*q^4 + 3*q^5 - q^7 + q^9 + 3*q^11 + 4*q^12 - 4*q^13 - 6*q^15 + 4*q^16 - 3*q^17 + q^19 - 6*q^20 + 2*q^21 + 4*q^23 + 4*q^27 + 2*q^28 + 6*q^29 + O(q^30)
```

For more details on modular symbols consult the following

REFERENCES:
AUTHORS:

- Chris Wuthrich (2008): add scaling and reference to eclib
- John Cremona (2016): reworked eclib interface

class sage.schemes.elliptic_curves.ell_modular_symbols.ModularSymbol
Bases: sage.structure.sage_object.SageObject

A modular symbol attached to an elliptic curve, which is the map \( \mathbb{Q} \to \mathbb{Q} \) obtained by sending \( r \) to the normalized symmetrized (or anti-symmetrized) integral \( \infty \) to \( r \).

This is as defined in [MTT1986], but normalized to depend on the curve and not only its isogeny class as in [SW2013].

See the documentation of \( E\text{.modular_symbol()} \) in elliptic curves over the rational numbers for help.

\textbf{base_ring()}

Return the base ring for this modular symbol.

**EXAMPLES:**

```python
sage: m = EllipticCurve('11a1').modular_symbol()
sage: m.base_ring()
Rational Field
```

\textbf{elliptic_curve()}

Return the elliptic curve of this modular symbol.

**EXAMPLES:**

```python
sage: m = EllipticCurve('11a1').modular_symbol()
sage: m.elliptic_curve()
Elliptic Curve defined by y^2 + y = x^3 - x^2 - 10*x - 20 over Rational Field
```

\textbf{sign()}

Return the sign of this elliptic curve modular symbol.

**EXAMPLES:**

```python
sage: m = EllipticCurve('11a1').modular_symbol()
sage: m.sign()
1
sage: m = EllipticCurve('11a1').modular_symbol(sign=-1, implementation="sage")
sage: m.sign()
-1
```

\textbf{class} sage.schemes.elliptic_curves.ell_modular_symbols.ModularSymbolECLIB\( (E, \text{sign, nap}=1000) \)
Bases: sage.schemes.elliptic_curves.ell_modular_symbols.ModularSymbol

Modular symbols attached to \( E \) using eclib.

Note that the normalization used within eclib differs from the normalization chosen here by a factor of 2 in the case of elliptic curves with negative discriminant (with one real component) since the convention there is to
Elliptic curves, Release 9.7

write the above integral as \([r]^+=x + [r]^y i\), where the lattice is \((2x, x + yi)\), so that \(\Omega^+ = 2x\) and \(\Omega^- = 2yi\). We allow for this below.

INPUT:

- E – an elliptic curve
- sign – an integer, -1 or 1
- nap – (int, default 1000): the number of ap of E to use in determining the normalisation of the modular symbols.

EXAMPLES:

```python
sage: import sage.schemes.elliptic_curves.ell_modular_symbols
sage: E = EllipticCurve('11a1')
sage: M = sage.schemes.elliptic_curves.ell_modular_symbols.ModularSymbolECLIB(E,+1)
sage: M
Modular symbol with sign 1 over Rational Field attached to Elliptic Curve defined by y^2 + y = x^3 - x^2 - 10*x - 20 over Rational Field
sage: M(0)
1/5
sage: E = EllipticCurve('11a2')
sage: M = sage.schemes.elliptic_curves.ell_modular_symbols.ModularSymbolECLIB(E,+1)
sage: M(0)
1
```

This is a rank 1 case with vanishing positive twists:

```python
sage: E = EllipticCurve('121b1')
sage: M = sage.schemes.elliptic_curves.ell_modular_symbols.ModularSymbolECLIB(E,+1)
sage: M(0)
0
sage: M(1/7)
1/2
```

```python
sage: E = EllipticCurve('121d1').modular_symbol(implementation="eclib")
```

```python
sage: M(0)
2
```

```python
sage: E = EllipticCurve('15a1')
```

```python
sage: [C.modular_symbol(implementation="eclib") for C in E.isogeny_class()]
[1/4, 1/8, 1/4, 1/2, 1/8, 1/16, 1/2, 1]
```

Since trac ticket #10256, the interface for negative modular symbols in eclib is available:

```python
sage: E = EllipticCurve('11a1')
```

```python
sage: Mplus = E.modular_symbol(+1); Mplus
```

```python
sage: [Mplus(1/i) for i in [1..11]]
[1/5, -4/5, -3/10, 7/10, 6/5, 6/5, 7/10, -3/10, -4/5, 1/5, 0]
```

```python
sage: Mminus = E.modular_symbol(-1); Mminus
```

```python
sage: [Mminus(1/i) for i in [1..11]]
[0, 0, 1/2, 1/2, 0, 0, -1/2, -1/2, 0, 0, 0]
```

486 Chapter 14. Elliptic curves over number fields
The scaling factor relative to eclib’s normalization is 1/2 for curves of negative discriminant:

```python
sage: [E.discriminant() for E in cremona_curves([14])]
[-21952, 941192, -1835008, -28, 25088, 98]
sage: [E.modular_symbol()._scaling for E in cremona_curves([14])]
[1/2, 1, 1/2, 1/2, 1, 1]
```

TESTS (for trac ticket #10236):

```python
sage: E = EllipticCurve('11a1')
sage: m = E.modular_symbol(implementation="eclib")
sage: m(1/7)
7/10
sage: m(0)
1/5
```

If nap is too small, the normalization in eclib used to be incorrect (see trac ticket #31317), but since eclib version v20210310 the value of nap is increased automatically by eclib:

```python
sage: from sage.schemes.elliptic_curves.ell_modular_symbols import ModularSymbolECLIB
sage: E = EllipticCurve('1590g1')
sage: m = ModularSymbolECLIB(E, sign=+1, nap=300)
sage: [m(a/5) for a in [1..4]]
[13/2, -13/2, -13/2, 13/2]
```

These values are correct, and increasing nap has no effect. The correct values may verified by the numerical implementation:

```python
sage: m = ModularSymbolECLIB(E, sign=+1, nap=400)
sage: [m(a/5) for a in [1..4]]
[13/2, -13/2, -13/2, 13/2]
sage: m = E.modular_symbol(implementation='num')
sage: [m(a/5) for a in [1..4]]
[13/2, -13/2, -13/2, 13/2]
```

```
class sage.schemes.elliptic_curves.ell_modular_symbols.ModularSymbolSage(E, sign, normalize='L_ratio')
Bases: sage.schemes.elliptic_curves.ell_modular_symbols.ModularSymbol

Modular symbols attached to E using sage.

INPUT:

- E – an elliptic curve
- sign – an integer, -1 or 1
- normalize – either ‘L_ratio’ (default), ‘period’, or ‘none’; For ‘L_ratio’, the modular symbol is correctly normalized by comparing it to the quotient of L(E, 1) by the least positive period for the curve and some small twists. The normalization ‘period’ uses the integral_period_map for modular symbols and is known to be equal to the above normalization up to the sign and a possible power of 2. For ‘none’, the modular symbol is almost certainly not correctly normalized, i.e. all values will be a fixed scalar multiple of what they should be. But the initial computation of the modular symbol is much faster, though evaluation of it after computing it won’t be any faster.

EXAMPLES:
```

14.20. Modular symbols attached to elliptic curves over Q 487
sage: E = EllipticCurve('11a1')
sage: import sage.schemes.elliptic_curves.ell_modular_symbols
sage: M = sage.schemes.elliptic_curves.ell_modular_symbols.ModularSymbolSage(E,+1)
sage: M
Modular symbol with sign 1 over Rational Field attached to Elliptic Curve defined by y^2 + y = x^3 - x^2 - 10*x - 20 over Rational Field
sage: M(0)
1/5
sage: E = EllipticCurve('11a2')
sage: M = sage.schemes.elliptic_curves.ell_modular_symbols.ModularSymbolSage(E,+1)
sage: M(0)
1
sage: M = sage.schemes.elliptic_curves.ell_modular_symbols.ModularSymbolSage(E,-1)
sage: M(1/3)
1/2

This is a rank 1 case with vanishing positive twists. The modular symbol is adjusted by -2:

sage: E = EllipticCurve('121b1')
sage: M = sage.schemes.elliptic_curves.ell_modular_symbols.ModularSymbolSage(E,-1, normalize='L_ratio')
sage: M(1/3)
1
sage: M._scaling
1
sage: M = EllipticCurve('121d1').modular_symbol(implementation="sage")
sage: M(0)
2
sage: M = EllipticCurve('121d1').modular_symbol(implementation="sage", normalize='none')
sage: M(0)
1
sage: E = EllipticCurve('15a1')
sage: [C.modular_symbol(implementation="sage", normalize='L_ratio')(0) for C in E.isogeny_class()]
[1/4, 1/8, 1/4, 1/2, 1/8, 1/16, 1/2, 1]
sage: [C.modular_symbol(implementation="sage", normalize='period')(0) for C in E.isogeny_class()]
[1/8, 1/16, 1/8, 1/4, 1/16, 1/32, 1/4, 1/2]
sage: [C.modular_symbol(implementation="sage", normalize='none')(0) for C in E.isogeny_class()]
[1, 1, 1, 1, 1, 1, 1, 1]

sage.schemes.elliptic_curves.ell_modular_symbols.modular_symbol_space(E, sign, base_ring, bound=None)

Creates the space of modular symbols of a given sign over a give base_ring, attached to the isogeny class of the elliptic curve E.

INPUT:

- E – an elliptic curve over Q
- sign – integer, -1, 0, or 1
• **base_ring** – ring
  
• **bound** – (default: None) maximum number of Hecke operators to use to cut out modular symbols factor. If None, use enough to provably get the correct answer.

**OUTPUT:** a space of modular symbols

**EXAMPLES:**

```python
sage: import sage.schemes.elliptic_curves.ell_modular_symbols
sage: E = EllipticCurve('11a1')

sage: M = sage.schemes.elliptic_curves.ell_modular_symbols.modular_symbol_space(E,-1,GF(37))

sage: M
Modular Symbols space of dimension 1 for Gamma_0(11) of weight 2 with sign -1 over Finite Field of size 37
```

## 14.21 Modular symbols by numerical integration

We describe here the method for computing modular symbols by numerical approximations of the integral of the modular form on a path between cusps.

More precisely, let $E$ be an elliptic curve and $f$ the newform associated to the isogeny class of $E$. If

$$
\lambda(r \to r') = 2\pi i \int_r^{r'} f(\tau) d\tau
$$

then the modular symbol $[r]^+$ is defined as the quotient of the real part of $\lambda(\infty \to r)$ by the least positive real period of $E$. Similarly for the negative modular symbol, it is the quotient of the imaginary part of the above by the smallest positive imaginary part of a period on the imaginary axis.

The theorem of Manin-Drinfeld shows that the modular symbols are rational numbers with small denominator. They are used for the computation of special values of the L-function of $E$ twisted by Dirichlet characters and for the computation of $p$-adic L-functions.

**ALGORITHM:**

The implementation of modular symbols in eclib and directly in sage uses the algorithm described in Cremona’s book [Cre1997] and Stein’s book [St2007]. First the space of all modular symbols of the given level is computed, then the space corresponding to the given newform is determined. Even if these initial steps may take a while, the evaluation afterwards is instantaneous. All computations are done with rational numbers and hence are exact.

Instead the method used here (see [Wu2018] for details) is by evaluating the above integrals $\lambda(r \to r')$ by numerical approximation. Since we know precise bounds on the denominator, we can make rigorous estimates on the error to guarantee that the result is proven to be the correct rational number.

The paths over which we integrate are split up and Atkin-Lehner operators are used to compute the badly converging part of the integrals by using the Fourier expansion at other cusps than $\infty$.

**Note:** There is one assumption for the correctness of these computations: The Manin constant for the $X_0$-optimal curve should be 1 if the curve lies outside the Cremona tables. This is known for all curves in the Cremona table, but only conjectured for general curves.

**EXAMPLES:**

The most likely usage for the code is through the functions `modular_symbol` with implementation set to “num” and through `modular_symbol_numerical`:
In more details. A numerical modular symbols $M$ is created from an elliptic curve with a chosen sign (though the other sign will also be accessible, too):

```python
sage: E = EllipticCurve([101,103])
sage: E.conductor()
35261176
sage: M = E.modular_symbol(implementation="num", sign=-1)
sage: M
Numerical modular symbol attached to Elliptic Curve defined by y^2 = x^3 + 101*x + 103 over Rational Field
```

We can then compute the value $[13/17]^{-}$ and $[1/17]^{+}$ by calling the function $M$. The value of $[0]^{+} = 0$ tells us that the rank of this curve is positive:

```python
sage: M(13/17)
-1/2
sage: M(1/17,sign=+1)
-3
sage: M(0, sign=+1)
0
```

One can compute the numerical approximation to these rational numbers to any proven binary precision:

```python
sage: M.approximative_value(13/17, prec=2) #abs tol 1e-4
-0.500003172770455
sage: M.approximative_value(13/17, prec=4) #abs tol 1e-6
-0.50000296037388
sage: M.approximative_value(0, sign=+1, prec=6) #abs tol 1e-8
0.000000000000000
```

There are a few other things that one can do with $M$. The Manin symbol $M(c : d)$ for a point $(c : d)$ in the projective line can be computed:

```python
sage: M.manin_symbol(1,5)
-1
```

In some cases useful, there is a function that returns all $[a/m]^{+}$ for a fixed denominator $m$. This is rather quicker for small $m$ than computing them individually:

```python
sage: M.all_values_for_one_denominator(7)
{1/7: 0, 2/7: 3/2, 3/7: 3/2, 4/7: -3/2, 5/7: -3/2, 6/7: 0}
```

Finally a word of warning. The algorithm is fast when the cusps involved are unitary. If the curve is semistable, all cusps are unitary. But rational numbers with a prime $p$ dividing the denominator once, but the conductor more than
once, are very difficult. For instance for the above example, a seemingly harmless command like $M(1/2)$ would take a very very long time to return a value. However it is possible to compute them for smaller conductors:

```python
sage: E = EllipticCurve("664a1")
sage: M = E.modular_symbol(implementation="num")
sage: M(1/2)
0
```

The problem with non-unitary cusps is dealt with rather easily when one can twist to a semistable curve, like in this example:

```python
sage: C = EllipticCurve("11a1")
sage: E = C.quadratic_twist(101)
sage: M = E.modular_symbol(implementation="num")
sage: M(1/101)
41
```

AUTHORS:

• Chris Wuthrich (2013-16)

class sage.schemes.elliptic_curves.mod_sym_num.ModularSymbolNumerical
    Bases: object

This class assigning to an elliptic curve over $\mathbb{Q}$ a modular symbol. Unlike the other implementations this class does not precompute a basis for this space. Instead at each call, it evaluates the integral using numerical approximation. All bounds are very strictly implemented and the output is a correct proven rational number.

INPUT:

• $E$ – an elliptic curve over the rational numbers.
• $\text{sign}$ – either -1 or +1 (default). This sets the default value of $\text{sign}$ throughout the class. Both are still accessible.

OUTPUT: a modular symbol

EXAMPLES:

```python
sage: E = EllipticCurve("5077a1")
sage: M = E.modular_symbol(implementation="num")
sage: M(0)
0
sage: M(77/57)
-1
sage: M(33/37, -1)
2
sage: M = E.modular_symbol(sign=-1, implementation="num")
sage: M(2/7)
2
sage: from sage.schemes.elliptic_curves.mod_sym_num ...
    import ModularSymbolNumerical
sage: M = ModularSymbolNumerical(EllipticCurve("11a1"))
sage: M(1/3, -1)
1/2
sage: M(1/2)
-4/5
```
**all_values_for_one_denominator** \((m, \text{sign}=0)\)

Given an integer \(m\) and a sign, this returns the modular symbols \(\frac{a}{m}\) for all \(a\) coprime to \(m\) using partial sums. This is much quicker than computing them one by one.

This will only work if \(m\) is relatively small and if the cusps \(a/m\) are unitary.

**INPUT:**
- \(m\) – a natural number
- \(\text{sign}\) – optional either +1 or -1, or 0 (default), in which case the sign passed to the class is taken.

**OUTPUT:** a dictionary of fractions with denominator \(m\) giving rational numbers.

**EXAMPLES:**

```sage
E = EllipticCurve('5077a1')
M = E.modular_symbol(implementation="num")
M.all_values_for_one_denominator(7)
{1/7: 3, 2/7: 0, 3/7: -3, 4/7: -3, 5/7: 0, 6/7: 3}

M(M(a/7) for a in [1..6])
[3, 0, -3, -3, 0, 3]

M.all_values_for_one_denominator(3,-1)
{1/3: 4, 2/3: -4}
```

```sage
E = EllipticCurve('11a1')
M = E.modular_symbol(implementation="num")
M.all_values_for_one_denominator(12)
{1/12: 1/5, 5/12: -23/10, 7/12: -23/10, 11/12: 1/5}

M.all_values_for_one_denominator(12,-1)
{1/12: 0, 5/12: 1/2, 7/12: -1/2, 11/12: 0}
```

```sage
E = EllipticCurve('20a1')
M = E.modular_symbol(implementation="num")
M.all_values_for_one_denominator(4)
{1/4: 0, 3/4: 0}

M.all_values_for_one_denominator(8)
{1/8: 1/2, 3/8: -1/2, 5/8: -1/2, 7/8: 1/2}
```

**approximative_value** \((r, \text{sign}=0, \text{prec}=20, \text{use_twist}=\text{True})\)

The numerical modular symbol evaluated at rational.

It returns a real number, which should be equal to a rational number to the given binary precision \(\text{prec}\). In practice the precision is often much higher. See the examples below.

**INPUT:**
- \(r\) – a rational (or integer)
- \(\text{sign}\) – optional either +1 or -1, or 0 (default), in which case the sign passed to the class is taken.
- \(\text{prec}\) – an integer (default 20)
- \(\text{use_twist}\) – True (default) allows to use a quadratic twist of the curve to lower the conductor.

**OUTPUT:** a real number

**EXAMPLES:**

```sage
E = EllipticCurve('5077a1')
M = E.modular_symbol(implementation="num")
M.approximative_value(7)
```

```sage
E = EllipticCurve('11a1')
M = E.modular_symbol(implementation="num")
M.approximative_value(12)
```

```sage
E = EllipticCurve('20a1')
M = E.modular_symbol(implementation="num")
M.approximative_value(4)
```

```sage
E = EllipticCurve('20a1')
M = E.modular_symbol(implementation="num")
M.approximative_value(8)
```
sage: E = EllipticCurve("5077a1")
sage: M = E.modular_symbol(implementation="num")
sage: M.approximative_value(123/567) # abs tol 1e-11
-4.00000000000845
sage: M.approximative_value(123/567,prec=2) # abs tol 1e-9
-4.0002815242902

sage: E = EllipticCurve([11,88])
sage: E.conductor()
1715296
sage: M = E.modular_symbol(implementation="num")
sage: M.approximative_value(0,prec=2) # abs tol 1e-11
0.999981178147778
sage: M.approximative_value(1/7,prec=2) # abs tol 1e-11
0.999999972802649
sage: M.approximative_value(1/7,prec=10) # abs tol 1e-11
0.999999999999999

**clear_cache()**

Clear the cached values in all methods of this class

**elliptic_curve()**

Return the elliptic curve of this modular symbol.

**manin_symbol(u, v, sign=0)**

Given a pair \((u, v)\) presenting a point in \(\mathbb{P}^1(\mathbb{Z}/N\mathbb{Z})\) and hence a coset of \(\Gamma_0(N)\), this computes the value of the Manin symbol \(M(u : v)\).

**INPUT:**

- \(u\) – an integer
- \(v\) – an integer such that \((u : v)\) is a projective point modulo \(N\)
- \(sign\) – optional either +1 or -1, or 0 (default), in which case the sign passed to the class is taken.

**EXAMPLES:**
Elliptic curves, Release 9.7

\begin{verbatim}
sage: E = EllipticCurve('11a1')
sage: M = E.modular_symbol(implementation="num")
sage: M.manin_symbol(1,3)
-1/2
sage: M.manin_symbol(1,3, sign=-1)
-1/2
sage: M.manin_symbol(1,5)
1
sage: M.manin_symbol(1,5)
1

sage: E = EllipticCurve('14a1')
sage: M = E.modular_symbol(implementation="num")
sage: M.manin_symbol(1,2)
-1/2
sage: M.manin_symbol(17,6)
-1/2
sage: M.manin_symbol(-1,12)
-1/2

transportable_symbol(r, rr, sign=0)
Return the symbol \([r]' = [r] + \gamma([r])\) where \(r' = \gamma(r)\) for some \(\gamma \in \Gamma_0(N)\). These symbols can be computed by transporting the path into the upper half plane close to one of the unitary cusps. Here we have implemented it only to move close to \(i\infty\) and 0.

INPUT:
- \(r\) and \(rr\) – two rational numbers
- \(sign\) – optional either +1 or -1, or 0 (default), in which case the sign passed to the class is taken.

OUTPUT: a rational number

EXAMPLES:

\begin{verbatim}
sage: E = EllipticCurve("11a1")
sage: M = E.modular_symbol(implementation="num")
sage: M.transportable_symbol(0/1,-2/7)
-1/2

sage: E = EllipticCurve("37a1")
sage: M = E.modular_symbol(implementation="num")
sage: M.transportable_symbol(0/1,-1/19)
0
sage: M.transportable_symbol(0/1,-1/19,-1)
0

sage: E = EllipticCurve("5077a1")
sage: M = E.modular_symbol(implementation="num")
sage: M.transportable_symbol(0/1,-35/144)
-3
sage: M.transportable_symbol(0/1,-35/144,-1)
0
sage: M.transportable_symbol(0/1,-7/31798)
0
\end{verbatim}
\end{verbatim}

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Elliptic curves, Release 9.7

(continued from previous page)

```sage
M.transportable_symbol(0/1, -7/31798, -1)
-5
```

14.22 \(L\)-series for elliptic curves

AUTHORS:
- Simon Spicer (2014-08-15): Added \texttt{LFunctionZeroSum} class interface method
- William Stein et al. (2005 and later)

```python
class sage.schemes.elliptic_curves.lseries_ell.Lseries_ell(E):
    Bases: sage.structure.sage_object.SageObject

    An elliptic curve \(L\)-series.

    \texttt{L1\_vanishes()}
    Returns whether or not \(L(E, 1) = 0\). The result is provably correct if the Manin constant of the associated
    optimal quotient is \(\leq 2\). This hypothesis on the Manin constant is true for all curves of conductor \(\leq 40000\)
    (by Cremona) and all semistable curves (i.e., squarefree conductor).

    ALGORITHM: see \texttt{L\_ratio()}.  

    EXAMPLES:

```sage
sage: E = EllipticCurve([0, -1, 1, -10, -20])  # 11A = X_0(11)
sage: E.lseries().L1_vanishes()
False
sage: E = EllipticCurve([0, -1, 1, 0, 0])  # X_1(11)
sage: E.lseries().L1_vanishes()
False
sage: E = EllipticCurve([0, 0, 1, -1, 0])  # 37A (rank 1)
sage: E.lseries().L1_vanishes()
True
sage: E = EllipticCurve([0, 1, -1, -2, 0])  # 389A (rank 2)
sage: E.lseries().L1_vanishes()
True
sage: E = EllipticCurve([0, 0, 1, -38, 90])  # 361A (CM curve))
sage: E.lseries().L1_vanishes()
True
sage: E = EllipticCurve([0,-1,1,-2,-1])  # 141C (13-isogeny)
```


\texttt{L\_ratio()}

Return the ratio \(L(E, 1)/\Omega\) as an exact rational number.

The result is \textit{provably} correct if the Manin constant of the associated optimal quotient is \(\leq 2\). This hypothesis on the Manin constant is true for all semistable curves (i.e., squarefree conductor), by a theorem of Mazur from his \textit{Rational Isogenies of Prime Degree} paper.

EXAMPLES:
sage: E = EllipticCurve([0, -1, 1, -10, -20])  # 11A = X_0(11)
sage: E.lseries().L_ratio()
1/5

sage: E = EllipticCurve([0, -1, 1, 0, 0])  # X_1(11)
sage: E.lseries().L_ratio()
1/25

sage: E = EllipticCurve([0, 0, 1, -1, 0])  # 37A (rank 1)
sage: E.lseries().L_ratio()
0

sage: E = EllipticCurve([0, 1, 1, -2, 0])  # 389A (rank 2)
sage: E.lseries().L_ratio()
0

sage: E = EllipticCurve([0, 0, 1, -38, 90])  # 361A (CM curve))
sage: E.lseries().L_ratio()
0

sage: E = EllipticCurve([0, -1, 1, -2, -1])  # 141C (13-isogeny)
sage: E.lseries().L_ratio()
1

sage: E = EllipticCurve(RationalField(), [1, 0, 0, 1/24624, 1/886464])
sage: E.lseries().L_ratio()
2

See trac ticket #3651 and trac ticket #15299:

sage: EllipticCurve([0,0,0,-193^2,0]).sha().an()
4
sage: EllipticCurve([1, 0, 1, -131, 558]).sha().an()  # long time
1.00000000000000

ALGORITHM: Compute the root number. If it is -1 then $L(E, s)$ vanishes to odd order at 1, hence vanishes. If it is +1, use a result about modular symbols and Mazur's *Rational Isogenies* paper to determine a provably correct bound (assuming Manin constant is <= 2) so that we can determine whether $L(E, 1) = 0$.


\textbf{ati}(k=None, prec=None)

Compute $L(E, 1)$ using $k$ terms of the series for $L(E, 1)$ as explained in Section 7.5.3 of Henri Cohen's book *A Course in Computational Algebraic Number Theory*. If the argument $k$ is not specified, then it defaults to $\sqrt{N}$, where $N$ is the conductor.

**INPUT:**

* $k$ – number of terms of the series. If zero or None, use $k = \sqrt{N}$, where $N$ is the conductor.
* $\text{prec}$ – numerical precision in bits. If zero or None, use a reasonable automatic default.

**OUTPUT:**

A tuple of real numbers $(L, \text{err})$ where $L$ is an approximation for $L(E, 1)$ and $\text{err}$ is a bound on the error in the approximation.

This function is disjoint from the PARI \texttt{pari:ellseries} command, which is for a similar purpose. To use that command (via the PARI C library), simply type \texttt{E.pari_mincurve().elllseries(1)}.

**ALGORITHM:**

* Compute the root number \texttt{eps}. If it is -1, return 0.
* Compute the Fourier coefficients $a_n$, for $n$ up to and including $k$. 496 Chapter 14. Elliptic curves over number fields
• Compute the sum

\[ 2 \cdot \sum_{n=1}^{k} \frac{a_n}{n} \cdot \exp\left(-2 \pi i \cdot \frac{n}{\sqrt{N}} \right), \]

where \( N \) is the conductor of \( E \).

• Compute a bound on the tail end of the series, which is

\[ 2e^{-2\pi(k+1)/\sqrt{N}}/(1 - e^{-2\pi/\sqrt{N}}). \]

For a proof see [Grigov-Jorza-Patrascu-Patrikis-Stein].

EXAMPLES:

```python
sage: L, err = EllipticCurve('11a1').lseries().at1()
sage: L, err
(0.253804, 0.000181444)
sage: parent(L)
Real Field with 24 bits of precision
sage: E = EllipticCurve('37b')
sage: E.lseries().at1()
(0.7257177, 0.000800697)
sage: E.lseries().at1(100)
(0.725681061936152782336205410263965487367603361763, 1.52469e-45)
sage: L, err = E.lseries().at1(100, prec=128)
sage: L
0.7256810619361527823362054102639654873
sage: parent(L)
Real Field with 128 bits of precision
sage: err
1.70693e-37
sage: parent(err)
Real Field with 24 bits of precision and rounding RNDU
```

Rank 1 through 3 elliptic curves:

```python
sage: E = EllipticCurve('37a1')
sage: E.lseries().at1()
(0.000000, 0.000000)
sage: E = EllipticCurve('389a1')
sage: E.lseries().at1()
(-0.001769566, 0.00911776)
sage: E = EllipticCurve('5077a1')
sage: E.lseries().at1()
(0.000000, 0.000000)
```

\texttt{deriv\_at1}(k=None, prec=None)

Compute \( L'(E, 1) \) using \( k \) terms of the series for \( L'(E, 1) \), under the assumption that \( L(E, 1) = 0 \).

The algorithm used is from Section 7.5.3 of Henri Cohen’s book \textit{A Course in Computational Algebraic Number Theory}.

INPUT:

• \( k \) – number of terms of the series. If zero or \texttt{None}, use \( k = \sqrt{N} \), where \( N \) is the conductor.

• \( \texttt{prec} \) – numerical precision in bits. If zero or \texttt{None}, use a reasonable automatic default.
OUTPUT:
A tuple of real numbers \((L_1, \text{err})\) where \(L_1\) is an approximation for \(L'(E, 1)\) and \(\text{err}\) is a bound on the error in the approximation.

**Warning:** This function only makes sense if \(L(E)\) has positive order of vanishing at 1, or equivalently if \(L(E, 1) = 0\).

**ALGORITHM:**
- Compute the root number \(\epsilon\). If it is 1, return 0.
- Compute the Fourier coefficients \(a_n\), for \(n\) up to and including \(k\).
- Compute the sum
  \[
  2 \cdot \sum_{n=1}^{k} \left(\frac{a_n}{n}\right) \cdot E_1\left(2\pi n / \sqrt{N}\right),
  \]
  where \(N\) is the conductor of \(E\), and \(E_1\) is the exponential integral function.
- Compute a bound on the tail end of the series, which is
  \[
  2e^{-2\pi(k+1)/\sqrt{N}}/(1 - e^{-2\pi/\sqrt{N}}).
  \]

For a proof see [Grigorov-Jorza-Patrascu-Patrikis-Stein]. This is exactly the same as the bound for the approximation to \(L(E, 1)\) produced by \(at1()\).

**EXAMPLES:**

```sage
sage: E = EllipticCurve('37a')
sage: E.lseries().deriv_at1()
(0.3059866, 0.000801045)
sage: E.lseries().deriv_at1(100)
(0.3059997738340523018204836833216764744526377745903, 1.52493e-45)
sage: E.lseries().deriv_at1(1000)
(0.305999773834052301820483683321676474452637774590771998..., 2.75031e-449)
```

With less numerical precision, the error is bounded by numerical accuracy:

```sage
sage: L, err = E.lseries().deriv_at1(100, prec=64)
sage: L, err
(0.305999773834052302, 5.55318e-18)
sage: parent(L)
Real Field with 64 bits of precision
sage: parent(err)
Real Field with 24 bits of precision and rounding RNDU
```

Rank 2 and rank 3 elliptic curves:

```sage
sage: E = EllipticCurve('389a1')
sage: E.lseries().deriv_at1()
(0.0000000, 0.000000)
sage: E = EllipticCurve((1, 0, 1, -131, 558))  # curve 59450i1
sage: E.lseries().deriv_at1()
```

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Elliptic curves, Release 9.7

(continued from previous page)

(-0.00010911444, 0.142428)
sage: E.lseries().deriv_at1(4000)
(6.990...e-50, 1.31318e-43)

dokchitser(prec=53, max_imaginary_part=0, max_asympt_coeff=40, algorithm=None)

Return an interface for computing with the $L$-series of this elliptic curve.

This provides a way to compute Taylor expansions and higher derivatives of $L$-series.

INPUT:

• prec – optional integer (default 53) bits precision
• max_imaginary_part – optional real number (default 0)
• max_asympt_coeff – optional integer (default 40)
• algorithm – optional string: ‘gp’ (default), ‘pari’ or ‘magma’

If algorithm is “gp”, this returns an interface to Tim Dokchitser’s program for computing with the $L$-functions.

If algorithm is “pari”, this returns instead an interface to Pari’s own general implementation of $L$-functions.

Note: If algorithm='magma', then the precision is in digits rather than bits and the object returned is a Magma $L$-series, which has different functionality from the Sage $L$-series.

EXAMPLES:

sage: E = EllipticCurve('37a')
sage: L = E.lseries().dokchitser()
sage: L(2)
0.381575408260711

sage: L = E.lseries().dokchitser(algorithm='magma')          # optional - magma
sage: L.Evaluate(2)                                           # optional - magma
0.38157540826071121129371040958008663667709753398892116

If the curve has too large a conductor, it is not possible to compute with the $L$-series using this command. Instead a RuntimeError is raised:

sage: e = EllipticCurve([1,1,0,-63900,-1964465932632])
sage: L = e.lseries().dokchitser(15, algorithm='gp')
Traceback (most recent call last):
...
RuntimeError: unable to create L-series, due to precision or other limits in PARI

Using the “pari” algorithm:

sage: E = EllipticCurve('37a')
sage: L = E.lseries().dokchitser(algorithm='pari')
sage: L(2)
0.381575408260711

elliptic_curve()

Return the elliptic curve that this $L$-series is attached to.
EXAMPLES:

```
sage: E = EllipticCurve('389a')
sage: L = E.lseries()
sage: L.elliptic_curve()
Elliptic Curve defined by y^2 + y = x^3 + x^2 - 2*x over Rational Field
```

**sympow**($n$, $prec$)

Return $L(Sym^n(E, \text{edge}))$ to $prec$ digits of precision.

**INPUT:**

- $n$ – integer
- $prec$ – integer

**OUTPUT:**

- (string) – real number to $prec$ digits of precision as a string.

**Note:** Before using this function for the first time for a given $n$, you may have to type `sympow(' -new_data <n>')`, where `<n>` is replaced by your value of $n$. This command takes a long time to run.

EXAMPLES:

```
sage: E = EllipticCurve('37a')
sage: a = E.lseries().sympow(2,16) # not tested -- requires precomputing
sympow(' -new_data 2')
sage: a  # not tested
'2.49226204427365E+00'
sage: RR(a)  # not tested
2.49226204427365
```

**sympow**$_d$(n, prec, d)

Return 0-th to $d$-th derivatives of $L(Sym^n(E, \text{edge}))$ to $prec$ digits of precision.

**INPUT:**

- $n$ – integer
- $prec$ – integer
- $d$ – integer

**OUTPUT:**

- a string, exactly as output by sympow

**Note:** To use this function you may have to run a few commands like `sympow(' -new_data 1d2')`, each which takes a few minutes. If this function fails it will indicate what commands have to be run.

EXAMPLES:

```
sage: E = EllipticCurve('37a')
sage: print(E.lseries().sympow_derivs(1,16,2) # not tested -- requires precomputing
"sympow(' -new_data 2')")
sage: sympow 1.018 RELEASE (c) Mark Watkins --- see README and COPYING for details
```
Minimal model of curve is \([0, 0, 1, -1, 0]\)
At 37: Inertia Group is C1 MULTIPLICATIVE REDUCTION
Conductor is 37
sp 1: Conductor at 37 is 1+0, root number is 1
sp 1: Euler factor at 37 is 1+1^x
1st sym power conductor is 37, global root number is -1
NT 1d0: 35
NT 1d1: 32
NT 1d2: 28
Maximal number of terms is 35
Done with small primes 1049
Computed: 1d0 1d1 1d2
Checked out: 1d1

\[ \begin{align*}
1n0 & : 3.837774351482055 \times 10^{-1} \\
1w0 & : 3.777214305638848 \times 10^{-1} \\
1n1 & : 3.059977383405222 \times 10^{-1} \\
1w1 & : 3.059977383405224 \times 10^{-1} \\
1n2 & : 1.519054910497531 \times 10^{-1} \\
1w2 & : 1.545605024292642 \times 10^{-1}
\end{align*} \]

\textbf{taylor\_series}(a=1, prec=53, series\_prec=6, var='z')
Return the Taylor series of this \(L\)-series about \(a\) to the given precision (in bits) and the number of terms.

The output is a series in \(var\), where you should view \(var\) as equal to \(s - a\). Thus this function returns the formal power series whose coefficients are \(L^{(n)}(a)/n!\).

\textbf{INPUT:}

- \(a\) – complex number
- \(\text{prec}\) – integer, precision in bits (default 53)
- \(\text{series\_prec}\) – integer (default 6)
- \(\var\) – variable (default 'z')

\textbf{EXAMPLES:}

\begin{verbatim}
sage: E = EllipticCurve('389a')
sage: L = E.lseries()
sage: L.taylor_series(series_prec=3)  # abs tol 1e-14
-1.27685190980159e-23 + (7.23588070754027e-24)*z + 0.759316500288427*z^2 + O(z^3)  # 32-bit
1.34667664606157e-19 + (-7.6315753163667e-20)*z + 0.759316500288427*z^2 + O(z^3)  # 64-bit
\end{verbatim}

\textbf{twist\_values}(s, dmin, dmax)
Return values of \(L(E, s, \chi_d)\) for each quadratic character \(\chi_d\) for \(d_{\text{min}} \leq d \leq d_{\text{max}}\).

\textbf{Note:} The \(L\)-series is normalized so that the center of the critical strip is 1.

\textbf{INPUT:}

- \(s\) – complex numbers
- \(d_{\text{min}}\) – integer
• dmax – integer

OUTPUT:

• list of pairs \((d, L(E, s, \chi_d))\)

EXAMPLES:

```python
sage: E = EllipticCurve('37a')
sage: vals = E.lseries().twist_values(1, -12, -4)
sage: vals[0][0]
-11
sage: vals[0][1]  # abs tol 1e-8
1.47824342 + 0.0*I
sage: vals[1][0]
-8
sage: vals[1][1]  # abs tol 1e-8
0.0 + 0.0*I
sage: vals[2][0]
-7
sage: vals[2][1]  # abs tol 1e-8
1.85307619 + 0.0*I
sage: vals[3][0]
-4
sage: vals[3][1]  # abs tol 1e-8
2.45138938 + 0.0*I
sage: F = E.quadratic_twist(-8)
sage: F.rank()
1
sage: F = E.quadratic_twist(-7)
sage: F.rank()
0
```

twist_zeros\((n, dmin, dmax)\)

Return first \(n\) real parts of nontrivial zeros of \(L(E, s, \chi_d)\) for each quadratic character \(\chi_d\) with \(d_{\text{min}} \leq d \leq d_{\text{max}}\).

Note: The L-series is normalized so that the center of the critical strip is 1.
values_along_line(s0, s1, number_samples)

Return values of $L(E, s)$ at number_samples equally-spaced sample points along the line from $s_0$ to $s_1$ in the complex plane.

Note: The $L$-series is normalized so that the center of the critical strip is 1.

INPUT:
- $s_0, s_1$ – complex numbers
- number_samples – integer

OUTPUT:
list – list of pairs $(s, L(E, s))$, where the $s$ are equally spaced sampled points on the line from $s_0$ to $s_1$.

EXAMPLES:

```
sage: E = EllipticCurve('37a')
sage: E.lseries().values_along_line(0.5 + 20*I, 5)
[(0.5000000000, ...),
 (0.4000000000 + 4.000000000*I, 3.31920245 - 2.60028054*I),
 (0.3000000000 + 8.000000000*I, -0.886341185 - 0.422640337*I),
 (0.2000000000 + 12.00000000*I, -3.50558936 - 0.108531690*I),
 (0.1000000000 + 16.00000000*I, -3.87043288 - 1.88049411*I)]
```

zero_sums(N=None)

Return an LFunctionZeroSum class object for efficient computation of sums over the zeros of self.

This can be used to bound analytic rank from above without having to compute with the $L$-series directly.

INPUT:
- N – (default: None) If not None, the conductor of the elliptic curve attached to self. This is passable so that zero sum computations can be done on curves for which the conductor has been precomputed.

OUTPUT:
A LFunctionZeroSum_EllipticCurve instance.

EXAMPLES:

```
sage: E = EllipticCurve("5077a")
sage: E.lseries().zero_sums()
Zero sum estimator for L-function attached to Elliptic Curve defined by y^2 + y → x^3 - 7*x + 6 over Rational Field
```

zeros(n)

Return the imaginary parts of the first $n$ nontrivial zeros on the critical line of the $L$-function in the upper half plane, as 32-bit reals.

EXAMPLES:

```
sage: E = EllipticCurve('37a')
sage: E.lseries().zeros(2)
[0.000000000, 5.00317001]
sage: a = E.lseries().zeros(20) # long time
```

(continues on next page)
AUTHORS: Uses Rubinstein’s L-functions calculator.

zeros_in_interval(x, y, stepsize)

Return the imaginary parts of (most of) the nontrivial zeros on the critical line $\Re(s) = 1$ with positive imaginary part between $x$ and $y$, along with a technical quantity for each.

INPUT:

• $x$– positive floating point number
• $y$– positive floating point number
• stepsize – positive floating point number

OUTPUT:

• list of pairs (zero, $S(T)$).

Rubinstein writes: The first column outputs the imaginary part of the zero, the second column a quantity related to $S(T)$ (it increases roughly by 2 whenever a sign change, i.e. pair of zeros, is missed). Higher up the critical strip you should use a smaller stepsize so as not to miss zeros.

EXAMPLES:

sage: E = EllipticCurve('37a')
sage: E.lseries().zeros_in_interval(6, 10, 0.1) # long time
[(6.87039122, 0.248922780), (8.01433081, -0.140168533), (9.93309835, -0.129943029)]

14.23 Heegner points on elliptic curves over the rational numbers

AUTHORS:

• William Stein (August 2009) – most of the initial version
• Robert Bradshaw (July 2009) – an early version of some specific code

EXAMPLES:

sage: E = EllipticCurve('433a')
sage: P = E.heegner_point(-8,3)
sage: z = P.point_exact(201); z
(-4/3 : 1/9*a : 1)
sage: parent(z)
Abelian group of points on Elliptic Curve defined by y^2 + x*y = x^3 + 1 over Number Field in a with defining polynomial x^2 - 12*x + 111
sage: parent(z[0]).discriminant()
-3
sage: E.quadratic_twist(-3).rank()
1
sage: K.<a> = QuadraticField(-8)
sage: K.factor(3)
(Fractional ideal (1/2*a + 1)) * (Fractional ideal (-1/2*a + 1))
Next try an inert prime:

```
sage: K.factor(5)
Fractional ideal (5)
sage: P = E.heegner_point(-8, 5)
sage: z = P.point_exact(300)
sage: z[0].charpoly().factor()
(x^6 + x^5 - 1/4*x^4 + 19/10*x^3 + 31/20*x^2 - 7/10*x + 49/100)^2
sage: z[1].charpoly().factor()
x^12 - x^11 + 6/5*x^10 - 33/40*x^9 - 89/320*x^8 + 3287/8000*x^7 - 5273/16000*x^6 + 993/
˓
→
84000*x^5 + 823/320*x^4 - 2424/625*x^3 + 12059/12500*x^2 + 3329/25000*x + 123251/250000
sage: f = P.x_poly_exact(300); f
x^6 + x^5 - 1/4*x^4 + 19/10*x^3 + 31/20*x^2 - 7/10*x + 49/100
sage: f.discriminant().factor()
-1 * 2^-9 * 5^-9 * 7^2 * 281^2 * 1021^2
```

We find some Mordell-Weil generators in the rank 1 case using Heegner points:

```
sage: E = EllipticCurve('43a'); P = E.heegner_point(-7)
sage: P.x_poly_exact()
x
sage: P.point_exact()
(0 : 0 : 1)
sage: E = EllipticCurve('997a1')
sage: E.rank()
1
sage: E.heegner_discriminants_list(10)
sage: P = E.heegner_point(-19)
sage: P.x_poly_exact()
x - 141/49
sage: P.point_exact()
(141/49 : -162/343 : 1)
```

Here we find that the Heegner point generates a subgroup of index 3:

```
sage: E = EllipticCurve('92b1')
sage: E.heegner_discriminants_list(1)
[-7]
sage: P = E.heegner_point(-7); z = P.point_exact(); z
(0 : 1 : 1)
sage: E.regulator()
0.0498083972980648
sage: z.height()
0.44827557682583
sage: P = E(1, 1); P # a generator
(1 : 1 : 1)
sage: -3*P
(0 : 1 : 1)
sage: E.tamagawa_product()
3
```

The above is consistent with the following analytic computation:

14.23. Heegner points on elliptic curves over the rational numbers
Elliptic curves, Release 9.7

```python
sage: E.heegner_index(-7)
3.0000?
```

class `sage.schemes.elliptic_curves.heegner.GaloisAutomorphism`(parent)

Bases: `sage.structure.sage_object.SageObject`

An abstract automorphism of a ring class field.

**Todo:** make `GaloisAutomorphism` derive from `GroupElement`, so that one gets powers for free, etc.

```python
domain()

Return the domain of this automorphism.

EXAMPLES:

```python
sage: E = EllipticCurve('389a')
sage: s = E.heegner_point(-7,5).ring_class_field().galois_group().complex_conjugation()
sage: s.domain()
Ring class field extension of QQ[sqrt(-7)] of conductor 5
```

```python
parent()

Return the parent of this automorphism, which is a Galois group of a ring class field.

EXAMPLES:

```python
sage: E = EllipticCurve('389a')
sage: s = E.heegner_point(-7,5).ring_class_field().galois_group().complex_conjugation()
sage: s.parent()
Galois group of Ring class field extension of QQ[sqrt(-7)] of conductor 5
```

class `sage.schemes.elliptic_curves.heegner.GaloisAutomorphismComplexConjugation`(parent)

Bases: `sage.schemes.elliptic_curves.heegner.GaloisAutomorphism`

The complex conjugation automorphism of a ring class field.

EXAMPLES:

```python
sage: conj = heegner_point(37,-7,5).ring_class_field().galois_group().complex_conjugation()
sage: conj
Complex conjugation automorphism of Ring class field extension of QQ[sqrt(-7)] of conductor 5
sage: conj.domain()
Ring class field extension of QQ[sqrt(-7)] of conductor 5
```

```python
order()

EXAMPLES:

```python
sage: conj = heegner_point(37,-7,5).ring_class_field().galois_group().complex_conjugation()
sage: conj.order()
2
```
class sage.schemes.elliptic_curves.heegner.GaloisAutomorphismQuadraticForm(parent, quadratic_form, alpha=None)

Bases: sage.schemes.elliptic_curves.heegner.GaloisAutomorphism

An automorphism of a ring class field defined by a quadratic form.

EXAMPLES:

```
sage: H = heegner_points(389,-20,3)
sage: sigma = H.ring_class_field().galois_group(H.quadratic_field())[0]; sigma
Class field automorphism defined by x^2 + 45*y^2
sage: type(sigma)
<class 'sage.schemes.elliptic_curves.heegner.GaloisAutomorphismQuadraticForm'>
sage: loads(dumps(sigma)) == sigma
True
```

\(\alpha()\)

Optional data that specified element corresponding element of \((\mathcal{O}_K/c\mathcal{O}_K)^*/(\mathbb{Z}/c\mathbb{Z})^*\), via class field theory.

This is a generator of the ideal corresponding to this automorphism.

EXAMPLES:

```
sage: K3 = heegner_points(389,-52,3).ring_class_field()
sage: K1 = heegner_points(389,-52,1).ring_class_field()
sage: G = K3.galois_group(K1)
sage: orb = sorted([g.alpha() for g in G]); orb # random (the sign depends on the database being installed or not)
[1, 1/2*sqrt_minus_52 + 1, -1/2*sqrt_minus_52, 1/2*sqrt_minus_52 - 1]
sage: sorted([x^2 for x in orb]) # this is just for testing
[-13, -sqrt_minus_52 - 12, sqrt_minus_52 - 12, -2*sqrt_minus_52 - 9, 2*sqrt_minus_52 - 9, 1]
sage: K5 = heegner_points(389,-52,5).ring_class_field()
sage: K1 = heegner_points(389,-52,1).ring_class_field()
sage: G = K5.galois_group(K1)
sage: orb = sorted([g.alpha() for g in G]); orb # random (the sign depends on the database being installed or not)
[1, -1/2*sqrt_minus_52, 1/2*sqrt_minus_52 + 1, -1/2*sqrt_minus_52 + 1, 1/2*sqrt_minus_52 - 1, 1/2*sqrt_minus_52 - 2]
sage: sorted([x^2 for x in orb]) # just for testing
[-13, -sqrt_minus_52 - 12, sqrt_minus_52 - 12, -2*sqrt_minus_52 - 9, 2*sqrt_minus_52 - 9, 1]
```

\(\text{ideal()}\)

Return ideal of ring of integers of quadratic imaginary field corresponding to this quadratic form. This is the ideal

\[ I = \left( A, \frac{-B+c\sqrt{D}}{2} \right) \mathcal{O}_K. \]

EXAMPLES:

```
sage: E = EllipticCurve('389a'); F= E.heegner_point(-20,3).ring_class_field()
sage: G = F.galois_group(F.quadratic_field())
sage: G[1].ideal()
Fractional ideal (2, 1/2*sqrt_minus_20 + 1)
```

(continues on next page)
Elliptic curves, Release 9.7

\begin{verbatim}
sage: [s.ideal().gens() for s in G]
[(1, 3/2*sqrt_minus_20), (2, 3/2*sqrt_minus_20 - 1), (5, 3/2*sqrt_minus_20), (7, 3/2*sqrt_minus_20 - 2)]
\end{verbatim}

**order()**

Return the multiplicative order of this Galois group automorphism.

**EXAMPLES:**

\begin{verbatim}
sage: K3 = heegner_points(389,-52,3).ring_class_field()
sage: K1 = heegner_points(389,-52,1).ring_class_field()
sage: G = K3.galois_group(K1)
sage: sorted([g.order() for g in G])
[1, 2, 4, 4]
sage: K5 = heegner_points(389,-52,5).ring_class_field()
sage: K1 = heegner_points(389,-52,1).ring_class_field()
sage: G = K5.galois_group(K1)
sage: sorted([g.order() for g in G])
[1, 2, 3, 3, 6, 6]
\end{verbatim}

**p1_element()**

Return element of the projective line corresponding to this automorphism.

This only makes sense if this automorphism is in the Galois group Gal($K_c/K_1$).

**EXAMPLES:**

\begin{verbatim}
sage: K3 = heegner_points(389,-52,3).ring_class_field()
sage: K1 = heegner_points(389,-52,1).ring_class_field()
sage: G = K3.galois_group(K1)
sage: sorted([g.p1_element() for g in G])
[(0, 1), (1, 0), (1, 1), (1, 2)]
sage: K5 = heegner_points(389,-52,5).ring_class_field()
sage: K1 = heegner_points(389,-52,1).ring_class_field()
sage: G = K5.galois_group(K1)
sage: sorted([g.p1_element() for g in G])
[(0, 1), (1, 0), (1, 1), (1, 2), (1, 3), (1, 4)]
\end{verbatim}

**quadratic_form()**

Return reduced quadratic form corresponding to this Galois automorphism.

**EXAMPLES:**

\begin{verbatim}
sage: H = heegner_points(389,-20,3); s = H.ring_class_field().galois_group(H.quadratic_field())[0]
sage: s.quadratic_form()
x^2 + 45*y^2
\end{verbatim}

**class** sage.schemes.elliptic_curves.heegner.GaloisGroup(field, base=Rational Field)

Bases: sage.structure.sage_object.SageObject

A Galois group of a ring class field.

**EXAMPLES:**
sage: E = EllipticCurve('389a')
sage: G = E.heegner_point(-7,5).ring_class_field().galois_group(); G
Galois group of Ring class field extension of QQ[sqrt(-7)] of conductor 5
sage: G.field()
Ring class field extension of QQ[sqrt(-7)] of conductor 5
sage: G.cardinality()
12

base_field()

Return the base field, which is the field fixed by all the automorphisms in this Galois group.

EXAMPLES:

sage: x = heegner_point(37,-7,5)
sage: Kc = x.ring_class_field(); Kc
Ring class field extension of QQ[sqrt(-7)] of conductor 5
sage: K = x.quadratic_field()
sage: G = Kc.galois_group(); G
Galois group of Ring class field extension of QQ[sqrt(-7)] of conductor 5
sage: G.base_field()
Rational Field
sage: G.cardinality()
12
sage: Kc.absolute_degree()
12
sage: G = Kc.galois_group(K); G
Galois group of Ring class field extension of QQ[sqrt(-7)] of conductor 5 overNumber Field in sqrt_minus_7 with defining polynomial x^2 + 7 with sqrt_minus_7 = 2.6457513110645917*I
sage: G.cardinality()
6
sage: G.base_field()
Number Field in sqrt_minus_7 with defining polynomial x^2 + 7 with sqrt_minus_7 = 2.6457513110645917*I
sage: G = Kc.galois_group(Kc); G
Galois group of Ring class field extension of QQ[sqrt(-7)] of conductor 5 overRing class field extension of QQ[sqrt(-7)] of conductor 5
sage: G.cardinality()
1
sage: G.base_field()
Ring class field extension of QQ[sqrt(-7)] of conductor 5

cardinality()

Return the cardinality of this Galois group.

EXAMPLES:

sage: E = EllipticCurve('389a')
sage: G = E.heegner_point(-7,5).ring_class_field().galois_group(); G
Galois group of Ring class field extension of QQ[sqrt(-7)] of conductor 5
sage: G.cardinality()
(continues on next page)
Elliptic curves, Release 9.7

(continued from previous page)

12
sage: G = E.heegner_point(-7).ring_class_field().galois_group()
sage: G.cardinality()
2
sage: G = E.heegner_point(-7, 55).ring_class_field().galois_group()
sage: G.cardinality()
120

complex_conjugation()
Return the automorphism of self determined by complex conjugation. The base field must be the rational numbers.

EXAMPLES:

sage: E = EllipticCurve('389a')
sage: G = E.heegner_point(-7, 5).ring_class_field().galois_group()
sage: G.complex_conjugation()
Complex conjugation automorphism of Ring class field extension of QQ[sqrt(-7)], of conductor 5

field()
Return the ring class field that this Galois group acts on.

EXAMPLES:

sage: G = heegner_point(389, -7, 5).ring_class_field().galois_group()
sage: G.field()
Ring class field extension of QQ[sqrt(-7)] of conductor 5

is_kolyvagin()
Return True if conductor c is prime to the discriminant of the quadratic field, c is squarefree and each prime dividing c is inert.

EXAMPLES:

sage: K5 = heegner_points(389, -52, 5).ring_class_field()
sage: K1 = heegner_points(389, -52, 1).ring_class_field()
sage: K5.galois_group(K1).is_kolyvagin()
True
sage: K7 = heegner_points(389, -52, 7).ring_class_field()
sage: K7.galois_group(K1).is_kolyvagin()
False
sage: K25 = heegner_points(389, -52, 25).ring_class_field()
sage: K25.galois_group(K1).is_kolyvagin()
False

kolyvagin_generators()
Assuming this Galois group G is of the form $G = \text{Gal}(K_c/K_1)$, with $c = p_1 \cdots p_n$ satisfying the Kolyvagin hypothesis, this function returns noncanonical choices of lifts of generators for each of the cyclic factors of G corresponding to the primes dividing c. Thus the i-th returned valued is an element of G that maps to the identity element of $\text{Gal}(K_{p_i}/K_1)$ for all $p \neq p_i$ and to a choice of generator of $\text{Gal}(K_{p_i}/K_1)$.

OUTPUT:

• list of elements of self
EXAMPLES:

```
sage: K3 = heegner_points(389,-52,3).ring_class_field()
sage: K1 = heegner_points(389,-52,1).ring_class_field()
sage: G = K3.galois_group(K1)
sage: G.kolyvagin_generators()
(Class field automorphism defined by 9*x^2 - 6*x*y + 14*y^2,)
```

```
sage: K5 = heegner_points(389,-52,5).ring_class_field()
sage: K1 = heegner_points(389,-52,1).ring_class_field()
sage: G = K5.galois_group(K1)
sage: G.kolyvagin_generators()
(Class field automorphism defined by 17*x^2 - 14*x*y + 22*y^2,)
```

**lift_of_hilbert_class_field_galois_group()**

Assuming this Galois group \( G \) is of the form \( G = \text{Gal}(\mathcal{K}_c/\mathcal{K}) \), this function returns noncanonical choices of lifts of the elements of the quotient group \( \text{Gal}(\mathcal{K}_1/\mathcal{K}) \).

OUTPUT:

- tuple of elements of self

EXAMPLES:

```
sage: K5 = heegner_points(389,-52,5).ring_class_field()
sage: G = K5.galois_group(K5.quadratic_field())
sage: G.lift_of_hilbert_class_field_galois_group()
(Class field automorphism defined by x^2 + 325*y^2, Class field automorphism defined by 2*x^2 + 2*x*y + 163*y^2)
sage: G.cardinality()
12
sage: K5.quadratic_field().class_number()
2
```

**class** `sage.schemes.elliptic_curves.heegner.HeegnerPoint(N, D, c)`

Bases: `sage.structure.sage_object.SageObject`

A Heegner point of level \( N \), discriminant \( D \) and conductor \( c \) is any point on a modular curve or elliptic curve that is concocted in some way from a quadratic imaginary \( \tau \) in the upper half plane with \( \Delta(\tau) = Dc = \Delta(N\tau) \).

EXAMPLES:

```
sage: x = sage.schemes.elliptic_curves.heegner.HeegnerPoint(389,-7,13); x
Heegner point of level 389, discriminant -7, and conductor 13
sage: type(x)
<class 'sage.schemes.elliptic_curves.heegner.HeegnerPoint'>
sage: loads(dumps(x)) == x
True
```

**conductor()**

Return the conductor of this Heegner point.

EXAMPLES:

```
sage: heegner_point(389,-7,5).conductor()
5
sage: E = EllipticCurve('37a1'); P = E.kolyvagin_point(-67,7); P
```
Kolyvagin point of discriminant -67 and conductor 7 on elliptic curve of conductor 37.
sage: P.conductor()
7
sage: E = EllipticCurve('389a'); P = E.heegner_point(-7, 5); P.conductor()
5

discriminant()
Return the discriminant of the quadratic imaginary field associated to this Heegner point.

EXAMPLES:

sage: heegner_point(389,-7,5).discriminant()
-7
sage: E = EllipticCurve('37a1'); P = E.kolyvagin_point(-67,7); P
Kolyvagin point of discriminant -67 and conductor 7 on elliptic curve of conductor 37.
sage: P.discriminant()
-67
sage: E = EllipticCurve('389a'); P = E.heegner_point(-7, 5); P.discriminant()
-7

level()
Return the level of this Heegner point, which is the level of the modular curve $\mathcal{X}_0(N)$ on which this is a Heegner point.

EXAMPLES:

sage: heegner_point(37,-7,5).level()
389

quadratic_field()
Return the quadratic number field of discriminant $D$.

EXAMPLES:

sage: x = heegner_point(37,-7,5)
sage: x.quadratic_field()
Number Field in sqrt_minus_7 with defining polynomial x^2 + 7 with sqrt_minus_7 = 2.6457513110645917*I
sage: E = EllipticCurve('37a'); P = E.heegner_point(-40)
sage: P.quadratic_field()
Number Field in sqrt_minus_40 with defining polynomial x^2 + 40 with sqrt_minus_40 = 6.3245553203367598*I
sage: P.quadratic_field() is P.quadratic_field()
True
sage: type(P.quadratic_field())
<class 'sage.rings.number_field.number_field.NumberField_quadratic_with_category'>

quadratic_order()
Return the order in the quadratic imaginary field of conductor $c$, where $c$ is the conductor of this Heegner point.
EXAMPLES:

```python
sage: heegner_point(389, -7, 5).quadratic_order()
Order in Number Field in sqrt_minus_7 with defining polynomial x^2 + 7 with_
→sqrt_minus_7 = 2.645751311064591*I
sage: heegner_point(389, -7, 5).quadratic_order().basis()
[1, 5*sqrt_minus_7]
```

```python
e = EllipticCurve('37a'); P = e.heegner_point(-40, 11)
sage: P.quadratic_order()
Order in Number Field in sqrt_minus_40 with defining polynomial x^2 + 40 with_
→sqrt_minus_40 = 6.324555320336759*I
sage: P.quadratic_order().basis()
[1, 11*sqrt_minus_40]
```

`ring_class_field()`

Return the ring class field associated to this Heegner point. This is an extension $K_c$ over $K$, where $K$ is the quadratic imaginary field and $c$ is the conductor associated to this Heegner point. This Heegner point is defined over $K_c$ and the Galois group $Gal(K_c/K)$ acts transitively on the Galois conjugates of this Heegner point.

EXAMPLES:

```python
sage: E = EllipticCurve('389a'); K.<a> = QuadraticField(-5)
sage: len(K.factor(5))
1
sage: len(K.factor(23))
2
sage: E.heegner_point(-7, 5).ring_class_field().degree_over_K()
6
sage: E.heegner_point(-7, 23).ring_class_field().degree_over_K()
22
sage: E.heegner_point(-7, 5*23).ring_class_field().degree_over_K()
132
sage: E.heegner_point(-7, 5^2).ring_class_field().degree_over_K()
30
sage: E.heegner_point(-7, 7).ring_class_field().degree_over_K()
7
```

class `sage.schemes.elliptic_curves.heegner.HeegnerPointOnEllipticCurve`($E, x, check=True$)

Bases: `sage.schemes.elliptic_curves.heegner.HeegnerPoint`

A Heegner point on a curve associated to an order in a quadratic imaginary field.

EXAMPLES:

```python
sage: E = EllipticCurve('37a'); P = E.heegner_point(-7, 5); P
Heegner point of discriminant -7 and conductor 5 on elliptic curve of conductor 37
sage: type(P)
<class 'sage.schemes.elliptic_curves.heegner.HeegnerPointOnEllipticCurve'>
```

`conjugates_over_K()`

Return the $Gal(K_c/K)$ conjugates of this Heegner point.

EXAMPLES:
Elliptic curves, Release 9.7

```python
sage: E = EllipticCurve('77a')
sage: y = E.heegner_point(-52, 5); y
Heegner point of discriminant -52 and conductor 5 on elliptic curve of conductor 77
sage: print([z.quadratic_form() for z in y.conjugates_over_K()])
[77*x^2 + 52*x*y + 13*y^2, 154*x^2 + 206*x*y + 71*y^2, 539*x^2 + 822*x*y + 13*y^2, 847*x^2 + 1284*x*y + 487*y^2, 1001*x^2 + 52*x*y + y^2, 1078*x^2 + 822*x*y + 157*y^2, 1309*x^2 + 360*x*y + 25*y^2, 1309*x^2 + 2054*x*y + 806*y^2, 2233*x^2 + 2824*x*y + 893*y^2, 2387*x^2 + 2054*x*y + 442*y^2, 3619*x^2 + 3286*x*y + 746*y^2]
sage: y.quadratic_form()
77*x^2 + 52*x*y + 13*y^2
```

curve()

Return the elliptic curve on which this is a Heegner point.

EXAMPLES:

```python
sage: E = EllipticCurve('389a'); P = E.heegner_point(-7, 5)
sage: P.curve()
Elliptic Curve defined by y^2 + y = x^3 + x^2 - 2*x over Rational Field
sage: P.curve() is E
True
```

heegner_point_on_X0N()

Return Heegner point on $X_0(N)$ that maps to this Heegner point on $E$.

EXAMPLES:

```python
sage: E = EllipticCurve('37a'); P = E.heegner_point(-7,5); P
Heegner point of discriminant -7 and conductor 5 on elliptic curve of conductor 37
sage: P.heegner_point_on_X0N()
Heegner point 5/74*sqrt(-7) - 11/74 of discriminant -7 and conductor 5 on X_0(37)
```

kolyvagin_cohomology_class$(n=None)$

Return the Kolyvagin class associated to this Heegner point.

INPUT:

- $n$ – positive integer that divides the gcd of $a_p$ and $p + 1$ for all $p$ dividing the conductor. If $n$ is None, choose the largest valid $n$.

EXAMPLES:

```python
sage: y = EllipticCurve('389a').heegner_point(-7,5)
sage: y.kolyvagin_cohomology_class(3)
Kolyvagin cohomology class c(5) in H^1(K,E[3])
```

kolyvagin_point()

Return the Kolyvagin point corresponding to this Heegner point.

This is the point obtained by applying the Kolyvagin operator $J_c I_c$ in the group ring of the Galois group to this Heegner point. It is a point that defines an element of $H^1(K, E[n])$, under certain hypotheses on $n$.

EXAMPLES:
sage: E = EllipticCurve('37a1'); y = E.heegner_point(-7); y
Heegner point of discriminant -7 on elliptic curve of conductor 37
sage: P = y.kolyvagin_point(); P
Kolyvagin point of discriminant -7 on elliptic curve of conductor 37
sage: P.numerical_approx()  # abs tol 1e-15
(-3.36910401903861e-16 - 2.22076195576076e-16*I : 3.33066907387547e-16 + 2.22076195576075e-16*I : 1.00000000000000)

map_to_complex_numbers(\texttt{prec=53})
Return the point in the subfield \( M \) of the complex numbers (well defined only modulo the period lattice) corresponding to this Heegner point.

EXAMPLES:

We compute a nonzero Heegner point over a ring class field on a curve of rank 2:

sage: E = EllipticCurve('389a'); y = E.heegner_point(-7,5)
sage: y.map_to_complex_numbers()
1.49979679635196 + 0.369156204821526*I
sage: y.map_to_complex_numbers(100)
1.4997967963519640592142411892 + 0.36915620482152626830089145962*I
sage: y.map_to_complex_numbers(10)
1.5 + 0.37*I

Here we see that the Heegner point is 0 since it lies in the lattice:

sage: E = EllipticCurve('389a'); y = E.heegner_point(-7)
sage: y.map_to_complex_numbers(10)
0.0034 - 3.9*I
sage: y.map_to_complex_numbers()
4.71844785465692e-15 - 3.94347540310330*I
sage: E.period_lattice().basis()
(2.49021256085505, 1.97173770155165*I)
sage: 2*E.period_lattice().basis()[1]
3.94347540310330*I

You can also directly coerce to the complex field:

sage: E = EllipticCurve('389a'); y = E.heegner_point(-7)
sage: z = ComplexField(100)(y); z  # real part approx. 0
-3.94347540310330999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999
EXAMPLES:

```python
sage: E = EllipticCurve('37a'); P = E.heegner_point(-7); P
Heegner point of discriminant -7 on elliptic curve of conductor 37
sage: P.numerical_approx() # abs tol 1e-15
(-3.36910401903861e-16 - 2.22076195576076e-16*I : 3.33066907387547e-16 + 2.
  → 1.00000000000000)

sage: P.numerical_approx(10) # expect random digits
(0.0030 - 0.0028*I : -0.0030 + 0.0028*I : 1.0)

sage: P.numerical_approx(100)[0] # expect random digits
8.4...e-31 + 6.0...e-31*I

sage: E = EllipticCurve('37a'); P = E.heegner_point(-40); P
Heegner point of discriminant -40 on elliptic curve of conductor 37
sage: P.numerical_approx() # abs tol 1e-14
(-3.15940603400359e-16 + 1.41421356237309*I : 1.00000000000000 - 1.
  → 41421356237309*I : 1.00000000000000)

A rank 2 curve, where all Heegner points of conductor 1 are 0:

```python
sage: E = EllipticCurve('389a'); E.rank()
2
sage: P = E.heegner_point(-7); P
Heegner point of discriminant -7 on elliptic curve of conductor 389
sage: P.numerical_approx()
(0.000000000000000 : 1.00000000000000 : 0.000000000000000)

However, Heegner points of bigger conductor are often nonzero:

```python
sage: E = EllipticCurve('389a'); P = E.heegner_point(-7, 5); P
Heegner point of discriminant -7 and conductor 5 on elliptic curve of conductor
  → 389
sage: P.numerical_approx()
(0.675507556926807 + 0.344749649302635*I : -0.377142931401887 + 0.
  → 843366227137146*I : 1.00000000000000)

sage: E.heegner_point(-7, 11).numerical_approx()
(0.1795583794118... + 0.02035501750912...*I : -0.5573941377055... + 0.
  → 2738940831635...*I : 1.00000000000000)

sage: E.heegner_point(-7, 13).numerical_approx()
(1.034302915374... - 3.302744319777...*I : 1.323937875767... + 6.908264226850...
  → I : 1.00000000000000)
```

We find (probably) the defining polynomial of the $x$-coordinate of $P$, which defines a class field. The shape of the discriminant below is strong confirmation – but not proof – that this polynomial is correct:

```python
sage: f = P.numerical_approx(70)[0].algdep(6); f
1225*x^6 + 1750*x^5 - 21675*x^4 - 3800*x^3 + 1180180*x^2 - 129720*x + 48771
sage: f.discriminant().factor()
2^6 * 3^2 * 5^11 * 7^4 * 13^2 * 19^6 * 199^2 * 719^2 * 26161^2
```

point_exact(prec=53, algorithm='lll', var='a', optimize=False)

Return exact point on the elliptic curve over a number field defined by computing this Heegner point to the given number of bits of precision. A ValueError is raised if the precision is clearly insignificant to define a

516 Chapter 14. Elliptic curves over number fields
point on the curve.

**Warning:** It is in theory possible for this function to not raise a ValueError, find a point on the curve, but via some very unlikely coincidence that point is not actually this Heegner point.

**Warning:** Currently we make an arbitrary choice of $y$-coordinate for the lift of the $x$-coordinate.

**INPUT:**
- `prec` – integer (default: 53)
- `algorithm` – see the description of the algorithm parameter for the `x_poly_exact` method.
- `var` – string (default: ‘a’)
- `optimize` – bool (default; False) if True, try to optimize defining polynomial for the number field that the point is defined over. Off by default, since this can be very expensive.

**EXAMPLES:**

```python
sage: E = EllipticCurve('389a'); P = E.heegner_point(-7, 5); P
Heegner point of discriminant -7 and conductor 5 on elliptic curve of conductor 389
sage: z = P.point_exact(200, optimize=True)
sage: z[1].charpoly()
x^12 + 6*x^11 + 90089/1715*x^10 + 71224/343*x^9 + 52563964/588245*x^8 -
→ 483814934/588245*x^7 - 156744579/16807*x^6 - 2041518032/84035*x^5 +
→ 1259355443184/14706125*x^4 + 3094420220918/14706125*x^3 + 123060442043827/
→ 367653125*x^2 + 82963044474852/367653125*x + 211679465261391/1838265625
sage: f = P.numerical_approx(500)[1].algdep(12); f / f.leading_coefficient()
x^12 + 6*x^11 + 90089/1715*x^10 + 71224/343*x^9 + 52563964/588245*x^8 -
→ 483814934/588245*x^7 - 156744579/16807*x^6 - 2041518032/84035*x^5 +
→ 1259355443184/14706125*x^4 + 3094420220918/14706125*x^3 + 123060442043827/
→ 367653125*x^2 + 82963044474852/367653125*x + 211679465261391/1838265625
sage: E = EllipticCurve('5077a')
sage: P = E.heegner_point(-7)
sage: P.point_exact(prec=100)
(0 : 1 : 0)
```

**quadratic_form()**

Return the integral primitive positive definite binary quadratic form associated to this Heegner point.

**EXAMPLES:**

```python
sage: E = EllipticCurve('389a').heegner_point(-7, 5).quadratic_form()
389*x^2 + 147*x*y + 14*y^2
sage: P = EllipticCurve('389a').heegner_point(-7, 5, (778,925,275)); P
Heegner point of discriminant -7 and conductor 5 on elliptic curve of conductor 389
sage: P.quadratic_form()
778*x^2 + 925*x*y + 275*y^2
```
satisfies_kolyvagin_hypothesis(n=None)

Return True if this Heegner point and \( n \) satisfy the Kolyvagin hypothesis, i.e., that each prime dividing the conductor \( c \) of self is inert in \( K \) and coprime to \( ND \). Moreover, if \( n \) is not None, also check that for each prime \( p \) dividing \( c \) we have that \( n | \gcd(a_p(E), p + 1) \).

INPUT:

\( n \) – positive integer

EXAMPLES:

```sage
EllipticCurve('389a').heegner_point(-7).satisfies_kolyvagin_hypothesis()
True
EllipticCurve('389a').heegner_point(-7, 5).satisfies_kolyvagin_hypothesis()
True
EllipticCurve('389a').heegner_point(-7, 11).satisfies_kolyvagin_hypothesis()
False
```

tau()

Return \( \tau \) in the upper half plane that maps via the modular parametrization to this Heegner point.

EXAMPLES:

```sage
E = EllipticCurve('389a'); P = E.heegner_point(-7, 5)
P.tau()
5/778*sqrt_minus_7 - 147/778
```

x_poly_exact(prec=53, algorithm='lll')

Return irreducible polynomial over the rational numbers satisfied by the \( x \) coordinate of this Heegner point. A ValueError is raised if the precision is clearly insignificant to define a point on the curve.

**Warning:** It is in theory possible for this function to not raise a ValueError, find a polynomial, but via some very unlikely coincidence that point is not actually this Heegner point.

INPUT:

- \( \text{prec} \) – integer (default: 53)
- \( \text{algorithm} \) – ‘conjugates’ or ‘lll’ (default); if ‘conjugates’, compute numerically all the conjugates \( y[i] \) of the Heegner point and construct the characteristic polynomial as the product \( f(X) = (X - y[i]) \). If ‘lll’, compute only one of the conjugates \( y[0] \), then uses the LLL algorithm to guess \( f(X) \).

EXAMPLES:

We compute some \( x \)-coordinate polynomials of some conductor 1 Heegner points:

```sage
E = EllipticCurve('37a')
v = E.heegner_discriminants_list(10)
[E.heegner_point(D).x_poly_exact() for D in v]
[x, x, x^2 + 2, x^5 - x^4 + x^3 + x^2 - 2*x + 1, x - 6, x^7 - 2*x^6 + 9*x^5 -
-10*x^4 - x^3 + 8*x^2 - 5*x + 1, x^3 + 5*x^2 + 10*x + 4, x^4 - 10*x^3 + 10*x^2-]
-12*x - 12, x^8 - 5*x^7 + 7*x^6 + 13*x^5 - 10*x^4 - 4*x^3 + x^2 - 5*x + 7, x^-
-6 - 2*x^5 + 11*x^4 - 24*x^3 + 30*x^2 - 16*x + 4]
```
We compute $x$-coordinate polynomials for some Heegner points of conductor bigger than 1 on a rank 2 curve:

```
sage: E = EllipticCurve('389a'); P = E.heegner_point(-7, 5); P
Heegner point of discriminant -7 and conductor 5 on elliptic curve of conductor
˓→389
sage: P.x_poly_exact()
Traceback (most recent call last):
...
ValueError: insufficient precision to determine Heegner point (fails˓→discriminant test)
sage: P.x_poly_exact(120)
x^6 + 10/7*x^5 - 867/49*x^4 - 76/245*x^3 + 3148/35*x^2 - 25944/245*x + 48771/
˓→1225
sage: E.heegner_point(-7,11).x_poly_exact(500)
x^10 + 282527/52441*x^9 + 27049007420/2750058481*x^8 - 22058564794/2750058481*x^7 - 140054237301/2750058481*x^6 + 696429998952/30250643291*x^5 +˓→2791387923058/30250643291*x^4 - 3148473886134/30250643291*x^3 + 1359454055022/
˓→30250643291*x^2 - 250620385365/30250643291*x + 181599685425/332757076201
```

Here we compute a Heegner point of conductor 5 on a rank 3 curve:

```
sage: E = EllipticCurve('5077a'); P = E.heegner_point(-7,5); P
Heegner point of discriminant -7 and conductor 5 on elliptic curve of conductor˓→5077
sage: P.x_poly_exact(500)
x^6 + 110875485372159228/72351048803252547*x^5 + 888750555118408168/
˓→1953478317687818769*x^4 - 221620027421225599*473273/325579719614634615*t^3 +˓→14976392057128390493845*x^2 - 3456417460183342963918/
˓→325410314635461*x + 37697528358575050459/5426328660243941025
```

See trac ticket #34121:

```
sage: E = EllipticCurve('11a1')
sage: P = E.heegner_point(-7)
sage: PE = P.point_exact()
sage: PE
(a : -4*a + 3 : 1)
sage: all(c.parent().disc() == -7 for c in PE)
True
```

class sage.schemes.elliptic_curves.heegner.HeegnerPointOnX0N(N, D, c=1, f=None, check=True)

Bases: sage.schemes.elliptic_curves.heegner.HeegnerPoint

A Heegner point as a point on the modular curve $X_0(N)$, which we view as the upper half plane modulo the action of $\Gamma_0(N)$.

EXAMPLES:

```
sage: x = heegner_point(37,-7,5); x
Heegner point 5/74*sqrt(-7) - 11/74 of discriminant -7 and conductor 5 on X_0(37)
sage: type(x)
<class 'sage.schemes.elliptic_curves.heegner.HeegnerPointOnX0N'>
sage: x.level()
37
```
Elliptic curves, Release 9.7

(continued from previous page)

```python
sage: x.conductor()
5
sage: x.discriminant()
-7
sage: x.quadratic_field()
Number Field in sqrt_minus_7 with defining polynomial x^2 + 7 with sqrt_minus_7 = 2.645751311064591?*I
sage: x.quadratic_form()
37*x^2 + 11*x*y + 2*y^2
sage: x.quadratic_order()
Order in Number Field in sqrt_minus_7 with defining polynomial x^2 + 7 with sqrt_minus_7 = 2.645751311064591?*I
sage: x.tau()
5/74*sqrt_minus_7 - 11/74
sage: loads(dumps(x)) == x
True
```

`atkin_lehner_act(Q=None)`

Given an integer Q dividing the level N such that gcd(Q, N/Q) = 1, returns the image of this Heegner point under the Atkin-Lehner operator W_Q.

**INPUT:**

- Q – positive divisor of N; if not given, default to N

**EXAMPLES:**

```python
sage: x = heegner_point(389,-7,5)
sage: x.atkin_lehner_act()
Heegner point 5/199168*sqrt(-7) - 631/199168 of discriminant -7 and conductor 5 on X_0(389)
sage: x = heegner_point(45,D=-11,c=1); x
Heegner point 1/90*sqrt(-11) - 13/90 of discriminant -11 on X_0(45)
sage: x.atkin_lehner_act(5)
Heegner point 1/90*sqrt(-11) + 23/90 of discriminant -11 on X_0(45)
sage: y = x.atkin_lehner_act(9); y
Heegner point 1/90*sqrt(-11) - 23/90 of discriminant -11 on X_0(45)
sage: z = y.atkin_lehner_act(9); z
Heegner point 1/90*sqrt(-11) - 13/90 of discriminant -11 on X_0(45)
sage: z == x
True
```

galois_orbit_over_K()

Return the Gal(K_c/K)-orbit of this Heegner point.

**EXAMPLES:**

```python
sage: x = heegner_point(389,-7,3);
Heegner point 3/778*sqrt(-7) - 223/778 of discriminant -7 and conductor 3 on X_0(389)
sage: x.galois_orbit_over_K()
[Heegner point 3/778*sqrt(-7) - 223/778 of discriminant -7 and conductor 3 on X_0(389), Heegner point 3/1556*sqrt(-7) - 1001/1556 of discriminant -7 and conductor 3 on X_0(389), Heegner point 3/3112*sqrt(-7) - 223/3112 of discriminant -7 and conductor 3 on X_0(389)]
```
map_to_curve($E$)
Return the image of this Heegner point on the elliptic curve $E$, which must also have conductor $N$, where $N$ is the level of self.

EXAMPLES:

```
sage: x = heegner_point(389,-7,5); x
Heegner point 5/778*sqrt(-7) - 147/778 of discriminant -7 and conductor 5 on X_˓→0(389)
sage: y = x.map_to_curve(EllipticCurve('389a')); y
Heegner point of discriminant -7 and conductor 5 on elliptic curve of conductor ˓→389
sage: y.curve().cremona_label()
'389a1'
sage: y.heegner_point_on_X0N()
Heegner point 5/778*sqrt(-7) - 147/778 of discriminant -7 and conductor 5 on X_˓→0(389)
```

You can also directly apply the modular parametrization of the elliptic curve:

```
sage: x = heegner_point(37,-7); x
Heegner point 1/74*sqrt(-7) - 17/74 of discriminant -7 on X_0(37)
sage: E = EllipticCurve('37a'); phi = E.modular_parametrization()
sage: phi(x)
Heegner point of discriminant -7 on elliptic curve of conductor 37
```

plot(**kwds)
Draw a point at $(x, y)$ where this Heegner point is represented by the point $\tau = x + iy$ in the upper half plane.

The kwds get passed onto the point plotting command.

EXAMPLES:

```
sage: heegner_point(389,-7,1).plot(pointsize=50)
Graphics object consisting of 1 graphics primitive
```

quadratic_form()
Return the integral primitive positive-definite binary quadratic form associated to this Heegner point.

EXAMPLES:

```
sage: heegner_point(389,-7,5).quadratic_form()
389*x^2 + 147*x*y + 14*y^2
```

reduced_quadratic_form()
Return reduced binary quadratic corresponding to this Heegner point.

EXAMPLES:

```
sage: x = heegner_point(389,-7,5)
sage: x.quadratic_form()
389*x^2 + 147*x*y + 14*y^2
```

(continues on next page)
sage: x.reduced_quadratic_form()
4*x^2 - x*y + 11*y^2

\textbf{tau()}

Return an element \( \tau \) in the upper half plane that corresponds to this particular Heegner point. Actually, \( \tau \) is in the quadratic imaginary field \( K \) associated to this Heegner point.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: x = heegner_point(37,-7,5); tau = x.tau(); tau
5/74*sqrt_minus_7 - 11/74
sage: 37 * tau.minpoly()
37*x^2 + 11*x + 2
sage: x.quadratic_form()
37*x^2 + 11*x*y + 2*y^2
\end{verbatim}

\textbf{class} \ 	exttt{sage.schemes.elliptic_curves.heegner.HeegnerPoints}(\texttt{N})

\textbf{Bases:} \ 	exttt{sage.structure.sage_object.SageObject}

The set of Heegner points with given parameters.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: H = heegner_points(389); H
Set of all Heegner points on X_0(389)
sage: type(H)
<class 'sage.schemes.elliptic_curves.heegner.HeegnerPoints_level'>
sage: isinstance(H, sage.schemes.elliptic_curves.heegner.HeegnerPoints)
True
\end{verbatim}

\textbf{level()}

Return the level \( N \) of the modular curve \( X_0(N) \).

\textbf{EXAMPLES:}

\begin{verbatim}
sage: heegner_points(389).level()
389
\end{verbatim}

\textbf{class} \ 	exttt{sage.schemes.elliptic_curves.heegner.HeegnerPoints_level}(\texttt{N})

\textbf{Bases:} \ 	exttt{sage.schemes.elliptic_curves.heegner.HeegnerPoints}

Return the infinite set of all Heegner points on \( X_0(N) \) for all quadratic imaginary fields.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: H = heegner_points(11); H
Set of all Heegner points on X_0(11)
sage: type(H)
<class 'sage.schemes.elliptic_curves.heegner.HeegnerPoints_level'>
sage: loads(dumps(H)) == H
True
\end{verbatim}

\textbf{discriminants}(n=10, weak=False)

Return the first \( n \) quadratic imaginary discriminants that satisfy the Heegner hypothesis for \( N \).

\textbf{INPUT:}
• \( n \) – nonnegative integer
• weak – bool (default: False): if True only require weak Heegner hypothesis, which is the same as usual but without the condition that \( \gcd(D, N) = 1 \).

EXAMPLES:

```python
sage: X = heegner_points(37)
sage: X.discriminants(5)
[-7, -11, -40, -47, -67]
```

The default is 10:

```python
sage: X.discriminants()
[-7, -11, -40, -47, -67, -71, -83, -84, -95, -104]
sage: X.discriminants(15)
[-7, -11, -40, -47, -67, -71, -83, -84, -95, -104, -107, -115, -120, -123, -127]
```

The discriminant -111 satisfies only the weak Heegner hypothesis, since it is divisible by 37:

```python
sage: X.discriminants(15, weak=True)
[-7, -11, -40, -47, -67, -71, -83, -84, -95, -104, -107, -111, -115, -120, -123]
```

\texttt{reduce\_mod}(\texttt{ell})

Return object that allows for computation with Heegner points of level \( N \) modulo the prime \( \ell \), represented using quaternion algebras.

INPUT:

• \( \ell \) – prime

EXAMPLES:

```python
sage: heegner_points(389).reduce_mod(7).quaternion_algebra()
Quaternion Algebra (-1, -7) with base ring Rational Field
```

\texttt{class} \texttt{sage.schemes.elliptic_curves.heegner.HeegnerPoints\_level\_disc}(\texttt{N, D})

\texttt{Bases:} \texttt{sage.schemes.elliptic_curves.heegner.HeegnerPoints}

Set of Heegner points of given level and all conductors associated to a quadratic imaginary field.

EXAMPLES:

```python
sage: H = heegner_points(389, -7); H
Set of all Heegner points on X_0(389) associated to QQ[sqrt(-7)]
sage: type(H)
<class 'sage.schemes.elliptic_curves.heegner.HeegnerPoints_level_disc'>
sage: H._repr_()
'Set of all Heegner points on X_0(389) associated to QQ[sqrt(-7)]'
sage: H.discriminant()
-7
sage: H.quadratic_field()
Number Field in sqrt_minus_7 with defining polynomial \( x^2 + 7 \) with sqrt_minus_7 = 2.\n\rightarrow 64575131106459170*I
sage: H.kolyvagin_conductors()
[1, 3, 5, 13, 15, 17, 19, 31, 39, 41]
```

(continues on next page)
Elliptic curves, Release 9.7

loads(dumps(H)) == H
True

**discriminant()**
Return the discriminant of the quadratic imaginary extension $K$.

EXAMPLES:

sage: heegner_points(389,-7).discriminant()
-7

**kolyvagin_conductors**(r=None, n=10, E=None, m=None)
Return the first $n$ conductors that are squarefree products of distinct primes inert in the quadratic imaginary field $K = \mathbb{Q}(\sqrt{D})$. If $r$ is specified, return only conductors that are a product of $r$ distinct primes all inert in $K$. If $r = 0$, always return the list [1], no matter what.

If the optional elliptic curve $E$ and integer $m$ are given, then only include conductors $c$ such that for each prime divisor $p$ of $c$ we have $m \mid \gcd(a_p(E), p + 1)$.

INPUT:
• $r$ – (default: None) nonnegative integer or None
• $n$ – positive integer
• $E$ – an elliptic curve
• $m$ – a positive integer

EXAMPLES:

sage: H = heegner_points(389,-7)
sage: H.kolyvagin_conductors(0)
[1]
sage: H.kolyvagin_conductors(1)
[3, 5, 13, 17, 19, 31, 41, 47, 59, 61]
sage: H.kolyvagin_conductors(1,15)
[3, 5, 13, 17, 19, 31, 41, 47, 59, 61, 73, 83, 89, 97, 101]
sage: H.kolyvagin_conductors(1,5)
[3, 5, 13, 17, 19]
sage: H.kolyvagin_conductors(1,5,EllipticCurve('389a'),3)
[5, 17, 41, 59, 83]
sage: H.kolyvagin_conductors(2,5,EllipticCurve('389a'),3)
[85, 205, 295, 415, 697]

**quadratic_field()**
Return the quadratic imaginary field $K = \mathbb{Q}(\sqrt{D})$.

EXAMPLES:

sage: E = EllipticCurve('389a'); K = E.heegner_point(-7,5).ring_class_field()
sage: K.quadratic_field()
Number Field in sqrt_minus_7 with defining polynomial x^2 + 7 with sqrt_minus_7 → 2.6457513110645917*I

**class** sage.schemes.elliptic_curves.heegner.HeegnerPoints_level_disc_cond(N, D, c=1)
Bases: sage.schemes.elliptic_curves.heegner.HeegnerPoints_level, sage.schemes.elliptic_curves.heegner.HeegnerPoints_level_disc
The set of Heegner points of given level, discriminant, and conductor.

**EXAMPLES:**

```sage
sage: H = heegner_points(389,-7,5); H
All Heegner points of conductor 5 on X_0(389) associated to QQ[sqrt(-7)]
sage: type(H)
<class 'sage.schemes.elliptic_curves.heegner.HeegnerPoints_level_disc_cond'>
sage: H.discriminant()
-7
sage: H.level()
389
sage: len(H.points())
12
sage: H.points()[0]
Heegner point 5/778*sqrt(-7) - 147/778 of discriminant -7 and conductor 5 on X_0(389)
sage: H.betas()
(147, 631)
sage: H.quadratic_field()
Number Field in sqrt_minus_7 with defining polynomial x^2 + 7 with sqrt_minus_7 = 2.
˓→645751311064591?*I
sage: H.ring_class_field()
Ring class field extension of QQ[sqrt(-7)] of conductor 5
sage: H.kolyvagin_conductors()
[1, 3, 5, 13, 15, 17, 19, 31, 39, 41]
sage: H.satisfies_kolyvagin_hypothesis()
True
sage: H = heegner_points(389,-7,5)
sage: loads(dumps(H)) == H
True
```

**betas()**

Return the square roots of $Dc^2$ modulo $4N$ all reduced mod $2N$, without multiplicity.

**EXAMPLES:**

```sage
sage: X = heegner_points(45,-11,1); X
All Heegner points of conductor 1 on X_0(45) associated to QQ[sqrt(-11)]
sage: [x.quadratic_form() for x in X]
[45*x^2 + 13*x*y + y^2,
 45*x^2 + 23*x*y + 3*y^2,
 45*x^2 + 67*x*y + 25*y^2,
 45*x^2 + 77*x*y + 33*y^2]
sage: X.betas()
(13, 23, 67, 77)
sage: X.points(13)
(Heegner point 1/90*sqrt(-11) - 13/90 of discriminant -11 on X_0(45),)
sage: [x.quadratic_form() for x in X.points(13)]
[45*x^2 + 13*x*y + y^2]
```
**conductor()**
Return the level of the conductor.

**EXAMPLES:**
```
sage: heegner_points(389,-7,5).conductor()
5
```

**plot(*args, **kwds)**
Returns plot of all the representatives in the upper half plane of the Heegner points in this set of Heegner points.

The inputs to this function get passed onto the point command.

**EXAMPLES:**
```
sage: heegner_points(389,-7,5).plot(pointsize=50, rgbcolor='red')
Graphics object consisting of 12 graphics primitives
sage: heegner_points(53,-7,15).plot(pointsize=50, rgbcolor='purple')
Graphics object consisting of 48 graphics primitives
```

**points(beta=None)**
Return the Heegner points in self. If β is given, return only those Heegner points with given β, i.e., whose quadratic form has B congruent to β modulo 2N.

Use self.beta() to get a list of betas.

**EXAMPLES:**
```
sage: H = heegner_points(389,-7,5); H
All Heegner points of conductor 5 on X_0(389) associated to QQ[sqrt(-7)]
sage: H.points()
(Heegner point 5/778*sqrt(-7) - 147/778 of discriminant -7 and conductor 5 on X_0(389), ..., Heegner point 5/5446*sqrt(-7) - 757/778 of discriminant -7 and conductor 5 on X_0(389))
sage: H.betas()
(147, 631)
sage: [x.tau() for x in H.points(147)]
sage: [x.tau() for x in H.points(631)]
```

The result is cached and is a tuple (since it is immutable):
```
sage: H.points() is H.points()
True
sage: type(H.points())
<... 'tuple'>
```

**ring_class_field()**
Return the ring class field associated to this set of Heegner points. This is an extension $K_c$ over $K$, where $K$ is the quadratic imaginary field and $c$ the conductor associated to this Heegner point. This Heegner point
Elliptic curves, Release 9.7

point is defined over $K_c$ and the Galois group $Gal(K_c/K)$ acts transitively on the Galois conjugates of this Heegner point.

EXAMPLES:

```sage
sage: heegner_points(389,-7,5).ring_class_field()
Ring class field extension of QQ[sqrt(-7)] of conductor 5
```

`satisfies_kolyvagin_hypothesis()`
Return True if `self` satisfies the Kolyvagin hypothesis, i.e., that each prime dividing the conductor $c$ of `self` is inert in $K$ and coprime to $ND$.

EXAMPLES:

The prime 5 is inert, but the prime 11 is not:

```sage
sage: heegner_points(389,-7,5).satisfies_kolyvagin_hypothesis()
True
sage: heegner_points(389,-7,11).satisfies_kolyvagin_hypothesis()
False
```

```python
class sage.schemes.elliptic_curves.heegner.HeegnerQuatAlg(level, ell)

Bases: sage.structure.sage_object.SageObject

Heegner points viewed as supersingular points on the modular curve $X_0(N)/\mathbb{F}_\ell$.

EXAMPLES:

```sage
H = heegner_points(11).reduce_mod(13); H
Heegner points on $X_0(11)$ over $\mathbb{F}_{13}$
sage: type(H)
<class 'sage.schemes.elliptic_curves.heegner.HeegnerQuatAlg'>
sage: loads(dumps(H)) == H
True
```

`brandt_module()`
Return the Brandt module of right ideal classes that we used to represent the set of supersingular points on the modular curve.

EXAMPLES:

```sage
sage: heegner_points(11).reduce_mod(3).brandt_module()
Brandt module of dimension 2 of level 3*11 of weight 2 over Rational Field
```

```python

cyclic_subideal_p1(I, c)
Compute dictionary mapping 2-tuples that defined normalized elements of $P^1(\mathbb{Z}/c\mathbb{Z})$

INPUT:
• $I$ – right ideal of Eichler order or in quaternion algebra
• $c$ – square free integer (currently must be odd prime) and coprime to level, discriminant, characteristic, etc.

OUTPUT:
• dictionary mapping 2-tuples (u,v) to ideals

EXAMPLES:
```
```
sage: H = heegner_points(11).reduce_mod(7)
sage: I = H.brandt_module().right_ideals()[0]
sage: sorted(H.cyclic_subideal_p1(I,3).items())
[(0, 1),
 Fractional ideal (2 + 2*j + 32*k, 2*i + 8*j + 82*k, 12*j + 60*k, 132*k)),
((1, 0),
 Fractional ideal (2 + 10*j + 28*k, 2*i + 4*j + 62*k, 12*j + 60*k, 132*k)),
((1, 1),
 Fractional ideal (2 + 2*j + 76*k, 2*i + 4*j + 106*k, 12*j + 60*k, 132*k)),
((1, 2),
 Fractional ideal (2 + 10*j + 116*k, 2*i + 8*j + 38*k, 12*j + 60*k, 132*k))]
sage: len(H.cyclic_subideal_p1(I,17))
18

ell()  
Return the prime ℓ modulo which we are working.

EXAMPLES:

sage: heegner_points(11).reduce_mod(3).ell()
3
galois_group_over_hilbert_class_field(D, c)  
Return the Galois group of the extension of ring class fields \( K_c \) over the Hilbert class field \( K_1 \) of the quadratic imaginary field of discriminant \( D \).

INPUT:

- \( D \) – fundamental discriminant
- \( c \) – conductor (square-free integer)

EXAMPLES:

sage: N = 37; D = -7; ell = 17; c = 41; p = 3
sage: H = heegner_points(N).reduce_mod(ell)
sage: H.galois_group_over_hilbert_class_field(D, c)
Galois group of Ring class field extension of QQ[sqrt(-7)] of conductor 41 over α → Hilbert class field of QQ[sqrt(-7)]
galois_group_over_quadratic_field(D, c)  
Return the Galois group of the extension of ring class fields \( K_c \) over the quadratic imaginary field \( K \) of discriminant \( D \).

INPUT:

- \( D \) – fundamental discriminant
- \( c \) – conductor (square-free integer)

EXAMPLES:

sage: N = 37; D = -7; ell = 17; c = 41; p = 3
sage: H = heegner_points(N).reduce_mod(ell)
sage: H.galois_group_over_quadratic_field(D, c)
Galois group of Ring class field extension of QQ[sqrt(-7)] of conductor 41 over α → Number Field in sqrt_minus_7 with defining polynomial x^2 + 7 with sqrt_minus_7 = 2.6457513110645917*I
heegner_conductors($D, n=5$)
Return the first $n$ negative fundamental discriminants coprime to $N\ell$ such that $\ell$ is inert in the corresponding quadratic imaginary field and that field satisfies the Heegner hypothesis.

INPUT:
- $D$ – negative integer; a fundamental Heegner discriminant
- $n$ – positive integer (default: 5)

OUTPUT:
- list

EXAMPLES:

```sage
H = heegner_points(11).reduce_mod(3)
sage: H.heegner_conductors(-7)
[1, 2, 4, 5, 8]
sage: H.heegner_conductors(-7, 10)
[1, 2, 4, 5, 8, 10, 13, 16, 17, 19]
```

heegner_discriminants($n=5$)
Return the first $n$ negative fundamental discriminants coprime to $N\ell$ such that $\ell$ is inert in the corresponding quadratic imaginary field and that field satisfies the Heegner hypothesis, and $N$ is the level.

INPUT:
- $n$ – positive integer (default: 5)

OUTPUT:
- list

EXAMPLES:

```sage
H = heegner_points(11).reduce_mod(3)
sage: H.heegner_discriminants()
[-7, -19, -40, -43, -52]
sage: H.heegner_discriminants(10)
[-7, -19, -40, -43, -52, -79, -127, -139, -151, -184]
```

heegner_divisor($D, c=1$)
Return Heegner divisor as an element of the Brandt module corresponding to the discriminant $D$ and conductor $c$, which both must be coprime to $N\ell$.

More precisely, we compute the sum of the reductions of the $\Gal(K_1/K)$-conjugates of each choice of $y_1$, where the choice comes from choosing the ideal $\mathcal{N}$. Then we apply the Hecke operator $T_c$ to this sum.

INPUT:
- $D$ – discriminant (negative integer)
- $c$ – conductor (positive integer)

OUTPUT:
- Brandt module element

EXAMPLES:
```python
sage: H = heegner_points(11).reduce_mod(7)
sage: H.heegner_discriminants()
[-8, -39, -43, -51, -79]
sage: H.heegner_divisor(-8)
(1, 0, 0, 1, 0, 0)
sage: H.heegner_divisor(-39)
(1, 2, 1, 2, 0)
sage: H.heegner_divisor(-43)
(1, 0, 0, 1, 0, 0)
sage: H.heegner_divisor(-51)
(1, 0, 1, 0, 2)
sage: H.heegner_divisor(-79)
(3, 2, 3, 0, 0)
sage: sum(H.heegner_divisor(-39).element())
8
sage: QuadraticField(-39, 'a').class_number()
4
```

**kolyvagin_cyclic_subideals** (*I, p, alpha_quaternion*)

Return list of pairs (*J, n*) where *J* runs through the cyclic subideals of *I* of index (*Z*/p*Z*)², and *J ~ alpha^n(J₀)* for some fixed choice of cyclic subideal *J₀*.

**INPUT:**
- *I* – right ideal of the quaternion algebra
- *p* – prime number
- *alpha_quaternion* – image in the quaternion algebra of generator *alpha* for (*𝒪*ₖ/*.𝒪*ₖ)**/(*Z*/c*Z*).²

**OUTPUT:**
- list of 2-tuples

**EXAMPLES:**

```python
sage: N = 37; D = -7; ell = 17; c=5
sage: H = heegner_points(N).reduce_mod(ell)
sage: I = H.brandt_module().right_ideals()[49]
sage: f = H.optimal_embeddings(D, 1, I.left_order())[1]
sage: g = H.kolyvagin_generators(f.domain().number_field(), c)
sage: alpha_quaternion = f(g[0]); alpha_quaternion
1 - 77/192*i - 5/128*j - 137/384*k
sage: H.kolyvagin_cyclic_subideals(I, 5, alpha_quaternion)
[(Fractional ideal (2 + 2/3*i + 364*j + 31480/3*k, 4/3*i + 1202*j + 99290/3*k, ← 1280*j + 49920*k, 94720*k), 0),
 (Fractional ideal (2 + 2/3*i + 876*j + 236762/3*k, 4/3*i + 434*j + 236762/3*k, ← 1280*j + 49920*k, 94720*k), 1),
 (Fractional ideal (2 + 2/3*i + 364*j + 61432/3*k, 4/3*i + 1202*j + 99290/3*k, ← 1280*j + 49920*k, 94720*k), 2),
 (Fractional ideal (2 + 2/3*i + 876*j + 236762/3*k, 4/3*i + 61432/3*k, ← 1280*j + 49920*k, 94720*k), 3),
 (Fractional ideal (2 + 2/3*i + 876*j + 7672/3*k, 4/3*i + 342*j + 236672/3*k, ← 1280*j + 49920*k, 94720*k), 4),
 (Fractional ideal (2 + 2/3*i + 1132*j + 208120/3*k, 4/3*i + 946*j + 183002/3*k, ← 1280*j + 49920*k, 94720*k), 5)]```
**kolyvagin_generator**($K, p$)
Return element in $K$ that maps to the multiplicative generator for the quotient group

$$(\mathcal{O}_K/p\mathcal{O}_K)^* / (\mathbb{Z}/p\mathbb{Z})^*$$

of the form $\sqrt{D} + n$ with $n \geq 1$ minimal.

**INPUT:**
- $K$ – quadratic imaginary field
- $p$ – inert prime

**EXAMPLES:**

```sage
sage: N = 37; D = -7; ell = 17; p=5
sage: H = heegner_points(N).reduce_mod(ell)
sage: I = H.brandt_module().right_ideals()[49]
sage: f = H.optimal_embeddings(D, 1, I.left_order())[0]
sage: H.kolyvagin_generator(f.domain().number_field(), 5)
  a + 1
```

This function requires that $p$ be prime, but `kolyvagin_generators` works in general:

```sage
sage: H.kolyvagin_generator(f.domain().number_field(), 5*17)
Traceback (most recent call last):
  ...  NotImplementedError: p must be prime
sage: H.kolyvagin_generators(f.domain().number_field(), 5*17)
  [-34*a + 1, 35*a + 106]
```

**kolyvagin_generators**($K, c$)
Return elements in $\mathcal{O}_K$ that map to multiplicative generators for the factors of the quotient group

$$(\mathcal{O}_K/c\mathcal{O}_K)^* / (\mathbb{Z}/c\mathbb{Z})^*$$

corresponding to the prime divisors of $c$. Each generator is of the form $\sqrt{D} + n$ with $n \geq 1$ minimal.

**INPUT:**
- $K$ – quadratic imaginary field
- $c$ – square free product of inert prime

**EXAMPLES:**

```sage
sage: N = 37; D = -7; ell = 17; p=5
sage: H = heegner_points(N).reduce_mod(ell)
sage: I = H.brandt_module().right_ideals()[49]
sage: f = H.optimal_embeddings(D, 1, I.left_order())[0]
sage: H.kolyvagin_generators(f.domain().number_field(), 5*17)
  [-34*a + 1, 35*a + 106]
```

**kolyvagin_point_on_curve**($D, c, E, p, bound=10$)
Compute image of the Kolyvagin divisor $P_c$ in $E(F_\ell)/pE(F_\ell)$.

Note that this image is by definition only well defined up to scalars. However, doing multiple computations will always yield the same result, and working modulo different $\ell$ is compatible (since we always choose the same generator for $\text{Gal}(K_c/K_1)$).

**INPUT:**
• $D$ – fundamental negative discriminant
• $c$ – conductor
• $E$ – elliptic curve of conductor the level of self
• $p$ – odd prime number such that we consider image in $E(F_{\ell^2})/pE(F_{\ell^2})$
• bound – integer (default: 10)

EXAMPLES:

```
sage: N = 37; D = -7; ell = 17; c = 41; p = 3
sage: H = heegner_points(N).reduce_mod(ell)
sage: H.kolyvagin_point_on_curve(D, c, EllipticCurve('37a'), p)
[1, 1]
```

\textbf{kolyvagin\_sigma\_operator$(D, c, r, \text{bound=\texttt{None}})$}

Return the action of the Kolyvagin sigma operator on the $r$-th basis vector.

INPUT:

• $D$ – fundamental discriminant
• $c$ – conductor (square-free integer, need not be prime)
• $r$ – nonnegative integer
• bound – (default: \texttt{None}), if given, controls precision of computation of theta series, which could impact performance, but does not impact correctness

EXAMPLES:

We first try to verify Kolyvagin’s conjecture for a rank 2 curve by working modulo 5, but we are unlucky with $c = 17$:

```
sage: N = 389; D = -7; ell = 5; c = 17; q = 3
sage: H = heegner_points(N).reduce_mod(ell)
sage: E = EllipticCurve('389a')
sage: V = H.modp_dual_elliptic_curve_factor(E, q, 5)  # long time (4s on sage.math, 2012)
sage: k118 = H.kolyvagin\_sigma\_operator(D, c, 118)
sage: k104 = H.kolyvagin\_sigma\_operator(D, c, 104)
sage: [b.dot_product(k104.element().change\_ring(GF(3))) for b in V.basis()]  # long time
[0, 0]
sage: [b.dot_product(k118.element().change\_ring(GF(3))) for b in V.basis()]  # long time
[0, 0]
```

Next we try again with $c = 41$ and this does work, in that we get something nonzero, when dotting with $V$:

```
sage: c = 41
sage: k118 = H.kolyvagin\_sigma\_operator(D, c, 118)
sage: k104 = H.kolyvagin\_sigma\_operator(D, c, 104)
sage: [b.dot_product(k118.element().change\_ring(GF(3))) for b in V.basis()]  # long time
[2, 0]
```

(continues on next page)
By the way, the above is the first ever provable verification of Kolyvagin’s conjecture for any curve of rank at least 2.

Another example, but where the curve has rank 1:

```sage
N = 37; D = -7; ell = 17; c = 41; q = 3
H = heegner_points(N).reduce_mod(ell)
H.heegner_divisor(D,1).element().nonzero_positions()
[49, 51]
k49 = H.kolyvagin_sigma_operator(D, c, 49); k49
(79, 32, 31, 11, 53, 37, 1, 23, 15, 7, 0, 0, 0, 64, 32, 34, 53, 0, 27, 27, 0, 0, 0, 26, 0, 0, 18, 0, 22, 0, 53, 19, 27, 10, 0, 0, 30, 35, 38, 0, 0, 53, 37, 0, 0, 4, 0, 0, 0, 0)
k51 = H.kolyvagin_sigma_operator(D, c, 51); k51
(20, 12, 57, 0, 0, 0, 52, 23, 15, 7, 0, 0, 0, 19, 4, 0, 73, 11, 0, 104, 31, 0, 38, 31, 0, 0, 31, 5, 47, 0, 27, 35, 0, 57, 32, 24, 10, 0, 8, 0, 31, 41, 0, 0, 0, 16, 0, 0, 0, 0)
V = H.modp_dual_elliptic_curve_factor(EllipticCurve('37a1'), q, 5); V
Vector space of degree 52 and dimension 2 over Ring of integers modulo 3
Basis matrix:
2 x 52 dense matrix over Ring of integers modulo 3
[b.dot_product(k49.element().change_ring(GF(q))) for b in V.basis()]
[1, 1]
[b.dot_product(k51.element().change_ring(GF(q))) for b in V.basis()]
[1, 1]
```

An example with c a product of two primes:

```sage
N = 389; D = -7; ell = 5; q = 3
H = heegner_points(N).reduce_mod(ell)
V = H.modp_dual_elliptic_curve_factor(EllipticCurve('389a1'), q, 5)
k = H.kolyvagin_sigma_operator(D, 17*41, 104) # long time
k
# long time
(990, 656, 219, ..., 246, 534, 1254)
[b.dot_product(k.element().change_ring(GF(3))) for b in V.basis()] # long time (but only because depends on something slow)
[0, 0]
```

```left_orders()

Return the left orders associated to the representative right ideals in the Brandt module.

EXAMPLES:

```sage
heegner_points(11).reduce_mod(3).left_orders()
[Order of Quaternion Algebra (-1, -3) with base ring Rational Field with basis...
(1/2 + 1/2*j + 7*k, 1/2*i + 13/2*k, j + 3*k, 11*k),
Order of Quaternion Algebra (-1, -3) with base ring Rational Field with basis...
(1/2 + 1/2*j + 7*k, 1/4*i + 1/2*j + 63/4*k, j + 14*k, 22*k)]
```

14.23. Heegner points on elliptic curves over the rational numbers
level()  
Return the level.

EXAMPLES:

```sage
sage: heegner_points(11).reduce_mod(3).level()
11
```

modp_dual_elliptic_curve_factor($E$, $p$, $bound=10$)  
Return the factor of the Brandt module space modulo $p$ corresponding to the elliptic curve $E$, cut out using Hecke operators up to $bound$.

INPUT:

- $E$ – elliptic curve of conductor equal to the level of self
- $p$ – prime number
- $bound$ – positive integer (default: 10)

EXAMPLES:

```sage
sage: N = 37; D = -7; ell = 17; c = 41; q = 3
sage: H = heegner_points(N).reduce_mod(ell)
sage: V = H.modp_dual_elliptic_curve_factor(EllipticCurve('37a'), q, 5); V
Vector space of degree 52 and dimension 2 over Ring of integers modulo 3
Basis matrix:
2 x 52 dense matrix over Ring of integers modulo 3
```

modp_splitting_data($p$)  
Return mod $p$ splitting data for the quaternion algebra at the unramified prime $p$. This is a pair of $2 \times 2$ matrices $A$, $B$ over the finite field $\mathbb{F}_p$ such that if the quaternion algebra has generators $i, j, k$, then the homomorphism sending $i$ to $A$ and $j$ to $B$ maps any maximal order homomorphically onto the ring of $2 \times 2$ matrices.

Because of how the homomorphism is defined, we must assume that the prime $p$ is odd.

INPUT:

- $p$ – unramified odd prime

OUTPUT:

- 2-tuple of matrices over finite field

EXAMPLES:

```sage
sage: H = heegner_points(11).reduce_mod(7)
sage: H.quaternion_algebra()
Quaternion Algebra (-1, -7) with base ring Rational Field
sage: I, J = H.modp_splitting_data(13)
```

(continues on next page)
The following is a good test because of the asserts in the code:

```sage
v = [H.modp_splitting_data(p) for p in primes(13,200)]
```

Some edge cases:

```sage
H.modp_splitting_data(11)
```

```
( [[ 0 10] [6 1]], [[1 0], [1 5]])
```

Proper error handling:

```sage
H.modp_splitting_data(7)
```

```
Traceback (most recent call last):
... ValueError: p (=7) must be an unramified prime
```

```sage
H.modp_splitting_data(2)
```

```
Traceback (most recent call last):
... ValueError: p must be odd
```

**modp_splitting_map**\( (p) \)

Return (algebra) map from the \((p\text{-integral})\) quaternion algebra to the set of \(2 \times 2\) matrices over \(F_p\).

**INPUT:**

- \(p\) – prime number

**EXAMPLES:**

```sage
H = heegner_points(11).reduce_mod(7)
sage: f = H.modp_splitting_map(13)
sage: B = H.quaternion_algebra(); B
Quaternion Algebra (-1, -7) with base ring Rational Field
sage: i,j,k = H.quaternion_algebra().gens()
sage: a = 2+i-j+3*k; b = 7+2*i-4*j+k
sage: f(a*b)
[[12 3]
 [10 5]]
sage: f(a)*f(b)
[[12 3]
 [10 5]]
```

**optimal_embeddings**\((D, c, R)\)

**INPUT:**

- \(D\) – negative fundamental discriminant
• $c$ – integer coprime
• $R$ – Eichler order

EXAMPLES:

```
sage: H = heegner_points(11).reduce_mod(3)
sage: R = H.left_orders()[0]
sage: H.optimal_embeddings(-7, 1, R)
[Embedding sending $\sqrt{-7}$ to $i - j - k$,
 Embedding sending $\sqrt{-7}$ to $-i + j + k$]
sage: H.optimal_embeddings(-7, 2, R)
[Embedding sending $2\sqrt{-7}$ to $5i - k$,
 Embedding sending $2\sqrt{-7}$ to $-5i + k$,
 Embedding sending $2\sqrt{-7}$ to $2i - 2j - 2k$,
 Embedding sending $2\sqrt{-7}$ to $-2i + 2j + 2k$]
```

`quadratic_field(D)`

Return our fixed choice of quadratic imaginary field of discriminant $D$.

INPUT:
• $D$ – fundamental discriminant

OUTPUT:
• a quadratic number field

EXAMPLES:

```
sage: H = heegner_points(389).reduce_mod(5)
sage: H.quadratic_field(-7)
Number Field in sqrt_minus_7 with defining polynomial $x^2 + 7$ with sqrt_minus_7 → 2.645751311064591*I
```

`quaternion_algebra()`

Return the rational quaternion algebra used to implement self.

EXAMPLES:

```
sage: heegner_points(389).reduce_mod(7).quaternion_algebra()
Quaternion Algebra (-1, -7) with base ring Rational Field
```

`rational_kolyvagin_divisor(D, c)`

Return the Kolyvagin divisor as an element of the Brandt module corresponding to the discriminant $D$ and conductor $c$, which both must be coprime to $N\ell$.

INPUT:
• $D$ – discriminant (negative integer)
• $c$ – conductor (positive integer)

OUTPUT:
• Brandt module element (or tuple of them)

EXAMPLES:
sage: N = 389; D = -7; ell = 5; c = 17; q = 3
sage: H = heegner_points(N).reduce_mod(ell)
sage: k = H.rational_kolyvagin_divisor(D, c); k  # long time (5s on sage.math, 2013)
(2, 0, 0, 0, 0, 16, 0, 0, 0, 4, 0, 0, 9, 11, 0, 0, 0, 7, 0, 0, 0, 0, ...
 → 14, 12, 13, 15, 17, 0, 0, 0, 8, 0, 0, 0, 10, 0, 0, 0, 0, 0, 0, 0, 0, ...
 → 5, 0, 0, 0, 0, 3, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, ...
 → 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, ...
 → 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, ...
 → 0, 0, 0, 0, 0, 0)
sage: V = H.modp_dual_elliptic_curve_factor(EllipticCurve('389a'), q, 2)
sage: [b.dot_product(k.element().change_ring(GF(q))) for b in V.basis()]  # long time
[0, 0]
sage: k = H.rational_kolyvagin_divisor(D, 59)
sage: [b.dot_product(k.element().change_ring(GF(q))) for b in V.basis()]
[2, 0]

right_ideals()

Return representative right ideals in the Brandt module.

EXAMPLES:

sage: heegner_points(11).reduce_mod(3).right_ideals()
(Fractional ideal (2 + 2*j + 28*k, 2*i + 26*k, 4*j + 12*k, 44*k),
 Fractional ideal (2 + 2*j + 28*k, 2*i + 4*j + 38*k, 8*j + 24*k, 88*k))

satisfies_heegner_hypothesis(D, c=1)

The fundamental discriminant $D$ must be coprime to $N\ell$, and must define a quadratic imaginary field $K$ in which $\ell$ is inert. Also, all primes dividing $N$ must split in $K$, and $c$ must be squarefree and coprime to $ND\ell$.

INPUT:

- $D$ – negative integer
- $c$ – positive integer (default: 1)

OUTPUT:

- bool

EXAMPLES:

sage: H = heegner_points(11).reduce_mod(7)
sage: H.satisfies_heegner_hypothesis(-5)
False
sage: H.satisfies_heegner_hypothesis(-7)
False
sage: H.satisfies_heegner_hypothesis(-8)
True
sage: [D for D in [-1,-2..-100] if H.satisfies_heegner_hypothesis(D)]
[-8, -39, -43, -51, -79, -95]

class sage.schemes.elliptic_curves.heegner.HeegnerQuatAlgEmbedding(D, c, R, beta)

Bases: sage.structure.sage_object.SageObject

14.23. Heegner points on elliptic curves over the rational numbers 537
The homomorphism $\mathcal{O} \to R$, where $\mathcal{O}$ is the order of conductor $c$ in the quadratic field of discriminant $D$, and $R$ is an Eichler order in a quaternion algebra.

EXAMPLES:

```python
sage: H = heegner_points(11).reduce_mod(3); R = H.left_orders()[0]
sage: f = H.optimal_embeddings(-7, 2, R)[1]; f
Embedding sending $2\sqrt{-7}$ to $-5i + k$
sage: type(f)
<class 'sage.schemes.elliptic_curves.heegner.HeegnerQuatAlgEmbedding'>
sage: loads(dumps(f)) == f
True
```

**beta()**

Return the element $\beta$ in the quaternion algebra order that $c\sqrt{D}$ maps to.

EXAMPLES:

```python
sage: H = heegner_points(11).reduce_mod(3); R = H.left_orders()[0]
sage: H.optimal_embeddings(-7, 2, R)[1].beta()
-5i + k
```

**codomain()**

Return the codomain of this embedding.

EXAMPLES:

```python
sage: H = heegner_points(11).reduce_mod(3); R = H.left_orders()[0]
sage: H.optimal_embeddings(-7, 2, R)[0].codomain()
Order of Quaternion Algebra $(-1, -3)$ with base ring Rational Field with basis $\langle 1/2 + 1/2j + 7k, 1/2i + 13/2k, j + 3k, 11k \rangle$
```

**conjugate()**

Return the conjugate of this embedding, which is also an embedding.

EXAMPLES:

```python
sage: H = heegner_points(11).reduce_mod(3); R = H.left_orders()[0]
sage: f = H.optimal_embeddings(-7, 2, R)[1]
sage: f.conjugate()
Embedding sending $2\sqrt{-7}$ to $5i - k$
sage: f
Embedding sending $2\sqrt{-7}$ to $-5i + k$
```

**domain()**

Return the domain of this embedding.

EXAMPLES:

```python
sage: H = heegner_points(11).reduce_mod(3); R = H.left_orders()[0]
sage: H.optimal_embeddings(-7, 2, R)[0].domain()
Order in Number Field in a with defining polynomial $x^2 + 7$ with a = 2.
\langle 645751311064591*I \rangle
```

**domain_conductor()**

Return the conductor of the domain.

EXAMPLES:
Elliptic curves, Release 9.7

```
sage: H = heegner_points(11).reduce_mod(3); R = H.left_orders()[0]
sage: H.optimal_embeddings(-7, 2, R)[0].domain_conductor()
2

domain_gen()

Return the specific generator $c\sqrt{D}$ for the domain order.

EXAMPLES:
```
sage: H = heegner_points(11).reduce_mod(3); R = H.left_orders()[0]
sage: f = H.optimal_embeddings(-7, 2, R)[0]
sage: f.domain_gen()
2*a
sage: f.domain_gen()^2
-28
```

matrix()

Return matrix over $\mathbb{Q}$ of this morphism, with respect to the basis $1, c\sqrt{D}$ of the domain and the basis $1, i, j, k$ of the ambient rational quaternion algebra (which contains the domain).

EXAMPLES:
```
sage: H = heegner_points(11).reduce_mod(3); R = H.left_orders()[0]
sage: f = H.optimal_embeddings(-7, 1, R)[1]; f
Embedding sending sqrt(-7) to -i + j + k
sage: f.matrix()
[ 1 0 0 0]
[ 0 -1 1 1]
sage: f.conjugate().matrix()
[ 1 0 0 0]
[ 0 1 -1 -1]
```

class sage.schemes.elliptic_curves.heegner.KolyvaginCohomologyClass(kolyvagin_point, n)

Bases: sage.structure.sage_object.SageObject

A Kolyvagin cohomology class in $H^1(K, E[n])$ or $H^1(K, E)[n]$ attached to a Heegner point.

EXAMPLES:
```
sage: y = EllipticCurve('37a').heegner_point(-7)
sage: c = y.kolyvagin_cohomology_class(3); c
Kolyvagin cohomology class c(1) in H^1(K,E[3])
sage: type(c)
<class 'sage.schemes.elliptic_curves.heegner.KolyvaginCohomologyClassEn'>
sage: loads(dumps(c)) == c
True
sage: y.kolyvagin_cohomology_class(5)
Kolyvagin cohomology class c(1) in H^1(K,E[5])
```

conductor()

Return the integer $c$ such that this cohomology class is associated to the Heegner point $y_c$.

EXAMPLES:
```
sage: y = EllipticCurve('37a').heegner_point(-7,5)
sage: t = y.kolyvagin_cohomology_class()
```

(continues on next page)
heegner_point()
Return the Heegner \(y_c\) to which this cohomology class is associated.

EXAMPLES:

```
sage: y = EllipticCurve('37a').heegner_point(-7,5)
sage: t = y.kolyvagin_cohomology_class()
sage: t.heegner_point()
Heegner point of discriminant -7 and conductor 5 on elliptic curve of conductor 37
```

colyvagin_point()

Return the Kolyvagin point \(P_c\) to which this cohomology class is associated.

EXAMPLES:

```
sage: y = EllipticCurve('37a').heegner_point(-7,5)
sage: t = y.kolyvagin_cohomology_class()
sage: t.kolyvagin_point()
Kolyvagin point of discriminant -7 and conductor 5 on elliptic curve of conductor 37
```

n()

Return the integer \(n\) so that this is a cohomology class in \(H^1(K, E[n])\) or \(H^1(K, E)[n]\).

EXAMPLES:

```
sage: y = EllipticCurve('37a').heegner_point(-7)
sage: t = y.kolyvagin_cohomology_class(3); t
Kolyvagin cohomology class c(1) in H^1(K,E[3])
sage: t.n()
3
```

class sage.schemes.elliptic_curves.heegner.KolyvaginCohomologyClassEn(kolyvagin_point, n)

Bases: sage.schemes.elliptic_curves.heegner.KolyvaginCohomologyClass

EXAMPLES:

class sage.schemes.elliptic_curves.heegner.KolyvaginPoint(heegner_point)

Bases: sage.schemes.elliptic_curves.heegner.HeegnerPoint

A Kolyvagin point.

EXAMPLES:

We create a few Kolyvagin points:

```
sage: EllipticCurve('11a1').kolyvagin_point(-7)
Kolyvagin point of discriminant -7 on elliptic curve of conductor 11
sage: EllipticCurve('37a1').kolyvagin_point(-7)
Kolyvagin point of discriminant -7 on elliptic curve of conductor 37
sage: EllipticCurve('37a1').kolyvagin_point(-67)
Kolyvagin point of discriminant -67 on elliptic curve of conductor 37
```
One can also associated a Kolyvagin point to a Heegner point:

```python
sage: y = EllipticCurve('37a1').heegner_point(-7); y
Heegner point of discriminant -7 on elliptic curve of conductor 37
```

```python
sage: y.kolyvagin_point()
Kolyvagin point of discriminant -7 on elliptic curve of conductor 37
```

\textbf{curve()}

Return the elliptic curve over $\mathbb{Q}$ on which this Kolyvagin point sits.

**EXAMPLES:**

```python
sage: E = EllipticCurve('37a1'); P = E.kolyvagin_point(-67, 3)
sage: P.curve()
Elliptic Curve defined by y^2 + y = x^3 - x over Rational Field
```

\textbf{heegner_point()}

This Kolyvagin point $P_c$ is associated to some Heegner point $y_c$ via Kolyvagin’s construction. This function returns that point $y_c$.

**EXAMPLES:**

```python
sage: E = EllipticCurve('37a1')
sage: P = E.kolyvagin_point(-67); P
Kolyvagin point of discriminant -67 on elliptic curve of conductor 37
```

```python
sage: y = P.heegner_point(); y
Heegner point of discriminant -67 on elliptic curve of conductor 37
```

```python
sage: y.kolyvagin_point() is P
True
```

\textbf{index(*args, **kwds)}

Return index of this Kolyvagin point in the full group of $K_c$ rational points on $E$.

When the conductor is 1, this is computed numerically using the Gross-Zagier formula and explicit point search, and it may be off by 2. See the documentation for $E$.heegner_index, where $E$ is the curve attached to self.

**EXAMPLES:**

```python
sage: E = EllipticCurve('37a1'); P = E.kolyvagin_point(-67); P.index()
6
```

\textbf{kolyvagin_cohomology_class(n=None)}

**INPUT:**

- $n$ – positive integer that divides the gcd of $a_p$ and $p + 1$ for all $p$ dividing the conductor. If $n$ is $\text{None}$, choose the largest valid $n$.

**EXAMPLES:**

```python
sage: y = EllipticCurve('389a1').heegner_point(-7, 5)
sage: P = y.kolyvagin_point()
```
Elliptic curves, Release 9.7

```python
sage: P.kolyvagin_cohomology_class(3)
Kolyvagin cohomology class c(5) in H^1(K,E[3])

sage: y = EllipticCurve('37a').heegner_point(-7,5).kolyvagin_point()
sage: y.kolyvagin_cohomology_class()
Kolyvagin cohomology class c(5) in H^1(K,E[2])
```

\[ \text{mod}(p, \text{prec}=53) \]

Return the trace of the reduction \( Q \) modulo a prime over \( p \) of this Kolyvagin point as an element of \( E(F_p) \), where \( p \) is any prime that is inert in \( K \) that is coprime to \( NDc \).

The point \( Q \) is only well defined up to an element of \( (p+1)E(F_p) \), i.e., it gives a well defined element of the abelian group \( E(F_p) / (p+1)E(F_p) \).

See [St2011b], Proposition 5.4 for a proof of the above well-definedness assertion.

EXAMPLES:

A Kolyvagin point on a rank 1 curve:

```python
sage: E = EllipticCurve('37a1'); P = E.kolyvagin_point(-67)
sage: P.mod(2)
(1 : 1 : 1)
sage: P.mod(3)
(1 : 0 : 1)
sage: P.mod(5)
(2 : 2 : 1)
sage: P.mod(7)
(6 : 0 : 1)
sage: P.trace_to_real_numerical()
(1.61355529131986 : -2.18446840788880 : 1.00000000000000)
sage: P._trace_exact_conductor_1() # the actual point we're reducing
(1357/841 : -53277/24389 : 1)
sage: (P._trace_exact_conductor_1().height() / E.regulator()).sqrt()
12.0000000000000
```

Here the Kolyvagin point is a torsion point (since \( E \) has rank 1), and we reduce it modulo several primes.

```python
sage: E = EllipticCurve('11a1'); P = E.kolyvagin_point(-7)
sage: P.mod(3,70) # long time (4s on sage.math, 2013)
(1 : 2 : 1)
sage: P.mod(5,70)
(1 : 4 : 1)
sage: P.mod(7,70)
Traceback (most recent call last):
... ValueError: p must be coprime to conductors and discriminant
sage: P.mod(11,70)
Traceback (most recent call last):
... ValueError: p must be coprime to conductors and discriminant
sage: P.mod(13,70)
(3 : 4 : 1)
```

542 Chapter 14. Elliptic curves over number fields
numerical_approx(\texttt{prec=53})

Return a numerical approximation to this Kolyvagin point using \texttt{prec} bits of working precision.

\textbf{INPUT:}

- \texttt{prec} – precision in bits (default: 53)

\textbf{EXAMPLES:}

```python
sage: P = EllipticCurve('37a1').kolyvagin_point(-7); P
Kolyvagin point of discriminant -7 on elliptic curve of conductor 37
sage: P.numerical_approx()  # approx. (0 : 0 : 1)
(...e-16 - ...e-16*I : ...e-16 + ...e-16*I : 1.00000000000000)
sage: P.numerical_approx(100)[0].abs() < 2.0^-99
True
```

Numerical approximation is only implemented for points of conductor 1:

```python
sage: P.numerical_approx()
Traceback (most recent call last):
...
NotImplementedError
```

\textbf{plot}(\texttt{prec=53}, \texttt{*args}, \texttt{**kwds})

Plot a Kolyvagin point \(P_1\) if it is defined over the rational numbers.

\textbf{EXAMPLES:}

```python
sage: E = EllipticCurve('37a'); P = E.heegner_point(-11).kolyvagin_point()
sage: P.plot(prec=30, pointsize=50, rgbcolor='red') + E.plot()
Graphics object consisting of 3 graphics primitives
```

point_exact(\texttt{prec=53})

\textbf{INPUT:}

- \texttt{prec} – precision in bits (default: 53)

\textbf{EXAMPLES:}

A rank 1 curve:

```python
sage: E = EllipticCurve('37a1'); P = E.kolyvagin_point(-67)
sage: P.point_exact()
(6 : -15 : 1)
sage: P.point_exact(40)
(6 : -15 : 1)
sage: P.point_exact(20)
Traceback (most recent call last):
...
RuntimeError: insufficient precision to find exact point
```

A rank 0 curve:
A rank 2 curve:

```
sage: E = EllipticCurve('389a1'); P = E.kolyvagin_point(-7)
sage: P.point_exact()
(0 : 1 : 0)
```

**satisfies_kolyvagin_hypothesis** (*n=None*)

Return True if this Kolyvagin point satisfies the Heegner hypothesis for *n*, so that it defines a Galois equivariant element of $\mathcal{E}(\mathbb{K}_c)/\mathcal{E}$. 

**EXAMPLES:**

```
sage: y = EllipticCurve('389a').heegner_point(-7,5); P = y.kolyvagin_point()
sage: P.kolyvagin_cohomology_class(3)
sage: P.satisfies_kolyvagin_hypothesis(3)
True
sage: P.satisfies_kolyvagin_hypothesis(5)
False
sage: P.satisfies_kolyvagin_hypothesis(7)
False
sage: P.satisfies_kolyvagin_hypothesis(11)
False
```

**trace_to_real_numerical** (*prec=53*)

Return the trace of this Kolyvagin point down to the real numbers, computed numerically using *prec* bits of working precision.

**EXAMPLES:**

```
sage: E = EllipticCurve('37a1'); P = E.kolyvagin_point(-67)
sage: PP = P.numerical_approx()
[1.61355529131986 : -2.18446840788880 : 1.00000000000000]
sage: all(c.imag().abs() < 1e-14 for c in PP)
True
```

**class** `sage.schemes.elliptic_curves.heegner.RingClassField(D, c, check=True)`

Bases: `sage.structure.sage_object.SageObject`

A Ring class field of a quadratic imaginary field of given conductor.

**Note:** This is a ring class field, not a ray class field. In general, the ring class field of given conductor is a subfield of the ray class field of the same conductor.

**EXAMPLES:**
Elliptic curves, Release 9.7

```python
sage: heegner_point(37,-7).ring_class_field()
Hilbert class field of QQ[sqrt(-7)]
sage: heegner_point(37,-7,5).ring_class_field()
Ring class field extension of QQ[sqrt(-7)] of conductor 5
sage: heegner_point(37,-7,55).ring_class_field()
Ring class field extension of QQ[sqrt(-7)] of conductor 55
```

**absolute_degree()**

Return the absolute degree of this field over \( \mathbb{Q} \).

**EXAMPLES:**

```python
sage: E = EllipticCurve('389a'); K = E.heegner_point(-7,5).ring_class_field()
sage: K.absolute_degree()
12
sage: K.degree_over_K()
6
```

**conductor()**

Return the conductor of this ring class field.

**EXAMPLES:**

```python
sage: E = EllipticCurve('389a'); K5 = E.heegner_point(-7,5).ring_class_field()
sage: K5.conductor()
5
```

**degree_over_H()**

Return the degree of this field over the Hilbert class field \( H \) of \( K \).

**EXAMPLES:**

```python
sage: E = EllipticCurve('389a')
sage: E.heegner_point(-59).ring_class_field().degree_over_H()
1
sage: E.heegner_point(-59).ring_class_field().degree_over_K()
3
sage: QuadraticField(-59,'a').class_number()
3
```

Some examples in which prime dividing \( c \) is inert:

```python
sage: heegner_point(37,-7,3).ring_class_field().degree_over_H()
4
sage: heegner_point(37,-7,3^2).ring_class_field().degree_over_H()
12
sage: heegner_point(37,-7,3^3).ring_class_field().degree_over_H()
36
```

The prime dividing \( c \) is split. For example, in the first case \( O_K/cO_K \) is isomorphic to a direct sum of two copies of \( \mathbb{GF}(2) \), so the units are trivial:

```python
sage: heegner_point(37,-7,2).ring_class_field().degree_over_H()
1
sage: heegner_point(37,-7,4).ring_class_field().degree_over_H()
```

(continues on next page)
2
sage: heegner_point(37,-7,8).ring_class_field().degree_over_H()
4

Now $c$ is ramified:

sage: heegner_point(37,-7,7).ring_class_field().degree_over_H()
7
sage: heegner_point(37,-7,7^2).ring_class_field().degree_over_H()
49

Check that trac ticket #15218 is solved:

sage: E = EllipticCurve("19a");
sage: s = E.heegner_point(-3,2).ring_class_field().galois_group().complex_→conjugation()
sage: H = s.domain(); H.absolute_degree()
2

\textbf{degree\_over\_K()}

Return the relative degree of this ring class field over the quadratic imaginary field $K$.

\textbf{EXAMPLES:}

sage: E = EllipticCurve('389a'); P = E.heegner_point(-7,5)
sage: K5 = P.ring_class_field(); K5
Ring class field extension of QQ[\sqrt{7}] of conductor 5
sage: K5.degree_over_K()
6
sage: type(K5.degree_over_K())
<... 'sage.rings.integer.Integer'>

sage: E = EllipticCurve('389a'); E.heegner_point(-20).ring_class_field().degree_→over_K()
2
sage: E.heegner_point(-20,3).ring_class_field().degree_over_K()
4
sage: kronecker(-20,11)
-1
sage: E.heegner_point(-20,11).ring_class_field().degree_over_K()
24

\textbf{degree\_over\_Q()}

Return the absolute degree of this field over $\mathbb{Q}$.

\textbf{EXAMPLES:}

sage: E = EllipticCurve('389a'); K = E.heegner_point(-7,5).ring_class_field()
sage: K.absolute_degree()
12
sage: K.degree_over_K()
6

\textbf{discriminant\_of\_K()}

Return the discriminant of the quadratic imaginary field $K$ contained in \texttt{self}.
EXAMPLES:

```
sage: E = EllipticCurve('389a'); K5 = E.heegner_point(-7,5).ring_class_field()
sage: K5.discriminant_of_K()
-7
```

**galois_group** *(base=Rational Field)*

Return the Galois group of *self* over *base*.

**INPUT:**

- *base* – (default: *Q*) a subfield of *self* or *Q*

**EXAMPLES:**

```
sage: E = EllipticCurve('389a')
sage: A = E.heegner_point(-7,5).ring_class_field()
sage: A.galois_group()
Galois group of Ring class field extension of QQ[sqrt(-7)] of conductor 5
sage: B = E.heegner_point(-7).ring_class_field()
sage: C = E.heegner_point(-7,15).ring_class_field()
sage: A.galois_group()
Galois group of Ring class field extension of QQ[sqrt(-7)] of conductor 5
sage: A.galois_group(B)
Galois group of Ring class field extension of QQ[sqrt(-7)] of conductor 5 over...
˓→Hilbert class field of QQ[sqrt(-7)]
sage: A.galois_group().cardinality()
12
sage: A.galois_group(B).cardinality()
6
sage: C.galois_group(A)
Galois group of Ring class field extension of QQ[sqrt(-7)] of conductor 15 over...
˓→Ring class field extension of QQ[sqrt(-7)] of conductor 5
sage: C.galois_group(A).cardinality()
4
```

**is_subfield** *(M)*

Return True if this ring class field is a subfield of the ring class field *M*. If *M* is not a ring class field, then a TypeError is raised.

**EXAMPLES:**

```
sage: E = EllipticCurve('389a')
sage: A = E.heegner_point(-7,5).ring_class_field()
sage: B = E.heegner_point(-7).ring_class_field()
sage: C = E.heegner_point(-20).ring_class_field()
sage: D = E.heegner_point(-7,15).ring_class_field()
sage: B.is_subfield(A)
True
sage: B.is_subfield(B)
True
sage: B.is_subfield(D)
True
sage: B.is_subfield(C)
False
sage: A.is_subfield(B)
```

(continues on next page)
quadratic_field()
Return the quadratic imaginary field $K = \mathbb{Q}(\sqrt{D})$.

EXAMPLES:

```sage
sage: E = EllipticCurve('389a'); K = E.heegner_point(-7,5).ring_class_field()
sage: K.quadratic_field()
Number Field in sqrt_minus_7 with defining polynomial x^2 + 7 with sqrt_minus_7 → 2.645751311064591?*I
```

ramified_primes()
Return the primes of $\mathbb{Z}$ that ramify in this ring class field.

EXAMPLES:

```sage
sage: E = EllipticCurve('389a'); K55 = E.heegner_point(-7,55).ring_class_field()
sage: K55.ramified_primes()
[5, 7, 11]
sage: E.heegner_point(-7).ring_class_field().ramified_primes()
[7]
```

sage.schemes.elliptic_curves.heegner.class_number($D$)
Return the class number of the quadratic field with fundamental discriminant $D$.

INPUT:

- $D$ – integer

EXAMPLES:

```sage
sage: sage.schemes.elliptic_curves.heegner.class_number(-20)
2
sage: sage.schemes.elliptic_curves.heegner.class_number(-23)
3
sage: sage.schemes.elliptic_curves.heegner.class_number(-163)
1
```

A ValueError is raised when $D$ is not a fundamental discriminant:

```sage
sage: sage.schemes.elliptic_curves.heegner.class_number(-5)
Traceback (most recent call last):
  ...
ValueError: D (-5) must be a fundamental discriminant
```

sage.schemes.elliptic_curves.heegner.ell_heegner_discriminants($self$, bound)
Return the list of $self$’s Heegner discriminants between -1 and -bound.

INPUT:

- bound (int) – upper bound for -discriminant

OUTPUT: The list of Heegner discriminants between -1 and -bound for the given elliptic curve.

EXAMPLES:
sage: E = EllipticCurve('11a')
sage: E.heegner_discriminants(30)  # indirect doctest
[-7, -8, -19, -24]

sage.schemes.elliptic_curves.heegner.ell_heegner_discriminants_list(self, n)
Return the list of self’s first n Heegner discriminants smaller than -5.

INPUT:
• n (int) – the number of discriminants to compute

OUTPUT: The list of the first n Heegner discriminants smaller than -5 for the given elliptic curve.

EXAMPLES:
sage: E = EllipticCurve('11a')
sage: E.heegner_discriminants_list(4)  # indirect doctest
[-7, -8, -19, -24]

sage.schemes.elliptic_curves.heegner.ell_heegner_point(self, D, c=1, f=None, check=True)
Returns the Heegner point on this curve associated to the quadratic imaginary field \( K = \mathbb{Q}(\sqrt{D}) \).

If the optional parameter \( c \) is given, returns the higher Heegner point associated to the order of conductor \( c \).

INPUT:
• \( D \) – a Heegner discriminant
• \( c \) – (default: 1) conductor, must be coprime to \( DN \)
• \( f \) – binary quadratic form or 3-tuple \((A, B, C)\) of coefficients of \( AX^2 + BXY + CY^2 \)
• check – bool (default: True)

OUTPUT:
The Heegner point \( y_c \).

EXAMPLES:
sage: E = EllipticCurve('37a')
sage: E.heegner_discriminants_list(10)
[-7, -11, -40, -47, -67, -71, -83, -84, -95, -104]
sage: P = E.heegner_point(-7); P  # indirect doctest
Heegner point of discriminant -7 on elliptic curve of conductor 37
sage: P.point_exact()
(0 : 0 : 1)
sage: P.curve()
Elliptic Curve defined by y^2 + y = x^3 - x over Rational Field
sage: P = E.heegner_point(-40).point_exact(); P
(a : -a + 1 : 1)
sage: P = E.heegner_point(-47).point_exact(); P
(a : a^4 + a - 1 : 1)
sage: P[0].parent()
Number Field in a with defining polynomial x^5 - x^4 + x^3 + x^2 - 2*x + 1

Working out the details manually:

14.23. Heegner points on elliptic curves over the rational numbers
sage: P = E.heegner_point(-47).numerical_approx(prec=200)
sage: f = algdep(P[0], 5); f
x^5 - x^4 + x^3 + x^2 - 2*x + 1
sage: f.discriminant().factor()
47^2
The Heegner hypothesis is checked:

sage: E = EllipticCurve('389a'); P = E.heegner_point(-5, 7);
Traceback (most recent call last):
...
ValueError: N (=389) and D (=5) must satisfy the Heegner hypothesis

We can specify the quadratic form:

sage: P = EllipticCurve('389a').heegner_point(-7, 5, (778, 925, 275)); P
Heegner point of discriminant -7 and conductor 5 on elliptic curve of conductor 389
sage: P.quadratic_form()
778*x^2 + 925*x*y + 275*y^2

sage.schemes.elliptic_curves.heegner.heegner_index(self, D, min_p=2, prec=5,
        descent_second_limit=12,
        verbose_mwrank=False, check_rank=True)

Return an interval that contains the index of the Heegner point \( y_K \) in the group of \( K \)-rational points modulo torsion on this elliptic curve, computed using the Gross-Zagier formula and/or a point search, or possibly half the index if the rank is greater than one.

If the curve has rank > 1, then the returned index is infinity.

Note: If \( \text{min}_p \) is bigger than 2 then the index can be off by any prime less than \( \text{min}_p \). This function returns the index divided by 2 exactly when the rank of \( E(K) \) is greater than 1 and \( E(\mathbb{Q})_{\text{tor}} \oplus E^D(\mathbb{Q})_{\text{tor}} \) has index 2 in \( E(K)_{\text{tor}} \), where the second factor undergoes a twist.

INPUT:

- \( D \) (int) – Heegner discriminant
- \( \text{min}_p \) (int) – (default: 2) only rule out primes = \( \text{min}_p \) dividing the index.
- \( \text{verbose}_\text{mwrank} \) (bool) – (default: False); print lots of mwrank search status information when computing regulator
- \( \text{prec} \) (int) – (default: 5), use \( \text{prec}*\sqrt{N} + 20 \) terms of L-series in computations, where \( N \) is the conductor.
- \( \text{descent}_\text{second}_\text{limit} \) – (default: 12)- used in 2-descent when computing regulator of the twist
- \( \text{check}_\text{rank} \) – whether to check if the rank is at least 2 by computing the Mordell-Weil rank directly.

OUTPUT: an interval that contains the index, or half the index

EXAMPLES:

sage: E = EllipticCurve('11a')
sage: E.heegner_discriminants(50)
[-7, -8, -19, -24, -35, -39, -40, -43]
Elliptic curves, Release 9.7

sage: E.heegner_index(-7)
1.0000?

sage: E = EllipticCurve('37b')
sage: E.heegner_discriminants(100)
[-3, -4, -7, -11, -40, -47, -67, -71, -83, -84, -95]
sage: E.heegner_index(-95)  # long time (1 second)
2.0000?

This tests doing direct computation of the Mordell-Weil group.

sage: EllipticCurve('675b').heegner_index(-11)
3.000?

Currently discriminants -3 and -4 are not supported:

sage: E.heegner_index(-3)
Traceback (most recent call last):
  ... ArithmeticError: Discriminant (=3) must not be -3 or -4.

The curve 681b returns the true index, which is 3:

sage: E = EllipticCurve('681b')
sage: I = E.heegner_index(-8); I
3.000?

In fact, whenever the returned index has a denominator of 2, the true index is got by multiplying the returned index by 2. Unfortunately, this is not an if and only if condition, i.e., sometimes the index must be multiplied by 2 even though the denominator is not 2.

This example demonstrates the descent_second_limit option, which can be used to fine tune the 2-descent used to compute the regulator of the twist:

sage: E = EllipticCurve([1,-1,0,-1228,-16267])
sage: E.heegner_index(-8)
Traceback (most recent call last):
  ... ArithmeticError: Discriminant (-8) must not be -3 or -4.

However when we search higher, we find the points we need:

sage: E.heegner_index(-8, descent_second_limit=16, check_rank=False)  # long time
2.0000?

Two higher rank examples (of ranks 2 and 3):

sage: E = EllipticCurve('389a')
sage: E.heegner_index(-7)
+Infinity
sage: E = EllipticCurve('5077a')
sage: E.heegner_index(-7)
+Infinity

(continues on next page)
sage: E.heegner_index(-7, check_rank=False)
0.001?
sage: E.heegner_index(-7, check_rank=False).lower() == 0
True

sage.schemes.elliptic_curves.heegner.heegner_index_bound(self, D=0, prec=5, max_height=None)
Assume self has rank 0.
Return a list \( v \) of primes such that if an odd prime \( p \) divides the index of the Heegner point in the group of rational points modulo torsion, then \( p \) is in \( v \).
If 0 is in the interval of the height of the Heegner point computed to the given \( \text{prec} \), then this function returns \( v = 0 \). This does not mean that the Heegner point is torsion, just that it is very likely torsion.
If we obtain no information from a search up to \( \text{max\_height} \), e.g., if the Siksek et al. bound is bigger than \( \text{max\_height} \), then we return \( v = -1 \).

INPUT:
• \( D \) (int) – (default: 0) Heegner discriminant; if 0, use the first discriminant -4 that satisfies the Heegner hypothesis
• verbose (bool) – (default: True)
• prec (int) – (default: 5), use \( \text{prec} \cdot \sqrt{\left(N\right)} + 20 \) terms of \( L \)-series in computations, where \( N \) is the conductor.
• max_height (float) – should be \( = 21 \); bound on logarithmic naive height used in point searches. Make smaller to make this function faster, at the expense of possibly obtaining a worse answer. A good range is between 13 and 21.

OUTPUT:
• \( v \) – list or int (bad primes or 0 or -1)
• \( D \) – the discriminant that was used (this is useful if \( D \) was automatically selected).
• exact – either False, or the exact Heegner index (up to factors of 2)

EXAMPLES:

sage: E = EllipticCurve('11a1')
sage: E.heegner_index_bound()
([2], -7, 2)

sage.schemes.elliptic_curves.heegner.heegner_point(N, D=None, c=1)
Return a specific Heegner point of level \( N \) with given discriminant and conductor. If \( D \) is not specified, then the first valid Heegner discriminant is used. If \( c \) is not given, then \( c = 1 \) is used.

INPUT:
• \( N \) – level (positive integer)
• \( D \) – discriminant (optional: default first valid \( D \))
• \( c \) – conductor (positive integer, optional, default: 1)

EXAMPLES:

sage: heegner_point(389)
Heegner point 1/778*sqrt(-7) - 185/778 of discriminant -7 on X_0(389)
sage: heegner_point(389,-7)
Heegner point 1/778*sqrt(-7) - 185/778 of discriminant -7 on X_0(389)
sage: heegner_point(389,-7,5)
Heegner point 5/778*sqrt(-7) - 147/778 of discriminant -7 and conductor 5 on X_0(389)
sage: heegner_point(389,-20)
Heegner point 1/778*sqrt(-20) - 165/389 of discriminant -20 on X_0(389)

sage.schemes.elliptic_curves.heegner.heegner_point_height(self, D, prec=2, check_rank=True)
Use the Gross-Zagier formula to compute the Neron-Tate canonical height over K of the Heegner point corresponding to D, as an interval (it is computed to some precision using L-functions).

If the curve has rank at least 2, then the returned height is the exact Sage integer 0.

INPUT:

• D (int) – fundamental discriminant (=/= -3, -4)
• prec (int) – (default: 2), use prec · √(N) + 20 terms of L-series in computations, where N is the conductor.
• check_rank – whether to check if the rank is at least 2 by computing the Mordell-Weil rank directly.

OUTPUT: Interval that contains the height of the Heegner point.

EXAMPLES:

sage: E = EllipticCurve('11a')
sage: E.heegner_point_height(-7)
0.22227?

Some higher rank examples:

sage: E = EllipticCurve('389a')
sage: E.heegner_point_height(-7)
0
sage: E = EllipticCurve('5077a')
sage: E.heegner_point_height(-7)
0
sage: E.heegner_point_height(-7,check_rank=False)
0.0000?

sage.schemes.elliptic_curves.heegner.heegner_points(N, D=None, c=None)
Return all Heegner points of given level N. Can also restrict to Heegner points with specified discriminant D and optionally conductor c.

INPUT:

• N – level (positive integer)
• D – discriminant (negative integer)
• c – conductor (positive integer)

EXAMPLES:

sage: heegner_points(389,-7)
Set of all Heegner points on X_0(389) associated to QQ[sqrt(-7)]
All Heegner points of conductor 1 on $X_0(389)$ associated to $\mathbb{Q}[\sqrt{-7}]$

```
sage: heegner_points(389,-7,1)
```

All Heegner points of conductor 5 on $X_0(389)$ associated to $\mathbb{Q}[\sqrt{-7}]$

```
sage: heegner_points(389,-7,5)
```

```
sage.schemes.elliptic_curves.heegner.heegner_sha_an(
    self, D, prec=53)
```

Return the conjectural (analytic) order of Sha for $E$ over the field $K = \mathbb{Q}(\sqrt{D})$.

**INPUT:**
- $D$ – negative integer; the Heegner discriminant
- $\text{prec}$ – integer (default: 53); bits of precision to compute analytic order of Sha

**OUTPUT:**
(floating point number) an approximation to the conjectural order of Sha.

**Note:** Often you'll want to do `proof.elliptic_curve(False)` when using this function, since often the twisted elliptic curves that come up have enormous conductor, and Sha is nontrivial, which makes provably finding the Mordell-Weil group using 2-descent difficult.

**EXAMPLES:**

An example where $E$ has conductor 11:

```
sage: E = EllipticCurve('11a')
sage: E.heegner_sha_an(-7)  # long time
1.00000000000000
```

The cache works:

```
sage: E.heegner_sha_an(-7) is E.heegner_sha_an(-7)  # long time
True
```

Lower precision:

```
sage: E.heegner_sha_an(-7,10)  # long time
1.0
```

Checking that the cache works for any precision:

```
sage: E.heegner_sha_an(-7,10) is E.heegner_sha_an(-7,10)  # long time
True
```

Next we consider a rank 1 curve with nontrivial Sha over the quadratic imaginary field $K$; however, there is no Sha for $E$ over $\mathbb{Q}$ or for the quadratic twist of $E$:

```
sage: E = EllipticCurve('37a')
sage: E.heegner_sha_an(-40)  # long time
4.00000000000000
sage: E.quadratic_twist(-40).sha().an()  # long time
1
sage: E.sha().an()  # long time
1
```
A rank 2 curve:

\[
\text{sage: } E = \text{EllipticCurve('389a')} \quad \text{# long time}
\]
\[
\text{sage: } E.\text{heegner_sha_an}(-7) \quad \text{# long time}
\]

1.00000000000000

If we remove the hypothesis that \(E(K)\) has rank 1 in Conjecture 2.3 in [GZ1986] page 311, then that conjecture is false, as the following example shows:

\[
\text{sage: } E = \text{EllipticCurve('65a')} \quad \text{# long time}
\]
\[
\text{sage: } E.\text{heegner_sha_an}(-56) \quad \text{# long time}
\]

1.00000000000000

\[
\text{sage: } E.\text{torsion_order()}\quad \text{# long time}
\]

2

\[
\text{sage: } E.\text{tamagawa_product()}\quad \text{# long time}
\]

1

\[
\text{sage: } E.\text{quadratic_twist}(-56).\text{rank()}\quad \text{# long time}
\]

2

\[
\text{sage.schemes.elliptic_curves.}\text{heegner.}\text{is_inert} (D, p)
\]

Return True if \(p\) is an inert prime in the field \(\mathbb{Q}(\sqrt{D})\).

INPUT:

- \(D\) – fundamental discriminant
- \(p\) – prime integer

EXAMPLES:

\[
\text{sage: } \text{sage.schemes.elliptic_curves.}\text{heegner.}\text{is_inert}(-7, 3)
\]

True

\[
\text{sage: } \text{sage.schemes.elliptic_curves.}\text{heegner.}\text{is_inert}(-7, 7)
\]

False

\[
\text{sage: } \text{sage.schemes.elliptic_curves.}\text{heegner.}\text{is_inert}(-7, 11)
\]

False

\[
\text{sage.schemes.elliptic_curves.}\text{heegner.}\text{is_kolyvagin_conductor}(N, E, D, r, n, c)
\]

Return True if \(c\) is a Kolyvagin conductor for level \(N\), discriminant \(D\), mod \(n\), etc., i.e., \(c\) is divisible by exactly \(r\) prime factors, is coprime to \(ND\), each prime dividing \(c\) is inert, and if \(E\) is not None then \(n|\gcd(p+1, a_p(E))\) for each prime \(p\) dividing \(c\).

INPUT:

- \(N\) – level (positive integer)
- \(E\) – elliptic curve or None
- \(D\) – negative fundamental discriminant
- \(r\) – number of prime factors (nonnegative integer) or None
- \(n\) – torsion order (i.e., do we get class in \((E(K_c)/nE(K_c))^\text{Gal}(K_c/K)\)?)
- \(c\) – conductor (positive integer)

EXAMPLES:
sage: from sage.schemes.elliptic_curves.heegner import is_kolyvagin_conductor
sage: is_kolyvagin_conductor(389,None,-7,1,None,5)
True
sage: is_kolyvagin_conductor(389,None,-7,1,None,7)
False
sage: is_kolyvagin_conductor(389,None,-7,1,None,11)
False
sage: is_kolyvagin_conductor(389,EllipticCurve('389a'),-7,1,3,5)
True
sage: is_kolyvagin_conductor(389,EllipticCurve('389a'),-7,1,11,5)
False

sage.schemes.elliptic_curves.heegner.is_ramified(D,p)
Return True if p is a ramified prime in the field $\mathbb{Q}(\sqrt{D})$.

INPUT:
- $D$ – fundamental discriminant
- $p$ – prime integer

EXAMPLES:

sage: sage.schemes.elliptic_curves.heegner.is_ramified(-7,2)
False
sage: sage.schemes.elliptic_curves.heegner.is_ramified(-7,7)
True
sage: sage.schemes.elliptic_curves.heegner.is_ramified(-1,2)
True

sage.schemes.elliptic_curves.heegner.is_split(D,p)
Return True if p is a split prime in the field $\mathbb{Q}(\sqrt{D})$.

INPUT:
- $D$ – fundamental discriminant
- $p$ – prime integer

EXAMPLES:

sage: sage.schemes.elliptic_curves.heegner.is_split(-7,3)
False
sage: sage.schemes.elliptic_curves.heegner.is_split(-7,7)
False
sage: sage.schemes.elliptic_curves.heegner.is_split(-7,11)
True

sage.schemes.elliptic_curves.heegner.kolyvagin_point(self, D, c=1, check=True)
Return the Kolyvagin point on this curve associated to the quadratic imaginary field $K = \mathbb{Q}(\sqrt{D})$ and conductor $c$.

INPUT:
- $D$ – a Heegner discriminant
- $c$ – (default: 1) conductor, must be coprime to $DN$
- check – bool (default: True)
OUTPUT:

The Kolyvagin point $P$ of conductor $c$.

EXAMPLES:

```python
sage: E = EllipticCurve('37a1')
sage: P = E.kolyvagin_point(-67); P
Kolyvagin point of discriminant -67 on elliptic curve of conductor 37
sage: P.numerical_approx()  # abs tol 1e-14
(6.00000000000000 : -15.0000000000000 : 1.00000000000000)
sage: P.index()
6
sage: g = E((0,-1,1))  # a generator
sage: E.regulator() == E.regulator_of_points([g])
True
sage: 6*g
(6 : -15 : 1)
```

```
sage.schemes.elliptic_curves.heegner.kolyvagin_reduction_data(E, q, first_only=True)
```

Given an elliptic curve of positive rank and a prime $q$, this function returns data about how to use Kolyvagin’s $q$-torsion Heegner point Euler system to do computations with this curve. See the precise description of the output below.

INPUT:

- $E$ – elliptic curve over $Q$ of rank 1 or 2
- $q$ – an odd prime that does not divide the order of the rational torsion subgroup of $E$
- `first_only` – bool (default: True) whether two only return the first prime that one can work modulo to get data about the Euler system

OUTPUT in the rank 1 case or when the default flag `first_only=True`:

- $\ell$ – first good odd prime satisfying the Kolyvagin condition that $q$ divides $\text{gcd}(a_{\ell},\ell+1)^{\ell}$ and the reduction map is surjective to $E(F_{\ell})/qE(F_{\ell})$
- $D$ – discriminant of the first quadratic imaginary field $K$ that satisfies the Heegner hypothesis for $E$ such that both $\ell$ is inert in $K$, and the twist $E^{D}$ has analytic rank $\leq 1$
- $h_{D}$ – the class number of $K$
- the dimension of the Brandt module $B(\ell, N)$, where $N$ is the conductor of $E$

OUTPUT in the rank 2 case:

- $\ell_{1}$ – first prime (as above in the rank 1 case) where reduction map is surjective
- $\ell_{2}$ – second prime (as above) where reduction map is surjective
- $D$ – discriminant of the first quadratic imaginary field $K$ that satisfies the Heegner hypothesis for $E$ such that both $\ell_{1}$ and $\ell_{2}$ are simultaneously inert in $K$, and the twist $E^{D}$ has analytic rank $\leq 1$
- $h_{D}$ – the class number of $K$
- the dimension of the Brandt module $B(\ell_{1}, N)$, where $N$ is the conductor of $E$
- the dimension of the Brandt module $B(\ell_{2}, N)$

EXAMPLES:

Import this function:
sage: from sage.schemes.elliptic_curves.heegner import kolyvagin_reduction_data

A rank 1 example:

sage: kolyvagin_reduction_data(EllipticCurve('37a1'),3)
(17, -7, 1, 52)

A rank 3 example:

sage: kolyvagin_reduction_data(EllipticCurve('5077a1'),3)
(11, -47, 5, 4234)
sage: H = heegner_points(5077, -47)
sage: [c for c in H.kolyvagin_conductors(2,10,EllipticCurve('5077a1'),3) if c%11]
[667, 943, 1189, 2461]
sage: factor(667)
23 * 29

A rank 4 example (the first Kolyvagin class that we could try to compute would be $P_{23 \cdot 29 \cdot 41}$, and would require working in a space of dimension 293060 (so prohibitive at present):

sage: E = elliptic_curves.rank(4)[0]
sage: kolyvagin_reduction_data(E,3) # long time
(11, -71, 7, 293060)
sage: H = heegner_points(293060, -71)
sage: H.kolyvagin_conductors(1,4,E,3)
[11, 17, 23, 41]

The first rank 2 example:

sage: kolyvagin_reduction_data(EllipticCurve('389a'),3)
(5, -7, 1, 130)
sage: kolyvagin_reduction_data(EllipticCurve('389a'),3, first_only=False)
(5, 17, -7, 1, 130, 520)

A large $q = 7$:

sage: kolyvagin_reduction_data(EllipticCurve('1143c1'),7, first_only=False)
(13, 83, -59, 3, 1536, 10496)

Additive reduction:

sage: kolyvagin_reduction_data(EllipticCurve('2350g1'),5, first_only=False)
(19, 239, -311, 19, 6480, 85680)

sage.schemes.elliptic_curves.heegner.make_monic(f)

Return a monic integral polynomial $g$ and an integer $d$ such that if $\alpha$ is a root of $g$, then $\alpha/d$ is a root of $f$. In other words, $cf(x) = g(dx)$ for some scalar $c$.

INPUT:

• $f$ – polynomial over the rational numbers

OUTPUT:

a monic integral polynomial and an integer

EXAMPLES:
In this example we verify that \texttt{make_monic} does what we claim it does:

sage: K.<a> = NumberField(x^3 + 17*x - 3)
sage: f = (a/7+2/3).minpoly(); f
x^3 - 2*x^2 + 247/147*x - 4967/9261
sage: g, d = make_monic(f); (g, d)
(x^3 - 42*x^2 + 741*x - 4967, 21)

sage: g, d = make_monic(f); (g, d)
(x^3 - 42*x^2 + 741*x - 4967, 21)

This example illustrates how \texttt{make_monic} can be used to make a polynomial monic.

---

sage.schemes.elliptic_curves.heegner.nearby_rational_poly(f, **kwds)

Return a polynomial whose coefficients are rational numbers close to the coefficients of \( f \).

**INPUT:**
- \( f \) – polynomial with real floating point entries
- **kwds** – passed on to \texttt{nearby_rational} method

**EXAMPLES:**

sage: R.<x> = RR[]
sage: sage.schemes.elliptic_curves.heegner.nearby_rational_poly(2.1*x^2 + 3.5*x - 1, \text{max_error=10e-16})
21/10*X^2 + 7/2*X - 6/5
sage: sage.schemes.elliptic_curves.heegner.nearby_rational_poly(2.1*x^2 + 3.5*x - 1, \text{max_error=10e-17})
4728779608739021/2251799813685248*X^2 + 7/2*X - 5404319552844595/4503599627370496

---

sage.schemes.elliptic_curves.heegner.quadratic_order(D, c, names='a')

Return order of conductor \( c \) in quadratic field with fundamental discriminant \( D \).

**INPUT:**
- \( D \) – fundamental discriminant
- \( c \) – conductor
- \text{names} – string (default: ‘a’)

**OUTPUT:**
- order \( R \) of conductor \( c \) in an imaginary quadratic field
- the element \( c\sqrt{D} \) as an element of \( R \)

The generator for the field is named ‘a’ by default.

**EXAMPLES:**
sage: sage.schemes.elliptic_curves.heegner.quadratic_order(-7,3)
(Order in Number Field in a with defining polynomial x^2 + 7 with a = 2.
→645751311064591*I,
3*a)
sage: sage.schemes.elliptic_curves.heegner.quadratic_order(-7,3,'alpha')
(Order in Number Field in alpha with defining polynomial x^2 + 7 with alpha = 2.
→645751311064591*I,
3*alpha)

sage.schemes.elliptic_curves.heegner.satisfies_heegner_hypothesis(self, D)
Returns True precisely when \( D \) is a fundamental discriminant that satisfies the Heegner hypothesis for this elliptic curve.

EXAMPLES:

sage: E = EllipticCurve('11a1')
sage: E.satisfies_heegner_hypothesis(-7)
True
sage: E.satisfies_heegner_hypothesis(-11)
False

sage.schemes.elliptic_curves.heegner.satisfies_weak_heegner_hypothesis(N, D)
Check that \( D \) satisfies the weak Heegner hypothesis relative to \( N \). This is all that is needed to define Heegner points.

The condition is that \( D < 0 \) is a fundamental discriminant and that each unramified prime dividing \( N \) splits in \( K = \mathbb{Q}(\sqrt{D}) \) and each ramified prime exactly divides \( N \). We also do not require that \( D < -4 \).

INPUT:

• \( N \) – positive integer
• \( D \) – negative integer

EXAMPLES:

sage: s = sage.schemes.elliptic_curves.heegner.satisfies_weak_heegner_hypothesis
sage: s(37,-7)
True
sage: s(37,-37)
False
sage: s(37,-37*4)
True
sage: s(100,-4)
False

sage: [D for D in [-1,-2,...,-40] if s(37,D)]
[-3, -4, -7, -11, -40]
sage: [D for D in [-1,-2,...,-100] if s(37,D)]
[-3, -4, -7, -11, -40, -47, -67, -71, -83, -84, -95]
sage: EllipticCurve('37a').heegner_discriminants_list(10)
[-7, -11, -40, -47, -67, -71, -83, -84, -95, -104]

sage.schemes.elliptic_curves.heegner.simplest_rational_poly(f, prec)
Return a polynomial whose coefficients are as simple as possible rationals that are also close to the coefficients of \( f \).

INPUT:
• $f$ – polynomial with real floating point entries
• $\text{prec}$ – positive integer

**EXAMPLES:**

```python
sage: R.<x> = RR[]
sage: sage.schemes.elliptic_curves.heegner.simplest_rational_poly(2.1*x^2 + 3.5*x - 1.2, 53)
21/10*X^2 + 7/2*X - 6/5
```

### 14.24 $p$-adic $L$-functions of elliptic curves

To an elliptic curve $E$ over the rational numbers and a prime $p$, one can associate a $p$-adic $L$-function; at least if $E$ does not have additive reduction at $p$. This function is defined by interpolation of $L$-values of $E$ at twists. Through the main conjecture of Iwasawa theory it should also be equal to a characteristic series of a certain Selmer group.

If $E$ is ordinary, then it is an element of the Iwasawa algebra $\Lambda(\mathbb{Z}_p^\times) = \mathbb{Z}_p[[T]]$, where $\Delta$ is the group of $(p-1)$-st roots of unity in $\mathbb{Z}_p^\times$, and $T = [\gamma] - 1$ where $\gamma = 1 + p$ is a generator of $1 + p\mathbb{Z}_p$. (There is a slightly different description for $p = 2$.)

One can decompose this algebra as the direct product of the subalgebras corresponding to the characters of $\Delta$, which are simply the powers $\tau^n (0 \leq \eta \leq p - 2)$ of the Teichmueller character $\tau : \Delta \to \mathbb{Z}_p^\times$. Projecting the $L$-function into these components gives $p - 1$ power series in $T$, each with coefficients in $\mathbb{Z}_p$.

If $E$ is supersingular, the series will have coefficients in a quadratic extension of $\mathbb{Q}_p$, and the coefficients will be unbounded. In this case we have only implemented the series for $\eta = 0$. We have also implemented the $p$-adic $L$-series as formulated by Perrin-Riou [BP1993], which has coefficients in the Dieudonné module $D_pE = H^1_{dR}(E/\mathbb{Q}_p)$ of $E$. There is a different description by Pollack [Pol2003] which is not available here.

According to the $p$-adic version of the Birch and Swinnerton-Dyer conjecture [MTT1986], the order of vanishing of the $L$-function at the trivial character (i.e. of the series for $\eta = 0$ at $T = 0$) is just the rank of $E(\mathbb{Q})$, or this rank plus one if the reduction at $p$ is split multiplicative.

See [SW2013] for more details.

**AUTHORS:**

- Chris Wuthrich (22/05/2007): changed minor issues and added supersingular things
- Chris Wuthrich (11/2008): added quadratic_twists
- David Loeffler (01/2011): added nontrivial Teichmueller components

```python
class sage.schemes.elliptic_curves.padic_lseries.pAdicLseries(E, p, implementation='eclib', normalize='L_ratio')

Bases: sage.structure.sage_object.SageObject

The $p$-adic $L$-series of an elliptic curve.

**EXAMPLES:**

An ordinary example:

```python
sage: e = EllipticCurve('389a1')
sage: L = e.padic_lseries(5)
sage: L.series(0)
```

(continues on next page)
Traceback (most recent call last):
...
ValueError: n (=0) must be a positive integer

```
sage: L.series(1)
O(T^1)
sage: L.series(2)
0(5^4) + O(5)*T^2 + (2 + O(5))*T^3 + (3 + O(5))*T^4 + O(T^5)
sage: L.series(3, prec=10)
O(5^4) + O(5^2)*T^2 + (4 + O(5))*T^3 + O(5)*T^4 + O(T^5)
sage: L.series(2, quadratic_twist=-3)
2 + 4*5 + O(5)*T + (1 + O(5))*T^2 + (4 + O(5))*T^3 + O(T^5)
```

A prime p such that E[p] is reducible:

```
sage: L = EllipticCurve('11a').padic_lseries(5)
sage: L.series(1)
5 + O(5^2) + O(T)
sage: L.series(2)
5 + 4*5^2 + O(5^3) + O(5)*T^2 + O(5)*T^3 + O(5)*T^4 + O(T^5)
sage: L.series(3)
5 + 4*5^2 + 4*5^3 + O(5^4) + O(5)*T^2 + O(5)*T^3 + O(5)*T^4 + O(T^5)
```

An example showing the calculation of nontrivial Teichmueller twists:

```
sage: E = EllipticCurve('11a1')
sage: lp = E.padic_lseries(7)
sage: lp.series(4, eta=1)
3 + 7^3 + 6*7^4 + 3*7^5 + O(7^6) + (2*7 + 7^2 + O(7^3))*T + (1 + 5*7^2 + O(7^3))*T^2 + (4 + 3*7 + 7^2 + O(7^3))*T^3 + (4 + 3*7 + 7^2 + O(7^3))*T^4 + O(T^5)
sage: lp.series(4, eta=2)
5 + 6*7 + 4*7^2 + 2*7^3 + 3*7^4 + 2*7^5 + O(7^6) + (6 + 4*7 + 7^2 + O(7^3))*T + (3 + 2*7^2 + O(7^3))*T^2 + (1 + 4*7 + 7^2 + O(7^3))*T^3 + (6 + 6*7 + 6*7^2 + O(7^3))*T^4 + O(T^5)
sage: lp.series(4, eta=3)
O(7^6) + (5 + 4*7 + 2*7^2 + O(7^3))*T + (6 + 5*7 + 2*7^2 + O(7^3))*T^2 + (5*7 + O(7^3))*T^3 + (7 + 4*7^2 + O(7^3))*T^4 + O(T^5)
```

(Nota the last series vanishes at \(T = 0\), which is consistent with

```
sage: E.quadratic_twist(-7).rank()
1
```

This proves that \(E\) has rank 1 over \( \mathbb{Q}(\zeta_7)\).)

**alpha***(\text{prec=20})*

Return a \( p \)-adic root \( \alpha \) of the polynomial \( x^2 - a_p x + p \) with \( ord_p(\alpha) < 1 \). In the ordinary case this is just the unit root.

**INPUT:**

- \text{prec} – positive integer, the \( p \)-adic precision of the root.
EXAMPLES:

Consider the elliptic curve 37a:

```
sage: E = EllipticCurve('37a')
```

An ordinary prime:

```
sage: L = E.padic_lseries(5)
sage: alpha = L.alpha(10); alpha
3 + 2*5 + 4*5^2 + 2*5^3 + 5^4 + 4*5^5 + 2*5^7 + 5^8 + 5^9 + O(5^10)
sage: alpha^2 - E.ap(5)*alpha + 5
O(5^10)
```

A supersingular prime:

```
sage: L = E.padic_lseries(3)
sage: alpha = L.alpha(10); alpha
alpha + O(alpha^21)
sage: alpha^2 - E.ap(3)*alpha + 3
O(alpha^22)
```

A reducible prime:

```
sage: L = EllipticCurve('11a').padic_lseries(5)
sage: L.alpha(5)
1 + 4*5 + 3*5^2 + 2*5^3 + 4*5^4 + O(5^5)
```

effective_curve()

Return the elliptic curve to which this $p$-adic L-series is associated.

EXAMPLES:

```
sage: L = EllipticCurve('11a').padic_lseries(5)
sage: L.elliptic_curve()
Elliptic Curve defined by y^2 + y = x^3 - x^2 - 10*x - 20 over Rational Field
```

measure($a$, $n$, prec, quadratic_twist=1, sign=1)

Return the measure on $\mathbb{Z}_p^\times$ defined by

$$
\mu_{E, \alpha}(a + p^n \mathbb{Z}_p) = \frac{1}{\alpha^n} \left[ \frac{a}{p^n} \right]^+ - \frac{1}{\alpha^{n+1}} \left[ \frac{a}{p^{n-1}} \right]^+
$$

where $[\cdot]^+$ is the modular symbol. This is used to define this $p$-adic L-function (at least when the reduction is good).

The optional argument sign allows the minus symbol $[\cdot]^-$ to be substituted for the plus symbol.

The optional argument quadratic_twist replaces $E$ by the twist in the above formula, but the twisted modular symbol is computed using a sum over modular symbols of $E$ rather than finding the modular symbols for the twist. Quadratic twists are only implemented if the sign is +1.

Note that the normalization is not correct at this stage: use _quotient_of_periods and _quotient_of_periods_to_twist to correct.

Note also that this function does not check if the condition on the quadratic_twist=D is satisfied. So the result will only be correct if for each prime $\ell$ dividing $D$, we have $ord_{\ell}(N) \leq ord_{\ell}(D)$, where $N$ is the conductor of the curve.

INPUT:
• $a$ – an integer
• $n$ – a non-negative integer
• $\text{prec}$ – an integer
• $\text{quadratic\_twist}$ (default = 1) – a fundamental discriminant of a quadratic field, should be coprime to the conductor of $E$
• $\text{sign}$ (default = 1) – an integer, which should be $\pm 1$.

EXAMPLES:

```python
sage: E = EllipticCurve('37a')
sage: L = E.padic_lseries(5)
sage: L.measure(1, 2, prec=9)
2 + 3*5 + 4*5^3 + 2*5^4 + 3*5^5 + 3*5^6 + 4*5^7 + 4*5^8 + O(5^9)
sage: L.measure(1, 2, quadratic\_twist=8, prec=15)
0(5^15)
sage: L.measure(1, 2, quadratic\_twist=-4, prec=15)
4 + 4*5 + 4*5^2 + 3*5^3 + 2*5^4 + 5*5^5 + 3*5^6 + 5^8 + 2*5^9 + 3*5^12 + 2*5^13 +...
˓→ 4*5^14 + O(5^15)
```

```python
sage: E = EllipticCurve('11a1')
sage: a = E.quadratic\_twist(-3).padic\_lseries(5).measure(1, 2, prec=15)
sage: b = E.padic\_lseries(5).measure(1, 2, quadratic\_twist=-3, prec=15)
sage: a == b * E.padic\_lseries(5).\_quotient\_of\_periods\_to\_twist(-3)
True
```

`modular\_symbol(r, sign=1, quadratic\_twist=1)`

Return the modular symbol evaluated at $r$.

This is used to compute this $p$-adic L-series.

Note that the normalization is not correct at this stage: use \_quotient\_of\_periods\_to\_twist to correct.

Note also that this function does not check if the condition on the quadratic\_twist=D is satisfied. So the result will only be correct if for each prime $\ell$ dividing $D$, we have $ord\_\ell(N) \leq ord\_\ell(D)$, where $N$ is the conductor of the curve.

INPUT:

• $r$ – a cusp given as either a rational number or oo
• $\text{sign}$ – +1 (default) or -1 (only implemented without twists)
• $\text{quadratic\_twist}$ – a fundamental discriminant of a quadratic field or +1 (default)

EXAMPLES:

```python
sage: E = EllipticCurve('11a1')
sage: lp = E.padic\_lseries(5)
sage: [lp.modular\_symbol(r) \textbf{for} \textbf{r} \textbf{in} [0, 1/5, oo, 1/11]]
[1/5, 6/5, 0, 0]
sage: [lp.modular\_symbol(r, sign=-1) \textbf{for} \textbf{r} \textbf{in} [0, 1/3, oo, 1/7]]
[0, 1/2, 0, -1/2]
sage: [lp.modular\_symbol(r, quadratic\_twist=-20) \textbf{for} \textbf{r} \textbf{in} [0, 1/5, oo, 1/11]]
[1, 1, 0, 1/2]
```

```python
sage: E = EllipticCurve('20a1')
```

(continues on next page)
order_of_vanishing()
Return the order of vanishing of this \( p \)-adic L-series.

The output of this function is provably correct, due to a theorem of Kato [Kat2004].

Note: currently \( p \) must be a prime of good ordinary reduction.

REFERENCES:
• [MTT1986]
• [Kat2004]

EXAMPLES:

```sage
sage: L = EllipticCurve('11a').padic_lseries(3)
sage: L.order_of_vanishing()
0
sage: L = EllipticCurve('11a').padic_lseries(5)
sage: L.order_of_vanishing()
0
sage: L = EllipticCurve('37a').padic_lseries(5)
sage: L.order_of_vanishing()
1
sage: L = EllipticCurve('43a').padic_lseries(3)
sage: L.order_of_vanishing()
1
sage: L = EllipticCurve('37b').padic_lseries(3)
sage: L.order_of_vanishing()
0
sage: L = EllipticCurve('389a').padic_lseries(3)
sage: L.order_of_vanishing()
2
sage: L = EllipticCurve('389a').padic_lseries(5)
sage: L.order_of_vanishing()
2
sage: L = EllipticCurve('5077a').padic_lseries(5, implementation = 'eclib')
sage: L.order_of_vanishing()
3
```

prime()
Return the prime \( p \) as in \('p\)-adic L-function'.

EXAMPLES:

```sage
sage: L = EllipticCurve('11a').padic_lseries(5)
sage: L.prime()
5
```
teichmuller(prec)
    Return Teichmuller lifts to the given precision.
    
    INPUT:
    • prec – a positive integer.
    
    OUTPUT:
    • a list of $p$-adic numbers, the cached Teichmuller lifts
    
    EXAMPLES:
    sage: L = EllipticCurve('11a').padic_lseries(7)
    sage: L.teichmuller(1)
     [0, 1, 2, 3, 4, 5, 6]
    sage: L.teichmuller(2)
     [0, 1, 30, 31, 18, 19, 48]

class sage.schemes.elliptic_curves.padic_lseries.pAdicLseriesOrdinary(E, p, implementation='eclib', normalize='L_ratio')

Bases: sage.schemes.elliptic_curves.padic_lseries.pAdicLseries

is_ordinary()
    Return True if the elliptic curve that this L-function is attached to is ordinary.
    
    EXAMPLES:
    sage: L = EllipticCurve('11a').padic_lseries(5)
    sage: L.is_ordinary()
     True

is_supersingular()
    Return True if the elliptic curve that this L function is attached to is supersingular.
    
    EXAMPLES:
    sage: L = EllipticCurve('11a').padic_lseries(5)
    sage: L.is_supersingular()
     False

power_series(n=2, quadratic_twist=1, prec=5, eta=0)
    Return the $n$-th approximation to the $p$-adic L-series, in the component corresponding to the $\eta$-th power of the Teichmüller character, as a power series in $T$ (corresponding to $\gamma - 1$ with $\gamma = 1 + p$ as a generator of $1 + p\mathbb{Z}_p$). Each coefficient is a $p$-adic number whose precision is provably correct.

    Here the normalization of the $p$-adic L-series is chosen such that $L_p(E,1) = (1 - 1/\alpha)^2 L(E,1)/\Omega_E$ where $\alpha$ is the unit root of the characteristic polynomial of Frobenius on $T_p E$ and $\Omega_E$ is the Néron period of $E$.

    INPUT:
    • n – (default: 2) a positive integer
    • quadratic_twist – (default: +1) a fundamental discriminant of a quadratic field, coprime to the conductor of the curve
    • prec – (default: 5) maximal number of terms of the series to compute; to compute as many as possible just give a very large number for prec; the result will still be correct.
• `eta` (default: 0) an integer (specifying the power of the Teichmuellier character on the group of roots of unity in \( \mathbb{Z}_p^\times \))

`power_series()` is identical to `series`.

**EXAMPLES:**

We compute some \( p \)-adic L-functions associated to the elliptic curve 11a:

```python
sage: E = EllipticCurve('11a')
sage: p = 3
sage: E.is_ordinary(p)
True
sage: L = E.padic_lseries(p)
sage: L.series(3)
2 + 3 + 3^2 + 2*3^3 + 0(3^5) + (1 + 3 + O(3^2))*T + (1 + 2*3 + O(3^2))*T^2 +
    O(3)*T^3 + O(3)*T^4 + O(T^5)
```

Another example at a prime of bad reduction, where the \( p \)-adic L-function has an extra 0 (compared to the non \( p \)-adic L-function):

```python
sage: E = EllipticCurve('11a')
sage: p = 11
sage: E.is_ordinary(p)
True
sage: L = E.padic_lseries(p)
sage: L.series(2)
O(11^4) + (10 + O(11))*T + (6 + O(11))*T^2 + (2 + O(11))*T^3 + (5 + O(11))*T^4 +
    O(T^5)
```

We compute a \( p \)-adic L-function that vanishes to order 2:

```python
sage: E = EllipticCurve('389a')
sage: p = 3
sage: E.is_ordinary(p)
True
sage: L = E.padic_lseries(p)
sage: L.series(1)
O(T^1)
sage: L.series(2)
O(3^4) + O(3)*T + (2 + O(3))*T^2 + O(T^3)
sage: L.series(3)
O(3^5) + O(3^2)*T + (2 + 2*3 + O(3^2))*T^2 + (2 + O(3))*T^3 + (1 + O(3))*T^4 +
    O(T^5)
```

Checks if the precision can be changed (trac ticket #5846):

```python
sage: L.series(3, prec=4)
O(3^5) + O(3^2)*T + (2 + 2*3 + O(3^2))*T^2 + (2 + O(3))*T^3 + O(T^4)
sage: L.series(3, prec=6)
O(3^5) + O(3^2)*T + (2 + 2*3 + O(3^2))*T^2 + (2 + O(3))*T^3 + (1 + O(3))*T^4 +
    O(1 + O(3))*T^5 + O(T^6)
```

Rather than computing the \( p \)-adic L-function for the curve ‘15523a1’, one can compute it as a quadratic_twist:
This proves that the rank of ‘15523a1’ is zero, even if mwrank cannot determine this.

We calculate the \( L \)-series in the nontrivial Teichmueller components:

\[
\begin{align*}
sage: & \ E = \text{EllipticCurve('110a1')} \\
sage: & \ lp = E.padic_lseries(5, \text{implementation}="sage") \\
sage: & \ \text{for } j \ \text{in} \ [0..3]: \ \text{print}(L.series(4, \eta=j)) \\
\end{align*}
\]

It should now also work with \( p = 2 \) (trac ticket #20798):

\[
\begin{align*}
sage: & \ E = \text{EllipticCurve('53a1')} \\
sage: & \ lp = E.padic_lseries(2) \\
sage: & \ \text{lp.series}(7) \\
\end{align*}
\]

Check that twists by odd Teichmuller characters are ok (trac ticket #32258):

\[
\begin{align*}
sage: & \ E = \text{EllipticCurve('443c1')} \\
sage: & \ lp = E.padic_lseries(17, \text{implementation}="num") \\
sage: & \ \text{lp.series}(2, \eta=8, \text{prec}=3) \\
\end{align*}
\]

\text{series}(n=2, \text{quadratic} \text{twist}=1, \text{prec}=5, \eta=0)

Return the \( n \)-th approximation to the \( p \)-adic \( L \)-series, in the component corresponding to the \( \eta \)-th power of the Teichmueller character, as a power series in \( T \) (corresponding to \( \gamma - 1 \) with \( \gamma = 1 + p \) as a generator of \( 1 + p\mathbb{Z}_p \)). Each coefficient is a \( p \)-adic number whose precision is provably correct.
Here the normalization of the $p$-adic $L$-series is chosen such that $L_p(E, 1) = (1 - 1/\alpha)^2 L(E, 1)/\Omega_E$ where $\alpha$ is the unit root of the characteristic polynomial of Frobenius on $T_pE$ and $\Omega_E$ is the Néron period of $E$.

INPUT:
- $n$ – (default: 2) a positive integer
- `quadratic_twist` – (default: +1) a fundamental discriminant of a quadratic field, coprime to the conductor of the curve
- `prec` – (default: 5) maximal number of terms of the series to compute; to compute as many as possible just give a very large number for `prec`; the result will still be correct.
- `eta` (default: 0) an integer (specifying the power of the Teichmueller character on the group of roots of unity in $\mathbb{Z}_p^\times$)

`power_series()` is identical to `series`.

EXAMPLES:

We compute some $p$-adic $L$-functions associated to the elliptic curve 11a:

```
sage: E = EllipticCurve('11a')
sage: p = 3
sage: E.is_ordinary(p)
True
sage: L = E.padic_lseries(p)
sage: L.series(3)
2 + 3 + 3^2 + 2*3^3 + O(3^5) + (1 + 3 + O(3^2))*T + (1 + 2*3 + O(3^2))*T^2 + ...O(3)*T^3 + O(3)*T^4 + O(T^5)
```

Another example at a prime of bad reduction, where the $p$-adic $L$-function has an extra 0 (compared to the non $p$-adic $L$-function):

```
sage: E = EllipticCurve('11a')
sage: p = 11
sage: E.is_ordinary(p)
True
sage: L = E.padic_lseries(p)
sage: L.series(2)
O(11^4) + (10 + O(11))*T + (6 + O(11))*T^2 + (2 + O(11))*T^3 + (5 + O(11))*T^4+ ...O(T^5)
```

We compute a $p$-adic $L$-function that vanishes to order 2:

```
sage: E = EllipticCurve('389a')
sage: p = 3
sage: E.is_ordinary(p)
True
sage: L = E.padic_lseries(p)
sage: L.series(1)
O(T^1)
sage: L.series(2)
O(3^4) + (3 + 3^2 + 0(3^2))*T + (2 + 0(3))*T^2 + O(T^3)
sage: L.series(3)
O(3^5) + O(3^2)*T + (2 + 2*3 + 0(3^2))*T^2 + (2 + 0(3))*T^3 + (1 + 0(3))*T^4 + ...O(T^5)
```
Checks if the precision can be changed (trac ticket #5846):

```
sage: L.series(3, prec=4)
O(3^5) + 0(3^2)*T + (2 + 2*3 + O(3^2))*T^2 + (2 + 0(3))*T^3 + O(T^4)
sage: L.series(3, prec=6)
O(3^5) + 0(3^2)*T + (2 + 2*3 + O(3^2))*T^2 + (2 + 0(3))*T^3 + (1 + 0(3))*T^4 + (1 + 0(3))*T^5 + O(T^6)
```

Rather than computing the \( p \)-adic L-function for the curve \('15523a1'\), one can compute it as a quadratic_twist:

```
sage: E = EllipticCurve('43a1')
sage: lp = E.padic_lseries(3)
sage: lp.series(2, quadratic_twist=-19)
2 + 2*3 + 2*3^2 + O(3^4) + (1 + O(3))*T + (1 + O(3))*T^2 + O(T^3)
sage: E.quadratic_twist(-19).label()  # optional -- database_cremona_ellcurve
'15523a1'
```

This proves that the rank of \('15523a1'\) is zero, even if mwrank cannot determine this.

We calculate the \( L \)-series in the nontrivial Teichmueller components:

```
sage: L = EllipticCurve('110a1').padic_lseries(5, implementation="sage")
sage: for j in [0..3]: print(L.series(4, eta=j))
O(5^6) + (2 + 2*5 + 2*5^2 + O(5^3))*T + (5 + 5^2 + O(5^3))*T^2 + (4 + 4*5 + 2*5^2 +
... 2 + O(5^3))*T^3 + (1 + 5 + 3*5^2 + O(5^3))*T^4 + O(T^5)
4 + 3*5 + 2*5^2 + 3*5^3 + 5^4 + O(5)^6 + (1 + 3*5 + 4*5^2 + 2*5^3)*T + (3 +
... 4*5 + 3*5^2 + O(5^3))*T^2 + (3 + 3*5^2 + 2*5^3 + O(5^3))*T^3 + (1 + 2*5 + 2*5^2 + 0(5^3))*T^4 + 0(T^5)
2 + 0(5^6) + (1 + 5 + O(5^3))*T + (2 + 4*5 + 3*5^2 + O(5^3))*T^2 + (4 + 5 + 2*5^2 +
... 2 + O(5^3))*T^3 + (4 + 0(5^3))*T^4 + 0(T^5)
3 + 5 + 2*5^2 + 5^3 + 3*5^4 + 4*5^5 + O(5^6) + (1 + 2*5 + 4*5^2 + 2*5^3)*T +
... (1 + 4*5 + 0(5^3))*T^2 + (3 + 2*5 + 2*5^2 + O(5^3))*T^3 + (5 + 5^2 + 0(5^3))*T^4 + 0(T^5)
```

It should now also work with \( p = 2 \) (trac ticket #20798):

```
sage: E = EllipticCurve("53a1")
sage: lp = E.padic_lseries(2)
sage: lp.series(7)
O(2^8) + (1 + 2^2 + 2^3 + O(2^5))*T + (1 + 2^3 + O(2^4))*T^2 + (2^2 + 2^3 + O(2^4))*T^3 +
... (2 + O(2^3))*T^4 + 0(T^5)
```

Check that twists by odd Teichmuller characters are ok (trac ticket #32258):

```
sage: E = EllipticCurve("443c1")
sage: lp = E.padic_lseries(17, implementation="num")
sage: l8 = lp.series(2, eta=8, prec=3)
sage: l8.list()[0] - 1/lp.alpha()
```

(continues on next page)
\begin{verbatim}
O(17^4)
sage: lp = E.padic_lseries(2, implementation="num")
sage: l1 = lp.series(8,eta=1,prec=3)
sage: l1.list()[0] - 4/lp.alpha()^2
O(2^9)
\end{verbatim}

\section*{class \texttt{sage.schemes.elliptic_curves.padic_lseries.pAdicLseriesSupersingular}}

\texttt{sage.schemes.elliptic_curves.padic_lseries.pAdicLseriesSupersingular}($E$, $p$, implementation='eclib',
normalization='L_ratio')

Bases: \texttt{sage.schemes.elliptic_curves.padic_lseries.pAdicLseries}

\textbf{Dp_valued_height} (\texttt{prec}=20)

Return the canonical $p$-adic height with values in the Dieudonné module $D_p(E)$.

It is defined to be

$$h_\eta \cdot \omega - h_\omega \cdot \eta$$

where $h_\eta$ is made out of the sigma function of Bernardi and $h_\omega$ is $\log^2_E$.

The answer $v$ is given as $v[1] \cdot \omega + v[2] \cdot \eta$. The coordinates of $v$ are dependent of the Weierstrass equation.

**EXAMPLES:**

\begin{verbatim}
sage: E = EllipticCurve('53a')
sage: L = E.padic_lseries(5)
sage: h = L.Dp_valued_height(7)
sage: h(E.gens()[0])
(3*5 + 5^2 + 2*5^3 + 3*5^4 + 4*5^5 + 5^6 + 5^7 + O(5^8), 0(2^9)
\end{verbatim}

\textbf{Dp_valued_regulator} (\texttt{prec}=20, \texttt{v1}=0, \texttt{v2}=0)

Return the canonical $p$-adic regulator with values in the Dieudonné module $D_p(E)$ as defined by Perrin-Riou using the $p$-adic height with values in $D_p(E)$.

The result is written in the basis $\omega, \varphi(\omega)$, and hence the coordinates of the result are independent of the chosen Weierstrass equation.

**Note:** The definition here is corrected with respect to Perrin-Riou's article \cite{PR2003}. See \cite{SW2013}.

**EXAMPLES:**

\begin{verbatim}
sage: E = EllipticCurve('43a')
sage: L = E.padic_lseries(7)
sage: L.Dp_valued_regulator(7)
(5*7 + 6*7^2 + 4*7^3 + 4*7^4 + 7^5 + 4*7^7 + O(7^8), 4*7^2 + 2*7^3 + 3*7^4 + 7^5 + O(7^8))
\end{verbatim}

\textbf{Dp_valued_series} (\texttt{n}=3, \texttt{quadratic_twist}=1, \texttt{prec}=5)

Return a vector of two components which are $p$-adic power series.

The answer $v$ is such that

$$\left(1 - \varphi\right)^{-2} \cdot L_p(E, T) = v[1] \cdot \omega + v[2] \cdot \varphi(\omega)$$
as an element of the Dieudonné module $D_p(E) = H^1_{dR}(E/Q_p)$ where $\omega$ is the invariant differential and $\varphi$ is the Frobenius on $D_p(E)$.

According to the $p$-adic Birch and Swinnerton-Dyer conjecture [BP1993] this function has a zero of order rank of $E(Q)$ and its leading term is contains the order of the Tate-Shafarevich group, the Tamagawa numbers, the order of the torsion subgroup and the $D_p$-valued $p$-adic regulator.

INPUT:

- $n$ – (default: 3) a positive integer
- $\text{prec}$ – (default: 5) a positive integer

EXAMPLES:

```python
sage: E = EllipticCurve('14a')
sage: L = E.padic_lseries(5)
sage: L.Dp_valued_series(4)  # long time (9s on sage.math, 2011)
(1 + 4*5 + O(5^2) + (4 + O(5))*T + (1 + O(5))*T^2 + (4 + O(5))*T^3 + (2 + ω
→ O(5))*T^4 + O(T^5), 5^2 + O(5^3) + O(5^2)*T + (4*5 + O(5^2))*T^2 + (2*5 + O(5^2
→ 2))*T^3 + (2 + 2*5 + O(5^2))*T^4 + O(T^5))
```

`bernardi_sigma_function(prec=20)`

Return the $p$-adic sigma function of Bernardi in terms of $z = \log(t)$.

This is the same as `padic_sigma` with $E2 = 0$.

EXAMPLES:

```python
sage: E = EllipticCurve('14a')
sage: L = E.padic_lseries(5)
sage: L.bernardi_sigma_function(prec=5)  # Todo: some sort of consistency check!?
z + 1/24*z^3 + 29/384*z^5 - 8399/322560*z^7 - 291743/92897280*z^9 + O(z^10)
```

`frobenius(prec=20, algorithm='mw')`

Return a geometric Frobenius $\varphi$ on the Dieudonné module $D_p(E)$ with respect to the basis $\omega$, the invariant differential, and $\eta = x\omega$.

It satisfies $\varphi^2 - a_p/p \varphi + 1/p = 0$.

INPUT:

- $\text{prec}$ – (default: 20) a positive integer
- $\text{algorithm}$ – either ‘$mw$’ (default) for Monsky-Washnitzer or ‘approx’ for the algorithm described by Bernardi and Perrin-Riou (much slower and not fully tested)

EXAMPLES:

```python
sage: E = EllipticCurve('14a')
sage: L = E.padic_lseries(5)
sage: phi = L.frobenius(5)
sage: phi
[ 2 + 5^2 + 5^4 + O(5^5) 3*5^-1 + 3 + 5 + 4*5^2 + 5^3 + O(5^4)
→ 4)]
[ 3 + 3*5^2 + 4*5^3 + 3*5^4 + O(5^5) 3 + 4*5 + 3*5^2 + 4*5^3 + 3*5^4 + O(5^5
→ 5)]
sage: -phi^2
[5^4 + O(5^4)]
```
**is_ordinary()**
Return True if the elliptic curve that this L-function is attached to is ordinary.

EXAMPLES:

```python
sage: L = EllipticCurve('11a').padic_lseries(19)
sage: L.is_ordinary()
False
```

**is_supersingular()**
Return True if the elliptic curve that this L function is attached to is supersingular.

EXAMPLES:

```python
sage: L = EllipticCurve('11a').padic_lseries(19)
sage: L.is_supersingular()
True
```

**power_series(n=3, quadratic_twist=1, prec=5, eta=0)**
Return the \(n\)-th approximation to the \(p\)-adic L-series as a power series in \(T\) (corresponding to \(\gamma - 1\) with \(\gamma = 1 + p\) as a generator of \(1 + p\mathbb{Z}_p\)). Each coefficient is an element of a quadratic extension of the \(p\)-adic number whose precision is provably correct.

Here the normalization of the \(p\)-adic L-series is chosen such that \(L_p(E,1) = (1 - 1/\alpha)^2 L(E,1)/\Omega_E\) where \(\alpha\) is a root of the characteristic polynomial of Frobenius on \(T_pE\) and \(\Omega_E\) is the Néron period of \(E\).

**INPUT:**
- \(n\) – (default: 2) a positive integer
- \(quadratic\_twist\) – (default: +1) a fundamental discriminant of a quadratic field, coprime to the conductor of the curve
- \(prec\) – (default: 5) maximal number of terms of the series to compute; to compute as many as possible just give a very large number for \(prec\); the result will still be correct.
- \(eta\) (default: 0) an integer (specifying the power of the Teichmüller character on the group of roots of unity in \(\mathbb{Z}_p^\times\))

**OUTPUT:**
a power series with coefficients in a quadratic ramified extension of the \(p\)-adic numbers generated by a root \(alpha\) of the characteristic polynomial of Frobenius on \(T_pE\).

**ALIAS:** power_series is identical to series.

**EXAMPLES:**
A supersingular example, where we must compute to higher precision to see anything:

```python
sage: e = EllipticCurve('37a')
sage: L = e.padic_lseries(3); L
3-adic L-series of Elliptic Curve defined by y^2 + y = x^3 - x over Rational
˓→ Field
sage: L.series(2)
O(T^3)
sage: L.series(4)
# takes a long time (several seconds)
O(alpha) + (alpha^-2 + O(alpha^0)) T + (alpha^-2 + O(alpha^0)) T^2 + O(T^5)
sage: L.alpha(2).parent()
3-adic Eisenstein Extension Field in alpha defined by x^2 + 3*x + 3
```
An example where we only compute the leading term (trac ticket #15737):

```python
sage: E = EllipticCurve("17a1")
sage: L = E.padic_lseries(3)
sage: L.series(4, prec=1)
alpha^-2 + alpha^-1 + 2 + 2*alpha + ... + O(alpha^38) + O(T)
```

It works also for $p = 2$:

```python
sage: E = EllipticCurve("11a1")
sage: lp = E.padic_lseries(2)
sage: lp.series(10)
O(alpha^-3) + (alpha^-4 + O(alpha^-3))*T + (alpha^-4 + O(alpha^-3))*T^2 + ...
```

```
\texttt{series}(n=3, \texttt{quadratic\_twist}=1, \texttt{prec}=5, \texttt{eta}=0)
```

Return the $n$-th approximation to the $p$-adic $L$-series as a power series in $T$ (corresponding to $\gamma - 1$ with $\gamma = 1 + p$ as a generator of $1 + p\mathbb{Z}_p$). Each coefficient is an element of a quadratic extension of the $p$-adic number whose precision is provably correct.

Here the normalization of the $p$-adic $L$-series is chosen such that $L_p(E,1) = (1 - 1/\alpha)^2 L(E,1)/\Omega_E$ where $\alpha$ is a root of the characteristic polynomial of Frobenius on $T_pE$ and $\Omega_E$ is the Néron period of $E$.

INPUT:

- $n$ – (default: 2) a positive integer
- \texttt{quadratic\_twist} – (default: +1) a fundamental discriminant of a quadratic field, coprime to the conductor of the curve
- \texttt{prec} – (default: 5) maximal number of terms of the series to compute; to compute as many as possible just give a very large number for \texttt{prec}; the result will still be correct.
- \texttt{eta} (default: 0) an integer (specifying the power of the Teichmueller character on the group of roots of unity in $\mathbb{Z}_p^\times$)

OUTPUT:

a power series with coefficients in a quadratic ramified extension of the $p$-adic numbers generated by a root $\alpha$ of the characteristic polynomial of Frobenius on $T_pE$.

ALIAS: power\_series is identical to series.

EXAMPLES:

A supersingular example, where we must compute to higher precision to see anything:

```python
sage: e = EllipticCurve('37a')
sage: L = e.padic_lseries(3); L
3-adic L-series of Elliptic Curve defined by y^2 + y = x^3 - x over Rational Field
sage: L.series(2)
O(T^3)
sage: L.series(4)  # takes a long time (several seconds)
O(alpha) + (alpha^-2 + O(alpha^0))*T + (alpha^-2 + O(alpha^0))*T^2 + O(T^5)
sage: L.alpha(2).parent()
3-adic Eisenstein Extension Field in alpha defined by x^2 + 3*x + 3
```

An example where we only compute the leading term (trac ticket #15737):
\begin{verbatim}
  sage: E = EllipticCurve("17a1")
  sage: L = E.padic_lseries(3)
  sage: L.series(4, prec=1)
  alpha^-2 + alpha^-1 + 2 + 2*alpha + ... + O(alpha^38) + O(T)
\end{verbatim}

It works also for $p = 2$:

\begin{verbatim}
  sage: E = EllipticCurve("11a1")
  sage: lp = E.padic_lseries(2)
  sage: lp.series(10)
  O(alpha^-3) + (alpha^-4 + O(alpha^-3))*T + (alpha^-4 + O(alpha^-3))*T^2 +
  (alpha^-5 + alpha^-4 + O(alpha^-3))*T^3 + (alpha^-4 + O(alpha^-3))*T^4 + O(T^5)
\end{verbatim}
15.1 Descent on elliptic curves over $\mathbb{Q}$ with a $2$-isogeny

sage.schemes.elliptic_curves.descent_two_isogeny.test_els($a, b, c, d, e$)
Doctest function for cdef int everywhere_locally_soluble(mpz_t, mpz_t, mpz_t, mpz_t, mpz_t).

```
sage: from sage.schemes.elliptic_curves.descent_two_isogeny import test_els
sage: for _ in range(1000):
    ....:     a, b, c, d, e = randint(1, 1000), randint(1, 1000), randint(1, 1000), randint(-1000, 1000)
    ....:     if pari.Pol([a, b, c, d, e]).hyperellratpoints(1000, 1):
    ....:         try:
    ....:             if not test_els(a, b, c, d, e):
    ....:                 print("This never happened", a, b, c, d, e)
    ....:         except ValueError:
    ....:             continue
```

sage.schemes.elliptic_curves.descent_two_isogeny.test_padic_square($a, p$)
Doctest function for cdef int padic_square(mpz_t, unsigned long).

```
sage: from sage.schemes.elliptic_curves.descent_two_isogeny import test_padic_square
sage: for i in [1..300]:
    ....:     for p in prime_range(100):
    ....:         if not Qp(p)(i).is_square()==bool(ps(i,p)):
    ....:             print(i, p)
```

sage.schemes.elliptic_curves.descent_two_isogeny.test_qpls($a, b, c, d, e, p$)
Testing function for Qp_soluble.

```
sage: from sage.schemes.elliptic_curves.descent_two_isogeny import test_qpls as tq
sage: tq(1, 2, 3, 4, 5, 7)
1
```

sage.schemes.elliptic_curves.descent_two_isogeny.test_valuation($a, p$)
Doctest function for cdef long valuation(mpz_t, mpz_t).

```
sage: from sage.schemes.elliptic_curves.descent_two_isogeny import test_valuation
```

577
sage: from sage.schemes.elliptic_curves.descent_two_isogeny import test_valuation
˓→as tv
sage: for i in [1..20]:
....:   print('{:>10} {} {} {}'.format(factor(i), tv(i,2), tv(i,3), tv(i,5)))
1   0   0   0
2   1   0   0
3   0   1   0
2^2  2   0   0
5   0   0   1
2   3   1   1
7   0   0   0
2*3  3   0   0
3*2  0   2   0
2   5   1   0
11  0   0   0
2^2  3   2   1
13  0   0   0
2   7   1   0
3   5   0   1
2*4  4   0   0
17  0   0   0
2   3*2  1   2
19  0   0   0
2^2  5   2   0
1

Given an elliptic curve $E$ with a two-isogeny $\phi : E \rightarrow E'$ and dual isogeny $\phi'$, runs a two-isogeny descent on $E$, returning $n_1, n_2, n_1'$ and $n_2'$. Here $n_1$ is the number of quartic covers found with a rational point, and $n_2$ is the number which are ELS.

EXAMPLES:

sage: E = EllipticCurve('14a')
sage: n1, n2, n1_prime, n2_prime = two_descent_by_two_isogeny(E)

0

sage: E = EllipticCurve('65a')

sage: n1, n2, n1_prime, n2_prime = two_descent_by_two_isogeny(E)

1

sage: x,y = var('x,y')

sage: E = EllipticCurve(y^2 + x*y + y == x^3 - 131*x + 558)

2

 uninterruptible}
Elliptic curves, Release 9.7

sage: n1, n2, n1_prime, n2_prime = two_descent_by_two_isogeny(E)
sage: log(n1,2) + log(n1_prime,2) - 2 # the rank
3

Using the verbosity option:

sage: E = EllipticCurve('14a')
sage: two_descent_by_two_isogeny(E, verbosity=1)
2-isogeny
Results:
2 <= #E(Q)/phi'(E'(Q)) <= 2
2 <= #E'(Q)/phi(E(Q)) <= 2
#Sel^(phi') (E'/Q) = 2
#Sel^(phi) (E/Q) = 2
1 <= #Sha(E'/Q)[phi'] <= 1
1 <= #Sha(E/Q)[phi] <= 1
1 <= #Sha(E/Q)[2], #Sha(E'/Q)[2] <= 1
0 <= rank of E(Q) = rank of E'(Q) <= 0
(2, 2, 2, 2)

Handling curves whose discriminants involve larger than wordsize primes:

sage: E = EllipticCurve('14a')
sage: E = E.quadratic_twist(next_prime(10^20))
sage: E
Elliptic Curve defined by y^2 = x^3 + x^2 + 716666666666666666666666666666666666775672*x - 391925925925925926384240370370370370549019837037037037060249356 over Rational Field
sage: E.discriminant().factor()
(-1 * 2^18 * 7^3 * 10000000000000039)^6
sage: log(10000000000000039.0, 2.0)
66.438...
sage: n1, n2, n1_prime, n2_prime = two_descent_by_two_isogeny(E)
sage: log(n1,2) + log(n1_prime,2) - 2 # the rank
0

sage.schemes.elliptic_curves.descent_two_isogeny.two_descent_by_two_isogeny_work(c, d, global_limit_small=10, global_limit_large=10000, verbosity=0, selmer_only=0, proof=1)

Do all the work in doing a two-isogeny descent.

EXAMPLES:

sage: from sage.schemes.elliptic_curves.descent_two_isogeny import two_descent_by_two_isogeny_work
sage: n1, n2, n1_prime, n2_prime = two_descent_by_two_isogeny_work(13,128)
sage: log(n1,2) + log(n1_prime,2) - 2 # the rank
0

(continues on next page)
15.2 Elliptic curves with prescribed good reduction

Construction of elliptic curves with good reduction outside a finite set of primes

A theorem of Shafarevich states that, over a number field $K$, given any finite set $S$ of primes of $K$, there are (up to isomorphism) only a finite set of elliptic curves defined over $K$ with good reduction at all primes outside $S$. An explicit form of the theorem with an algorithm for finding this finite set was given in “Finding all elliptic curves with good reduction outside a given set of primes” by John Cremona and Mark Lingham, Experimental Mathematics 16 No.3 (2007), 303-312. The method requires computation of the class and unit groups of $K$ as well as all the $S$-integral points on a collection of auxiliary elliptic curves defined over $K$.

This implementation (April 2009) is only for the case $K = \mathbb{Q}$, where in many cases the determination of the necessary sets of $S$-integral points is possible. The main user-level function is `EllipticCurves_with_good_reduction_outside_S()`, defined in constructor.py. Users should note carefully the following points:

(1) the number of auxiliary curves to be considered is exponential in the size of $S$ (specifically, $2^{6s}$ where $s = |S|$).

(2) For some of the auxiliary curves it is impossible at present to provably find all the $S$-integral points using the current algorithms, which rely on first finding a basis for their Mordell-Weil groups using 2-descent. A warning is output in cases where the set of points (and hence the final output) is not guaranteed to be complete. Using the `proof=False` flag suppresses these warnings.

EXAMPLES: We find all elliptic curves with good reduction outside 2, listing the label of each:

```
sage: [e.label() for e in EllipticCurves_with_good_reduction_outside_S([2])] # long...
            ...
['32a1',
 '32a2',
 '32a3',
 '32a4',
 '64a1',
 '64a2',
 '64a3',
 '64a4',
 '128a1',
 '128a2',
 '128b1',
 '128b2',
 '128c1',
 '128c2',
 '128d1',
 '128d2',
]```

(continues on next page)
Secondly we try the same with \( S = 11 \); note that warning messages are printed with \texttt{proof=False} (unless the optional database is installed: two of the auxiliary curves whose Mordell-Weil bases are required have conductors 13068 and 52272 so are in the database):

```
sage: [e.label() for e in EllipticCurves_with_good_reduction_outside_S([11], proof=False)] # long time (13s on sage.math, 2011)
['11a1', '11a2', '11a3', '121a1', '121a2', '121b1', '121b2', '121c1', '121c2', '121d1', '121d2', '121d3']
```

AUTHORS:

• John Cremona (6 April 2009): initial version (over \( \mathbb{Q} \) only).

\[
\text{sage.schemes.elliptic_curves.ell_egros.curve_key}(E1)
\]
Comparison key for elliptic curves over \( \mathbb{Q} \).
The key is a tuple:
• if the curve is in the database: (conductor, 0, label, number)
• otherwise: (conductor, 1, a_invariants)

EXAMPLES:

```
sage: from sage.schemes.elliptic_curves.ell_egros import curve_key
sage: E = EllipticCurve_from_j(1728)
sage: curve_key(E)
(32, 0, 0, 2)
sage: E = EllipticCurve_from_j(1729)
sage: curve_key(E)
(2989441, 1, (1, 0, 0, -36, -1))
```

\[
\text{sage.schemes.elliptic_curves.ell_egros.egros_from_j}(j, S=[])
\]
Given a rational \( j \) and a list of primes \( S \), returns a list of elliptic curves over \( \mathbb{Q} \) with \( j \)-invariant \( j \) and good reduction outside \( S \), by checking all relevant quadratic twists.

INPUT:

• \( j \) – a rational number.
• \( S \) – list of primes (default: empty list).

\textbf{Note:} Primality of elements of \( S \) is not checked, and the output is undefined if \( S \) is not a list or contains non-primes.

OUTPUT:
A sorted list of all elliptic curves defined over $\mathbb{Q}$ with $j$-invariant equal to $j$ and with good reduction at all primes outside the list $S$.

**EXAMPLES:**

```python
sage: from sage.schemes.elliptic_curves.ell_egros import egros_from_j
sage: [e.label() for e in egros_from_j(0, [3])]
['27a1', '27a3', '243a1', '243a2', '243b1', '243b2']
sage: [e.label() for e in egros_from_j(1728, [2])]
['32a1', '32a2', '64a1', '64a4', '256b1', '256b2', '256c1', '256c2']
sage: egros_from_j_0(S=[])  # long time (8s on sage.math, 2013)
432
```

**INPUT:**

- $S$ – list of primes (default: empty list).

**OUTPUT:**

A sorted list of all elliptic curves defined over $\mathbb{Q}$ with $j$-invariant equal to 0 and with good reduction at all primes outside the list $S$.

**EXAMPLES:**

```python
sage: egros_from_j_0(S=[])  # long time (8s on sage.math, 2013)
432
```

**OUTPUT:**

582 Chapter 15. To be sorted
A sorted list of all elliptic curves defined over $\mathbb{Q}$ with $j$-invariant equal to 1728 and with good reduction at all primes outside the list $S$.

EXAMPLES:

```python
sage: from sage.schemes.elliptic_curves.ell_egros import egros_from_j_1728
sage: egros_from_j_1728([])
[]
sage: egros_from_j_1728([3])
[]
sage: [e.cremona_label() for e in egros_from_j_1728([2])]
['32a1', '32a2', '64a1', '64a4', '256b1', '256b2', '256c1', '256c2']
```

`sage.schemes.elliptic_curves.ell_egros.egros_from_jlist(jlist, S=[])`

Given a list of rational $j$ and a list of primes $S$, returns a list of elliptic curves over $\mathbb{Q}$ with $j$-invariant in the list and good reduction outside $S$.

INPUT:

- $j$ – list of rational numbers.
- $S$ – list of primes (default: empty list).

**Note:** Primality of elements of $S$ is not checked, and the output is undefined if $S$ is not a list or contains non-primes.

OUTPUT:

A sorted list of all elliptic curves defined over $\mathbb{Q}$ with $j$-invariant in the list $jlist$ and with good reduction at all primes outside the list $S$.

EXAMPLES:

```python
sage: from sage.schemes.elliptic_curves.ell_egros import egros_get_j, egros_from_jlist
sage: jlist=egros_get_j([3])
sage: elist=egros_from_jlist(jlist,[3])
sage: [e.label() for e in elist]
['27a1', '27a2', '27a3', '27a4', '243a1', '243a2', '243b1', '243b2']
sage: [e.ainvs() for e in elist]
[(0, 0, 1, 0, -7),
 (0, 0, 1, -270, -1708),
 (0, 0, 1, -30, 63),
 (0, 0, 1, 0, -1),
 (0, 0, 1, 0, 20),
 (0, 0, 1, 0, 2),
 (0, 0, 1, 0, -61)]
```

`sage.schemes.elliptic_curves.ell_egros.egros_get_j(S=[], proof=None, verbose=False)`

Returns a list of rational $j$ such that all elliptic curves defined over $\mathbb{Q}$ with good reduction outside $S$ have $j$-invariant in the list, sorted by height.

INPUT:

- $S$ – list of primes (default: empty list).
Elliptic curves, Release 9.7

- **proof** – True/False (default True): the MW basis for auxiliary curves will be computed with this proof flag.
- **verbose** – True/False (default False): if True, some details of the computation will be output.

**Note:** Proof flag: The algorithm used requires determining all S-integral points on several auxiliary curves, which in turn requires the computation of their generators. This is not always possible (even in theory) using current knowledge.

The value of this flag is passed to the function which computes generators of various auxiliary elliptic curves, in order to find their S-integral points. Set to False if the default (True) causes warning messages, but note that you can then not rely on the set of invariants returned being complete.

**EXAMPLES:**

```sage
def egros_get_j(j):
    if j == 0:
        return False
    if j == 1728:
        return True
    # Additional cases...
```

sage.schemes.elliptic_curves.ell_egros.is_possible_j(j, S=[]) Tests if the rational \( j \) is a possible \( j \)-invariant of an elliptic curve with good reduction outside \( S \).

**Note:** The condition used is necessary but not sufficient unless \( S \) contains both 2 and 3.

**EXAMPLES:**

```sage
def is_possible_j(j, S=[]):
    # Additional conditions...
```

15.3 Elliptic curves over p-adic fields

class sage.schemes.elliptic_curves.ell_padic_field.EllipticCurve_padic_field(K, ainvs) Bases: sage.schemes.elliptic_curves.ell_field.EllipticCurve_field, sage.schemes.hyperelliptic_curves.hyperelliptic_padic_field.HyperellipticCurve_padic_field

Elliptic curve over a p-adic field.

**EXAMPLES:**
sage: Qp=pAdicField(17)
sage: E=EllipticCurve(Qp,[2,3]); E
Elliptic Curve defined by y^2 = x^3 + (2+O(17^20))*x + (3+O(17^20)) over 17-adic Field with capped relative precision 20
sage: E == loads(dumps(E))
True

frobenius(P=None)
Return the Frobenius as a function on the group of points of this elliptic curve.

EXAMPLES:

sage: Qp = pAdicField(13)
sage: E = EllipticCurve(Qp,[1,1])
sage: type(E.frobenius())
<... 'function'>
sage: point = E(0,1)
sage: E.frobenius(point)
(0 : 1 + O(13^20) : 1 + O(13^20))

Check that trac ticket #29709 is fixed:

sage: Qp = pAdicField(13)
sage: E = EllipticCurve(Qp,[0,0,1,0,1])
Traceback (most recent call last):
  ... Not ImplementedError: Curve must be in weierstrass normal form.
sage: E = EllipticCurve(Qp,[0,1,0,0,1])
sage: E.frobenius(E(0,1))
(0 : 1 + O(13^20) : 1 + O(13^20))

15.4 Denis Simon’s PARI scripts

sage.schemes.elliptic_curves.gp_simon.init()
Function to initialize the gp process

sage.schemes.elliptic_curves.gp_simon.simon_two_descent(E, verbose=0, lim1=None, lim3=None, limtriv=None, maxprob=20, limbigprime=30, known_points=[])

Interface to Simon’s gp script for two-descent.

Note: Users should instead run E.simon_two_descent()

EXAMPLES:

sage: import sage.schemes.elliptic_curves.gp_simon
sage: E=EllipticCurve('389a1')
sage: sage.schemes.elliptic_curves.gp_simon.simon_two_descent(E)
(2, 2, [(1 : 0 : 1), (-11/9 : 28/27 : 1)])
15.5 Elliptic curves with congruent mod-5 representation

AUTHORS:

- Alice Silverberg and Karl Rubin – original PARI/GP version
- William Stein – Sage version

sage.schemes.elliptic_curves.mod5family.mod5family(a, b)

Formulas for computing the family of elliptic curves with congruent mod-5 representation.

EXAMPLES:

```python
sage: from sage.schemes.elliptic_curves.mod5family import mod5family
sage: mod5family(0,1)
Elliptic Curve defined by y^2 = x^3 + (t^30+30*t^29+435*t^28+4060*t^27+27405*t^26+142506*t^25+593775*t^24+2035800*t^23+5852925*t^22+14307150*t^21+30045015*t^20+54627300*t^19+86493225*t^18+119759850*t^17+145422675*t^16+155117520*t^15+145422675*t^14+119759850*t^13+86493225*t^12+54627300*t^11+30045015*t^10+14307150*t^9+593775*t^8+2035800*t^7+5852925*t^6+142506*t^5+27405*t^4+4060*t^3+435*t^2+30*t+1) over Fraction Field of Univariate Polynomial Ring in t over Rational Field
```

15.6 Morphism to bring a genus-one curve into Weierstrass form

You should use `EllipticCurve_from_cubic()` or `EllipticCurve_from_curve()` to construct the transformation starting with a cubic or with a genus one curve.

EXAMPLES:

```python
sage: R.<u,v,w> = QQ[]
sage: f = EllipticCurve_from_cubic(u^3 + v^3 + w^3, [1,-1,0], morphism=True); f
Scheme morphism:
  From: Projective Plane Curve over Rational Field defined by u^3 + v^3 + w^3
  To:  Elliptic Curve defined by y^2 - 9*y = x^3 - 27 over Rational Field
  Defn: Defined on coordinates by sending (u : v : w) to
        (-w : 3*u : 1/3*u + 1/3*v)
sage: finv = f.inverse(); finv
Scheme morphism:
  From: Elliptic Curve defined by y^2 - 9*y = x^3 - 27 over Rational Field
  To:  Projective Plane Curve over Rational Field defined by u^3 + v^3 + w^3
  Defn: Defined on coordinates by sending (x : y : z) to
        (1/3*y : -1/3*y + 3*z : -x)
sage: (u^3 + v^3 + w^3)(f.inverse().defining_polynomials()) * f.inverse().post_rescaling()
-x^3 + y^2*z - 9*y*z^2 + 27*z^3
sage: E = finv.domain()
sage: E.defining_polynomial()(f.defining_polynomials()) * f.post_rescaling()
u^3 + v^3 + w^3
```

(continues on next page)
class sage.schemes.elliptic_curves.weierstrass_transform.WeierstrassTransformation(domain, codomain, defining_polynomials, post_multiplication)

Bases: sage.schemes.generic.morphism.SchemeMorphism_polynomial

A morphism of a genus-one curve to/from the Weierstrass form.

INPUT:

- domain, codomain – two schemes, one of which is an elliptic curve.
- defining_polynomials – triplet of polynomials that define the transformation.
- post_multiplication – a polynomial to homogeneously rescale after substituting the defining polynomials.

EXAMPLES:

```python
sage: P2.<u,v,w> = ProjectiveSpace(2,QQ)
sage: C = P2.subscheme(u^3 + v^3 + w^3)
sage: E = EllipticCurve([2, -1, -1/3, 1/3, -1/27])
sage: from sage.schemes.elliptic_curves.weierstrass_transform import WeierstrassTransformation
sage: f = WeierstrassTransformation(C, E, [w, -v-w, -3*u-3*v], 1); f
Scheme morphism:
From: Closed subscheme of Projective Space of dimension 2 over Rational Field
→ defined by:
  u^3 + v^3 + w^3
To:  Elliptic Curve defined by y^2 + 2*x*y - 1/3*y = x^3 - x^2 + 1/3*x - 1/27
     over Rational Field
Defn: Defined on coordinates by sending (u : v : w) to
  (w : -v - w : -3*u - 3*v)

sage: f([-1, 1, 0])
(0 : 1 : 0)
sage: f([-1, 0, 1])
(1/3 : -1/3 : 1)
sage: f([0,1,1])
(3 : 0 : 1)
```
a^3 + b^3 + 1
To:    Elliptic Curve defined by y^2 + 2*x*y - 1/3*y
       = x^3 - x^2 + 1/3*x - 1/27 over Rational Field
Defn: Defined on coordinates by sending (a, b) to
       (1 : -b - 1 : -3*a - 3*b)
sage: f([-1,0])
(1/3 : -1/3 : 1)
sage: f([0,-1])
(1/3 : 0 : 1)

post_rescaling()

Return the homogeneous rescaling to apply after the coordinate substitution.

OUTPUT:

A polynomial. See the example below.

EXAMPLES:

sage: R.<a,b,c> = QQ[

sage: cubic = a^3+7*b^3+64*c^3
sage: P = [2,2,-1]

sage: f = EllipticCurve_from_cubic(cubic, P, morphism=True).inverse()

sage: f.post_rescaling()
-1/7

So here is what it does. If we just plug in the coordinate transformation, we get the defining polynomial up to scale. This method returns the overall rescaling of the equation to bring the result into the standard form:

sage: cubic(f.defining_polynomials())
7*x^3 - 7*y^2*z + 1806336*y*z^2 - 155373797376*z^3

sage: cubic(f.defining_polynomials()) * f.post_rescaling()
-x^3 + y^2*z - 258048*y^2*z^2 + 22196256768*z^3

sage.schemes.elliptic_curves.weierstrass_transform.WeierstrassTransformationWithInverse(domain, codomain, defining_polynomials, post_multiplication, inv_defining_polynomials, inv_post_multiplication)

Construct morphism of a genus-one curve to/from the Weierstrass form with its inverse.

EXAMPLES:

sage: R.<u,v,w> = QQ[

sage: f = EllipticCurve_from_cubic(u^3 + v^3 + w^3, [1,-1,0], morphism=True); f

Scheme morphism:
From: Projective Plane Curve over Rational Field defined by u^3 + v^3 + w^3
To:    Elliptic Curve defined by y^2 - 9*y = x^3 - 27 over Rational Field
Defn: Defined on coordinates by sending (u : v : w) to
(-w : 3*u : 1/3*u + 1/3*v)

Scheme morphism:
From: Closed subscheme of Projective Space of dimension 2 over Rational Field
\[ u^3 + v^3 + w^3 \]
To: Elliptic Curve defined by \[ y^2 + 2x y + \frac{1}{3}y \]
\[ = x^3 - x^2 - \frac{1}{3}x - \frac{1}{27} \]
over Rational Field
Defn: Defined on coordinates by sending \((u : v : w)\) to
\[ (-w : -v + w : 3u + 3v) \]

class \texttt{sage.schemes.elliptic_curves.weierstrass_transform.WeierstrassTransformationWithInverse}\(\texttt{class}(\texttt{domain}, \texttt{codomain}, \texttt{defining\_polynomials}, \texttt{post\_multiplication})\)

Bases: \texttt{sage.schemes.elliptic_curves.weierstrass_transform.WeierstrassTransformation}

\texttt{inverse()}

Return the inverse.

OUTPUT:

A morphism in the opposite direction. This may be a rational inverse or an analytic inverse.

EXAMPLES:

\begin{verbatim}
\texttt{sage: R.<u,v,w> = QQ[]}
\texttt{sage: f = EllipticCurve\_from\_cubic(u^3 + v^3 + w^3, [1,-1,0], morphism=True)}
\texttt{sage: f.inverse()}
\end{verbatim}

Scheme morphism:
From: Elliptic Curve defined by \[ y^2 - 9y = x^3 - 27 \]
over Rational Field
To: Projective Plane Curve over Rational Field defined by \[ u^3 + v^3 + w^3 \]
Defn: Defined on coordinates by sending \((x : y : z)\) to
\[ (1/3*y : -1/3*y + 3*z : -x) \]
16.1 Hyperelliptic curve constructor

AUTHORS:
• David Kohel (2006): initial version
• Anna Somoza (2019-04): dynamic class creation

```
sage.schemes.hyperelliptic_curves.constructor.HyperellipticCurve(f, h=0, names=None, PP=None, check_squarefree=True)
```

Returns the hyperelliptic curve $y^2 + h y = f$, for univariate polynomials $h$ and $f$. If $h$ is not given, then it defaults to 0.

INPUT:
• $f$ - univariate polynomial
• $h$ - optional univariate polynomial
• names (default: ['x', 'y']) - names for the coordinate functions
• check_squarefree (default: True) - test if the input defines a hyperelliptic curve when $f$ is homogenized to degree $2g + 2$ and $h$ to degree $g + 1$ for some $g$.

**Warning:** When setting check_squarefree=False or using a base ring that is not a field, the output curves are not to be trusted. For example, the output of `is_singular` is always False, without this being properly tested in that case.

---

**Note:** The words “hyperelliptic curve” are normally only used for curves of genus at least two, but this class allows more general smooth double covers of the projective line (conics and elliptic curves), even though the class is not meant for those and some outputs may be incorrect.

**EXAMPLES:**

Basic examples:

```
sage: R.<x> = QQ[]
sage: HyperellipticCurve(x^5 + x + 1)
Hyperelliptic Curve over Rational Field defined by y^2 = x^5 + x + 1
sage: HyperellipticCurve(x^19 + x + 1, x-2)
```

(continues on next page)
Hyperelliptic Curve over Rational Field defined by \(y^2 + (x - 2)\hat{y} = x^{19} + x + 1\)

\[\text{sage: } k.<a> = GF(9); R.<x> = k[]\]
\[\text{sage: HyperellipticCurve}(x^3 + x - 1, x+a)\]

Hyperelliptic Curve over Finite Field in \(a\) of size 3^2 defined by \(y^2 + (x + a)\hat{y} = \_\]
\[\text{˓→} x^3 + x + 2\]

Characteristic two:

\[\text{sage: } P.<x> = GF(8, 'a')[]\]
\[\text{sage: HyperellipticCurve}(x^7+1, x)\]

Hyperelliptic Curve over Finite Field in \(a\) of size 2^3 defined by \(y^2 + x^7 = \_\]
\[\text{˓→} 1\]
\[\text{sage: HyperellipticCurve}(x^8+x^7+1, x^4+1)\]

Hyperelliptic Curve over Finite Field in \(a\) of size 2^3 defined by \(y^2 + (x^4 + 1)\hat{y} = \_\]
\[\text{˓→} x^8 + x^7 + 1\]
\[\text{sage: HyperellipticCurve}(x^8+1, x)\]

Traceback (most recent call last):
... ValueError: Not a hyperelliptic curve: highly singular at infinity.

\[\text{sage: HyperellipticCurve}(x^8+x^7+1, x^4)\]

Traceback (most recent call last):
... ValueError: Not a hyperelliptic curve: singularity in the provided affine patch.

We can change the names of the variables in the output:

\[\text{sage: } k.<a> = GF(9); R.<x> = k[]\]
\[\text{sage: HyperellipticCurve}(x^3 + x - 1, x+a, names=['X', 'Y'])\]

Hyperelliptic Curve over Finite Field in \(a\) of size 3^2 defined by \(Y^2 + (X + a)Y = \_\]
\[\text{˓→} X^3 + X + 2\]

This class also allows curves of genus zero or one, which are strictly speaking not hyperelliptic:

\[\text{sage: } P.<x> = QQ[]\]
\[\text{sage: HyperellipticCurve}(x^2+1)\]

Hyperelliptic Curve over Rational Field defined by \(y^2 = x^2 + 1\)
\[\text{sage: HyperellipticCurve}(x^4-1)\]

Hyperelliptic Curve over Rational Field defined by \(y^2 = x^4 - 1\)
\[\text{sage: HyperellipticCurve}(x^3+2*x+2)\]

Hyperelliptic Curve over Rational Field defined by \(y^2 = x^3 + 2x + 2\)

Double roots:
The input for a (smooth) hyperelliptic curve of genus $g$ should not contain polynomials of degree greater than $2g + 2$. In the following example, the hyperelliptic curve has genus 2 and there exists a model $y^2 = F$ of degree 6, so the model $y^2 + yh = f$ of degree 200 is not allowed:

```sage
sage: P.<x> = QQ[]
sage: h = x^100
sage: F = x^6+1
sage: f = F-h^2/4
sage: HyperellipticCurve(f, h)
Traceback (most recent call last):
... ValueError: Not a hyperelliptic curve: highly singular at infinity.
```

An example with a singularity over an inseparable extension of the base field:

```sage
sage: P.<x> = GF(5)[]
sage: F.<t> = GF(5)[]
sage: P.<x> = F[]
sage: HyperellipticCurve(x^5+t)
Traceback (most recent call last):
... ValueError: Not a hyperelliptic curve: singularity in the provided affine patch.
```

Input with integer coefficients creates objects with the integers as base ring, but only checks smoothness over $\mathbb{Q}$, not over $\text{Spec}(\mathbb{Z})$. In other words, it is checked that the discriminant is non-zero, but it is not checked whether the discriminant is a unit in $\mathbb{Z}^*$:

```sage
sage: P.<x> = ZZ[]
sage: HyperellipticCurve(3*x^7+6*x+6)
Hyperelliptic Curve over Integer Ring defined by $y^2 = 3x^7 + 6x + 6$
```

### 16.2 Hyperelliptic curves over a general ring

**EXAMPLES:**

```sage
sage: P.<x> = GF(5)[]
sage: f = x^5 - 3*x^4 - 2*x^3 + 6*x^2 + 3*x - 1
sage: C = HyperellipticCurve(f); C
Hyperelliptic Curve over Finite Field of size 5 defined by $y^2 = x^5 + 2x^4 + 3x^3 + x^2 + 2 + 3x + 4$
```
sage: P.<x> = QQ[]
sage: f = 4*x^5 - 30*x^3 + 45*x - 22
sage: C = HyperellipticCurve(f); C
Hyperelliptic Curve over Rational Field defined by y^2 = 4*x^5 - 30*x^3 + 45*x - 22
sage: C.genus()
2

sage: D = C.affine_patch(0)
sage: D.defining_polynomials()[0].parent()
Multivariate Polynomial Ring in x1, x2 over Rational Field

class sage.schemes.hyperelliptic_curves.hyperelliptic_generic.HyperellipticCurve_generic

Bases: sage.schemes.curves.projective_curve.ProjectivePlaneCurve

    base_extend(R)
    Returns this HyperellipticCurve over a new base ring R.

    EXAMPLES:

    sage: R.<x> = QQ[]
sage: H = HyperellipticCurve(x^5 - 10*x + 9)
sage: K = Qp(3,5)
sage: L.<a> = K.extension(x^30-3)
sage: HK = H.change_ring(K)
sage: HL = HK.change_ring(L); HL
Hyperelliptic Curve over 3-adic Eisenstein Extension Field in a defined by x^30 → -3 defined by (1 + 0(a^150))*y^2 = (1 + 0(a^150))*x^5 + (2 + 2*a^30 + a^60 + ⋯ + 2*a^90 + 2*a^120 + 0(a^150))*x + a^60 + O(a^210)

    sage: R.<x> = FiniteField(7)[]
sage: H = HyperellipticCurve(x^8 + x + 5)
sage: H.base_extend(FiniteField(7^2,'a'))
Hyperelliptic Curve over Finite Field in a of size 7^2 defined by y^2 = x^8 + x^⋯ + 5

change_ring(R)
    Returns this HyperellipticCurve over a new base ring R.

    EXAMPLES:

    sage: R.<x> = QQ[]
sage: H = HyperellipticCurve(x^5 - 10*x + 9)
sage: K = Qp(3,5)
sage: L.<a> = K.extension(x^30-3)
sage: HK = H.change_ring(K)
sage: HL = HK.change_ring(L); HL
Hyperelliptic Curve over 3-adic Eisenstein Extension Field in a defined by x^30 → -3 defined by (1 + 0(a^150))*y^2 = (1 + 0(a^150))*x^5 + (2 + 2*a^30 + a^60 + ⋯ + 2*a^90 + 2*a^120 + 0(a^150))*x + a^60 + O(a^210)
sage: H = HyperellipticCurve(x^8 + x + 5)
sage: H.base_extend(FiniteField(7^2, 'a'))
Hyperelliptic Curve over Finite Field in a of size 7^2 defined by y^2 = x^8 + x + 5

has_odd_degree_model

Return True if an odd degree model of self exists over the field of definition; False otherwise.
Use odd_degree_model to calculate an odd degree model.

EXAMPLES:

sage: x = QQ['x'].0
sage: HyperellipticCurve(x^5 + x).has_odd_degree_model()
True
sage: HyperellipticCurve(x^6 + x).has_odd_degree_model()
True
sage: HyperellipticCurve(x^6 + x + 1).has_odd_degree_model()
False

hyperelliptic_polynomials(K=None, var='t')

EXAMPLES:

sage: R.<x> = QQ[]; C = HyperellipticCurve(x^3 + x - 1, x^3/5); C
Hyperelliptic Curve over Rational Field defined by y^2 + 1/5*x^3*y = x^3 + x - 1
sage: C.hyperelliptic_polynomials()
(x^3 + x - 1, 1/5*x^3)

invariant_differential()

Returns \( \frac{dx}{2y} \), as an element of the Monsky-Washnitzer cohomology of self

EXAMPLES:

sage: R.<x> = QQ[]

sage: H = HyperellipticCurve(x^5 + 1)

sage: H.is_singular()
False

A hyperelliptic curve with genus at least 2 always has a singularity at infinity when viewed as a plane projective curve. This can be seen in the following example.

is_singular()

Returns False, because hyperelliptic curves are smooth projective curves, as checked on construction.

EXAMPLES:

sage: R.<x> = QQ[]
sage: H = HyperellipticCurve(x^5 + 1)
sage: H.is_singular()
False
Elliptic curves, Release 9.7

```
sage: R.<x> = QQ[]
sage: H = HyperellipticCurve(x^5+2)
sage: from sage.misc.verbose import set_verbose
sage: set_verbose(-1)
sage: H.is_singular()
False
sage: from sage.schemes.curves.projective_curve import ProjectivePlaneCurve
sage: ProjectivePlaneCurve.is_singular(H)
True
```

**is_smooth()**

Returns True, because hyperelliptic curves are smooth projective curves, as checked on construction.

**EXAMPLES:**

```
sage: R.<x> = GF(13)[]
sage: H = HyperellipticCurve(x^8+1)
sage: H.is_smooth()
True
```

A hyperelliptic curve with genus at least 2 always has a singularity at infinity when viewed as a *plane* projective curve. This can be seen in the following example:

```
sage: R.<x> = GF(27, 'a')[]
sage: H = HyperellipticCurve(x^10+2)
sage: from sage.misc.verbose import set_verbose
sage: set_verbose(-1)
sage: H.is_smooth()
True
sage: from sage.schemes.curves.projective_curve import ProjectivePlaneCurve
sage: ProjectivePlaneCurve.is_smooth(H)
False
```

**jacobian()**

**lift_x(x, all=False)**

**local Coord(P, prec=20, name='t')**

Calls the appropriate local_coordinates function

**INPUT:**

- P – a point on self
- prec – desired precision of the local coordinates
- name – generator of the power series ring (default: t)

**OUTPUT:**

\((x(t), y(t))\) such that \(y(t)^2 = f(x(t))\), where \(t\) is the local parameter at \(P\)

**EXAMPLES:**

```
sage: R.<x> = QQ['x']
sage: H = HyperellipticCurve(x^5-23*x^3+18*x^2+40*x)
sage: H.local_coord(H(1,6), prec=5)
(1 + t + O(t^5), 6 + t - 7/2*t^2 - 1/2*t^3 - 25/48*t^4 + O(t^5))
```

(continues on next page)
sage: H.local_coord(H(4, 0), prec=7)
(4 + 1/360*t^2 - 191/23238000*t^4 + 7579/18895680000000*t^6 + O(t^7), t + O(t^7))
sage: H.local_coord(H(0, 1, 0), prec=5)
(t^-2 + 23*t^2 - 18*t^4 - 569*t^6 + O(t^7), t^-5 + 46*t^-1 - 36*t - 609*t^3 + 1656*t^5 + O(t^6))

AUTHOR:
• Jennifer Balakrishnan (2007-12)

local_coordinates_at_infinity(\(\text{prec}=20, \text{name}=t'\))

For the genus \(g\) hyperelliptic curve \(y^2 = f(x)\), return \((x(t), y(t))\) such that \((y(t))^2 = f(x(t))\), where \(t = x^g/y\) is the local parameter at infinity

INPUT:
• \(\text{prec}\) – desired precision of the local coordinates
• \(\text{name}\) – generator of the power series ring (default: \(t\))

OUTPUT:
\((x(t), y(t))\) such that \(y(t)^2 = f(x(t))\) and \(t = x^g/y\) is the local parameter at infinity

EXAMPLES:

sage: R.<x> = QQ['x']
sage: H = HyperellipticCurve(x^5-5*x^2+1)
sage: x,y = H.local_coordinates_at_infinity(10)
sage: x
t^-2 + 5*t^4 - t^8 - 50*t^10 + O(t^12)
sage: y
t^-5 + 10*t - 2*t^5 - 75*t^7 + 50*t^11 + O(t^12)

sage: R.<x> = QQ['x']
sage: H = HyperellipticCurve(x^3-x+1)
sage: x,y = H.local_coordinates_at_infinity(10)
sage: x
t^-2 + t^2 - t^4 - t^6 + 3*t^8 + O(t^12)
sage: y
t^-3 + t - t^3 - t^5 + 3*t^7 - 10*t^11 + O(t^12)

AUTHOR:
• Jennifer Balakrishnan (2007-12)

local_coordinates_at_nonweierstrass(\(P, \text{prec}=20, \text{name}=t'\))

For a non-Weierstrass point \(P = (a, b)\) on the hyperelliptic curve \(y^2 = f(x)\), return \((x(t), y(t))\) such that \((y(t))^2 = f(x(t))\), where \(t = x - a\) is the local parameter.

INPUT:
• \(P = (a, b)\) – a non-Weierstrass point on self
• \(\text{prec}\) – desired precision of the local coordinates
• \(\text{name}\) – gen of the power series ring (default: \(t\))
OUTPUT:

\((x(t), y(t))\) such that \(y(t)^2 = f(x(t))\) and \(t = x - a\) is the local parameter at \(P\)

EXAMPLES:

```python
sage: R.<x> = QQ['x']
sage: H = HyperellipticCurve(x^5-23*x^3+18*x^2+40*x)
sage: P = H(1,6)
sage: x, y = H.local_coordinates_at_nonweierstrass(P, prec=5)
sage: x
1 + t + O(t^5)
sage: y
6 + t - 7/2*t^2 - 1/2*t^3 - 25/48*t^4 + O(t^5)
sage: Q = H(-2,12)
sage: x, y = H.local_coordinates_at_nonweierstrass(Q, prec=5)
sage: x
-2 + t + O(t^5)
sage: y
12 - 19/2*t - 19/32*t^2 + 61/256*t^3 - 5965/24576*t^4 + O(t^5)
```

AUTHOR:

- Jennifer Balakrishnan (2007-12)

`local_coordinates_at_weierstrass(P, prec=20, name='t')`

For a finite Weierstrass point on the hyperelliptic curve \(y^2 = f(x)\), returns \((x(t), y(t))\) such that \((y(t))^2 = f(x(t))\), where \(t = y\) is the local parameter.

INPUT:

- \(P\) – a finite Weierstrass point on self
- \(prec\) – desired precision of the local coordinates
- \(name\) – gen of the power series ring (default: \(t\))

OUTPUT:

\((x(t), y(t))\) such that \(y(t)^2 = f(x(t))\) and \(t = y\) is the local parameter at \(P\)

EXAMPLES:

```python
sage: R.<x> = QQ['x']
sage: H = HyperellipticCurve(x^5-23*x^3+18*x^2+40*x)
sage: A = H(4, 0)
sage: x, y = H.local_coordinates_at_weierstrass(A, prec=7)
sage: x
4 + 1/360*t^2 - 191/23328000*t^4 + 7579/188956800000*t^6 + O(t^7)
sage: y
t + O(t^7)
sage: B = H(-5, 0)
sage: x, y = H.local_coordinates_at_weierstrass(B, prec=5)
sage: x
-5 + 1/1260*t^2 + 887/2000376000*t^4 + O(t^5)
sage: y
t + O(t^5)
```

AUTHOR:
odd_degree_model()

Return an odd degree model of self, or raise ValueError if one does not exist over the field of definition.

EXAMPLES:

```sage
x = QQ['x'].gen()
H = HyperellipticCurve((x^2 + 2)*(x^2 + 3)*(x^2 + 5)); H
Hyperelliptic Curve over Rational Field defined by y^2 = x^6 + 10*x^4 + 31*x^2 + 30
sage: H.odd_degree_model()
Traceback (most recent call last):
... ValueError: No odd degree model exists over field of definition
```

```sage
K2 = QuadraticField(-2, 'a')
Hp2 = H.change_ring(K2).odd_degree_model(); Hp2
Hyperelliptic Curve over Number Field in a with defining polynomial x^2 + 2 with a = 1.414213562373095?*I defined by y^2 = 6*a*x^5 - 29*x^4 - 20*a*x^2 + 6*a*x + 1
sage
K3 = QuadraticField(-3, 'b')
Hp3 = H.change_ring(QuadraticField(-3, 'b')).odd_degree_model(); Hp3
Hyperelliptic Curve over Number Field in b with defining polynomial x^2 + 3 with b = 1.732050807568878?*I defined by y^2 = -4*b*x^5 - 14*x^4 - 20*b*x^3 + 35*x^2 + 6*b*x + 1
```

Of course, Hp2 and Hp3 are isomorphic over the composite extension. One consequence of this is that odd degree models reduced over "different" fields should have the same number of points on their reductions. 43 and 67 split completely in the compositum, so when we reduce we find:

```sage
P2 = K2.factor(43)[0][0]
P3 = K3.factor(43)[0][0]
Hp2.change_ring(K2.residue_field(P2)).frobenius_polynomial()
x^4 - 16*x^3 + 134*x^2 - 688*x + 1849
sage
P3 = K3.factor(43)[0][0]
Hp3.change_ring(K3.residue_field(P3)).frobenius_polynomial()
x^4 - 16*x^3 + 134*x^2 - 688*x + 1849
```

```sage
P2 = K2.factor(67)[0][0]
P3 = K3.factor(67)[0][0]
Hp2.change_ring(K2.residue_field(P2)).frobenius_polynomial()
x^4 - 8*x^3 + 150*x^2 - 536*x + 4489
sage
P3 = K3.factor(67)[0][0]
Hp3.change_ring(K3.residue_field(P3)).frobenius_polynomial()
x^4 - 8*x^3 + 150*x^2 - 536*x + 4489
```
**rational_points(****kwds**)**

Find rational points on the hyperelliptic curve, all arguments are passed on to `sage.schemes.generic.algebraic_scheme.rational_points()`.

**EXAMPLES:**

For the LMFDB genus 2 curve 932.a.3728.1 < https://www.lmfdb.org/Genus2Curve/Q/932/a/3728/1 >:

```
sage: R.<x> = PolynomialRing(QQ); C = HyperellipticCurve(R([0, -1, 1, 0, 1, -2, 1]), R([1]));
sage: C.rational_points(bound=8)
[(-1 : -3 : 1),
 (-1 : 2 : 1),
 (0 : -1 : 1),
 (0 : 0 : 1),
 (0 : 1 : 0),
 (1/2 : -5/8 : 1),
 (1/2 : -3/8 : 1),
 (1 : -1 : 1),
 (1 : 0 : 1)]
```

Check that trac ticket #29509 is fixed for the LMFDB genus 2 curve 169.a.169.1 < https://www.lmfdb.org/Genus2Curve/Q/169/a/169/1 >:

```
sage: C = HyperellipticCurve(R([0, 0, 0, 0, 1, 1]), R([1, 1, 0, 1]));
sage: C.rational_points(bound=10)
[(-1 : 0 : 1),
 (-1 : 1 : 1),
 (0 : -1 : 1),
 (0 : 0 : 1),
 (0 : 1 : 0)]
```

An example over a number field:

```
sage: R.<x> = PolynomialRing(QuadraticField(2));
sage: C = HyperellipticCurve(R([1, 0, 0, 0, 0, 1]));
sage: C.rational_points(bound=2)
[(-1 : 0 : 1),
 (0 : -1 : 1),
 (0 : 1 : 0),
 (0 : 1 : 1),
 (1 : -a : 1),
 (1 : a : 1)]
```

`sage.schemes.hyperelliptic_curves.hyperelliptic_generic.is_HyperellipticCurve(C)`

**EXAMPLES:**

```
sage: R.<x> = QQ[]; C = HyperellipticCurve(x^3 + x - 1); C
Hyperelliptic Curve over Rational Field defined by y^2 = x^3 + x - 1
sage: sage.schemes.hyperelliptic_curves.hyperelliptic_generic.is_HyperellipticCurve(C)
True
```
16.3 Hyperelliptic curves over a finite field

EXAMPLES:

```python
sage: K.<a> = GF(9, 'a')
sage: x = polygen(K)
sage: C = HyperellipticCurve(x^7 - x^5 - 2, x^2 + a)
sage: C._points_fast_sqrt()
[(0 : 1 : 0), (a + 1 : a : 1), (a + 1 : a + 1 : 1), (2 : a + 1 : 1), (2*a : 2*a + 2 : 1),
 (2*a : 2*a : 1), (1 : a + 1 : 1)]
```

AUTHORS:
- David Kohel (2006)
- Robert Bradshaw (2007)
- Daniel Krenn (2011)
- Jean-Pierre Flori, Jan Tuitman (2013)
- Kiran Kedlaya (2016)
- Dean Bisogno (2017): Fixed Hasse-Witt computation

```python
class sage.schemes.hyperelliptic_curves.hyperelliptic_finite_field.HyperellipticCurve_finite_field(
    PP, f, h=None, names=None, genus=None)

Cartier_matrix()
```

INPUT:
- E : Hyperelliptic Curve of the form $y^2 = f(x)$ over a finite field, $\mathbb{F}_q$

OUTPUT:
- $M$: The matrix $M = (c_{p-i})$, where $c_i$ are the coefficients of $f(x)^{(p-1)/2} = \sum c_ix^i$

REFERENCES:

EXAMPLES:

```python
sage: K.<x>=GF(9,'x')[]
sage: C=HyperellipticCurve(x^7-1,0)
sage: C.Cartier_matrix()
[0 0 2]
[0 0 0]
[0 1 0]
sage: K.<x>=GF(49,'x')[]
sage: C=HyperellipticCurve(x^5+1,0)
```

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Elliptic curves, Release 9.7

(continued from previous page)

```
sage: C.Cartier_matrix()
[0 3]
[0 0]

sage: P.<x>=GF(9,'a')[]
sage: E=HyperellipticCurve(x^29+1,0)
sage: E.Cartier_matrix()
[0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
[0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
[0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
[0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
[0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
[0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
[0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
[0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
[0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
[0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
[0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
[0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
[1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
[0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
[0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
[0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
[0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
```

**Hasse_Witt()**

**INPUT:**

- E : Hyperelliptic Curve of the form \( y^2 = f(x) \) over a finite field, \( \mathbb{F}_q \)

**OUTPUT:**

- \( N \) : The matrix \( N = M M_p \ldots M p^{n-1} \) where \( M = c_{p-i-j} \), and \( f(x)^{p-1/2} = \sum c_i x^i \)

Reference-N. Yui. On the Jacobian varieties of hyperelliptic curves over fields of characteristic \( p > 2 \).

**EXAMPLES:**

```
sage: K.<x>=GF(9,'x')[]
sage: C=HyperellipticCurve(x^7-1,0)
sage: C.Hasse_Witt()
[0 0]
[0 0]
[0 0]

sage: K.<x>=GF(49,'x')[]
sage: C=HyperellipticCurve(x^5+1,0)
sage: C.Hasse_Witt()
[0 0]
[0 0]

sage: P.<x>=GF(9,'a')[]
sage: E=HyperellipticCurve(x^29+1,0)
sage: E.Hasse_Witt()
[0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
[0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
[0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
[0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
```

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Elliptic curves, Release 9.7

(continued from previous page)

a_number()

INPUT:

• E: Hyperelliptic Curve of the form $y^2 = f(x)$ over a finite field, $\mathbb{F}_q$

OUTPUT:

• a: a-number

EXAMPLES:

sage: K.<x>=GF(49, 'x')[]
sage: C=HyperellipticCurve(x^5+1,0)
sage: C.a_number()
1

sage: K.<x>=GF(9, 'x')[]
sage: C=HyperellipticCurve(x^7-1,0)
sage: C.a_number()
1

sage: P.<x>=GF(9, 'a')[]
sage: E=HyperellipticCurve(x^29+1,0)
sage: E.a_number()
5

cardinality(extension_degree=1)

Count points on a single extension of the base field.

EXAMPLES:

sage: K = GF(101)
sage: R.<t> = PolynomialRing(K)
sage: H = HyperellipticCurve(t^9 + 3*t^5 + 5)
sage: H.cardinality()
106

sage: H.cardinality(15)
1160968955369925676405831000

sage: H.cardinality(100)
27948138294215260932671947108075308336779383827810027768902010491171015143067392794394560143462

sage: K = GF(37)
sage: R.<t> = PolynomialRing(K)
Elliptic curves, Release 9.7

The following example shows that trac ticket #20391 has been resolved:

```python
sage: F=GF(23)
sage: x=polygen(F)
sage: C=HyperellipticCurve(x^8+1)
sage: C.cardinality()
24
```

**cardinality_exhaustive** *(extension_degree=1, algorithm=None)*

Count points on a single extension of the base field by enumerating over x and solving the resulting quadratic equation for y.

**EXAMPLES:**

```python
sage: K.<a> = GF(9, 'a')
sage: x = polygen(K)
sage: C = HyperellipticCurve(x^7 - 1, x^2 + a)
sage: C.cardinality_exhaustive()
7
sage: K = GF(next_prime(1<<10))
sage: R.<t> = PolynomialRing(K)
sage: H = HyperellipticCurve(t^7 + 3*t^5 + 5)
sage: H.cardinality_exhaustive()
1025
```

```python
sage: P.<x> = PolynomialRing(GF(9, 'a'))
sage: H = HyperellipticCurve(x^5+x^2+1)
sage: H.count_points(5)
[18, 78, 738, 6366, 60018]
sage: F.<a> = GF(4); P.<x> = F[]
sage: H = HyperellipticCurve(x^5+a*x^2+1, x+a+1)
sage: H.count_points(6)
[2, 24, 74, 256, 1082, 4272]
```

**cardinality_hypellfrob** *(extension_degree=1, algorithm=None)*

Count points on a single extension of the base field using the hypellfrob program.

**EXAMPLES:**

```python
sage: K = GF(next_prime(1<<10))
sage: R.<t> = PolynomialRing(K)
sage: H = HyperellipticCurve(t^7 + 3*t^5 + 5)
sage: H.cardinality_hypellfrob()
1025
```
Elliptic curves, Release 9.7

count_points(n=1)
Count points over finite fields.

INPUT:

• n – integer.

OUTPUT:

An integer. The number of points over \( \mathbb{F}_q \), \ldots, \( \mathbb{F}_q^n \) on a hyperelliptic curve over a finite field \( \mathbb{F}_q \).

Warning: This is currently using exhaustive search for hyperelliptic curves over non-prime fields, which can be awfully slow.

EXAMPLES:

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

sage: K = GF(2**31-1)
sage: R.<t> = PolynomialRing(K)
sage: H = HyperellipticCurve(t^5 + 3*t + 5)
sage: H.count_points() # long time, 2.4 sec on a Corei7
[2147464821]
sage: H.count_points(n=2) # long time, 30s on a Corei7
[2147464821, 4611686018988310237]

sage: K = GF(2**7-1)
sage: R.<t> = PolynomialRing(K)
sage: H = HyperellipticCurve(t^13 + 3*t^5 + 5)
sage: H.count_points(n=6)
[112, 16360, 2045356, 260199160, 33038302802, 4195868633548]

sage: P.<x> = PolynomialRing(GF(3))
sage: H = HyperellipticCurve(x^3+x^2+1)
sage: C1 = H.count_points(4); C1
[6, 12, 18, 96]
sage: C2 = sage.schemes.generic.scheme.Scheme.count_points(H,4); C2 # long time,
    → 2s on a Corei7
[6, 12, 18, 96]
sage: C1 == C2 # long time, because we need C2 to be defined
True

sage: P.<x> = PolynomialRing(GF(9, 'a'))
sage: H = HyperellipticCurve(x^5+x^2+1)
sage: H.count_points(5)
[18, 78, 738, 6366, 60018]

sage: F.<a> = GF(4); P.<x> = F[]
sage: H = HyperellipticCurve(x^5+a*x^2+1, x+a+1)
sage: H.count_points(6)
[2, 24, 74, 256, 1082, 4272]

This example shows that trac ticket #20391 is resolved:

sage: x = polygen(GF(4099))
sage: H = HyperellipticCurve(x^6 + x + 1)
sage: H.count_points_exhaustive(n=1)
[4106]

count_points_exhaustive(n=I, naive=False)
Count the number of points on the curve over the first \( n \) extensions of
the base field by exhaustive search if \( n \) if smaller than \( g \), the genus of the curve, and by computing the frobenius polynomial after performing
exhaustive search on the first \( g \) extensions if \( n > g \) (unless naive == True).

EXAMPLES:

sage: K = GF(5)
sage: R.<t> = PolynomialRing(K)
sage: H = HyperellipticCurve(t^9 + t^3 + 1)
sage: H.count_points_exhaustive(n=5)
[9, 27, 108, 675, 3069]

When \( n > g \), the frobenius polynomial is computed from the numbers of points of the curve over the first
\( g \) extension, so that computing the number of points on extensions of degree \( n > g \) is not much more
expensive than for \( n == g \):

sage: H.count_points_exhaustive(n=15)
[9, 27, 108, 675, 3069, 16302, 78633, 389475, 1954044, 9768627, 48814533, 244072650, 1220693769, 6103414827, 30517927308]
This behavior can be disabled by passing `naive=True`:

```
sage: H.count_points_exhaustive(n=6, naive=True) # long time, 7s on a Corei7
[9, 27, 108, 675, 3069, 16302]
```

`count_points_frobenius_polynomial(n=1, f=None)`

Count the number of points on the curve over the first \( n \) extensions of the base field by computing the frobenius polynomial.

EXAMPLES:

```
sage: K = GF(49999)
sage: R.<t> = PolynomialRing(K)
sage: H = HyperellipticCurve(t^19 + t + 1)
```

The following computation takes a long time as the complete characteristic polynomial of the frobenius is computed:

```
sage: H.count_points_frobenius_polynomial(3) # long time, 20s on a Corei7 (when computed before the following test of course)
[49491, 2500024375, 124992509154249]
```

As the polynomial is cached, further computations of number of points are really fast:

```
sage: H.count_points_frobenius_polynomial(19) # long time, because of the previous test
[49491, 2500024375, 124992509154249, 6249500007135192947, 312468751250758776051811, 1562312593747382662737313867, 7811406315622833861289572576257, 3905625043748250041707992413002794587, 19527734656236875397342941120893147181079, 97636720507718753281169963459063147221761552935, 48817383886654299453052811871297787040588647367671824, 2440820376948828318353187644901381397354646240036293092851, 1220385780276646708934102903106811520015567632046432103159713, 6101806627751962899996211052002771035439567677719719151141201339, 30508424133189703939037081956389262704405225546438978173388673620145499, 1525390698235352006814610157008906752699329454643826047826098161898351623931, 7626809521069364988723693240288328729528917832735078791261015331201838856825193, ˓→
3813324208043947180071195938321176148147244128062172555558175783649006587868272993991, ˓→
190662397077989315056379725720120486231213267083965385975191172023090159769838983998903847]
```

`count_points_hypellfrob(n=1, N=None, algorithm=None)`

Count the number of points on the curve over the first \( n \) extensions of the base field using the hypellfrob program.

This only supports prime fields of large enough characteristic.

EXAMPLES:
Elliptic curves, Release 9.7

```python
sage: K = GF(49999)
sage: R.<t> = PolynomialRing(K)
sage: H = HyperellipticCurve(t^21 + 3*t^5 + 5)
sage: H.count_points_hypellfrob()
[49804]
sage: H.count_points_hypellfrob(2)
[49804, 2499799038]

sage: K = GF(2**7-1)
sage: R.<t> = PolynomialRing(K)
sage: H = HyperellipticCurve(t^11 + 3*t^5 + 5)
sage: H.count_points_hypellfrob()
[127]
sage: H.count_points_hypellfrob(n=5)
[127, 16335, 2045701, 260134299, 33038098487]

sage: K = GF(2**7-1)
sage: R.<t> = PolynomialRing(K)
sage: H = HyperellipticCurve(t^13 + 3*t^5 + 5)
sage: H.count_points(n=6)
[112, 16360, 2045356, 260199160, 33038302802, 4195868633548]

The base field should be prime:

```python
sage: K.<z> = GF(19**10)
sage: R.<t> = PolynomialRing(K)
sage: H = HyperellipticCurve(t^9 + (z+1)*t^5 + 1)
sage: H.count_points_hypellfrob()
Traceback (most recent call last):
...
ValueError: hypellfrob does not support non-prime fields
```

and the characteristic should be large enough:

```python
sage: K = GF(7)
sage: R.<t> = PolynomialRing(K)
sage: H = HyperellipticCurve(t^9 + t^3 + 1)
sage: H.count_points_hypellfrob()
Traceback (most recent call last):
...
ValueError: p=7 should be greater than (2^g+1)(2^N-1)=27
```

count_points_matrix_traces\((n=1, M=None, N=None)\)

Count the number of points on the curve over the first \(n\) extensions of the base field by computing traces of powers of the frobenius matrix. This requires less \(p\)-adic precision than computing the charpoly of the matrix when \(n < g\) where \(g\) is the genus of the curve.

EXAMPLES:

```python
sage: K = GF(49999)
sage: R.<t> = PolynomialRing(K)
sage: H = HyperellipticCurve(t^19 + t + 1)
sage: H.count_points_matrix_traces(3)
[49491, 2500024375, 12499250915429]
```

608 Chapter 16. Hyperelliptic curves
**frobenius_matrix**(*N=None, algorithm='hypellfrob')

Compute $p$-adic frobenius matrix to precision $p^N$. If $N$ not supplied, a default value is selected, which is the minimum needed to recover the charpoly unambiguously.

**Note:** Currently only implemented using hypellfrob, which means it only works over the prime field $GF(p)$, and requires $p > (2g+1)(2N-1)$.

**EXAMPLES:**

```sage
sage: R.<t> = PolynomialRing(GF(37))
sage: H = HyperellipticCurve(t^5 + t + 2)
sage: H.frobenius_matrix()
[[1258 + O(37^2) 925 + O(37^2) 132 + O(37^2) 587 + O(37^2)]
 [1147 + O(37^2) 814 + O(37^2) 241 + O(37^2) 1011 + O(37^2)]
 [1258 + O(37^2) 1184 + O(37^2) 1105 + O(37^2) 482 + O(37^2)]
 [1073 + O(37^2) 999 + O(37^2) 772 + O(37^2) 929 + O(37^2)]
```

The hypellfrob program doesn't support non-prime fields:

```sage
sage: K.<z> = GF(37**3)
sage: R.<t> = PolynomialRing(K)
sage: H = HyperellipticCurve(t^9 + z*t^3 + 1)
sage: H.frobenius_matrix(algorithm='hypellfrob')
Traceback (most recent call last):
... NotImplementedError: Computation of Frobenius matrix only implemented for hyperelliptic curves defined over prime fields.
```

nor too small characteristic:

```sage
sage: K = GF(7)
sage: R.<t> = PolynomialRing(K)
sage: H = HyperellipticCurve(t^9 + t^3 + 1)
sage: H.frobenius_matrix(algorithm='hypellfrob')
Traceback (most recent call last):
... ValueError: In the current implementation, p must be greater than (2g+1)(2N-1) = 81
```

**frobenius_matrix_hypellfrob**(*N=None*)

Compute $p$-adic frobenius matrix to precision $p^N$. If $N$ not supplied, a default value is selected, which is the minimum needed to recover the charpoly unambiguously.

**Note:** Implemented using hypellfrob, which means it only works over the prime field $GF(p)$, and requires $p > (2g+1)(2N-1)$.

**EXAMPLES:**

```sage
sage: R.<t> = PolynomialRing(GF(37))
sage: H = HyperellipticCurve(t^5 + t + 2)
sage: H.frobenius_matrix_hypellfrob()
[[1258 + 0(37^2) 925 + 0(37^2) 132 + 0(37^2) 587 + 0(37^2)]
 [1147 + 0(37^2) 814 + 0(37^2) 241 + 0(37^2) 1011 + 0(37^2)]
 [1258 + 0(37^2) 1184 + 0(37^2) 1105 + 0(37^2) 482 + 0(37^2)]
 [1073 + 0(37^2) 999 + 0(37^2) 772 + 0(37^2) 929 + 0(37^2)]
```

(continues on next page)
The hypellfrob program doesn't support non-prime fields:

```
sage: K.<z> = GF(37**3)
sage: R.<t> = PolynomialRing(K)
sage: H = HyperellipticCurve(t^9 + z*t^3 + 1)
sage: H.frobenius_matrix_hypellfrob()
Traceback (most recent call last):
...  
NotImplementedError: Computation of Frobenius matrix only implemented for hyperelliptic curves defined over prime fields.
```

nor too small characteristic:

```
sage: K = GF(7)
sage: R.<t> = PolynomialRing(K)
sage: H = HyperellipticCurve(t^9 + t^3 + 1)
sage: H.frobenius_matrix_hypellfrob()
Traceback (most recent call last):
...  
ValueError: In the current implementation, p must be greater than (2g+1)(2N-1) = 81
```

**frobenius_polynomial()**

Compute the charpoly of frobenius, as an element of \(\mathbb{Z}[x]\).

**EXAMPLES:**

```
sage: R.<t> = PolynomialRing(GF(37))
sage: H = HyperellipticCurve(t^5 + t + 2)
sage: H.frobenius_polynomial()
x^4 + x^3 - 52*x^2 + 37*x + 1369
```

A quadratic twist:

```
sage: H = HyperellipticCurve(2*t^5 + 2*t + 4)
sage: H.frobenius_polynomial()
x^4 - x^3 - 52*x^2 - 37*x + 1369
```

Slightly larger example:

```
sage: K = GF(2003)
sage: R.<t> = PolynomialRing(K)
sage: H = HyperellipticCurve(t^7 + 487*t^5 + 9*t + 1)
sage: H.frobenius_polynomial()
x^6 - 14*x^5 + 1512*x^4 - 66290*x^3 + 3028536*x^2 - 56168126*x + 8036054027
```

Curves defined over a non-prime field of odd characteristic, or an odd prime field which is too small compared to the genus, are supported via PARI:
sage: K.<z> = GF(23**3)
sage: R.<t> = PolynomialRing(K)
sage: H = HyperellipticCurve(t^3 + z*t + 4)
sage: H.frobenius_polynomial()
x^2 - 15*x + 12167

sage: K.<z> = GF(3**3)
sage: R.<t> = PolynomialRing(K)
sage: H = HyperellipticCurve(t^5 + z*t + z**3)
sage: H.frobenius_polynomial()
x^4 - 3*x^3 + 10*x^2 - 81*x + 729

Over prime fields of odd characteristic, $h$ may be non-zero:

sage: K = GF(101)
sage: R.<t> = PolynomialRing(K)
sage: H = HyperellipticCurve(t^5 + 27*t + 3, t)
sage: H.frobenius_polynomial()
x^4 + 2*x^3 - 58*x^2 + 202*x + 10201

Over prime fields of odd characteristic, $f$ may have even degree:

sage: H = HyperellipticCurve(t^6 + 27*t + 3)
sage: H.frobenius_polynomial()
x^4 + 25*x^3 + 322*x^2 + 2525*x + 10201

In even characteristic, the naive algorithm could cover all cases because we can easily check for squareness in quotient rings of polynomial rings over finite fields but these rings unfortunately do not support iteration:

sage: K.<z> = GF(2**5)
sage: R.<t> = PolynomialRing(K)
sage: H = HyperellipticCurve(t^5 + z*t + z**3, t)
sage: H.frobenius_polynomial()
x^4 - x^3 + 16*x^2 - 32*x + 1024

frobenius_polynomial_cardinalities($a=None$)
Compute the charpoly of frobenius, as an element of $\mathbb{Z}[x]$, by computing the number of points on the curve over $g$ extensions of the base field where $g$ is the genus of the curve.

Warning: This is highly inefficient when the base field or the genus of the curve are large.

EXAMPLES:

sage: R.<t> = PolynomialRing(GF(37))
sage: H = HyperellipticCurve(t^5 + t + 2)
sage: H.frobenius_polynomial_cardinalities()
x^4 + x^3 - 52*x^2 + 37*x + 1369

A quadratic twist:

sage: H = HyperellipticCurve(2*t^5 + 2*t + 4)
sage: H.frobenius_polynomial_cardinalities()
x^4 - x^3 - 52*x^2 - 37*x + 1369

16.3. Hyperelliptic curves over a finite field
Curve over a non-prime field:

```python
sage: K.<z> = GF(7**2)
sage: R.<t> = PolynomialRing(K)
sage: H = HyperellipticCurve(t^5 + z*t + z^2)
sage: H.frobenius_polynomial_cardinalities()
x^4 + 8*x^3 + 70*x^2 + 392*x + 2401
```

This method may actually be useful when `hypellfrob` does not work:

```python
sage: K = GF(7)
sage: R.<t> = PolynomialRing(K)
sage: H = HyperellipticCurve(t^9 + t^3 + 1)
sage: H.frobenius_polynomial_matrix(algorithm='hypellfrob')
Traceback (most recent call last):
...
ValueError: In the current implementation, p must be greater than (2g+1)(2N-1) = 81
sage: H.frobenius_polynomial_cardinalities()
x^8 - 5*x^7 + 7*x^6 + 36*x^5 - 180*x^4 + 252*x^3 + 343*x^2 - 1715*x + 2401
```

**frobenius_polynomial_matrix**(M=None, algorithm='hypellfrob')

Compute the charpoly of frobenius, as an element of \(\mathbb{Z}[x]\), by computing the charpoly of the frobenius matrix.

This is currently only supported when the base field is prime and large enough using the `hypellfrob` library.

**EXAMPLES:**

```python
sage: R.<t> = PolynomialRing(GF(37))
sage: H = HyperellipticCurve(t^5 + t + 2)
sage: H.frobenius_polynomial_matrix()
x^4 + x^3 - 52*x^2 + 37*x + 1369
```

A quadratic twist:

```python
sage: H = HyperellipticCurve(2*t^5 + 2*t + 4)
sage: H.frobenius_polynomial_matrix()
x^4 - x^3 - 52*x^2 - 37*x + 1369
```

Curves defined over larger prime fields:

```python
sage: K = GF(49999)
sage: R.<t> = PolynomialRing(K)
sage: H = HyperellipticCurve(t^9 + t^5 + 1)
sage: H.frobenius_polynomial_matrix() # long time, 8s on a Corei7
```

(continues on next page)
This hypellfrob program doesn’t support non-prime fields:

```python
sage: K.<z> = GF(37**3)
sage: R.<t> = PolynomialRing(K)
sage: H = HyperellipticCurve(t^9 + z*t^3 + 1)
sage: H.frobenius_polynomial_matrix(algorithm='hypellfrob')
Traceback (most recent call last):
... Not ImplementedError: Computation of Frobenius matrix only implemented for hyperelliptic curves defined over prime fields.
```

**frobenius_polynomial_pari()**

Compute the charpoly of frobenius, as an element of \( \mathbb{Z}[x] \), by calling the PARI function `hyperellcharpoly`.

**EXAMPLES:**

```python
sage: R.<t> = PolynomialRing(GF(37))
sage: H = HyperellipticCurve(t^5 + t + 2)
sage: H.frobenius_polynomial_pari()
x^4 + x^3 - 52*x^2 + 37*x + 1369
```

A quadratic twist:

```python
sage: H = HyperellipticCurve(2*t^5 + 2*t + 4)
sage: H.frobenius_polynomial_pari()
x^4 - x^3 - 52*x^2 - 37*x + 1369
```

Slightly larger example:

```python
sage: K = GF(2003)
sage: R.<t> = PolynomialRing(K)
sage: H = HyperellipticCurve(t^7 + 487*t^5 + 9*t + 1)
sage: H.frobenius_polynomial_pari()
x^6 - 14*x^5 + 1512*x^4 - 66290*x^3 + 3028536*x^2 - 56168126*x + 8036054027
```

Curves defined over a non-prime field are supported as well:

```python
sage: K.<a> = GF(7**2)
sage: R.<t> = PolynomialRing(K)
sage: H = HyperellipticCurve(t^5 + a*t + 1)
sage: H.frobenius_polynomial_pari()
x^4 + 4*x^3 + 84*x^2 + 196*x + 2401

sage: K.<z> = GF(23**3)
sage: R.<t> = PolynomialRing(K)
sage: H = HyperellipticCurve(t^3 + z*t + 4)
sage: H.frobenius_polynomial_pari()
x^2 - 15*x + 12167
```

Over prime fields of odd characteristic, \( h \) may be non-zero:
sage: K = GF(101)
sage: R.<t> = PolynomialRing(K)
sage: H = HyperellipticCurve(t^5 + 27*t + 3, t)
sage: H.frobenius_polynomial_pari()
x^4 + 2*x^3 - 58*x^2 + 202*x + 10201

p_rank()  
INPUT:
   • E : Hyperelliptic Curve of the form \( y^2 = f(x) \) over a finite field, \( F_q \)
OUTPUT:
   • pr : p-rank
EXAMPLES:

sage: K.<x>=GF(49,'x')[]
sage: C=HyperellipticCurve(x^5+1,0)
sage: C.p_rank()
0
sage: K.<x>=GF(9,'x')[]
sage: C=HyperellipticCurve(x^7-1,0)
sage: C.p_rank()
0
sage: P.<x>=GF(9,'a')[]
sage: E=HyperellipticCurve(x^29+1,0)
sage: E.p_rank()
0
points()  
All the points on this hyperelliptic curve.
EXAMPLES:

sage: x = polygen(GF(7))
sage: C = HyperellipticCurve(x^7 - x^2 - 1)
sage: C.points()
[(0 : 1 : 0), (2 : 5 : 1), (2 : 2 : 1), (3 : 0 : 1), (4 : 6 : 1), (4 : 1 : 1),
  (5 : 0 : 1), (6 : 5 : 1), (6 : 2 : 1)]

sage: x = polygen(GF(121, 'a'))
sage: C = HyperellipticCurve(x^5 + x - 1, x^2 + 2)
sage: len(C.points())
122

Conics are allowed (the issue reported at trac ticket #11800 has been resolved):

sage: R.<x> = GF(7)[]
sage: H = HyperellipticCurve(3*x^2 + 5*x + 1)
sage: H.points()
[(0 : 6 : 1), (0 : 1 : 1), (1 : 4 : 1), (1 : 3 : 1), (2 : 4 : 1), (2 : 3 : 1),
  (3 : 6 : 1), (3 : 1 : 1)]
The method currently lists points on the plane projective model, that is the closure in \( \mathbb{P}^2 \) of the curve defined by \( y^2 + hy = f \). This means that one point \((0 : 1 : 0)\) at infinity is returned if the degree of the curve is at least 4 and \( \text{deg}(f) > \text{deg}(h) + 1 \). This point is a singular point of the plane model. Later implementations may consider a smooth model instead since that would be a more relevant object. Then, for a curve whose only singularity is at \((0 : 1 : 0)\), the point at infinity would be replaced by a number of rational points of the smooth model. We illustrate this with an example of a genus 2 hyperelliptic curve:

```python
sage: R.<x> = GF(11)[]
sage: H = HyperellipticCurve(x*(x+1)*(x+2)*(x+3)*(x+4)*(x+5))
sage: H.points()
[(0 : 1 : 0), (0 : 0 : 1), (1 : 7 : 1), (1 : 4 : 1), (5 : 7 : 1), (5 : 4 : 1),
 (6 : 0 : 1), (7 : 0 : 1), (8 : 0 : 1), (9 : 0 : 1), (10 : 0 : 1)]
```

The plane model of the genus 2 hyperelliptic curve in the above example is the curve in \( \mathbb{P}^2 \) defined by \( y^2 z^4 = g(x, z) \) where \( g(x, z) = x(x + z)(x + 2z)(x + 3z)(x + 4z)(x + 5z) \). This model has one point at infinity \((0 : 1 : 0)\) which is also the only singular point of the plane model. In contrast, the hyperelliptic curve is smooth and imbeds via the equation \( y^2 = g(x, z) \) into weighted projected space \( \mathbb{P}(1, 3, 1) \). The latter model has two points at infinity: \((1 : 1 : 0)\) and \((1 : -1 : 0)\).

**zeta_function()**

Compute the zeta function of the hyperelliptic curve.

**EXAMPLES:**

```python
sage: F = GF(2); R.<t> = F[]
sage: H = HyperellipticCurve(t^9 + t, t^4)
sage: H.zeta_function()
(16*x^8 + 8*x^7 + 8*x^6 + 4*x^5 + 6*x^4 + 2*x^3 + 2*x^2 + x + 1)/(2*x^2 - 3*x + 1)
```

A quadratic twist:

```python
sage: R.<t> = PolynomialRing(GF(37))
sage: H = HyperellipticCurve(2*t^5 + 2*t + 4)
sage: H.zeta_function()
(1369*x^4 - 37*x^3 - 52*x^2 - x + 1)/(37*x^2 - 38*x + 1)
```
16.4 Hyperelliptic curves over a \( p \)-adic field

```python
class sage.schemes.hyperelliptic_curves.hyperelliptic_padic_field.HyperellipticCurve_padic_field(PP, f, h=None, names=None, genus=None):
    # Bases:
    #    sage.schemes.hyperelliptic_curves.hyperelliptic_generic.HyperellipticCurve_generic
    #    sage.schemes.curves.projective_curve.ProjectivePlaneCurve_field

    P_to_S(P, S):
        # Given a finite Weierstrass point \( P \) and a point \( S \) in the same disc, computes the Coleman integrals
        # \( \{ \int_S^P x^i dx/2y \}_{i=0}^{2g-1} \)
        # INPUT:
        #     \* P: finite Weierstrass point
        #     \* S: point in disc of P
        # OUTPUT:
        # Coleman integrals \( \{ \int_P^S x^i dx/2y \}_{i=0}^{2g-1} \)
        # EXAMPLES:

        sage: R.<x> = QQ['x']
        sage: H = HyperellipticCurve(x^3-10*x+9)
        sage: K = Qp(5,4)
        sage: HK = H.change_ring(K)
        sage: P = HK(1,0)
        sage: HJ = HK.curve_over_ram_extn(10)
        sage: S = HK.get_boundary_point(HJ,P)
        sage: HK.P_to_S(P, S)
        (2*a + 4*a^3 + 2*a^11 + 4*a^13 + 2*a^17 + 2*a^19 + a^21 + 4*a^23 + a^25 + 2*a^27 + 2*a^29 + 3*a^31 + 4*a^33 + O(a^35), a^-5 + 2*a + 2*a^3 + a^7 + 3*a^11 + a^13 + 3*a^15 + 3*a^17 + 2*a^19 + 4*a^21 + 4*a^23 + 4*a^25 + 2*a^27 + a^29 + O(a^33))

    S_to_Q(S, Q):
        # Given \( S \) a point on self over an extension field, computes the Coleman integrals \( \{ \int_S^Q x^i dx/2y \}_{i=0}^{2g-1} \)
        # one should be able to feed `S,Q` into coleman_integral, but currently that segfaults
        # INPUT:
        #     \* S: a point with coordinates in an extension of \( \mathbb{Q}_p \) (with unif. \( a \))
        #     \* Q: a non-Weierstrass point defined over \( \mathbb{Q}_p \)
        # OUTPUT:
        # the Coleman integrals \( \{ \int_S^Q x^i dx/2y \}_{i=0}^{2g-1} \) in terms of \( a \)
        # EXAMPLES:
```

AUTHOR:

- Jennifer Balakrishnan
sage: R.<x> = QQ['x']
sage: H = HyperellipticCurve(x^3-10*x+9)
sage: K = Qp(5,6)
sage: HK = H.change_ring(K)
sage: J.<a> = K.extension(x^20-5)
sage: HJ = H.change_ring(J)
sage: w = HK.invariant_differential()
sage: x,y = HK.monsky_washnitzer_gens()
sage: P = HK(1,0)
sage: Q = HK(0,3)
sage: S = HK.get_boundary_point(HJ,P)

sage: P_to_S = HK.P_to_S(P,S)
sage: S_to_Q = HJ.S_to_Q(S,Q)
sage: P_to_S + S_to_Q
(2*a^40 + a^80 + a^100 + O(a^105), a^20 + 2*a^40 + 4*a^60 + 2*a^80 + O(a^103))
sage: HK.coleman_integrals_on_basis(P,Q)
(2*5^2 + 5^4 + 5^5 + 3*5^6 + O(5^7), 5 + 2*5^2 + 4*5^3 + 2*5^4 + 5^6 + O(5^7))

AUTHOR:
  • Jennifer Balakrishnan

coleman_integral$(w, P, Q, algorithm='None')$
Returns the Coleman integral $\int_{P}^{Q} w$

INPUT:
  • $w$ differential (if one of $P,Q$ is Weierstrass, $w$ must be odd)
  • $P$ point on self
  • $Q$ point on self
  • algorithm (optional) = None (uses Frobenius) or teichmuller (uses Teichmuller points)

OUTPUT:
the Coleman integral $\int_{P}^{Q} w$

EXAMPLES:
Example of Leprevost from Kiran Kedlaya The first two should be zero as $(P - Q) = 30(P - Q)$ in the Jacobian and $dx/2y$ and $xdx/2y$ are holomorphic.

sage: K = pAdicField(11, 6)
sage: x = polygen(K)
sage: C = HyperellipticCurve(x^5 + 33/16*x^4 + 3/4*x^3 + 3/8*x^2 - 1/4*x + 1/16)
sage: P = C(-1, 1); P1 = C(-1, -1)
sage: Q = C(0, 1/4); Q1 = C(0, -1/4)
sage: x, y = C.monsky_washnitzer_gens()
sage: w = C.invariant_differential()
sage: w.coleman_integral(P, Q)
0(11^6)
sage: C.coleman_integral(x*w, P, Q)
0(11^6)
sage: C.coleman_integral(x^2*w, P, Q)
7*11 + 6*11^2 + 3*11^3 + 11^4 + 5*11^5 + 0(11^6)
sage: p = 71; m = 4
sage: K = pAdicField(p, m)
sage: x = polygen(K)
sage: C = HyperellipticCurve(x^5 + 33/16*x^4 + 3/4*x^3 + 3/8*x^2 - 1/4*x + 1/16)
sage: P = C(-1, 1); P1 = C(-1, -1)
sage: Q = C(0, 1/4); Q1 = C(0, -1/4)
sage: x, y = C.monsky_washnitzer_gens()
sage: w = C.invariant_differential()
sage: w.integrate(P, Q), (x*w).integrate(P, Q)
(0(71^4), 0(71^4))
sage: R, R1 = C.lift_x(4, all=True)
sage: w.integrate(P, R)
21*71 + 67*71^2 + 27*71^3 + O(71^4)
sage: w.integrate(P, R) + w.integrate(P1, R1)
0(71^4)

A simple example, integrating dx:

sage: R.<x> = QQ['x']
sage: E = HyperellipticCurve(x^3-4*x+4)
sage: K = Qp(5,10)
sage: EK = E.change_ring(K)
sage: P = EK(2, 2)
sage: Q = EK.teichmuller(P)
sage: x, y = EK.monsky_washnitzer_gens()
sage: EK.coleman_integral(x.diff(), P, Q)
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: Q[0] - P[0]
5 + 2*5^2 + 5^3 + 3*5^4 + 4*5^5 + 2*5^6 + 3*5^7 + 3*5^9 + O(5^10)

Yet another example:

sage: R.<x> = QQ['x']
sage: H = HyperellipticCurve(x*(x-1)*(x+9))
sage: K = Qp(7,10)
sage: HK = H.change_ring(K)
sage: import sage.schemes.hyperelliptic_curves.monsky_washnitzer as mw
sage: M_frob, forms = mw.matrix_of_frobenius_hyperelliptic(HK)
sage: w = HK.invariant_differential()
sage: x,y = HK.monsky_washnitzer_gens()
sage: f = forms[0]
sage: S = HK(9,36)
sage: Q = HK.teichmuller(S)
sage: P = HK(-1,4)
sage: b = x*w*w._coeff_parent()(f)
sage: HK.coleman_integral(b,P,Q)
7 + 7^2 + 4*7^3 + 5*7^4 + 3*7^5 + 7^6 + 5*7^7 + 3*7^8 + 4*7^9 + 4*7^10 + O(7^11)

sage: R.<x> = QQ['x']
sage: H = HyperellipticCurve(x^3+1)
sage: K = Qp(5,8)
sage: HK = H.change_ring(K)
sage: w = HK.invariant_differential()
sage: P = HK(0,1)
sage: Q = HK.lift_x(5)
sage: x,y = HK.monsky_washnitzer_gens()
sage: (2*y*w).coleman_integral(P,Q)
5 + O(5^9)
sage: xloc,yloc,zloc = HK.local_analytic_interpolation(P,Q)
sage: I2 = (xloc.derivative()/(2*yloc)).integral()
sage: I2.polynomial()(1) - I2(0)
3*5 + 2*5^2 + 2*5^3 + 5^4 + 4*5^6 + 5^7 + O(5^9)
sage: HK.coleman_integral(w,P,Q)
3*5 + 2*5^2 + 2*5^3 + 5^4 + 4*5^6 + 5^7 + O(5^9)

Integrals involving Weierstrass points:

sage: R.<x> = QQ['x']
sage: H = HyperellipticCurve(x^3-10*x+9)
sage: K = Qp(5,8)
sage: HK = H.change_ring(K)
sage: S = HK(1,0)
sage: P = HK(0,3)
sage: negP = HK(0,-3)
sage: T = HK(0,1,0)
sage: w = HK.invariant_differential()
sage: x,y = HK.monsky_washnitzer_gens()
sage: HK.coleman_integral(w*x^3,S,T)
0
sage: HK.coleman_integral(w*x^3,T,S)
0
sage: HK.coleman_integral(w,S,P)
2*5^2 + 5^4 + 5^5 + 3*5^6 + 5^7 + 0(5^9)
sage: HK.coleman_integral(w,T,P)
2*5^2 + 5^4 + 5^5 + 3*5^6 + 5^7 + 2*5^8 + O(5^9)
sage: HK.coleman_integral(w*x^3,T,P)
5^2 + 2*5^3 + 5^4 + 3*5^6 + 3*5^7 + O(5^8)
sage: HK.coleman_integral(w*x^3,S,P)
5^2 + 2*5^3 + 5^4 + 3*5^6 + 3*5^7 + O(5^8)
sage: HK.coleman_integral(w,P, negP, algorithm='teichmuller')
5^2 + 4*5^3 + 2*5^4 + 2*5^5 + 3*5^6 + 2*5^7 + 4*5^8 + 0(5^9)
sage: HK.coleman_integral(w, P, negP)
5^2 + 4*5^3 + 2*5^4 + 2*5^5 + 3*5^6 + 2*5^7 + 4*5^8 + 0(5^9)

AUTHORS:

• Robert Bradshaw (2007-03)
• Kiran Kedlaya (2008-05)
• Jennifer Balakrishnan (2010-02)

coleman_integral_P_to_S(w, P, S)
Given a finite Weierstrass point P and a point S in the same disc, computes the Coleman integral \( \int_P^S w \)

INPUT:

• w: differential
Elliptic curves, Release 9.7

- P: Weierstrass point

- S: point in the same disc of P (S is defined over an extension of \( \mathbb{Q}_p \); coordinates of S are given in terms of uniformizer \( a \))

OUTPUT:

Coleman integral \( \int_P^S w \) in terms of \( a \)

EXAMPLES:

```python
sage: R.<x> = QQ['x']
sage: H = HyperellipticCurve(x^3-10*x^9+9)
sage: K = Qp(5,4)
sage: HK = H.change_ring(K)
sage: P = HK(1,0)
sage: J.<a> = K.extension(x^10-5)
sage: HJ = H.change_ring(J)
sage: S = HK.get_boundary_point(HJ,P)
sage: x,y = HK.monsky_washnitzer_gens()
sage: S[0]-P[0] == HK.coleman_integral_P_to_S(x.diff(),P,S)
True
sage: HK.coleman_integral_P_to_S(HK.invariant_differential(),P,S) == HK.P_to_S(P,S)[0]
True
```

AUTHOR:

- Jennifer Balakrishnan

\texttt{coleman_integral	extunderscore S	extunderscore to	extunderscore Q}(w, S, Q)

Compute the Coleman integral \( \int_S^Q w \)

one should be able to feed \( S, Q \) into \texttt{coleman_integral}, but currently that segfaults

INPUT:

- w: a differential

- S: a point with coordinates in an extension of \( \mathbb{Q}_p \)

- Q: a non-Weierstrass point defined over \( \mathbb{Q}_p \)

OUTPUT:

the Coleman integral \( \int_S^Q w \)

EXAMPLES:

```python
sage: R.<x> = QQ['x']
sage: H = HyperellipticCurve(x^3-10*x+9)
sage: K = Qp(5,6)
sage: HK = H.change_ring(K)
sage: J.<a> = K.extension(x^20-5)
sage: HJ = H.change_ring(J)
sage: x,y = HK.monsky_washnitzer_gens()
sage: P = HK(1,0)
sage: Q = HK(0,3)
sage: S = HK.get_boundary_point(HJ,P)
sage: P
to	extunderscore S = HK.coleman_integral_P
to	extunderscore S(y.diff(),P,S)
```

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AUTHOR:

• Jennifer Balakrishnan

coleman_integral_from_weierstrass_via_boundary\( (w, P, Q, d) \)

Computes the Coleman integral \( \int_{P}^{Q} w \) via a boundary point in the disc of \( P \), defined over a degree \( d \) extension

INPUT:

• \( w \): a differential
• \( P \): a Weierstrass point
• \( Q \): a non-Weierstrass point
• \( d \): degree of extension where coordinates of boundary point lie

OUTPUT:

the Coleman integral \( \int_{P}^{Q} w \), written in terms of the uniformizer \( a \) of the degree \( d \) extension

EXAMPLES:

\begin{verbatim}
sage: R.<x> = QQ['x']
sage: H = HyperellipticCurve(x^3-10*x+9)
sage: K = Qp(5,6)
sage: HK = H.change_ring(K)
sage: P = HK(1,0)
sage: Q = HK(0,3)
sage: x,y = HK.monsky_washnitzer_gens()
sage: HK.coleman_integral_from_weierstrass_via_boundary(y.diff(),P,Q,20)
3 + 0(a^119)
sage: HK.coleman_integral(y.diff(),P,Q)
3 + 0(5^6)
sage: w = HK.invariant_differential()
sage: HK.coleman_integral_from_weierstrass_via_boundary(w,P,Q,20)
2*a^40 + a^80 + a^100 + O(a^105)
sage: HK.coleman_integral(w,P,Q)
2*5^2 + 5^4 + 5^5 + 3*5^6 + O(5^7)
\end{verbatim}

AUTHOR:

• Jennifer Balakrishnan

coleman_integrals_on_basis\( (P, Q, algorithm=None) \)

Computes the Coleman integrals \( \{ \int_{P}^{Q} x^i dx / 2y \}_{i=0}^{2g-1} \)

INPUT:

• \( P \) point on self
• \( Q \) point on self
• algorithm (optional) = None (uses Frobenius) or teichmuller (uses Teichmuller points)

OUTPUT:

the Coleman integrals \( \{ \int_P^Q \frac{x^i dx}{2y} \}_{i=0}^{2g-1} \)

EXAMPLES:

```
sage: K = pAdicField(11, 5)
sage: x = polygen(K)
sage: C = HyperellipticCurve(x^5 + 33/16*x^4 + 3/4*x^3 + 3/8*x^2 - 1/4*x + 1/16)
sage: P = C.lift_x(2)
sage: Q = C.lift_x(3)
sage: C.coleman_integrals_on_basis(P, Q)  
(10*11 + 6*11^3 + 5*11^4 + 0(11^5), 11 + 9*11^2 + 7*11^3 + 9*11^4 + 0(11^5), 3_,  
-> 10*11 + 5*11^2 + 9*11^3 + 4*11^4 + 0(11^5), 3 + 11 + 5*11^2 + 4*11^4 + 0(11^5)  
)
sage: C.coleman_integrals_on_basis(P, Q, algorithm='teichmuller')  
(10*11 + 6*11^3 + 5*11^4 + 0(11^5), 11 + 9*11^2 + 7*11^3 + 9*11^4 + 0(11^5), 3_,  
-> 10*11 + 5*11^2 + 9*11^3 + 4*11^4 + 0(11^5), 3 + 11 + 5*11^2 + 4*11^4 + 0(11^5)  
)
```

```
sage: K = pAdicField(11,5)
sage: x = polygen(K)
sage: C = HyperellipticCurve(x^5 + 33/16*x^4 + 3/4*x^3 + 3/8*x^2 - 1/4*x + 1/16)
sage: P = C.lift_x(11^-2)
sage: Q = C.lift_x(3*11^-2)
sage: C.coleman_integrals_on_basis(P, Q)  
(3*11^3 + 7*11^4 + 5*11^5 + 3*11^6 + 4*11^7 + 0(11^8), 3*11 + 10*11^2 + 8*11^3 +  
-> 9*11^4 + 7*11^5 + 0(11^6), 4*11^7 + 1 + 2 + 6*11 + 6*11^2 + 7*11^3 + 0(11^4)  
-> 11^-3 + 6*11^-2 + 2*11^-1 + 2 + 0(11^2))
sage: R = C(0,1/4)
sage: a = C.coleman_integrals_on_basis(P,R)  
# long time (7s on sage.math, 2011)
sage: b = C.coleman_integrals_on_basis(R,Q)  
# long time (9s on sage.math, 2011)
sage: c = C.coleman_integrals_on_basis(P,Q)  
# long time  
sage: a+b == c  
# long time  
True
```

```
sage: R.<x> = QQ[ 'x' ]
sage: H = HyperellipticCurve(x^3-10*x+9)
sage: K = Qp(5,8)
sage: HK = H.change_ring(K)
sage: S = HK(1,0)
sage: P = HK(0,3)
sage: T = HK(0,1,0)
sage: Q = HK.lift_x(5^(-2))
sage: R = HK.lift_x(4*5^(-2))
sage: HK.coleman_integrals_on_basis(S,P)  
(2*5^2 + 8*5^4 + 5*5^5 + 3*5^6 + 3*5^7 + 2*5^8 + 0(5^9), 5 + 2*5^2 + 4*5^3 + 2*5^4 +  
-> 3*5^6 + 4*5^7 + 2*5^8 + 0(5^9))
sage: HK.coleman_integrals_on_basis(T,P)  
(2*5^2 + 5*5^4 + 5*5^5 + 3*5^6 + 3*5^7 + 2*5^8 + 0(5^9), 5 + 2*5^2 + 4*5^3 + 2*5^4 +  
-> 3*5^6 + 4*5^7 + 2*5^8 + 0(5^9))
```

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AUTHORS:

- Robert Bradshaw (2007-03): non-Weierstrass points
- Jennifer Balakrishnan and Robert Bradshaw (2010-02): Weierstrass points

coleman_integrals_on_basis_hyperelliptic(P, Q, algorithm=None)

Computes the Coleman integrals \( \{ \int_{P}^{Q} x^{i}dx/(2y) \}_{i=0}^{2g-1} \)

INPUT:

- P point on self
- Q point on self
- algorithm (optional) = None (uses Frobenius) or teichmuller (uses Teichmuller points)

OUTPUT:

the Coleman integrals \( \{ \int_{P}^{Q} x^{i}dx/(2y) \}_{i=0}^{2g-1} \)

EXAMPLES:

```python
sage: K = pAdicField(11, 5)
sage: x = polygen(K)
sage: C = HyperellipticCurve(x^5 + 33/16*x^4 + 3/4*x^3 + 3/8*x^2 - 1/4*x + 1/16)
sage: P = C.lift_x(2)
sage: Q = C.lift_x(3)
sage: C.coleman_integrals_on_basis(P, Q)
(10*11 + 6*11^3 + 2*11^4 + O(11^5), 11 + 9*11^2 + 7*11^3 + 9*11^4 + O(11^5), 3 + 10*11 + 5*11^2 + 9*11^3 + 4*11^4 + O(11^5), 3 + 11 + 5*11^2 + 4*11^4 + O(11^5))
sage: C.coleman_integrals_on_basis(P, Q, algorithm='teichmuller')
(10*11 + 6*11^3 + 2*11^4 + O(11^5), 11 + 9*11^2 + 7*11^3 + 9*11^4 + O(11^5), 3 + 10*11 + 5*11^2 + 9*11^3 + 4*11^4 + O(11^5), 3 + 11 + 5*11^2 + 4*11^4 + O(11^5))
```

```python
sage: K = pAdicField(11, 5)
sage: x = polygen(K)
sage: C = HyperellipticCurve(x^5 + 33/16*x^4 + 3/4*x^3 + 3/8*x^2 - 1/4*x + 1/16)
sage: P = C.lift_x(11^(-2))
sage: Q = C.lift_x(3*11^(-2))
```

(continues on next page)
sage: C.coleman_integrals_on_basis(P, Q)
(3*11^3 + 7*11^4 + 4*11^5 + 7*11^6 + 5*11^7 + O(11^8), 3*11 + 10*11^2 + 8*11^3 + 9*11^4 + 7*11^5 + O(11^6), 4*11^-1 + 2 + 6*11 + 6*11^2 + 7*11^3 + O(11^4), 5*11^-3 + 6*11^-2 + 2*11^-1 + 2 + O(11^2))

sage: R = C(0, 1/4)
sage: a = C.coleman_integrals_on_basis(P, R)  # long time (7s on sage.math, 2011)
sage: b = C.coleman_integrals_on_basis(R, Q)  # long time (9s on sage.math, 2011)
sage: c = C.coleman_integrals_on_basis(P, Q)  # long time
sage: a + b == c  # long time
True

sage: R.<x> = QQ['x']
sage: H = HyperellipticCurve(x^3 - 10*x + 9)
sage: K = Qp(5, 8)
sage: HK = H.change_ring(K)
sage: S = HK(1, 0)
sage: P = HK(0, 3)
sage: T = HK(1, 0)
sage: Q = HK.lift_x(5^-2)
sage: R = HK.lift_x(4*5^-2)
sage: HK.coleman_integrals_on_basis(S, P)
(2*5^2 + 5^4 + 5^5 + 3*5^6 + 3*5^7 + 2*5^8 + O(5^9), 5 + 2*5^2 + 4*5^3 + 2*5^4 + 3*5^6 + 4*5^7 + 2*5^8 + O(5^9))

sage: HK.coleman_integrals_on_basis(T, P)
(2*5^2 + 5^4 + 5^5 + 3*5^6 + 3*5^7 + 2*5^8 + O(5^9), 5 + 2*5^2 + 4*5^3 + 2*5^4 + 3*5^6 + 4*5^7 + 2*5^8 + O(5^9))

sage: HK.coleman_integrals_on_basis(P, S) == -HK.coleman_integrals_on_basis(S, P)
True

sage: HK.coleman_integrals_on_basis(S, Q)
(4*5 + 4*5^2 + 4*5^3 + O(5^4), 5^-1 + O(5^3))

sage: HK.coleman_integrals_on_basis(Q, R)
(4*5 + 2*5^2 + 2*5^3 + 2*5^4 + 5*5 + 5^6 + 5^7 + 3*5^8 + 0(5^9), 2*5^-1 + 4 + 4*5 + 4*5^2 + 4*5^3 + 2*5^4 + 3*5^5 + 2*5^6 + O(5^7))

sage: HK.coleman_integrals_on_basis(S, R) == HK.coleman_integrals_on_basis(S, Q)
True

sage: HK.coleman_integrals_on_basis(T, T)
(0, 0)

AUTHORS:

• Robert Bradshaw (2007-03): non-Weierstrass points
• Jennifer Balakrishnan and Robert Bradshaw (2010-02): Weierstrass points

curve_over_ram_extn(deg)

Return self over \(\mathbb{Q}_p(p^{1/deg})\).

INPUT:

• deg: the degree of the ramified extension
OUTPUT:

self over \( \mathbb{Q}_p(p^{1/\text{deg}}) \)

EXAMPLES:

```
sage: R.<x> = QQ['x']
sage: H = HyperellipticCurve(x^5-23*x^3+18*x^2+40*x)
sage: K = Qp(11,5)
sage: HK = H.change_ring(K)
sage: HL = HK.curve_over_ram_extn(2)
sage: HL
Hyperelliptic Curve over 11-adic Eisenstein Extension Field in a defined by x^2 → - 11 defined by (1 + O(a^10)) y^2 = (1 + O(a^10)) x^5 + (10 + 8*a^2 + 10*a^4 → + 10*a^6 + 10*a^8 + 0(a^10)) x^3 + (7 + a^2 + O(a^10)) x^2 + (7 + 3*a^2 + 0(a^10 + 10)) x
```

AUTHOR:

• Jennifer Balakrishnan

**find_char_zero_weier_point**\( (Q) \)

Given \( Q \) a point on self in a Weierstrass disc, finds the center of the Weierstrass disc (if defined over self.base_ring())

EXAMPLES:

```
sage: R.<x> = QQ['x']
sage: H = HyperellipticCurve(x^3-10*x+9)
sage: K = Qp(5,8)
sage: HK = H.change_ring(K)
sage: P = HK.lift_x(1 + 2*5^2)
sage: Q = HK.lift_x(5^-2)
sage: S = HK(1,0)
sage: T = HK(0,1,0)
sage: HK.find_char_zero_weier_point(P)
(1 + O(5^8) : 0 : 1 + O(5^8))
sage: HK.find_char_zero_weier_point(Q)
(0 : 1 + O(5^8) : 0)
sage: HK.find_char_zero_weier_point(S)
(1 + O(5^8) : 0 : 1 + O(5^8))
sage: HK.find_char_zero_weier_point(T)
(0 : 1 + O(5^8) : 0)
```

AUTHOR:

• Jennifer Balakrishnan

**frobenius**\( (P=None) \)

Returns the \( p \)-th power lift of Frobenius of \( P \)

EXAMPLES:

```
sage: K = Qp(11, 5)
sage: R.<x> = K[]
sage: E = HyperellipticCurve(x^5 - 21*x - 20)
sage: P = E.lift_x(2)
sage: E.frobenius(P)
```

(continues on next page)
sage: R.<x> = QQ[]
sage: H = HyperellipticCurve(x^5-23*x^3+18*x^2+40*x)
sage: Q = H(0,0)
sage: u,v = H.local_coord(Q,prec=100)
sage: K = Qp(11,5)
sage: L.<a> = K.extension(x^20-11)
sage: HL = H.change_ring(L)
sage: S = HL(u(a),v(a))
sage: HL.frobenius(S)

(8*a^22 + 10*a^42 + 4*a^44 + 2*a^46 + 9*a^48 + 8*a^50 + a^52 + 7*a^54 + 7*a^56 + 5*a^58 + 9*a^62 + 6*a^64 + 6*a^68 + a^70 + 6*a^74 + 2*a^76 + 7*a^78 + 4*a^82 + 5*a^84 + 2*a^86 + 7*a^88 + a^90 + 6*a^92 + a^96 + 5*a^98 + 2*a^100 + 2*a^102 + 2*a^106 + 6*a^108 + 8*a^110 + 3*a^112 + a^114 + 8*a^116 + 10*a^118 + 3*a^120 + 0(a^122) : 
7*a^11 + 7*a^33 + 7*a^35 + 4*a^37 + 6*a^39 + 9*a^41 + 8*a^43 + 8*a^45 + a^47 + 7*a^51 + 4*a^53 + 5*a^55 + a^57 + 7*a^59 + 5*a^61 + 9*a^63 + 4*a^65 + 10*a^69 + 3*a^71 + 2*a^73 + 9*a^75 + 10*a^77 + 6*a^79 + 10*a^81 + 7*a^85 + a^87 + 4*a^89 + 8*a^91 + a^93 + 8*a^95 + 2*a^97 + 7*a^99 + a^101 + 3*a^103 + 6*a^105 + 7*a^107 + 4*a^109 + 0(a^111) : 
1 + 0(a^100))

AUTHORS:

• Robert Bradshaw and Jennifer Balakrishnan (2010-02)

get_boundary_point(curve_over_extn, P)

Given self over an extension field, find a point in the disc of P near the boundary

INPUT:

• curve_over_extn: self over a totally ramified extension

• P: Weierstrass point

OUTPUT:

a point in the disc of P near the boundary

EXAMPLES:

sage: R.<x> = QQ['x']
sage: H = HyperellipticCurve(x^3-10*x+9)
sage: K = Qp(3,6)
sage: HK = H.change_ring(K)
sage: P = HK(1,0)
sage: J.<a> = K.extension(x^30-3)
sage: HJ = H.change_ring(J)

(continues on next page)
**Elliptic curves, Release 9.7**

(continued from previous page)

```python
sage: S = HK.get_boundary_point(HJ,P)
sage: S
(1 + 2*a^2 + 2*a^6 + 2*a^18 + a^32 + a^34 + a^36 + 2*a^38 + 2*a^40 + a^42 + 2*a^44 + a^48 + 2*a^50 + 2*a^52 + a^54 + a^56 + 2*a^60 + 2*a^62 + a^70 + 2*a^72 + a^76 + 2*a^78 + a^82 + a^88 + a^96 + 2*a^98 + 2*a^102 + a^104 + 2*a^106 + a^108 + 2*a^110 + a^112 + 2*a^116 + a^126 + 2*a^130 + 2*a^132 + a^144 + 2*a^148 + a^150 + a^152 + 2*a^154 + a^162 + a^164 + a^166 + a^168 + a^170 + a^176 + a^178 + O(a^180) : a + O(a^180) : 1 + O(a^180))
```

**AUTHOR:**

- Jennifer Balakrishnan

**is_in_weierstrass_disc(P)**

Checks if $P$ is in a Weierstrass disc

**EXAMPLES:**

```python
sage: R.<x> = QQ['x']
sage: H = HyperellipticCurve(x^3-10*x+9)
sage: K = Qp(5,8)
sage: HK = H.change_ring(K)
sage: P = HK(0,3)
sage: HK.is_in_weierstrass_disc(P)
False
sage: Q = HK(0,1,0)
sage: HK.is_in_weierstrass_disc(Q)
True
sage: S = HK(1,0)
sage: HK.is_in_weierstrass_disc(S)
True
sage: T = HK.lift_x(1+3*5^2); T
(1 + 3*5^2 + O(5^8) : 2*5 + 4*5^3 + 3*5^4 + 5^5 + 3*5^6 + O(5^7) : 1 + O(5^8))
sage: HK.is_in_weierstrass_disc(T)
True
```

**AUTHOR:**

- Jennifer Balakrishnan (2010-02)

**is_same_disc(P, Q)**

Checks if $P, Q$ are in same residue disc

**EXAMPLES:**

```python
sage: R.<x> = QQ['x']
sage: H = HyperellipticCurve(x^3-10*x+9)
sage: K = Qp(5,8)
sage: HK = H.change_ring(K)
sage: P = HK.lift_x(1 + 2*5^2)
sage: Q = HK.lift_x(5^-2)
sage: HK.is_same_disc(P,Q)
False
sage: HK.is_same_disc(P,S)
True
```

(continues on next page)
is_weierstrass($P$)
Checks if $P$ is a Weierstrass point (i.e., fixed by the hyperelliptic involution)

EXAMPLES:

```sage
sage: R.<x> = QQ['x']
sage: H = HyperellipticCurve(x^3-10*x+9)
sage: K = Qp(5, 8)
sage: HK = H.change_ring(K)
sage: P = HK(0, 3)
sage: HK.is_weierstrass(P)
False
sage: Q = HK(0, 1, 0)
sage: HK.is_weierstrass(Q)
True
sage: S = HK(1, 0)
sage: HK.is_weierstrass(S)
True
sage: T = HK.lift_x(1+3*5^2); T
(1 + 3*5^2 + O(5^8) : 2*5 + 4*5^3 + 3*5^4 + 5*5 + 3*5^6 + O(5^7) : 1 + O(5^8))
sage: HK.is_weierstrass(T)
False
```

AUTHOR:
• Jennifer Balakrishnan (2010-02)

local_analytic_interpolation($P$, $Q$)
For points $P$, $Q$ in the same residue disc, this constructs an interpolation from $P$ to $Q$ (in homogeneous coordinates) in a power series in the local parameter $t$, with precision equal to the $p$-adic precision of the underlying ring.

INPUT:
• $P$ and $Q$ points on self in the same residue disc

OUTPUT:
Returns a point $X(t) = (x(t) : y(t) : z(t))$ such that:

1. $X(0) = P$ and $X(1) = Q$ if $P, Q$ are not in the infinite disc
2. $X(P[0]/P[1]) = P$ and $X(Q[0]/Q[1]) = Q$ if $P, Q$ are in the infinite disc

EXAMPLES:

```sage
sage: R.<x> = QQ['x']
sage: H = HyperellipticCurve(x^3-10*x+9)
sage: K = Qp(5, 8)
sage: HK = H.change_ring(K)
```

A non-Weierstrass disc:
Elliptic curves, Release 9.7

\begin{verbatim}
sage: P = HK(0,3)
sage: Q = HK(5, 3 + 3*5^2 + 2*5^3 + 3*5^4 + 2*5^5 + 2*5^6 + 3*5^7 + O(5^8))
sage: x,y,z, = HK.local_analytic_interpolation(P,Q)
sage: x(0) == P[0], x(1) == Q[0], y(0) == P[1], y.polynomial()(1) == Q[1]
(True, True, True, True)

A finite Weierstrass disc:

\begin{verbatim}
sage: P = HK.lift_x(1 + 2*5^2)
sage: Q = HK.lift_x(1 + 3*5^2)
sage: x,y,z = HK.local_analytic_interpolation(P,Q)
sage: x(0) == P[0], x.polynomial()(1) == Q[0], y(0) == P[1], y(1) == Q[1]
(True, True, True, True)
\end{verbatim}

The infinite disc:

\begin{verbatim}
sage: P = HK.lift_x(5^-2)
sage: Q = HK.lift_x(4*5^-2)
sage: x,y,z = HK.local_analytic_interpolation(P,Q)
sage: x = x/z
sage: y = y/z
sage: x(P[0]/P[1]) == P[0]
True
sage: x(Q[0]/Q[1]) == Q[0]
True
sage: y(P[0]/P[1]) == P[1]
True
sage: y(Q[0]/Q[1]) == Q[1]
True
\end{verbatim}

An error if points are not in the same disc:

\begin{verbatim}
sage: x,y,z = HK.local_analytic_interpolation(P,HK(1,0))
Traceback (most recent call last):
...
ValueError: (5^-2 + O(5^6) : 5^-3 + 4*5^2 + 5^3 + 3*5^4 + O(5^5) : 1 + O(5^8))
and (1 + O(5^8) : 0 : 1 + O(5^8)) are not in the same residue disc
\end{verbatim}

AUTHORS:

- Robert Bradshaw (2007-03)
- Jennifer Balakrishnan (2010-02)

\texttt{newton_sqrt}(f, x0, prec)

Takes the square root of the power series \( f \) by Newton’s method

\textbf{NOTE:}

this function should eventually be moved to \( p \)-adic power series ring

\textbf{INPUT:}

- \( f \) – power series with coefficients in \( Q_p \) or an extension
- \( x0 \) – seeds the Newton iteration
- \( prec \) – precision

16.4. Hyperelliptic curves over a \( p \)-adic field
OUTPUT: the square root of $f$

**EXAMPLES:**

```sage
sage: R.<x> = QQ['x']
sage: H = HyperellipticCurve(x^5-23*x^3+18*x^2+40*x)
sage: Q = H(0,0)
sage: u,v = H.local_coord(Q, prec=100)
sage: K = Qp(11,5)
sage: HK = H.change_ring(K)
sage: L.<a> = K.extension(x^20-11)
sage: HL = H.change_ring(L)
sage: S = HL(u(a),v(a))
sage: f = H.hyperelliptic_polynomials()[0]
sage: y = HK.newton_sqrt(f(u(a)^11), a^11,5)
sage: y^2 - f(u(a)^11)
O(a^122)
```

**AUTHOR:**
- Jennifer Balakrishnan

**residue_disc($P$)**

Gives the residue disc of $P$

**EXAMPLES:**

```sage
sage: R.<x> = QQ['x']
sage: H = HyperellipticCurve(x^3-10*x+9)
sage: K = Qp(5,8)
sage: HK = H.change_ring(K)
sage: P = HK.lift_x(1 + 2*5^2)
sage: HK.residue_disc(P)
(1 : 0 : 1)
sage: Q = HK(0,3)
sage: HK.residue_disc(Q)
(0 : 3 : 1)
sage: S = HK.lift_x(5^-2)
sage: HK.residue_disc(S)
(0 : 1 : 0)
sage: T = HK(0,1,0)
sage: HK.residue_disc(T)
(0 : 1 : 0)
```

**AUTHOR:**
- Jennifer Balakrishnan

**teichmuller($P$)**

Find a Teichmüller point in the same residue class of $P$.

Because this lift of frobenius acts as $x \mapsto x^p$, take the Teichmüller lift of $x$ and then find a matching $y$ from that.

**EXAMPLES:**

```sage
sage: K = pAdicField(7, 5)
sage: E = EllipticCurve(K, [-31/3, -2501/108]) # 11a
```

(continues on next page)
tiny_integrals($F, P, Q$)

Evaluate the integrals of $f_i dx/2y$ from $P$ to $Q$ for each $f_i$ in $F$ by formally integrating a power series in a local parameter $t$.

$P$ and $Q$ MUST be in the same residue disc for this result to make sense.

**INPUT:**

- $F$ a list of functions $f_i$
- $P$ a point on self
- $Q$ a point on self (in the same residue disc as P)

**OUTPUT:**

The integrals $\int_P^Q f_i dx/2y$

**EXAMPLES:**

```python
sage: K = pAdicField(17, 5)
sage: E = EllipticCurve(K, [-31/3, -2501/108]) # 11a
sage: P = E(K(14/3), K(11/2))
sage: TP = E.teichmuller(P);
sage: x,y = E.monsky_washnitzer_gens()
sage: E.tiny_integrals([1,x],P, TP) == E.tiny_integrals_on_basis(P,TP)
True
```

```python
sage: K = pAdicField(11, 5)
sage: x = polygen(K)
sage: C = HyperellipticCurve(x^5 + 33/16*x^4 + 3/4*x^3 + 3/8*x^2 - 1/4*x + 1/16)
sage: P = C.lift_x(11^(-2))
sage: Q = C.lift_x(3*11^(-2))
sage: C.tiny_integrals([1],P,Q)
(3*11^3 + 7*11^4 + 4*11^5 + 7*11^6 + 5*11^7 + O(11^8))
```

Note that this fails if the points are not in the same residue disc:

```python
sage: S = C(0,1/4)
sage: C.tiny_integrals([1,x,x^2,x^3],P,S)
Traceback (most recent call last):
...
ValueError: (11^-2 + O(11^3) : 11^-5 + 8*11^-2 + O(11^-0) : 1 + 0(11^5)) and (0 → 3 + 8*11 + 2*11^2 + 8*11^3 + 2*11^4 + O(11^5) : 1 + 0(11^5)) are not in the same residue disc
```
tiny_integrals_on_basis\((P, Q)\)
Evaluate the integrals \(\left\{ \int_P^Q x^i dx/2y \right\}_{i=0}^{2g-1} \) by formally integrating a power series in a local parameter \(t\). \(P\) and \(Q\) MUST be in the same residue disc for this result to make sense.

**INPUT:**
- \(P\) a point on self
- \(Q\) a point on self (in the same residue disc as \(P\))

**OUTPUT:**
The integrals \(\left\{ \int_P^Q x^i dx/2y \right\}_{i=0}^{2g-1} \)

**EXAMPLES:**

```python
sage: K = pAdicField(17, 5)
sage: E = EllipticCurve(K, [-31/3, -2501/108]) # 11a
sage: P = E(K(14/3), K(11/2))
sage: TP = E.teichmuller(P);
sage: E.tiny_integrals_on_basis(P, TP)
(17 + 14*17^2 + 17^3 + 8*17^4 + O(17^5), 16*17 + 5*17^2 + 8*17^3 + 14*17^4 + ...
˓→ O(17^5))
```

```python
sage: K = pAdicField(11, 5)
sage: x = polygen(K)
sage: C = HyperellipticCurve(x^5 + 33/16*x^4 + 3/4*x^3 + 3/8*x^2 - 1/4*x + 1/16)
sage: P = C.lift_x(11*(-2))
sage: Q = C.lift_x(3*11*(-2))
sage: C.tiny_integrals_on_basis(P, Q)
(3*11^3 + 7*11^4 + 4*11^5 + 7*11^6 + 5*11^7 + O(11^8), 3*11 + 10*11^2 + 8*11^3 ...
˓→ O(11^4), 4*11^-1 + 2 + 6*11 + 6*11^2 + 7*11^3 + O(11^4), ...
˓→ O(11^4), 2*11^-1 + 2 + O(11^2))
```

Note that this fails if the points are not in the same residue disc:

```python
sage: S = C(0,1/4)
sage: C.tiny_integrals_on_basis(P,S)
Traceback (most recent call last):
  ...
ValueError: (11^-2 + O(11^3) : 11^-5 + 8*11^-2 + O(11^0) : 1 + O(11^5)) and (0, ...
˓→ : 3 + 8*11 + 2*11^-2 + 8*11^-3 + 2*11^4 + O(11^5) : 1 + 0(11^5)) are not in the ...
˓→ same residue disc
```

weierstrass_points()
Return the Weierstrass points of self defined over self.base_ring(), that is, the point at infinity and those points in the support of the divisor of \(y\)

**EXAMPLES:**

```python
sage: K = pAdicField(11, 5)
sage: x = polygen(K)
sage: C = HyperellipticCurve(x^5 + 33/16*x^4 + 3/4*x^3 + 3/8*x^2 - 1/4*x + 1/16)
sage: C.weierstrass_points()
[(0 : 1 + O(11^5) : 0), (7 + 10*11 + 4*11^3 + O(11^5) : 0 : 1 + 0(11^5))]
```
16.5 Hyperelliptic curves over the rationals

```python
class sage.schemes.hyperelliptic_curves.hyperelliptic_rational_field.HyperellipticCurve_rational_field(PP, f, h=None, names=None, genus=None):
    Bases: sage.schemes.hyperelliptic_curves.hyperelliptic_generic.HyperellipticCurve_generic,
            sage.schemes.curves.projective_curve.ProjectivePlaneCurve_field

    lseries(prec=53)
        Return the L-series of this hyperelliptic curve of genus 2.
       
        EXAMPLES:
        sage: x = polygen(QQ, 'x')
        sage: C = HyperellipticCurve(x^2+x, x^3+x^2+1)
        sage: C.lseries()
        PARI L-function associated to Hyperelliptic Curve
        over Rational Field defined by y^2 + (x^3 + x^2 + 1)*y = x^2 + x

    matrix_of_frobenius(p, prec=20)
```

16.6 Mestre’s algorithm

This file contains functions that:

- create hyperelliptic curves from the Igusa-Clebsch invariants (over \( \mathbb{Q} \) and finite fields)
- create Mestre’s conic from the Igusa-Clebsch invariants

AUTHORS:

- Florian Bouyer
- Marco Streng

```python
sage.schemes.hyperelliptic_curves.mestre.HyperellipticCurve_from_invariants(i, reduced=True, precision=None, algorithm='default')
```

Returns a hyperelliptic curve with the given Igusa-Clebsch invariants up to scaling.

The output is a curve over the field in which the Igusa-Clebsch invariants are given. The output curve is unique up to isomorphism over the algebraic closure. If no such curve exists over the given field, then raise a ValueError.

INPUT:

- \( i \) - list or tuple of length 4 containing the four Igusa-Clebsch invariants: 12,14,16,110.
- \( \text{reduced} \) - Boolean (default = True) If True, tries to reduce the polynomial defining the hyperelliptic curve using the function reduce_polynomial() (see the reduce_polynomial() documentation for more details).
- \( \text{precision} \) - integer (default = None) Which precision for real and complex numbers should the reduction use. This only affects the reduction, not the correctness. If None, the algorithm uses the default 53 bit precision.
• algorithm - 'default' or 'magma'. If set to 'magma', uses Magma to parameterize Mestre's conic (needs Magma to be installed).

OUTPUT:
A hyperelliptic curve object.

EXAMPLES:
Examples over the rationals:

```
sage: HyperellipticCurve_from_invariants([3840,414720,491028480,2437709561856])
Traceback (most recent call last):
... 
NotImplementedError: Reduction of hyperelliptic curves not yet implemented. See trac #14755 and #14756.
sage: HyperellipticCurve_from_invariants([3840,414720,491028480,2437709561856], reduced = False)
Hyperelliptic Curve over Rational Field defined by y^2 = -46656*x^6 + 46656*x^5 - 
-19440*x^4 + 4320*x^3 - 540*x^2 + 4410*x - 1
sage: HyperellipticCurve_from_invariants([21, 225/64, 22941/512, 1])
Traceback (most recent call last):
... 
NotImplementedError: Reduction of hyperelliptic curves not yet implemented. See trac #14755 and #14756.
```

An example over a finite field:

```
sage: H = HyperellipticCurve_from_invariants([GF(13)(1),3,7,5]); H
Hyperelliptic Curve over Finite Field of size 13 defined by ... 
sage: H.igusa_clebsch_invariants()
(4, 9, 6, 11)
```

An example over a number field:

```
sage: K = QuadraticField(353, 'a')
sage: H = HyperellipticCurve_from_invariants([21, 225/64, 22941/512, 1], reduced = False)
sage: f = K['x'](H.hyperelliptic_polynomials()[0])
```

If the Mestre Conic defined by the Igusa-Clebsch invariants has no rational points, then there exists no hyperelliptic curve over the base field with the given invariants:

```
sage: HyperellipticCurve_from_invariants([1,2,3,4])
Traceback (most recent call last):
... 
ValueError: No such curve exists over Rational Field as there are no rational points on Projective Conic Curve over Rational Field defined by -2572155000*u^2 - 
-317736000*v^2 + 1250755459200*v^2 + 2501510918400*u*w + 39276887040*v*w + 
-273621968912*w^2
```

Mestre’s algorithm only works for generic curves of genus two, so another algorithm is needed for those curves with extra automorphism. See also trac ticket #12199:

```
sage: P.<x> = QQ[]
sage: C = HyperellipticCurve(x^6+1)
```

(continues on next page)
Elliptic curves, Release 9.7

```
sage: i = C.igusa_clebsch_invariants()
sage: HyperellipticCurve_from_invariants(i)
Traceback (most recent call last):
...
TypeError: F (=0) must have degree 2
```

Igusa-Clebsch invariants also only work over fields of characteristic different from 2, 3, and 5, so another algorithm will be needed for fields of those characteristics. See also trac ticket #12200:

```
sage: P.<x> = GF(3)[]
sage: HyperellipticCurve(x^6+x+1).igusa_clebsch_invariants()
Traceback (most recent call last):
...
NotImplementedError: Invariants of binary sextics/genus 2 hyperelliptic curves not implemented in characteristics 2, 3, and 5
sage: HyperellipticCurve_from_invariants([GF(5)(1),1,0,1])
Traceback (most recent call last):
...
ZeroDivisionError: inverse of Mod(0, 5) does not exist
```

**ALGORITHM:**

This is Mestre’s algorithm [Mes1991]. Our implementation is based on the formulae on page 957 of [LY2001], cross-referenced with [Wam1999b] to correct typos.

First construct Mestre’s conic using the `Mestre_conic()` function. Parametrize the conic if possible. Let $f_1, f_2, f_3$ be the three coordinates of the parametrization of the conic by the projective line, and change them into one variable by letting $F_i = f_i(t,1)$. Note that each $F_i$ has degree at most 2.

Then construct a sextic polynomial $f = \sum_{0 \leq i,j,k \leq 3} c_{ijk} * F_i * F_j * F_k$, where $c_{ijk}$ are defined as rational functions in the invariants (see the source code for detailed formulae for $c_{ijk}$). The output is the hyperelliptic curve $y^2 = f$.

```
sage.schemes.hyperelliptic_curves.mestre.Mestre_conic(i, xyz=False, names=’u,v,w’)
```

Return the conic equation from Mestre’s algorithm given the Igusa-Clebsch invariants.

It has a rational point if and only if a hyperelliptic curve corresponding to the invariants exists.

**INPUT:**

- `i` - list or tuple of length 4 containing the four Igusa-Clebsch invariants: $I_2, I_4, I_6, I_{10}$
- `xyz` - Boolean (default: False) if True, the algorithm also returns three invariants $x,y,z$ used in Mestre’s algorithm
- `names` (default: ‘u,v,w’) - the variable names for the Conic

**OUTPUT:**

A Conic object

**EXAMPLES:**

A standard example:

```
sage: Mestre_conic([1,2,3,4])
Projective Conic Curve over Rational Field defined by -2572155000*u^2 - 317736000*u*v + 1250755459200*v^2 + 2501510918400*u*w + 39276887040*v*w + 2736219686912*w^2
```

16.6. Mestre’s algorithm 635
Note that the algorithm works over number fields as well:

```python
sage: k = NumberField(x^2-41,'a')
sage: a = k.an_element()
sage: Mestre_conic([1,2+a,a,4+a])
```

Projective Conic Curve over Number Field in a with defining polynomial x^2 - 41
→ defined by (-801990000*a + 343845000)*u^2 + (855360000*a + 15795864000)*u*v +
→ (31229280000*a + 1284808579200)*v^2 + (62458560000*a + 2569617158400)*u*w +
→ (15799910400*a + 234573143040)*v*w + (2034199306240*a + 16429854656512)*w^2

And over finite fields:

```python
sage: Mestre_conic([GF(7)(10),GF(7)(1),GF(7)(2),GF(7)(3)])
```

Projective Conic Curve over Finite Field of size 7 defined by -2*u*v - v^2 - 2*u*w
→ + 2*v*w - 3*w^2

An example with xyz:

```python
sage: Mestre_conic([5,6,7,8], xyz=True)
```

(Projection Conic Curve over Rational Field defined by -415125000*u^2 +
→ 608040000*u*v + 33065136000*v^2 + 66130272000*u*w + 2408294400*v*w + 10208835584*w^2
→ -2, 232/1125, -1072/16875, 14695616/2109375)

ALGORITHM:

The formulas are taken from pages 956 - 957 of [LY2001] and based on pages 321 and 332 of [Mes1991].

See the code or [LY2001] for the detailed formulae defining x, y, z and L.

### 16.7 Computation of Frobenius matrix on Monsky-Washnitzer cohomology

The most interesting functions to be exported here are `matrix_of_frobenius()` and `adjusted_prec()`.

Currently this code is limited to the case $p \geq 5$ (no $GF(p^n)$ for $n > 1$), and only handles the elliptic curve case (not more general hyperelliptic curves).

REFERENCES:

• [Ked2001]
• [Edix]

AUTHORS:

• David Harvey and Robert Bradshaw: initial code developed at the 2006 MSRI graduate workshop, working with Jennifer Balakrishnan and Liang Xiao
• David Harvey (2006-08): cleaned up, rewrote some chunks, lots more documentation, added Newton iteration method, added more complete ‘trace trick’, integrated better into Sage.
• David Harvey (2007-02): added algorithm with sqrt(p) complexity (removed in May 2007 due to better C++ implementation)
• Robert Bradshaw (2007-03): keep track of exact form in reduction algorithms
• Robert Bradshaw (2007-04): generalization to hyperelliptic curves
• Julian Rueth (2014-05-09): improved caching
class sage.schemes.hyperelliptic_curves.monsky_washnitzer.MonskyWashnitzerDifferential(parent, val, offset=0)

Bases: sage.structure.element.ModuleElement

An element of the Monsky-Washnitzer ring of differentials, of the form $F \frac{dx}{2y}$.

EXAMPLES:

```python
sage: R.<x> = QQ['x']
sage: C = HyperellipticCurve(x^5 - 4*x + 4)
sage: x,y = C.monsky_washnitzer_gens()
sage: MW = C.invariant_differential().parent()
sage: MW(x)
x \frac{dx}{2y}
sage: MW(y)
y \frac{1}{2y}
sage: MW(x, 10)
y^{10} \frac{x}{2y}
```

coeff()  
Return $A$, where this element is $A \frac{dx}{2y}$.

EXAMPLES:

```python
sage: R.<x> = QQ['x']
sage: C = HyperellipticCurve(x^5 - 4*x + 4)
sage: x,y = C.monsky_washnitzer_gens()
sage: w = C.invariant_differential()
sage: w.coeff()  
1
sage: (x*y*w).coeff()  
y^x
```

coeffs($R=None$)  
Used to obtain the raw coefficients of a differential, see `SpecialHyperellipticQuotientElement.coeffs()`

INPUT:
- $R$ – An (optional) base ring in which to cast the coefficients

OUTPUT:
The raw coefficients of $A$ where self is $A \frac{dx}{2y}$.

EXAMPLES:

```python
sage: R.<x> = QQ['x']
sage: C = HyperellipticCurve(x^5 - 4*x + 4)
sage: x,y = C.monsky_washnitzer_gens()
sage: w = C.invariant_differential()
sage: w.coeffs()
([(1, 0, 0, 0, 0)], 0)
sage: (x*w).coeffs()
```
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(continued from previous page)

```python
sage: (y^w).coeffs()
([(0, 1, 0, 0, 0), (1, 0, 0, 0, 0)], 0)
sage: (y^-2*w).coeffs()
([(1, 0, 0, 0, 0), (0, 0, 0, 0, 0), (0, 0, 0, 0, 0)], -2)
```

coleman_integral($P, Q$)

Compute the definite integral of self from $P$ to $Q$.

**INPUT:**
- $P, Q$ – two points on the underlying curve

**OUTPUT:**
\[ \int_P^Q \text{self} \]

**EXAMPLES:**

```python
sage: K = pAdicField(5,7)
sage: E = EllipticCurve(K,[-31/3,-2501/108]) #11a
sage: P = E(K(14/3), K(11/2))
sage: w = E.invariant_differential()
sage: w.coleman_integral(P,2*P)
O(5^6)
sage: Q = E([3,58332])
sage: w.coleman_integral(P,Q)
2*5 + 4*5^2 + 3*5^3 + 4*5^4 + 3*5^5 + O(5^6)
sage: w.coleman_integral(2*P,Q)
2*5 + 4*5^2 + 3*5^3 + 4*5^4 + 3*5^5 + O(5^6)
sage: (2*w).coleman_integral(P, Q) == 2*(w.coleman_integral(P, Q))
True
```

extract_pow_y($k$)

Return the power of $y$ in $A$ where self is $Adx/2y$.

**EXAMPLES:**

```python
sage: R.<x> = QQ['x']
sage: C = HyperellipticCurve(x^5-3*x+1)
sage: x,y = C.monsky_washnitzer_gens()
sage: A = y^5 - x*y^3
sage: A.extract_pow_y(5)
[1, 0, 0, 0, 0]
sage: (A * C.invariant_differential()).extract_pow_y(5)
[1, 0, 0, 0, 0]
```

integrate($P, Q$)

Compute the definite integral of self from $P$ to $Q$.

**INPUT:**
- $P, Q$ – two points on the underlying curve

**OUTPUT:**
\[ \int_P^Q \text{self} \]
EXAMPLES:

```
sage: K = pAdicField(5,7)
sage: E = EllipticCurve(K,[-31/3,-2501/108]) #11a
sage: P = E(K(14/3), K(11/2))
sage: w = E.invariant_differential()
sage: w.coleman_integral(P,2*P)
O(5^6)

sage: Q = E([3,58332])
sage: w.coleman_integral(P,Q)
2*5 + 4*5^2 + 3*5^3 + 4*5^4 + 3*5^5 + O(5^6)

sage: w.coleman_integral(2*P,Q)
2*5 + 4*5^2 + 3*5^3 + 4*5^4 + 3*5^5 + O(5^6)

sage: (2*w).coleman_integral(P,Q) == 2*(w.coleman_integral(P,Q))
True
```

**max_pow_y()**

Return the maximum power of $y$ in $A$ where self is $Adx/2y$.

EXAMPLES:

```
sage: R.<x> = QQ['x']
sage: C = HyperellipticCurve(x^5-3*x+1)
sage: x,y = C.monsky_washnitzer_gens()
sage: w = y^5 * C.invariant_differential()
sage: w.max_pow_y()
5

sage: w = (x^2*y^4 + y^5) * C.invariant_differential()
sage: w.max_pow_y()
5
```

**min_pow_y()**

Return the minimum power of $y$ in $A$ where self is $Adx/2y$.

EXAMPLES:

```
sage: R.<x> = QQ['x']
sage: C = HyperellipticCurve(x^5-3*x+1)
sage: x,y = C.monsky_washnitzer_gens()
sage: w = y^5 * C.invariant_differential()
sage: w.min_pow_y()
5

sage: w = (x^2*y^4 + y^5) * C.invariant_differential()
sage: w.min_pow_y()
4
```

**reduce()**

Use homology relations to find $a$ and $f$ such that this element is equal to $a + df$, where $a$ is given in terms of the $x'dx/2y$.

EXAMPLES:

```
sage: R.<x> = QQ['x']
sage: C = HyperellipticCurve(x^5-4*x+4)
```

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reduce_fast(even_degree_only=False)
Use homology relations to find $a$ and $f$ such that this element is equal to $a + df$, where $a$ is given in terms of the $x^i dx/2y$.

EXAMPLES:

```python
sage: R.<x> = QQ['x']
sage: C = HyperellipticCurve(x^5-3*x+1)
sage: x,y = C.monsky_washnitzer_gens()
sage: (y^-1).diff().reduce_neg_y()
((y^-1)*x + (y^-5)*x^2, 0 dx/2y)
```

reduce_neg_y_fast(even_degree_only=False)
Use homology relations to eliminate negative powers of $y$.

EXAMPLES:
Elliptic curves, Release 9.7

```
sage: R.<x> = QQ['x']
sage: E = HyperellipticCurve(x^5 - 3*x + 1)
sage: x, y = E.monsky_washnitzer_gens()
sage: (y^-1).diff().reduce_neg_y_fast()
((y^-1)*1, 0 dx/2y)
sage: (y^-5*x^2 + y^-1*x).diff().reduce_neg_y_fast()
((y^-1)*x + (y^-5)*x^2, 0 dx/2y)
```

It leaves non-negative powers of \( y \) alone:

```
sage: y.diff()
(-3*1 + 5*x^4) dx/2y
sage: y.diff().reduce_neg_y_fast()
(0, (-3*1 + 5*x^4) dx/2y)
```

**reduce_neg_y_faster** *(even_degree_only=False)*
Use homology relations to eliminate negative powers of \( y \).

**EXAMPLES:**

```
sage: R.<x> = QQ['x']
sage: C = HyperellipticCurve(x^5 - 3*x + 1)
sage: x,y = C.monsky_washnitzer_gens()
sage: (y^-1).diff().reduce_neg_y()
((y^-1)*1, 0 dx/2y)
sage: (y^-5*x^2 + y^-1*x).diff().reduce_neg_y_faster()
((y^-1)*x + (y^-5)*x^2, 0 dx/2y)
```

**reduce_pos_y()**
Use homology relations to eliminate positive powers of \( y \).

**EXAMPLES:**

```
sage: R.<x> = QQ['x']
sage: C = HyperellipticCurve(x^3 - 4*x + 4)
sage: x,y = C.monsky_washnitzer_gens()
sage: (y^2).diff().reduce_pos_y()
(y^2*1, 0 dx/2y)
sage: (y^2*x).diff().reduce_pos_y()
(y^2*x, 0 dx/2y)
sage: (y^92*x).diff().reduce_pos_y()
(y^92*x, 0 dx/2y)
sage: w = (y^3 + x).diff()
sage: w += w.parent()(x)
sage: w.reduce_pos_y_fast()
(y^3*1 + x, x dx/2y)
```

**reduce_pos_y_fast** *(even_degree_only=False)*
Use homology relations to eliminate positive powers of \( y \).

**EXAMPLES:**

```
sage: R.<x> = QQ['x']
sage: E = HyperellipticCurve(x^3 - 4*x + 4)
sage: x, y = E.monsky_washnitzer_gens()
```
(continues on next page)
sage: y.diff().reduce_pos_y_fast()
(y^1, 0 dx/2y)
sage: (y^2).diff().reduce_pos_y_fast()
(y^2, 0 dx/2y)
sage: (y^2*x).diff().reduce_pos_y_fast()
(y^2*x, 0 dx/2y)
sage: (y^92*x).diff().reduce_pos_y_fast()
(y^92*x, 0 dx/2y)
sage: w = (y^3 + x).diff()
sage: w += w.parent()(x)
sage: w.reduce_pos_y_fast()
(y^3 + x, x dx/2y)

class sage.schemes.hyperelliptic_curves.monsky_washnitzer.MonskyWashnitzerDifferentialRing(base_ring)


A ring of Monsky–Washnitzer differentials over base_ring.

Element alias of MonskyWashnitzerDifferential

Q()

Return \( Q(x) \) where the model of the underlying hyperelliptic curve of self is given by \( y^2 = Q(x) \).

EXAMPLES:

sage: R.<x> = QQ['x']
sage: C = HyperellipticCurve(x^5-4*x+4)
sage: MW = C.invariant_differential().parent()
sage: MW.Q()

\( x^5 - 4*x + 4 \)

base_extend(R)

Return a new differential ring which is self base-extended to \( R \).

INPUT:

* \( R \) – ring

OUTPUT:

Self, base-extended to \( R \).

EXAMPLES:

sage: R.<x> = QQ['x']
sage: C = HyperellipticCurve(x^5-4*x+4)
sage: MW = C.invariant_differential().parent()
sage: MW.base_ring()

SpecialHyperellipticQuotientRing \( K[x,y,y^{-1}] \) / \( (y^2 = x^5 - 4*x + 4) \) over Rational Field

sage: MW.base_extend(Qp(5,5)).base_ring()

SpecialHyperellipticQuotientRing \( K[x,y,y^{-1}] \) / \( (y^2 = (1 + O(5^5))*x^5 + (1 + O(5^5)) \cdot 4^5 + 4^5 \cdot 2 + 4^5 \cdot 3 + 4^5 \cdot 4 + 0(5^5)) \cdot x + 4 + O(5^5)) \) over 5-adic Field with capped relative precision 5
change_ring($R$)
Return a new differential ring which is self with the coefficient ring changed to $R$.

INPUT:

• $R$ – ring of coefficients

OUTPUT:

self with the coefficient ring changed to $R$.

EXAMPLES:

```
sage: R.<x> = QQ['x']
sage: C = HyperellipticCurve(x^5-4*x+4)
sage: MW = C.invariant_differential().parent()
sage: MW.base_ring()
SpecialHyperellipticQuotientRing K[x,y,y^-1] / (y^2 = x^5 - 4*x + 4) over
        Rational Field
sage: MW.change_ring(Qp(5,5)).base_ring()
SpecialHyperellipticQuotientRing K[x,y,y^-1] / (y^2 = (1 + O(5^5))*x^5 + (1 +
        4*5 + 4*5^2 + 4*5^3 + 4*5^4 + O(5^5))*x + 4 + O(5^5))
over 5-adic Field with capped relative precision 5
```

degree()
Return the degree of $Q(x)$, where the model of the underlying hyperelliptic curve of self is given by $y^2 = Q(x)$.

EXAMPLES:

```
sage: R.<x> = QQ['x']
sage: C = HyperellipticCurve(x^5-4*x+4)
sage: MW = C.invariant_differential().parent()
sage: MW.Q()
x^5 - 4*x + 4
sage: MW.degree()
5
```

dimension()
Return the dimension of self.

EXAMPLES:

```
sage: R.<x> = QQ['x']
sage: C = HyperellipticCurve(x^5-4*x+4)
sage: K = Qp(7,5)
sage: CK = C.change_ring(K)
sage: MW = CK.invariant_differential().parent()
sage: MW.dimension()
4
```

frob_Q($p$)
Return and cache $Q(x^p)$, which is used in computing the image of $y$ under a $p$-power lift of Frobenius to $A^1$.

EXAMPLES:
sage: R.<x> = QQ['x']
sage: C = HyperellipticCurve(x^5-4*x+4)
sage: MW = C.invariant_differential().parent()
sage: MW.frob_Q(3)
-(60-48*y^2+12*y^4-y^6)*1 + (192-96*y^2+12*y^4)*x - (192-48*y^2)*x^2 + 60*x^3
sage: MW.frob_Q(11)
is MW.frob_Q(11)
True

\textbf{frob\_basis\_elements}(prec, p)

Return the action of a \(p\)-power lift of Frobenius on the basis.

\[ \left\{ \frac{dx}{2y}, \frac{xdx}{2y}, \ldots, \frac{x^{d-2}dx}{2y} \right\}, \]

where \(d\) is the degree of the underlying hyperelliptic curve.

\textbf{EXAMPLES}:

sage: R.<x> = QQ['x']
sage: C = HyperellipticCurve(x^5-4*x+4)
sage: prec = 1
sage: p = 5
sage: MW = C.invariant_differential().parent()
sage: MW.frob_basis_elements(prec,p)
[((92000*y^-14-74200*y^-12+32000*y^-10-8000*y^-8+1000*y^-6-50*y^-4)*1
- (194400*y^-14-153600*y^-12+57600*y^-10-9600*y^-8+600*y^-6)*x
+ (204800*y^-14-153600*y^-12+38400*y^-10-3200*y^-8)*x^2
- (153600*y^-14-76800*y^-12+9600*y^-10)*x^3
+ (63950*y^-14-18550*y^-12+1600*y^-10-400*y^-8+50*y^-6+5*y^-4)*x^4) dx/2y,
(-1391200*y^-14+941400*y^-12-302000*y^-10+76800*y^-8-14400*y^-6-1320*y^-4+30*y^-2)*1
+ (2168800*y^-14-1402400*y^-12+537600*y^-10-134400*y^-8+16800*y^-6-720*y^-4)*x
- (1596800*y^-14-1433600*y^-12+537600*y^-10-89600*y^-8+5600*y^-6)*x^2
+ (1433600*y^-14-1075200*y^-12+268800*y^-10-22400*y^-8)*x^3
- (870200*y^-14+445350*y^-12+63350*y^-10-3200*y^-8+600*y^-6-30*y^-4-5*y^-2)*x^4) dx/2y,
((1948800*y^-14-15763200*y^-12+4944400*y^-10-913800*y^-8+156800*y^-6-22560*y^-4+1480*y^-2-10)*1
- (28163200*y^-14-18669600*y^-12+5774400*y^-10-1433600*y^-8+268800*y^-6-25440*y^-4+760*y^-2)*x
+ (15062400*y^-14-12940800*y^-12+5734400*y^-10-1433600*y^-8+179200*y^-6-8480*y^-4)*x^2
- (12112600*y^-14-11468800*y^-12+4308800*y^-10-1176800*y^-8+44800*y^-6)*x^3
+ (9215200*y^-14-6952400*y^-12+1739500*y^-10-165750*y^-8+5600*y^-6-720*y^-4+10*y^-2+5)*x^4) dx/2y,
((225395200*y^-14-230640000*y^-12+91733600*y^-10-18347400*y^-8+2293600*y^-6-288960*y^-4+31520*y^-2-1480*y^-2-10)*1
+ (338048000*y^-14-277132800*y^-12+89928000*y^-10-17816000*y^-8+3225600*y^-6-472320*y^-4+34560*y^-2-720)*x
- (172902400*y^-14-141584000*y^-12+58976000*y^-10-17203200*y^-8+3225600*y^-6-314880*y^-4+11520*y^-2)*x^2
+ (108736000*y^-14-109760000*y^-12+51609600*y^-10-12902400*y^-8+1612800*y^-6-78720*y^-4)*x^3)
(continues on next page)
frob_invariant_differential(\text{prec}, p)

Kedlaya’s algorithm allows us to calculate the action of Frobenius on the Monsky-Washnitzer cohomology. First we lift $\phi$ to $A^1$ by setting

$$\phi(x) = x^p, \quad \phi(y) = y^p \left(1 + \frac{Q(x^p) - Q(x)^p}{Q(x)^p}\right).$$

Pulling back the differential $dx/2y$, we get

$$\phi^*(dx/2y) = px^{p-1}y(\phi(y))^{-1}dx/2y = px^{p-1}y^{1-p} \left(1 + \frac{Q(x^p) - Q(x)^p}{Q(x)^p}\right) dx/2y.$$

Use Newton’s method to calculate the square root.

EXAMPLES:

\begin{verbatim}
sage: R.<x> = QQ['x']
sage: C = HyperellipticCurve(x^5-4*x+4)
sage: prec = 2
sage: p = 7
sage: MW = C.invariant_differential().parent()
sage: MW.frob_invariant_differential(prec, p)
\end{verbatim}

$$- (85347200*y^8-8290000*y^7+31251400*y^6-5304150*y^5+8367350*y^4-8480*y^3+760*y^2-10-5*y)*x^4) dx/2y$$

helper_matrix()

We use this to solve for the linear combination of $x^i y^j$ needed to clear all terms with $y^{j-1}$.

EXAMPLES:

\begin{verbatim}
sage: R.<x> = QQ['x']
sage: C = HyperellipticCurve(x^5-4*x+4)
sage: MW = C.invariant_differential().parent()
sage: MW.helper_matrix()
\end{verbatim}

$$\begin{bmatrix}
256/2101 & 320/2101 & 400/2101 & 500/2101 & 625/2101 \\
-625/8404 & -64/2101 & -500/2101 & -100/2101 & -125/2101 \\
-125/2101 & -80/2101 & -80/2101 & -80/2101 & -100/2101 \\
[ -100/2101 & -125/2101 & -625/8404 & -125/2101 & -80/2101 } \\
[ -80/2101 & -100/2101 & -125/2101 & -625/8404 & -80/2101]
\end{bmatrix}$$

invariant_differential()

Return $dx/2y$ as an element of self.

EXAMPLES:

\begin{verbatim}
\end{verbatim}
Elliptic curves, Release 9.7

```sage
sage: R.<x> = QQ['x']
sage: C = HyperellipticCurve(x^5-4*x+4)
sage: MW = C.invariant_differential().parent()
sage: MW.invariant_differential()
dx/2y
```

\textbf{\texttt{x_to_p}(p)}

Return and cache $x^p$, reduced via the relations coming from the defining polynomial of the hyperelliptic curve.

\textbf{EXAMPLES:}

```sage
sage: R.<x> = QQ['x']
sage: C = HyperellipticCurve(x^5-4*x+4)
sage: MW = C.invariant_differential().parent()
sage: MW.x_to_p(3)
x^3
sage: MW.x_to_p(5)
-(4-y^2)^*1 + 4*x
sage: MW.x_to_p(101) is MW.x_to_p(101)
True
```

\texttt{sage.schemes.hyperelliptic_curves.monsky_washnitzer.}
\texttt{MonskyWashnitzerDifferentialRing_class}

\texttt{alias of sage.schemes.hyperelliptic_curves.monsky_washnitzer.}
\texttt{MonskyWashnitzerDifferentialRing}

\texttt{class sage.schemes.hyperelliptic_curves.monsky_washnitzer.SpecialCubicQuotientRing}(Q, laurent_series=False)

\texttt{Bases: sage.rings.ring.CommutativeAlgebra}

Specialised class for representing the quotient ring $R[x, T]/(T - x^3 - ax - b)$, where $R$ is an arbitrary commutative base ring (in which 2 and 3 are invertible), $a$ and $b$ are elements of that ring.

Polynomials are represented internally in the form $p_0 + p_1 x + p_2 x^2$ where the $p_i$ are polynomials in $T$. Multiplication of polynomials always reduces high powers of $x$ (i.e. beyond $x^2$) to powers of $T$.

Hopefully this ring is faster than a general quotient ring because it uses the special structure of this ring to speed multiplication (which is the dominant operation in the frobenius matrix calculation). I haven’t actually tested this theory though...

\texttt{Todo:} Eventually we will want to run this in characteristic 3, so we need to: (a) Allow $Q(x)$ to contain an $x^2$ term, and (b) Remove the requirement that 3 be invertible. Currently this is used in the Toom-Cook algorithm to speed multiplication.

\textbf{EXAMPLES:}

```sage
sage: B.<t> = PolynomialRing(Integers(125))
sage: R = monsky_washnitzer.SpecialCubicQuotientRing(t^3 - t + B(1/4))
sage: R
SpecialCubicQuotientRing over Ring of integers modulo 125
with polynomial $T = x^3 + 124*x + 94$
```

Get generators:
sage: x, T = R.gens()
sage: x
(0) + (1)*x + (0)*x^2
sage: T
(T) + (0)*x + (0)*x^2

Coercions:

sage: R(7)
(7) + (0)*x + (0)*x^2

Create elements directly from polynomials:

sage: A = R.poly_ring()
sage: A
Univariate Polynomial Ring in T over Ring of integers modulo 125
sage: z = A.gen()
sage: R.create_element(z^2, z+1, 3)
(T^2) + (T + 1)*x + (3)*x^2

Some arithmetic:

sage: x^3
(T + 31) + (1)*x + (0)*x^2
sage: 3 * x**15 * T**2 + x - T
(3*T^7 + 90*T^6 + 110*T^5 + 20*T^4 + 58*T^3 + 26*T^2 + 124*T) +
(15*T^6 + 110*T^5 + 35*T^4 + 63*T^2 + 1)*x +
(30*T^5 + 40*T^4 + 8*T^3 + 38*T^2)*x^2

Retrieve coefficients (output is zero-padded):

sage: x^10
(3*T^2 + 61*T + 8) + (T^3 + 93*T^2 + 12*T + 40)*x + (3*T^2 + 61*T + 9)*x^2
sage: (x^10).coeffs()
[[8, 61, 3, 0], [40, 12, 93, 1], [9, 61, 3, 0]]

Todo: write an example checking multiplication of these polynomials against Sage’s ordinary quotient ring arithmetic. I cannot seem to get the quotient ring stuff happening right now…

Element

alias of SpecialCubicQuotientRingElement

create_element(check, *args)
Create the element \( p_0 + p_1 \cdot x + p_2 \cdot x^2 \), where the \( p_i \) are polynomials in \( T \).

INPUT:

- \( p_0, p_1, p_2 \) – coefficients; must be coercible into poly_ring()
- check – bool (default True): whether to carry out coercion

EXAMPLES:

sage: B.<t> = PolynomialRing(Integers(125))
sage: R = monsky_washnitzer.SpecialCubicQuotientRing(t^3 - t + B(1/4))
sage: A, z = R.poly_ring().objgen()
sage: R.create_element(z^2, z+1, 3)  # indirect doctest
(T^2) + (T + 1)*x + (3)*x^2

gens()
Return a list [x, T] where x and T are the generators of the ring (as element of this ring).

Note: I have no idea if this is compatible with the usual Sage ‘gens’ interface.

EXAMPLES:

```sage
definition = PolynomialRing(Integers(125))
sage: R = monsky_washnitzer.SpecialCubicQuotientRing(t^3 - t + B(1/4))
sage: x, T = R.gens()
sage: x
(0) + (1)*x + (0)*x^2
sage: T
(T) + (0)*x + (0)*x^2
```

one()
Return the unit of self.

EXAMPLES:

```sage
definition = PolynomialRing(Integers(125))
sage: R = monsky_washnitzer.SpecialCubicQuotientRing(t^3 - t + B(1/4))
sage: R.one()
(1) + (0)*x + (0)*x^2
```

poly_ring()
Return the underlying polynomial ring in T.

EXAMPLES:

```sage
definition = PolynomialRing(Integers(125))
sage: R = monsky_washnitzer.SpecialCubicQuotientRing(t^3 - t + B(1/4))
sage: R.poly_ring()
Univariate Polynomial Ring in T over Ring of integers modulo 125
```

class sage.schemes.hyperelliptic_curves.monsky_washnitzer.SpecialCubicQuotientRingElement
Bases: sage.structure.element.CommutativeAlgebraElement

An element of a SpecialCubicQuotientRing.

coeffs()
Return list of three lists of coefficients, corresponding to the x^0, x^1, x^2 coefficients.
The lists are zero padded to the same length. The list entries belong to the base ring.

EXAMPLES:
sage: B.<t> = PolynomialRing(Integers(125))
sage: R = monsky_washnitzer.SpecialCubicQuotientRing(t^3 - t + B(1/4))
sage: p = R.create_element(t, t^2 - 2, 3)
sage: p.coeffs()
[[0, 1, 0], [123, 0, 1], [3, 0, 0]]

**scalar_multiply**(scalar)

Multiply this element by a scalar, i.e. just multiply each coefficient of $x^j$ by the scalar.

**INPUT:**

- scalar – either an element of base_ring, or an element of poly_ring.

**EXAMPLES:**

sage: B.<t> = PolynomialRing(Integers(125))
sage: R = monsky_washnitzer.SpecialCubicQuotientRing(t^3 - t + B(1/4))
sage: x, T = R.gens()
sage: f = R.create_element(2, t, t^2 - 3)
sage: f
(2) + (T)*x + (T^2 + 122)*x^2
sage: f.scalar_multiply(2)
(4) + (2*T)*x + (2*T^2 + 119)*x^2
sage: f.scalar_multiply(t)
(2*T) + (T^2)*x + (T^3 + 122*T)*x^2

**shift**(n)

Return this element multiplied by $T^n$.

**EXAMPLES:**

sage: B.<t> = PolynomialRing(Integers(125))
sage: R = monsky_washnitzer.SpecialCubicQuotientRing(t^3 - t + B(1/4))
sage: f = R.create_element(2, t, t^2 - 3)
sage: f
(2) + (T)*x + (T^2 + 122)*x^2
sage: f.shift(1)
(2*T) + (T^2)*x + (T^3 + 122*T)*x^2
sage: f.shift(2)
(2*T^2) + (T^3)*x + (T^4 + 122*T^2)*x^2

**square()**

Return the square of the element.

**EXAMPLES:**

sage: B.<t> = PolynomialRing(Integers(125))
sage: R = monsky_washnitzer.SpecialCubicQuotientRing(t^3 - t + B(1/4))
sage: x, T = R.gens()
sage: f = R.create_element(1 + 2*t + 3*t^2, 4 + 7*t + 9*t^2, 3 + 5*t + 11*t^2)
sage: f.square()
(73*T^5 + 16*T^4 + 38*T^3 + 39*T^2 + 70*T + 120) + (121*T^5 + 113*T^4 + 73*T^3 +
16*T^2 + 51*T + 61)*x + (18*T^4 + 60*T^3 + 22*T^2 + 108*T + 31)*x^2

16.7. Computation of Frobenius matrix on Monsky-Washnitzer cohomology
class sage.schemes.hyperelliptic_curves.monsky_washnitzer.SpecialHyperellipticQuotientElement(parent, val=0, offset=0, check=True):

Bases: sage.structure.element.CommutativeAlgebraElement

Element in the Hyperelliptic quotient ring.

EXAMPLES:

sage: R.<x> = QQ['x']
sage: E = HyperellipticCurve(x^5-36*x+1)
sage: x,y = E.monsky_washnitzer_gens()
sage: MW = x.parent()
sage: MW(x+x^2+y-77) -(77-y)*1 + x + x^2

change_ring(R)

Return the same element after changing the base ring to $R$.

EXAMPLES:

sage: R.<x> = QQ['x']
sage: E = HyperellipticCurve(x^5-36*x+1)
sage: x,y = E.monsky_washnitzer_gens()
sage: MW = x.parent()
sage: z = MW(x+x^2+y-77)
sage: z.change_ring(AA).parent() SpecialHyperellipticQuotientRing K[x,y,y^-1] / (y^2 = x^5 - 36*x + 1) over Algebraic Real Field

coeffs(R=None)

Return the raw coefficients of this element.

INPUT:

• $R$ – an (optional) base-ring in which to cast the coefficients

OUTPUT:

• coeffs – a list of coefficients of powers of $x$ for each power of $y$

• n – an offset indicating the power of $y$ of the first list element

EXAMPLES:

sage: R.<x> = QQ['x']
sage: E = HyperellipticCurve(x^5-36*x+1)
sage: x,y = E.monsky_washnitzer_gens()
sage: x.coeffs() ((0, 1, 0, 0, 0), 0)
sage: y.coeffs() ((0, 0, 0, 0, 0), (1, 0, 0, 0, 0), 0)
sage: a = sum(n*x^n for n in range(5)); a x + 2*x^2 + 3*x^3 + 4*x^4
sage: a.coeffs()

(continues on next page)
Elliptic curves, Release 9.7

[[[0, 1, 2, 3, 4], 0]

**sage:** a.coeffs(Qp(7))

[[[0, 1 + O(7^20), 2 + O(7^20), 3 + O(7^20), 4 + O(7^20)], 0]

**sage:** (a*y).coeffs()

[[0, 0, 0, 0, 0], (0, 1, 2, 3, 4], 0]

**sage:** (a*y^2).coeffs()

[[0, 1, 2, 3, 4], (0, 0, 0, 0, 0), (0, 0, 0, 0, 0], -2]

Note that the coefficient list is transposed compared to how they are stored and printed:

**sage:** a*y^-2

(y^-2)*x + (2*y^-2)*x^2 + (3*y^-2)*x^3 + (4*y^-2)*x^4

A more complicated example:

**sage:** a = x^20*y^-3 - x^11*y^2; a

(y^-3-4*y^-1+6*y-4*y^3+y^5)*1 - (12*y^-3-36*y^-1+36*y+y^2-12*y^3-2*y^4+y^6)*x

+(54*y^-3-108*y^-1+54*y+6*y^2-2*y^4)*x^2 - (108*y^-3-108*y^-1+9*y^2)*x^3

+ (81*y^-3)*x^4

**sage:** raw, offset = a.coeffs()

**sage:** a.min_pow_y()

-3

**sage:** offset

-3

**sage:** raw

[(1, -12, 54, -108, 81),

(0, 0, 0, 0, 0),

(-4, 36, -108, 108, 0),

(0, 0, 0, 0, 0),

(6, -36, 54, 0, 0),

(0, -1, 6, -9, 0),

(-4, 12, 0, 0, 0),

(0, 2, -6, 0, 0),

(1, 0, 0, 0, 0),

(0, -1, 0, 0, 0)]

**sage:** sum(c * x^i * y^(j+offset) for j, L in enumerate(raw) for i, c in enumerate(L)) == a

True

Can also be used to construct elements:

**sage:** a.parent()(raw, offset) == a

True

**diff()**

Return the differential of self.

**EXAMPLES:**

**sage:** R.<x> = QQ[::-]

**sage:** E = HyperellipticCurve(x^5-3*x+1)

**sage:** x,y = E.monsky_washnitzer_gens()

**sage:** (x+3*y).diff()

\((-(9-2*y)*1 + 15*x^4) \, dx/2y\)
extract_pow_y(k)

Return the coefficients of \(y^k\) in self as a list.

EXAMPLES:

```python
 sage: R.<x> = QQ['x']
 sage: E = HyperellipticCurve(x^5-3*x+1)
 sage: x,y = E.monsky_washnitzer_gens()
 sage: (x+3*y+9*x*y).extract_pow_y(1)
[3, 9, 0, 0, 0]
```

max_pow_y()

Return the maximal degree of self with respect to \(y\).

EXAMPLES:

```python
 sage: R.<x> = QQ['x']
 sage: E = HyperellipticCurve(x^5-3*x+1)
 sage: x,y = E.monsky_washnitzer_gens()
 sage: (x+3*y).max_pow_y()
1
```

min_pow_y()

Return the minimal degree of self with respect to \(y\).

EXAMPLES:

```python
 sage: R.<x> = QQ['x']
 sage: E = HyperellipticCurve(x^5-3*x+1)
 sage: x,y = E.monsky_washnitzer_gens()
 sage: (x+3*y).min_pow_y()
0
```

truncate_neg(n)

Return self minus its terms of degree less than \(n\) wrt \(y\).

EXAMPLES:

```python
 sage: R.<x> = QQ['x']
 sage: E = HyperellipticCurve(x^5-3*x+1)
 sage: x,y = E.monsky_washnitzer_gens()
 sage: (x+3*y+7*x^2*y^4).truncate_neg(1)
3*y+1 + 14*y^4*x
```

class sage.schemes.hyperelliptic_curves.monsky_washnitzer.SpecialHyperellipticQuotientRing(Q, R=None, invert_y=True)

Bases: sage.structure.unique_representation.UniqueRepresentation, sage.rings.ring.CommutativeAlgebra

The special hyperelliptic quotient ring.

Element

alias of SpecialHyperellipticQuotientElement

Q()  

Return the defining polynomial of the underlying hyperelliptic curve.
EXAMPLES:

```python
sage: R.<x> = QQ['x']
sage: E = HyperellipticCurve(x^5-2*x+1)
sage: x,y = E.monsky_washnitzer_gens()
sage: x.parent().Q()
x^5 - 2*x + 1
```

`base_extend(R)`
Return the base extension of `self` to the ring `R` if possible.

EXAMPLES:

```python
sage: R.<x> = QQ['x']
sage: E = HyperellipticCurve(x^5-3*x+1)
sage: x,y = E.monsky_washnitzer_gens()
sage: x.parent().base_extend(UniversalCyclotomicField())
SpecialHyperellipticQuotientRing K[x,y,y^-1] / (y^2 = x^5 - 3*x + 1) over Universal Cyclotomic Field
sage: x.parent().base_extend(ZZ)
Traceback (most recent call last):
... TypeError: no such base extension
```

`change_ring(R)`
Return the analog of `self` over the ring `R`.

EXAMPLES:

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

`curve()`
Return the underlying hyperelliptic curve.

EXAMPLES:

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

`degree()`
Return the degree of the underlying hyperelliptic curve.

EXAMPLES:
**gens()**

Return the generators of self

**EXAMPLES:**

```python
sage: R.<x> = QQ['x']
sage: E = HyperellipticCurve(x^5-3*x+1)
sage: x,y = E.monsky_washnitzer_gens()
sage: x.parent().gens()
(x, y^1)
```

**is_field(proof=True)**

Return False as self is not a field.

**EXAMPLES:**

```python
sage: R.<x> = QQ['x']
sage: E = HyperellipticCurve(x^5-3*x+1)
sage: x,y = E.monsky_washnitzer_gens()
sage: x.parent().is_field()
False
```

**monomial(i, j, b=None)**

Return \( b \cdot y^j x^i \), computed quickly.

**EXAMPLES:**

```python
sage: R.<x> = QQ['x']
sage: E = HyperellipticCurve(x^5-3*x+1)
sage: x,y = E.monsky_washnitzer_gens()
sage: x.parent().monomial(4,5)
y^5*x^4
```

**monomial_diff_coeffs(i, j)**

Compute coefficients of the basis representation of \( d(x^i y^j) \).

The key here is that the formula for \( d(x^i y^j) \) is messy in terms of \( i \), but varies nicely with \( j \).

\[
d(x^i y^j) = y^{j-1}(2ix^{i-1}y^2 + j(A_i(x) + B_i(x)y^2)) \frac{dx}{2y},
\]

where \( A, B \) have degree at most \( n - 1 \) for each \( i \). Pre-compute \( A_i, B_i \) for each \( i \) the “hard” way, and the rest are easy.

**EXAMPLES:**

```python
sage: R.<x> = QQ['x']
sage: E = HyperellipticCurve(x^5-3*x+1)
sage: x,y = E.monsky_washnitzer_gens()
sage: x.parent().monomial_diff_coeffs(4,5)
((0, -15, 36, 0, 0), (0, 19, 0, 0, 0))
```

**monomial_diff_coeffs_matrices()**

Compute tables of coefficients of the basis representation of \( d(x^i y^j) \) for small \( i, j \).

**EXAMPLES:**

```python
```
Elliptic curves, Release 9.7

```python
sage: R.<x> = QQ['x']
sage: E = HyperellipticCurve(x^5-3*x+1)
sage: x,y = E.monsky_washnitzer_gens()
sage: x.parent().monomial_diff_coeffs_matrices()
(  
[0 5 0 0 0] [0 2 0 0 0]
[0 0 5 0 0] [0 0 4 0 0]
[0 0 0 5 0] [0 0 0 6 0]
[0 0 0 0 5] [0 0 0 0 8]
[0 0 0 0 0], [0 0 0 0 0]
)
```

**monsky_washnitzer()**

Return the stored Monsky-Washnitzer differential ring.

**EXAMPLES:**

```python
sage: R.<x> = QQ['x']
sage: E = HyperellipticCurve(x^5-3*x+1)
sage: x,y = E.monsky_washnitzer_gens()
sage: type(x.parent().monsky_washnitzer())
<class 'sage.schemes.hyperelliptic_curves.monsky_washnitzer.MonskyWashnitzerDifferentialRing_with_category'>
```

**one()**

Return the unit of self.

**EXAMPLES:**

```python
sage: R.<x> = QQ['x']
sage: E = HyperellipticCurve(x^5-3*x+1)
sage: x,y = E.monsky_washnitzer_gens()
sage: x.parent().one()
1
```

**prime()**

Return the stored prime number $p$.

**EXAMPLES:**

```python
sage: R.<x> = QQ['x']
sage: E = HyperellipticCurve(x^5-3*x+1)
sage: x,y = E.monsky_washnitzer_gens()
sage: x.parent().prime().is_None
True
```

**x()**

Return the generator $x$ of self.

**EXAMPLES:**

```python
sage: R.<x> = QQ['x']
sage: E = HyperellipticCurve(x^5-3*x+1)
sage: x,y = E.monsky_washnitzer_gens()
sage: x.parent().x()
x
```

16.7. **Computation of Frobenius matrix on Monsky-Washnitzer cohomology**
Return the generator $y$ of self.

**EXAMPLES:**

```
sage: R.<x> = QQ['x']
sage: E = HyperellipticCurve(x^5-3*x+1)
sage: x,y = E.monsky_washnitzer_gens()
sage: x.parent().y()
y^*1
```

Return the zero of self.

**EXAMPLES:**

```
sage: R.<x> = QQ['x']
sage: E = HyperellipticCurve(x^5-3*x+1)
sage: x,y = E.monsky_washnitzer_gens()
sage: x.parent().zero()
0
```

Compute how much precision is required in `matrix_of_frobenius` to get an answer correct to `prec` $p$-adic digits.

The issue is that the algorithm used in `matrix_of_frobenius()` sometimes performs divisions by $p$, so precision is lost during the algorithm.

The estimate returned by this function is based on Kedlaya’s result (Lemmas 2 and 3 of [Ked2001]), which implies that if we start with $M$ $p$-adic digits, the total precision loss is at most $1 + \lceil \log_p(2M - 3) \rceil$ $p$-adic digits. (This estimate is somewhat less than the amount you would expect by naively counting the number of divisions by $p$.)

**INPUT:**

- `p` – a prime $p \geq 5$
- `prec` – integer, desired output precision, $prec \geq 1$

**OUTPUT:** adjusted precision (usually slightly more than `prec`)

**EXAMPLES:**

```
sage: from sage.schemes.hyperelliptic_curves.monsky_washnitzer import adjusted_prec
sage: adjusted_prec(5,2)
3
```

Compute the action of Frobenius on $dx/y$ and on $x dx/y$, using Newton’s method (as suggested in Kedlaya’s paper [Ked2001]).

(This function does not yet use the cohomology relations - that happens afterwards in the “reduction” step.)
More specifically, it finds $F_0$ and $F_1$ in the quotient ring $R[x, T]/(T - Q(x))$, such that

$$F(dx/y) = T^{-r}F0dx/y, \text{ and } F(xdx/y) = T^{-r}F1dx/y$$

where

$$r = ((2M - 3)p - 1)/2.$$  

(Here $T$ is $y^2 = z^{-2}$, and $R$ is the coefficient ring of $Q$.)

$F_0$ and $F_1$ are computed in the SpecialCubicQuotientRing associated to $Q$, so all powers of $x^j$ for $j \geq 3$ are reduced to powers of $T$.

**INPUT:**

- $Q$ – cubic polynomial of the form $Q(x) = x^3 + ax + b$, whose coefficient ring is a $\mathbb{Z}/(p^M)\mathbb{Z}$-algebra
- $p$ – residue characteristic of the $p$-adic field
- $M$ – $p$-adic precision of the coefficient ring (this will be used to determine the number of Newton iterations)

**OUTPUT:**

- $F0, F1$ – elements of SpecialCubicQuotientRing(Q), as described above
- $r$ – non-negative integer, as described above

**EXAMPLES:**

```python
sage: from sage.schemes.hyperelliptic_curves.monsky_washnitzer import frobenius_expansion_by_newton
sage: R.<x> = Integers(5^3)[x]

sage: Q = x^3 - x + R(1/4)

sage: frobenius_expansion_by_newton(Q, 5, 3)

((25*T^5 + 75*T^3 + 100*T^2 + 100*T + 100) + (5*T^6 + 80*T^5 + 100*T^3 + 25*T + 50)*x + (55*T^5 + 50*T^4 + 75*T^3 + 25*T^2 + 25*T + 25)*x^2,
 (5*T^8 + 15*T^7 + 95*T^6 + 10*T^5 + 25*T^4 + 25*T^3 + 100*T^2 + 50) + (65*T^7 + 55*T^6 + 70*T^5 + 100*T^4 + 25*T^2 + 100*T)*x + (15*T^6 + 115*T^5 + 75*T^4 + 100*T^3 + 50*T^2 + 75*T + 75)*x^2, 7)
```

sage.schemes.hyperelliptic_curves.monsky_washnitzer.frobenius_expansion_by_series(Q, p, M)

Compute the action of Frobenius on $dx/y$ and on $xdx/y$, using a series expansion.

(This function computes the same thing as frobenius_expansion_by_newton(), using a different method. Theoretically the Newton method should be asymptotically faster, when the precision gets large. However, in practice, this functions seems to be marginally faster for moderate precision, so I’m keeping it here until I figure out exactly why it is faster.)

(This function does not yet use the cohomology relations - that happens afterwards in the “reduction” step.)

More specifically, it finds $F_0$ and $F_1$ in the quotient ring $R[x, T]/(T - Q(x))$, such that $F(dx/y) = T^{-r}F0dx/y$, and $F(xdx/y) = T^{-r}F1dx/y$ where $r = ((2M - 3)p - 1)/2$. (Here $T$ is $y^2 = z^{-2}$, and $R$ is the coefficient ring of $Q$.)

$F_0$ and $F_1$ are computed in the SpecialCubicQuotientRing associated to $Q$, so all powers of $x^j$ for $j \geq 3$ are reduced to powers of $T$.

It uses the sum

$$F0 = \sum_{k=0}^{M-2} \binom{-1/2}{k} px^{p-1} E^k T^{(M-2-k)p}$$

16.7. Computation of Frobenius matrix on Monsky-Washnitzer cohomology 657
and

\[ F_1 = x^p F_0, \]

where \( E = Q(x^p) - Q(x)^p \).

INPUT:

- \( Q \) – cubic polynomial of the form \( Q(x) = x^3 + ax + b \), whose coefficient ring is a \( \mathbb{Z}/(p^M)\mathbb{Z} \)-algebra
- \( p \) – residue characteristic of the \( p \)-adic field
- \( M \) – \( p \)-adic precision of the coefficient ring (this will be used to determine the number of terms in the series)

OUTPUT:

- \( F_0, F_1 \) – elements of SpecialCubicQuotientRing(\( Q \)), as described above
- \( r \) – non-negative integer, as described above

EXAMPLES:

sage: from sage.schemes.hyperelliptic_curves.monsky_washnitzer import frobenius_exansion_by_series
sage: R.<x> = Integers(5^3)[x]
sage: Q = x^3 - x + R(1/4)
sage: frobenius_exansion_by_series(Q,5,3)
((25*T^5 + 75*T^3 + 100*T^2 + 100*T + 100) + (5*T^6 + 80*T^5 + 100*T^3 + 25*T + 50)*x + (55*T^5 + 50*T^4 + 75*T^3 + 25*T^2 + 25*T + 25)*x^2, (5*T^8 + 15*T^7 + 95*T^6 + 10*T^5 + 25*T^4 + 25*T^3 + 100*T^2 + 50) + (65*T^7 + 55*T^6 + 70*T^5 + 100*T^4 + 25*T^2 + 100*T)*x + (15*T^6 + 115*T^5 + 75*T^4 + 100*T^3 + 50*T^2 + 75*T + 75)*x^2, 7)

sage.schemes.hyperelliptic_curves.monsky_washnitzer.helper_matrix(\( Q \))

Compute the (constant) matrix used to calculate the linear combinations of the \( d(x^iy^j) \) needed to eliminate the negative powers of \( y \) in the cohomology (i.e. in reduce_negative()).

INPUT:

- \( Q \) – cubic polynomial

EXAMPLES:

sage: t = polygen(QQ,'t')
sage: from sage.schemes.hyperelliptic_curves.monsky_washnitzer import helper_matrix
sage: helper_matrix(t^3-4*t-691)
[ 64/12891731 -16584/12891731 4297329/12891731]
[ 6219/12891731 -32/12891731 8292/12891731]
[ -24/12891731 6219/12891731 -32/12891731]

sage.schemes.hyperelliptic_curves.monsky_washnitzer.lift(x)

Try to call \( x \).lift(), presumably from the \( p \)-adics to \( \mathbb{Z} \).

If this fails, it assumes the input is a power series, and tries to lift it to a power series over \( \mathbb{Q} \).

This function is just a very kludgy solution to the problem of trying to make the reduction code (below) work over both \( \mathbb{Z}_p \) and \( \mathbb{Z}_p[[u]] \).

EXAMPLES:
Elliptic curves, Release 9.7

```python
sage: from sage.schemes.hyperelliptic_curves.monsky_washnitzer import lift
sage: l = lift(Qp(13)(131)); l
131
sage: l.parent()
Integer Ring
sage: x=PowerSeriesRing(Qp(17), 'x').gen()
sage: l = lift(4+5*t+17*t^6); l
4 + 5*t + 17*t^6
sage: l.parent()
Power Series Ring in t over Rational Field
```

`sage.schemes.hyperelliptic_curves.monsky_washnitzer.matrix_of_frobenius(Q, p, M, trace=None, compute_exact_forms=False)`

Compute the matrix of Frobenius on Monsky-Washnitzer cohomology, with respect to the basis \((dx/y, xdx/y)\).

**INPUT:**

- `Q` – cubic polynomial \(Q(x) = x^3 + ax + b\) defining an elliptic curve \(E\) by \(y^2 = Q(x)\). The coefficient ring of \(Q\) should be a \(\mathbb{Z}/(p^M)\mathbb{Z}\)-algebra in which the matrix of frobenius will be constructed.
- `p` – prime >= 5 for which \(E\) has good reduction
- `M` – integer >= 2; \(p\)-adic precision of the coefficient ring
- `trace` – (optional) the trace of the matrix, if known in advance. This is easy to compute because it is just the \(a_p\) of the curve. If the trace is supplied, matrix_of_frobenius will use it to speed the computation (i.e. we know the determinant is \(p\), so we have two conditions, so really only column of the matrix needs to be computed. it is actually a little more complicated than that, but that’s the basic idea.) If trace=None, then both columns will be computed independently, and you can get a strong indication of correctness by verifying the trace afterwards.

**Warning:** THE RESULT WILL NOT NECESSARILY BE CORRECT TO \(M\) \(p\)-adic DIGITS. If you want prec digits of precision, you need to use the function adjusted_prec(), and then you need to reduce the answer mod \(p^{\text{prec}}\) at the end.

**OUTPUT:**

\(2 \times 2\) matrix of Frobenius acting on Monsky-Washnitzer cohomology, with entries in the coefficient ring of \(Q\).

**EXAMPLES:**

A simple example:

```python
sage: p = 5
sage: prec = 3
sage: M = monsky_washnitzer.adjusted_prec(p, prec); M
4
sage: R.<x> = PolynomialRing(Integers(p**M))
sage: A = monsky_washnitzer.matrix_of_frobenius(x^3 - x + R(1/4), p, M)
sage: A
[ 340 62]
[ 70 533]
```

But the result is only accurate to \(\text{prec}\) digits:
sage: B = A.change_ring(Integers(p**prec))
sage: B

\[
\begin{bmatrix}
90 & 62 \\
70 & 33 \\
\end{bmatrix}
\]

Check trace (123 = -2 mod 125) and determinant:

sage: B.det()
5
sage: B.trace()
123
sage: EllipticCurve([-1, 1/4]).ap(5)
-2

Try using the trace to speed up the calculation:

sage: A = monsky_washnitzer.matrix_of_frobenius(x^3 - x + R(1/4),
.....: p, M, -2)
sage: A

\[
\begin{bmatrix}
90 & 62 \\
320 & 533 \\
\end{bmatrix}
\]

Hmmm... it looks different, but that's because the trace of our first answer was only -2 modulo 5^3, not -2 modulo 5^5. So the right answer is:

sage: A.change_ring(Integers(p**prec))

\[
\begin{bmatrix}
90 & 62 \\
70 & 33 \\
\end{bmatrix}
\]

Check it works with only one digit of precision:

sage: p = 5
sage: prec = 1
sage: M = monsky_washnitzer.adjusted_prec(p, prec)
sage: R.<x> = PolynomialRing(Integers(p**M))
sage: A = monsky_washnitzer.matrix_of_frobenius(x^3 - x + R(1/4), p, M)
sage: A.change_ring(Integers(p))

\[
\begin{bmatrix}
0 & 2 \\
0 & 3 \\
\end{bmatrix}
\]

Here is an example that is particularly badly conditioned for using the trace trick:

sage: p = 11
sage: prec = 3
sage: M = monsky_washnitzer.adjusted_prec(p, prec)
sage: R.<x> = PolynomialRing(Integers(p**M))
sage: A = monsky_washnitzer.matrix_of_frobenius(x^3 + 7*x + 8, p, M)
sage: A.change_ring(Integers(p**prec))

\[
\begin{bmatrix}
1144 & 176 \\
847 & 185 \\
\end{bmatrix}
\]

The problem here is that the top-right entry is divisible by 11, and the bottom-left entry is divisible by 11^2. So when you apply the trace trick, neither $F(dx/y)$ nor $F(xdx/y)$ is enough to compute the whole matrix to the desired precision, even if you try increasing the target precision by one. Nevertheless, \texttt{matrix_of_frobenius} knows how to get the right answer by evaluating $F((x+1)dx/y)$ instead:
The running time is about \( O(p^{*\text{prec}}^2) \) (times some logarithmic factors), so it is feasible to run on fairly large primes, or precision (or both?!?!):

```
sage: p = 10007
sage: prec = 2
sage: M = monsky_washnitzer.adjusted_prec(p, prec)
sage: R.<x> = PolynomialRing(Integers(p**M))
sage: A = monsky_washnitzer.matrix_of_frobenius(x^3 - x + R(1/4), p, M)  # long time
sage: B = A.change_ring(Integers(p**prec)); B  # long time
[74311982 57996908]
[95877067 25828133]
sage: B.det()  # long time
10007
sage: -B.trace()  # long time
66
sage: EllipticCurve([-1, 1/4]).ap(10007)  # long time
66
```

```
sage: p = 5
sage: prec = 300
sage: M = monsky_washnitzer.adjusted_prec(p, prec)
sage: R.<x> = PolynomialRing(Integers(p**M))
sage: A = monsky_washnitzer.matrix_of_frobenius(x^3 - x + R(1/4), p, M)  # long time
sage: B = A.change_ring(Integers(p**prec)); B  # long time
5
sage: -B.trace()  # long time
2
sage: EllipticCurve([-1, 1/4]).ap(5)  # long time
-2
```

Let us check consistency of the results for a range of precisions:

```
sage: p = 5
sage: max_prec = 60
sage: M = monsky_washnitzer.adjusted_prec(p, max_prec)
sage: R.<x> = PolynomialRing(Integers(p**M))
sage: A = monsky_washnitzer.matrix_of_frobenius(x^3 - x + R(1/4), p, M)  # long time
sage: A = A.change_ring(Integers(p**max_prec))  # long time
sage: result = []  # long time
sage: for prec in range(1, max_prec):
....:     M = monsky_washnitzer.adjusted_prec(p, prec)  # long time
....:     R.<x> = PolynomialRing(Integers(p**M), 'x')  # long time
....:     B = monsky_washnitzer.matrix_of_frobenius(x^3 - x + R(1/4), p, M)  # long time
(continues on next page)
```
The remaining examples discuss what happens when you take the coefficient ring to be a power series ring; i.e.
in effect you’re looking at a family of curves.

The code does in fact work…

```plaintext
sage: p = 11
sage: prec = 3
sage: M = monsky_washnitzer.adjusted_prec(p, prec)
sage: S.<t> = PowerSeriesRing(Integers(p**M), default_prec=4)
sage: a = 7 + t + 3*t^2
sage: b = 8 - 6*t + 17*t^2
sage: R.<x> = PolynomialRing(S)
sage: Q = x**3 + a*x + b
sage: A = monsky_washnitzer.matrix_of_frobenius(Q, p, M)  # long time
sage: B = A.change_ring(PowerSeriesRing(Integers(p**prec), 't', default_prec=4))  # long time
sage: B
```

```plaintext
[1144 + 264*t + 841*t^2 + 1025*t^3 + O(t^4) 176 + 1052*t + 216*t^2 + 523*t^3 + O(t^4)]
[ 847 + 668*t + 81*t^2 + 424*t^3 + O(t^4) 185 + 341*t + 171*t^2 + 642*t^3 + O(t^4)]
```

The trace trick should work for power series rings too, even in the badly-conditioned case. Unfortunately I do
not know how to compute the trace in advance, so I am not sure exactly how this would help. Also, I suspect
the running time will be dominated by the expansion, so the trace trick will not really speed things up anyway.
Another problem is that the determinant is not always p:

```plaintext
sage: B.det()  # long time
11 + 484*t^2 + 451*t^3 + O(t^4)
```

However, it appears that the determinant always has the property that if you substitute t - 11t, you do get the
constant series p (mod p**prec). Similarly for the trace. And since the parameter only really makes sense when
it is divisible by p anyway, perhaps this is not a problem after all.

```plaintext
sage.schemes.hyperelliptic_curves.monsky_washnitzer.
matrix_of_frobenius_hyperelliptic(Q, p=None, prec=None, M=None)
```

Compute the matrix of Frobenius on Monsky-Washnitzer cohomology, with respect to the basis
\((dx/2y, xdx/2y, ...x^{d-2}dx/2y)\), where \(d\) is the degree of \(Q\).

**INPUT:**

- \(Q\) – monic polynomial \(Q(x)\)
- \(p\) – prime \(\geq 5\) for which \(E\) has good reduction
- \(\text{prec}\) – (optional) \(p\)-adic precision of the coefficient ring
- \(\text{M}\) – (optional) adjusted \(p\)-adic precision of the coefficient ring
OUTPUT:

\[(d-1) \times (d-1)\] matrix \(M\) of Frobenius on Monsky-Washnitzer cohomology, and list of differentials \(\{f_i\}\) such that

\[\phi^*(x^i dx/2y) = df_i + M[i] \ast \text{vec}(dx/2y, \ldots, x^{d-2} dx/2y)\]

EXAMPLES:

```python
sage: p = 5
sage: prec = 3
sage: R.<x> = QQ['x']

sage: A, f = monsky_washnitzer.matrix_of_frobenius_hyperelliptic(x^5 - 2*x + 3, p, ->prec)

sage: A

\[
\begin{bmatrix}
4^5 + 0(5^3) & 5 + 2^5 5^2 + 0(5^3) & 2 + 3^5 5^2 + 2^5 5^2 + 0(5^3) & 2 + \ldots \\
5 + 5^2 + 0(5^3) & 3^5 + 5^2 + 0(5^3) & 4^5 + 0(5^3) & \ldots \\
2 + 5^2 + 0(5^3) & 3 + 5^2 + 2^5 5^2 + 0(5^3) & 5 + 3^5 5^2 + 0(5^3) & 2^5 \ldots \\
-\ldots & 5 + 5^2 + 0(5^3) & 5 + 4^5 5^2 + 0(5^3) & 4^5 + 3^5 5^2 + 0(5^3) & \ldots \\
\end{bmatrix}
\]
```

```
sage.schemes.hyperelliptic_curves.monsky_washnitzer.reduce_all(Q, p, coeffs, offset, compute_exact_form=False)
```

Apply cohomology relations to reduce all terms to a linear combination of \(dx/y\) and \(x dx/y\).

INPUT:

- \(Q\) – cubic polynomial
- \(coeffs\) – list of length 3 lists. The \(i^{th}\) list \([a, b, c]\) represents \(y^{2(i+\text{offset})}(a + bx + cx^2) dx/y\).
- \(offset\) – nonnegative integer

OUTPUT:

- \(A, B\) - pair such that the input differential is cohomologous to \((A + Bx) dx/y\).

Note: The algorithm operates in-place, so the data in \(coeffs\) is destroyed.

EXAMPLES:

```python
sage: R.<x> = Integers(5^3)['x']

sage: Q = x^3 - x + R(1/4)

sage: coeffs = [[1, 2, 3], [4, 5, 6], [7, 8, 9]]

sage: coeffs = [[R.base_ring()(a) for a in row] for row in coeffs]

sage: monsky_washnitzer.reduce_all(Q, 5, coeffs, 1)

(21, 106)
```

```
sage.schemes.hyperelliptic_curves.monsky_washnitzer.reduce_negative(Q, p, coeffs, offset, exact_form=None)
```

Apply cohomology relations to incorporate negative powers of \(y\) into the \(y^0\) term.

INPUT:

- \(p\) – prime
• Q – cubic polynomial
• coeffs – list of length 3 lists. The $i^{th}$ list [a, b, c] represents $y^{2(i-offset)}(a + bx + cx^2)dx/y$.
• offset – nonnegative integer

OUTPUT:
The reduction is performed in-place. The output is placed in coeffs[offset]. Note that coeffs[i] will be meaningless for i offset after this function is finished.

EXAMPLES:

```sage
R.<x> = Integers(5^3)
Q = x^3 - x + R(1/4)
coeffs = [[[10, 15, 20], [1, 2, 3], [4, 5, 6], [7, 8, 9]]
coeffs = [[R.base_ring()(a) for a in row] for row in coeffs]
monsky_washnitzer.reduce_negative(Q, 5, coeffs, 3)
coeffs[3]
[28, 52, 9]
```

```sage
R.<x> = Integers(7^3)
Q = x^3 - x + R(1/4)
coeffs = [[[7, 14, 21], [1, 2, 3], [4, 5, 6], [7, 8, 9]]
coeffs = [[R.base_ring()(a) for a in row] for row in coeffs]
monsky_washnitzer.reduce_negative(Q, 7, coeffs, 3)
coeffs[3]
[245, 332, 9]
```

Apply cohomology relations to incorporate positive powers of $y$ into the $y^0$ term.

INPUT:
• Q – cubic polynomial
• coeffs – list of length 3 lists. The $i^{th}$ list [a, b, c] represents $y^{2(i-offset)}(a + bx + cx^2)dx/y$.
• offset – nonnegative integer

OUTPUT:
The reduction is performed in-place. The output is placed in coeffs[offset]. Note that coeffs[i] will be meaningless for i offset after this function is finished.

EXAMPLES:

```sage
R.<x> = Integers(5^3)
Q = x^3 - x + R(1/4)
coeffs = [[1, 2, 3], [10, 15, 20]]
coeffs = [[R.base_ring()(a) for a in row] for row in coeffs]
monsky_washnitzer.reduce_positive(Q, 5, coeffs, 0)
coeffs[0]
[16, 102, 88]
```
sage: coeffs = [[9, 8, 7], [10, 15, 20]]  
sage: coeffs = [[R.base_ring()(a) for a in row] for row in coeffs]  

sage: monsky_washnitzer.reduce_positive(Q, 5, coeffs, 0)  
[24, 108, 92]

sage.schemes.hyperelliptic_curves.monsky_washnitzer.reduce_zero(Q, coeffs, offset, exact_form=None)

Apply cohomology relation to incorporate $x^2y^0$ term into $x^0y^0$ and $x^1y^0$ terms.

INPUT:

- Q – cubic polynomial
- coeffs – list of length 3 lists. The $i^{th}$ list $[a, b, c]$ represents $y^{2(i-\text{offset})}(a + bx + cx^2)dx/\gamma$.
- offset – nonnegative integer

OUTPUT:

The reduction is performed in-place. The output is placed in coeffs[offset]. This method completely ignores coeffs[i] for i != offset.

EXAMPLES:

sage: R.<x> = Integers(5^3)[\'x\']  
sage: Q = x^3 - x + R(1/4)  
sage: coeffs = [[1, 2, 3], [4, 5, 6], [7, 8, 9]]  
sage: coeffs = [[R.base_ring()(a) for a in row] for row in coeffs]  
sage: monsky_washnitzer.reduce_zero(Q, coeffs, 1)  
sage: coeffs[1]  
[6, 5, 0]

sage.schemes.hyperelliptic_curves.monsky_washnitzer.transpose_list(input)

INPUT:

- input – a list of lists, each list of the same length

OUTPUT:

- output – a list of lists such that output[i][j] = input[j][i]

EXAMPLES:

sage: from sage.schemes.hyperelliptic_curves.monsky_washnitzer import transpose_list  
sage: L = [[1, 2], [3, 4], [5, 6]]  
sage: transpose_list(L)  
[[1, 3, 5], [2, 4, 6]]
16.8 Frobenius on Monsky-Washnitzer cohomology of a hyperelliptic curve over a largish prime finite field

This is a wrapper for the matrix() function in hypellfrob.cpp.

AUTHOR:

• David Harvey (2007-05)
• David Harvey (2007-12): rewrote for hypellfrob version 2.0

\[ \text{sage.schemes.hyperelliptic_curves.hypellfrob.hypellfrob}(p, N, Q) \]

Compute the matrix of Frobenius acting on the Monsky-Washnitzer cohomology of a hyperelliptic curve \( y^2 = Q(x) \), with respect to the basis \( x^i dx/y, 0 \leq i < 2g \).

INPUT:

- \( p \) – a prime
- \( Q \) – a monic polynomial in \( \mathbb{Z}[x] \) of odd degree. Must have no multiple roots mod \( p \).
- \( N \) – precision parameter; the output matrix will be correct modulo \( p^N \).

PRECONDITIONS:

Must have \( p > (2g + 1)(2N - 1) \), where \( g = (\deg(Q) - 1)/2 \) is the genus of the curve.

ALGORITHM:

Described in “Kedlaya’s algorithm in larger characteristic” by David Harvey. Running time is theoretically soft-\( O(p^{1/2}N^{5/2}g^3) \).

Todo: Remove the restriction on \( p \). Probably by merging in Robert’s code, which eventually needs a fast C++/NTL implementation.

EXAMPLES:

```python
sage: from sage.schemes.hyperelliptic_curves.hypellfrob import hypellfrob
sage: R.<x> = PolynomialRing(ZZ)
sage: f = x^5 + 2*x^2 + x + 1; p = 101
sage: M = hypellfrob(p, 4, f); M
\[
\begin{bmatrix}
91844754 + O(101^4) & 38295665 + O(101^4) & 44498269 + O(101^4) & 11854028 + O(101^4) \\
93514789 + O(101^4) & 48987424 + O(101^4) & 53287857 + O(101^4) & 61431148 + O(101^4) \\
77916046 + O(101^4) & 60656459 + O(101^4) & 101244586 + O(101^4) & 56237448 + O(101^4) \\
58643832 + O(101^4) & 81727988 + O(101^4) & 85294589 + O(101^4) & 70104432 + O(101^4)
\end{bmatrix}
\]
```

- \( \text{M.trace()} \)
  \( 7 + O(101^4) \)
- \( \text{sum(legendre_symbol(f(i), p) for i in range(p))} \)
  \( 7 \)
- \( \text{ZZ(M.det())} \)
  \( 10201 \)
- \( \text{M = hypellfrob(p, 1, f); M} \)
```
(continues on next page)
```
AUTHORS:

• David Harvey (2007-05)
• David Harvey (2007-12): updated for hypellfrob version 2.0

sage.schemes.hyperelliptic_curves.hypellfrob.interval_products(M0, M1, target)
Given a matrix $M$ with coefficients linear polynomials over $\mathbb{Z}/N\mathbb{Z}$ and a list of integers $a_0 < b_0 \leq a_1 < b_1 \leq \cdots < a_n < b_n$, compute the matrices $\prod_{t = a_i + 1}^{b_i} M(t)$ for $i = 0$ to $n$.

This is a wrapper for code in the hypellfrob package.

INPUT:

• $M_0, M_1$ – matrices over $\mathbb{Z}/N\mathbb{Z}$, so that $M = M_0 + M_1 \times x$
• target – a list of integers

ALGORITHM:

Described in [Harv2007]. Based on the work of Bostan-Gaudry-Schost [BGS2007].

EXAMPLES:

```
sage: from sage.schemes.hyperelliptic_curves.hypellfrob import interval_products
sage: interval_products(Matrix(Integers(9), 2,2, [1,0,1,0]),
...: Matrix(Integers(9), 2, 2, [1, 1, 0, 2],[0,2,2,4])
[  
[7 8] [5 4]
[5 1], [2 7]  
]
sage: [prod(Matrix(Integers(9), 2, 2, [t + 1, t, 1, 2*t])
...: for t in range(2*i + 1, 2*i + 1 + 2)) for i in range(2)]
[  
[7 8] [5 4]
[5 1], [2 7]  
]
```

An example with larger modulus:

```
sage: interval_products(Matrix(Integers(3^8), 1, 1, [1]),
...: Matrix(Integers(3^8), 1, 1, [1]), [2,4])
[[20]]
sage: [prod(Matrix(Integers(3^8), 1, 1, [t + 1]) for t in range(3,5))]
[[20]]
```

An even larger modulus:

```
sage: interval_products(Matrix(Integers(3^18), 1, 1, [1]),
...: Matrix(Integers(3^18), 1, 1, [1]), [2,4])
[[20]]
sage: [prod(Matrix(Integers(3^18), 1, 1, [t + 1]) for t in range(3,5))]
[[20]]
```
AUTHORS:

- David Harvey (2007-12): Original code
- Alex J. Best (2018-02): Wrapper

REFERENCES:

16.9 Jacobian of a general hyperelliptic curve

class sage.schemes.hyperelliptic_curves.jacobian_generic.HyperellipticJacobian_generic(C)
    Bases: sage.schemes.jacobians.abstract_jacobian.Jacobian_generic

EXAMPLES:

```
sage: FF = FiniteField(2003)
sage: R.<x> = PolynomialRing(FF)
sage: f = x**5 + 1184*x**3 + 1846*x**2 + 956*x + 560
sage: C = HyperellipticCurve(f)
sage: J = C.jacobian()
sage: a = x**2 + 376*x + 245; b = 1015*x + 1368
sage: X = J(FF)
sage: D = X([a,b])
sage: D
(x^2 + 376*x + 245, y + 988*x + 635)
sage: J(0)
(1)
sage: D == J([a,b])
True
sage: D == D + J(0)
True
```

An more extended example, demonstrating arithmetic in J(QQ) and J(K) for a number field K/QQ.

```
sage: P.<x> = PolynomialRing(QQ)
sage: f = x^5 - x + 1; h = x
sage: C = HyperellipticCurve(f,h,'u,v')
sage: C
Hyperelliptic Curve over Rational Field defined by v^2 + u*v = u^5 - u + 1
sage: PP = C.ambient_space()
sage: PP
Projective Space of dimension 2 over Rational Field
sage: PP
sage: C.defining_polynomial()
-x0^5 + x0*x1*x2^3 + x1^2*x2^3 + x0*x2^4 - x2^5
sage: C(QQ)
Set of rational points of Hyperelliptic Curve over Rational Field defined by v^2 + u*v = u^5 - u + 1
sage: K.<t> = NumberField(x^2-2)
sage: C(K)
Set of rational points of Hyperelliptic Curve over Number Field in t with defining polynomial x^2 - 2 defined by v^2 + u*v = u^5 - u + 1
sage: P = C(QQ)(0,1,1); P
(0 : 1 : 1)
sage: P == C(0,1,1)
```

(continues on next page)
Elliptic curves, Release 9.7

(continued from previous page)

True

```
sage: C(0,1,1).parent()
Set of rational points of Hyperelliptic Curve over Rational Field defined by v^2 + u*v = u^5 - u + 1

sage: P1 = C(K)(P)
sage: P2 = C(K)([2,4*t-1,1])
sage: P3 = C(K)([-1/2,1/8*(7*t+2),1])
sage: P1, P2, P3
((0 : 1 : 1), (2 : 4*t - 1 : 1), (-1/2 : 7/8*t + 1/4 : 1))

sage: J = C.jacobian()
sage: J
Jacobian of Hyperelliptic Curve over Rational Field defined by v^2 + u*v = u^5 - u + 1

sage: Q = J(QQ)(P); Q
(u, v - 1)

sage: for i in range(6): Q*i
(1)
(u, v - 1)
(u^2, v + u - 1)
(u^2, v + 1)
(u, v + 1)
(1)

sage: Q1 = J(K)(P1); print("%s -> %s"%( P1, Q1 ))
(0 : 1 : 1) -> (u, v - 1)

sage: Q2 = J(K)(P2); print("%s -> %s"%( P2, Q2 ))
(2 : 4*t - 1 : 1) -> (u - 2, v - 4*t + 1)

sage: Q3 = J(K)(P3); print("%s -> %s"%( P3, Q3 ))
(-1/2 : 7/8*t + 1/4 : 1) -> (u + 1/2, v - 7/8*t - 1/4)

sage: R.<x> = PolynomialRing(K)
sage: Q4 = J(K)([x^2-t,R(1)])
sage: for i in range(4): Q4*i
(1)
(u^2 + (-3/4*t - 9/16)*u + 1/2*t + 1/4, v + (-1/32*t - 57/64)*u + 1/2*t + 9/16)

sage: R2 = Q2*5; R2
(u^2 - 3789465233/116983808*u - 267915823/58491904, v + (233827256513849/1789384327168*t + 1/2)*u + 15782925357447/894692163584*t)

sage: R3 = Q3*5; R3
(u^2 + 563330080839913890623/14426454798950909645952*u - 26531814176395676231273/28852909597901819291904, v + (253155440321645614670860868199103/2450498420175733688903836378159104*t + 1/2)*u + 3350862929/122763473)
Moreover the following relation holds in the 5-torsion subgroup:

\[
\text{sage: } Q_2 + Q_4 == 2^n Q_1
\]

\[
\text{True}
\]

\section*{dimension()}

Return the dimension of this Jacobian.

\section*{OUTPUT:}

\section*{Integer}

\section*{EXAMPLES:}

\[
\text{sage: } k.<a> = GF(9); R.<x> = k[]
\]

\[
\text{sage: } \text{HyperellipticCurve}(x^3 + x - 1, x+a).\text{jacobian().dimension()}
1
\]

\[
\text{sage: } g = \text{HyperellipticCurve}(x^6 + x - 1, x+a).\text{jacobian().dimension()}; g
2
\]

\[
\text{sage: } \text{type(g)}
<..., 'sage.rings.integer.Integer'>
\]

\section*{geometric_endomorphism_algebra_is_field(B=200, proof=False)}

Return whether the geometric endomorphism algebra is a field.

This implies that the Jacobian of the curve is geometrically simple. It is based on Algorithm 4.10 from [Lom2019]

\section*{INPUT:}

\begin{itemize}
  \item \texttt{B} – (default: 200) the bound which appears in the statement of the algorithm from [Lom2019]
  \item \texttt{proof} – (default: False) whether or not to insist on a provably correct answer. This is related to the warning in the docstring of this module: if this function returns \texttt{False}, then strictly speaking this has not been proven to be \texttt{False} until one has exhibited a non-trivial endomorphism, which these methods are not designed to carry out. If one is convinced that this method should return \texttt{True}, but it is returning \texttt{False}, then this can be exhibited by increasing \texttt{B}.
\end{itemize}

\section*{OUTPUT:}

\section*{Boolean indicating whether or not the geometric endomorphism algebra is a field.}

\section*{EXAMPLES:}

This is LMFDB curve 262144.d.524288.2 which has QM. Although its Jacobian is geometrically simple, the geometric endomorphism algebra is not a field:

\[
\text{sage: } R.<x> = QQ[]
\]

\[
\text{sage: } f = x^5 + x^4 + 4^5 x^3 + 8^6 x^2 + 5^9 x + 1
\]

\[
\text{sage: } C = \text{HyperellipticCurve}(f)
\]

\[
\text{sage: } J = C.\text{jacobian()}
\]

\[
\text{sage: } J.\text{geometric_endomorphism_algebra_is_field()}
\]

\[
\text{False}
\]

This is LMFDB curve 50000.a.200000.1:
\begin{verbatim}
sage: f = 8*x^5 + 1
sage: C = HyperellipticCurve(f)
sage: J = C.jacobian()
sage: J.geometric_endomorphism_algebra_is_field()
True
\end{verbatim}

\textbf{geometric_endomorphism_ring_is_ZZ}(\texttt{B=200, proof=False})

Return whether the geometric endomorphism ring of \texttt{self} is the integer ring \texttt{Z}.

\textbf{INPUT:}

\begin{itemize}
\item \texttt{B} – (default: 200) the bound which appears in the statement of the algorithm from [Lom2019]
\item \texttt{proof} – (default: False) whether or not to insist on a provably correct answer. This is related to the warning in the module docstring of \texttt{jacobian_endomorphisms.py}: if this function returns \texttt{False}, then strictly speaking this has not been proven to be \texttt{False} until one has exhibited a non-trivial endomorphism, which the methods in that module are not designed to carry out. If one is convinced that this method should return \texttt{True}, but it is returning \texttt{False}, then this can be exhibited by increasing \texttt{B}.
\end{itemize}

\textbf{OUTPUT:}

Boolean indicating whether or not the geometric endomorphism ring is isomorphic to the integer ring.

\textbf{EXAMPLES:}

This is LMFDB curve 603.a.603.2:

\begin{verbatim}
sage: R.<x> = QQ[]
sage: f = 4*x^5 + x^4 - 4*x^3 + 2*x^2 + 4*x + 1
sage: C = HyperellipticCurve(f)
sage: J = C.jacobian()
sage: J.geometric_endomorphism_ring_is_ZZ()
True
\end{verbatim}

This is LMFDB curve 1152.a.147456.1 whose geometric endomorphism ring is isomorphic to the group of 2x2 matrices over \texttt{Q}:

\begin{verbatim}
sage: f = x^6 - 2*x^4 + 2*x^2 - 1
sage: C = HyperellipticCurve(f)
sage: J = C.jacobian()
sage: J.geometric_endomorphism_ring_is_ZZ()
False
\end{verbatim}

This is LMFDB curve 20736.k.373248.1 whose geometric endomorphism ring is isomorphic to the group of 2x2 matrices over a CM field:

\begin{verbatim}
sage: f = x^6 + 8
sage: C = HyperellipticCurve(f)
sage: J = C.jacobian()
sage: J.geometric_endomorphism_ring_is_ZZ()
False
\end{verbatim}

This is LMFDB curve 708.a.181248.1:

\begin{verbatim}
sage: R.<x> = QQ[]
sage: f = -3*x^6 - 16*x^5 + 36*x^4 + 194*x^3 - 164*x^2 - 392*x - 143
sage: C = HyperellipticCurve(f)
\end{verbatim}

(continues on next page)
This is LMFDB curve 10609.a.10609.1 whose geometric endomorphism ring is an order in a real quadratic field:

```sage
f = x^6 + 2*x^4 + 2*x^3 + 5*x^2 + 6*x + 1
C = HyperellipticCurve(f)
J = C.jacobian()
J.geometric_endomorphism_ring_is_ZZ()
```

False

This is LMFDB curve 160000.c.800000.1 whose geometric endomorphism ring is an order in a CM field:

```sage
f = x^5 - 1
C = HyperellipticCurve(f)
J = C.jacobian()
J.geometric_endomorphism_ring_is_ZZ()
```

False

This is LMFDB curve 262144.d.524288.2 whose geometric endomorphism ring is an order in a quaternion algebra:

```sage
f = x^5 + x^4 + 4*x^3 + 8*x^2 + 5*x + 1
C = HyperellipticCurve(f)
J = C.jacobian()
J.geometric_endomorphism_ring_is_ZZ()
```

False

This is LMFDB curve 578.a.2312.1 whose geometric endomorphism ring is \(\mathbb{Q} \times \mathbb{Q}\):

```sage
f = 4*x^5 - 7*x^4 + 10*x^3 - 7*x^2 + 4*x
C = HyperellipticCurve(f)
J = C.jacobian()
J.geometric_endomorphism_ring_is_ZZ()
```

False

**16.10 Jacobian of a hyperelliptic curve of genus 2**

```sage
point(mumford, check=True)
```

```class sage.schemes.hyperelliptic_curves.jacobian_g2.HyperellipticJacobian_g2(C)
    Bases: sage.schemes.hyperelliptic_curves.jacobian_generic.HyperellipticJacobian_generic

    kummer_surface()
```
16.11 Rational point sets on a Jacobian

EXAMPLES:

```sage
sage: x = QQ['x'].0
sage: f = x^5 + x + 1
sage: C = HyperellipticCurve(f); C
Hyperelliptic Curve over Rational Field defined by y^2 = x^5 + x + 1
sage: C(QQ)
Set of rational points of Hyperelliptic Curve over Rational Field defined by y^2 = x^5 + x + 1
sage: P = C([0,1,1])
```

```sage
sage: J = C.jacobian(); J
Jacobian of Hyperelliptic Curve over Rational Field defined by y^2 = x^5 + x + 1
sage: Q = J(QQ)(P); Q
(x, y - 1)
```

```sage
sage: Q + Q
(x^2, y - 1/2*x - 1)
```

```sage
sage: Q*3
(x^2 - 1/64*x + 1/8, y + 255/512*x + 65/64)
```

```sage
sage: F.<a> = GF(3)
```

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

```sage
sage: f = x^5-1
sage: C = HyperellipticCurve(f)
```

```sage
sage: J = C.jacobian()
```

```sage
sage: X = J(F)
```

```sage
class sage.schemes.hyperelliptic_curves.jacobian_homset.JacobianHomset_divisor_classes(Y, X, **kwds):
    Bases: sage.schemes.generic.homset.SchemeHomset_points
    base_extend(R)
    curve()
    value_ring()
    Return S for a homset X(T) where T = Spec(S).
```
**16.12 Jacobian ‘morphism’ as a class in the Picard group**

This module implements the group operation in the Picard group of a hyperelliptic curve, represented as divisors in Mumford representation, using Cantor’s algorithm.

A divisor on the hyperelliptic curve $y^2 + yh(x) = f(x)$ is stored in Mumford representation, that is, as two polynomials $u(x)$ and $v(x)$ such that:

- $u(x)$ is monic,
- $u(x)$ divides $f(x) - h(x)v(x) - v(x)^2$,
- $\text{deg}(v(x)) < \text{deg}(u(x)) \leq g$.

**REFERENCES:**

A readable introduction to divisors, the Picard group, Mumford representation, and Cantor’s algorithm:


A standard reference in the field of cryptography:


**EXAMPLES:** The following curve is the reduction of a curve whose Jacobian has complex multiplication.

```
sage: x = GF(37)['x'].gen()
sage: H = HyperellipticCurve(x^5 + 12*x^4 + 13*x^3 + 15*x^2 + 33*x); H
Hyperelliptic Curve over Finite Field of size 37 defined by y^2 = x^5 + 12*x^4 + 13*x^3 + 15*x^2 + 33*x
```

At this time, Jacobians of hyperelliptic curves are handled differently than elliptic curves:

```
sage: J = H.jacobian(); J
Jacobian of Hyperelliptic Curve over Finite Field of size 37 defined by y^2 = x^5 + 12*x^4 + 13*x^3 + 15*x^2 + 33*x
sage: J = J(J.base_ring()); J
Set of rational points of Jacobian of Hyperelliptic Curve over Finite Field of size 37 defined by y^2 = x^5 + 12*x^4 + 13*x^3 + 15*x^2 + 33*x
```

Points on the Jacobian are represented by Mumford’s polynomials. First we find a couple of points on the curve:

```
sage: P1 = H.lift_x(2); P1
(2 : 11 : 1)
sage: Q1 = H.lift_x(10); Q1
(10 : 18 : 1)
```

Observe that 2 and 10 are the roots of the polynomials in x, respectively:

```
sage: P = J(P1); P
(x + 35, y + 26)
sage: Q = J(Q1); Q
(x + 27, y + 19)
```
Elliptic curves, Release 9.7

sage: P + Q
(x^2 + 25*x + 20, y + 13*x)
sage: (x^2 + 25*x + 20).roots(multiplicities=False)
[10, 2]

Frobenius satisfies

\[ x^4 + 12 \cdot x^3 + 78 \cdot x^2 + 444 \cdot x + 1369 \]

on the Jacobian of this reduction and the order of the Jacobian is \( N = 1904 \).

sage: 1904*P
(1)
sage: 34*P == 0
True
sage: 35*P == P
True
sage: 33*P == -P
True

sage: Q*1904
(1)
sage: Q*238 == 0
True
sage: Q*239 == Q
True
sage: Q*237 == -Q
True

class sage.schemes.hyperelliptic_curves.jacobian_morphism.JacobianMorphism_divisor_class_field(parent, polys, check=True)

Bases:  
sage.structure.element.AdditiveGroupElement,  
sage.schemes.generic.morphism.SchemeMorphism

An element of a Jacobian defined over a field, i.e. in \( J(K) = \text{Pic}^0_K(C) \).

scheme()

Return the scheme this morphism maps to; or, where this divisor lives.

Warning: Although a pointset is defined over a specific field, the scheme returned may be over a different (usually smaller) field. The example below demonstrates this: the pointset is determined over a number field of absolute degree 2 but the scheme returned is defined over the rationals.

EXAMPLES:

sage: x = QQ['x'].gen()
sage: f = x^5 + x
sage: H = HyperellipticCurve(f)
sage: F.<a> = NumberField(x^2 - 2, 'a')
sage: J = H.jacobian()(F); J
Set of rational points of Jacobian of Hyperelliptic Curve over

(continues on next page)
Number Field in a with defining polynomial \(x^2 - 2\) defined by \(y^2 = x^5 + x\)

```python
sage: P = J(H.lift_x(F(1)))
sage: P.scheme()
```

Jacobian of Hyperelliptic Curve over Rational Field defined by \(y^2 = x^5 + x\)

`sage.schemes.hyperelliptic_curves.jacobian_morphism.cantor_composition(D1, D2, f, h, genus)`

**EXAMPLES:**

```python
sage: F.<a> = GF(7^2, 'a')
sage: x = F['x'].gen()
sage: f = x^7 + x^2 + a
sage: H = HyperellipticCurve(f, 2*x); H
Hyperelliptic Curve over Finite Field in a of size 7^2 defined by y^2 + 2*x*y = x^7 + x^2 + a
sage: J = H.jacobian()(F); J
Set of rational points of Jacobian of Hyperelliptic Curve over Finite Field in a of size 7^2 defined by y^2 + 2*x*y = x^7 + x^2 + a

sage: Q = J(H.lift_x(F(1))); Q
(x + 6, y + 2*a + 2)
sage: 10*Q  # indirect doctest
(x^3 + (3*a + 1)*x^2 + (2*a + 5)*x + a + 5, y + (4*a + 5)*x^2 + (a + 1)*x + 6*a + 3)
sage: 7*8297*Q  # indirect doctest
(1)
```

```python
sage: Q = J(H.lift_x(F(a+1))); Q
(x + 6*a + 6, y + 2*a)
sage: 7*8297*Q  # indirect doctest
(1)
```

A test over a prime field:

```python
sage: F = GF(next_prime(10^30))
sage: x = F['x'].gen()
sage: f = x^7 + x^2 + 1
sage: H = HyperellipticCurve(f, 2*x); H
Hyperelliptic Curve over Finite Field of size 10^30 defined by y^2 + 2*x*y = x^7 + x^2 + 1
sage: J = H.jacobian()(F); J
Set of rational points of Jacobian of Hyperelliptic Curve over Finite Field of size 10^30 defined by y^2 + 2*x*y = x^7 + x^2 + 1

sage: Q = J(H.lift_x(F(1))); Q
(x + 10000000000000000000000000000056, y + 10000000000000000000000000000056)
sage: 10*Q  # indirect doctest
(x^3 + 15029603716983893499714556727*x^2 + 377701248971234560956743242408*x + 
  509451014495791237681619598519*x^2 + 
  875375621665039398768235387900*x + 861429240012590886251910326876)
```

(continues on next page)
sage.schemes.hyperelliptic_curves.jacobian_morphism.cantor_composition_simple($D_1, D_2, f, genus$)

Given $D_1$ and $D_2$ two reduced Mumford divisors on the Jacobian of the curve $y^2 = f(x)$, computes a representative $D_1 + D_2$.

**Warning:** The representative computed is NOT reduced! Use `cantor_reduction_simple()` to reduce it.

**EXAMPLES:**

```python
sage: x = QQ['x'].gen()
sage: f = x^5 + x
sage: H = HyperellipticCurve(f); H
Hyperelliptic Curve over Rational Field defined by y^2 = x^5 + x

sage: P = H.lift_x(F(1)); P
(x - 1, y - a)
sage: Q = H.lift_x(F(0)); Q
(x, y)
sage: 2*P + 2*Q  # indirect doctest
(x^2 - 2*x + 1, y - 3/2*a*x + 1/2*a)
sage: 2*(P + Q)  # indirect doctest
(x^2 - 2*x + 1, y - 3/2*a*x + 1/2*a)
sage: 3*P  # indirect doctest
(x^2 - 25/32*x + 49/32, y - 45/256*a*x - 315/256*a)
```

sage.schemes.hyperelliptic_curves.jacobian_morphism.cantor_reduction($a, b, f, h, genus$)

Return the unique reduced divisor linearly equivalent to $(a, b)$ on the curve $y^2 + yh(x) = f(x)$.

See the docstring of `sage.schemes.hyperelliptic_curves.jacobian_morphism` for information about divisors, linear equivalence, and reduction.

**EXAMPLES:**

```python
sage: x = QQ['x'].gen()
sage: f = x^5 - x
sage: H = HyperellipticCurve(f, x); H
Hyperelliptic Curve over Rational Field defined by y^2 + x*y = x^5 - x
sage: J = H.jacobian()(QQ); J
Set of rational points of Jacobian of Hyperelliptic Curve over Rational Field defined by y^2 + x*y = x^5 - x
```

16.12. Jacobian ‘morphism’ as a class in the Picard group
The following point is 2-torsion:

```
sage: Q = J(H.lift_x(0)); Q
(x, y)
sage: 2*Q  # indirect doctest
(1)
```

The next point is not 2-torsion:

```
sage: P = J(H.lift_x(-1)); P
(x + 1, y - 1)
sage: 2 * J(H.lift_x(-1))  # indirect doctest
(x^2 + 2*x + 1, y - 3*x - 4)
sage: 3 * J(H.lift_x(-1))  # indirect doctest
(x^2 - 487*x - 324, y - 10754*x - 7146)
```

sage.schemes.hyperelliptic_curves.jacobian_morphism.cantor_reduction_simple(a, b, f, genus)

Return the unique reduced divisor linearly equivalent to \((a, b)\) on the curve \(y^2 = f(x)\).

See the docstring of sage.schemes.hyperelliptic_curves.jacobian_morphism for information about divisors, linear equivalence, and reduction.

EXAMPLES:

```
sage: x = QQ[‘x’].gen()
sage: f = x^5 - x
sage: H = HyperellipticCurve(f); H
Hyperelliptic Curve over Rational Field defined by y^2 = x^5 - x
sage: J = H.jacobian()(QQ); J
Set of rational points of Jacobian of Hyperelliptic Curve over Rational Field defined by y^2 = x^5 - x
```

The following point is 2-torsion:

```
sage: P = J(H.lift_x(-1)); P
(x + 1, y)
sage: 2 * P  # indirect doctest
(1)
```

16.13 Hyperelliptic curves of genus 2 over a general ring

class sage.schemes.hyperelliptic_curves.hyperelliptic_g2.HyperellipticCurve_g2(PP, f, h=None, names=None, genus=None)

Bases: sage.schemes.hyperelliptic_curves.hyperelliptic_generic.HyperellipticCurve_generic

```
absolute_igusa_invariants_kohel()
```

Return the three absolute Igusa invariants used by Kohel [KohEChIDNA].

See also:

```
sage.schemes.hyperelliptic_curves.invariants()
```

EXAMPLES:
Elliptic curves, Release 9.7

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

sage: HyperellipticCurve(x^5 - 1).absolute_igusa_invariants_kohel()
(0, 0, 0)
sage: HyperellipticCurve(x^5 - x + 1, x^2).absolute_igusa_invariants_kohel()
(-1030567/178769, 259686400/178769, 20806400/178769)
sage: HyperellipticCurve((x^5 - x + 1)(3*x + 1), (x^2)(3*x + 1)).absolute_igusa_invariants_kohel()
(-1030567/178769, 259686400/178769, 20806400/178769)
```

absolute_igusa_invariants_wamelen()

Return the three absolute Igusa invariants used by van Wamelen [Wam1999].

EXAMPLES:

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

sage: HyperellipticCurve(x^5 - 1).absolute_igusa_invariants_wamelen()
(0, 0, 0)
sage: HyperellipticCurve((x^5 - 1)(x - 2), (x^2)(x - 2)).absolute_igusa_invariants_wamelen()
(0, 0, 0)
```

clebsch_invariants()

Return the Clebsch invariants \( (A, B, C, D) \) of Mestre, p 317, [Meso1991].

See also:

```
sage.schemes.hyperelliptic_curves.invariants()
```

EXAMPLES:

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

sage: f = x^5 - x^4 + 3

sage: HyperellipticCurve(f).clebsch_invariants()
(0, -2048/375, -4096/25, -4881645568/84375)
sage: HyperellipticCurve(f(2*x)).clebsch_invariants()
(-512/15, 71696384/5625, -6072014209024/140625, -451865844002031331704832/7119140625)
sage: HyperellipticCurve(f, x).clebsch_invariants()
(-8/15, 17504/5625, -23162896/140625, -420832861216768/7119140625)
sage: HyperellipticCurve(f(2*x), 2*x).clebsch_invariants()
(-512/15, 71696384/5625, -6072014209024/140625, -451865844002031331704832/7119140625)
```

igusa_clebsch_invariants()

Return the Igusa-Clebsch invariants \( I_2, I_4, I_6, I_{10} \) of Igusa and Clebsch [IJ1960].

See also:

```
sage.schemes.hyperelliptic_curves.invariants()
```

EXAMPLES:

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

sage: f = x^5 - x + 2

sage: HyperellipticCurve(f).igusa_clebsch_invariants()
(-640, -20480, 1310720, 52160364544)
```

(continues on next page)
is_odd_degree()  
Return True if the curve is an odd degree model.  

EXAMPLES:  

```python  
sage: R.<x> = QQ[]  
sage: f = x^5 - x^4 + 3  
sage: HyperellipticCurve(f).is_odd_degree()  
True  ```

jacobian()  
Return the Jacobian of the hyperelliptic curve.  

EXAMPLES:  

```python  
sage: R.<x> = QQ[]  
sage: f = x^5 - x^4 + 3  
sage: HyperellipticCurve(f).jacobian()  
Jacobian of Hyperelliptic Curve over Rational Field defined by y^2 = x^5 - x^4 - 3  ```

kummer_morphism()  
Return the morphism of an odd degree hyperelliptic curve to the Kummer surface of its Jacobian.  
This could be extended to an even degree model if a prescribed embedding in its Jacobian is fixed.  

EXAMPLES:  

```python  
sage: R.<x> = QQ[]  
sage: f = x^5 - x^4 + 3  
sage: HyperellipticCurve(f).kummer_morphism()  
# not tested  ```

16.14 Compute invariants of quintics and sextics via ‘Ueberschiebung’

Todo:  
- Implement invariants in small positive characteristic.  
- Cardona-Quer and additional invariants for classifying automorphism groups.

AUTHOR:  
- Nick Alexander
sage.schemes.hyperelliptic_curves.invariants.Ueberschiebung(f, g, k)

Return the differential operator \((fg)_k\).

This is defined by Mestre on page 315 [Mes1991]:

\[
(fg)_k = \frac{(m-k)!(n-k)!}{m!n!} \left( \frac{\partial f \partial g}{\partial x \partial y} - \frac{\partial f \partial g}{\partial y \partial x} \right)^k.
\]

EXAMPLES:

```python
sage: from sage.schemes.hyperelliptic_curves.invariants import Ueberschiebung as ub
sage: R.<x, y> = QQ[]
sage: ub(x, y, 0)
x*y
sage: ub(x^5 + 1, x^5 + 1, 1)
0
sage: ub(x^5 + 5*x + 1, x^5 + 5*x + 1, 0)
x^10 + 10*x^6 + 2*x^5 + 25*x^2 + 10*x + 1
```

sage.schemes.hyperelliptic_curves.invariants.absolute_igusa_invariants_kohel(f)

Given a sextic form \(f\), return the three absolute Igusa invariants used by Kohel [KohECHIDNA].

\(f\) may be homogeneous in two variables or inhomogeneous in one.

EXAMPLES:

```python
sage: from sage.schemes.hyperelliptic_curves.invariants import absolute_igusa_invariants_kohel
sage: R.<x> = QQ[]
sage: absolute_igusa_invariants_kohel(x^5 - 1)
(0, 0, 0)
sage: absolute_igusa_invariants_kohel(x^5 - x)
(100, -20000, -2000)
```

The following example can be checked against Kohel’s database [KohECHIDNA]

```python
sage: i1, i2, i3 = absolute_igusa_invariants_kohel(-x^5 + 3*x^4 + 2*x^3 - 6*x^2 - 3*x + 1)
sage: list(map(factor, (i1, i2, i3)))
[2^2 * 3^5 * 5 * 31, 2^5 * 3^11 * 5, 2^4 * 3^9 * 31]
sage: list(map(factor, (150660, 28343520, 9762768)))
[2^2 * 3^5 * 5 * 31, 2^5 * 3^11 * 5, 2^4 * 3^9 * 31]
```

sage.schemes.hyperelliptic_curves.invariants.absolute_igusa_invariants_wamelen(f)

Given a sextic form \(f\), return the three absolute Igusa invariants used by van Wamelen [Wam1999].

\(f\) may be homogeneous in two variables or inhomogeneous in one.

REFERENCES:

- [Wam1999]

EXAMPLES:

```python
sage: from sage.schemes.hyperelliptic_curves.invariants import absolute_igusa_invariants_wamelen
sage: R.<x> = QQ[]
sage: absolute_igusa_invariants_wamelen(x^5 - 1)
(0, 0, 0)
```

The following example can be checked against van Wamelen’s paper:

```
sage: i1, i2, i3 = absolute_igusa_invariants_wamelen(-x^5 + 3*x^4 + 2*x^3 - 6*x^2 - 3*x + 1)
sage: list(map(factor, (i1, i2, i3)))
[2^7 * 3^15, 2^5 * 3^11 * 5, 2^4 * 3^9 * 31]
```

`sage.schemes.hyperelliptic_curves.invariants.clebsch_invariants(f)`

Given a sextic form $f$, return the Clebsch invariants $(A, B, C, D)$ of Mestre, p 317, [Mes1991].

$f$ may be homogeneous in two variables or inhomogeneous in one.

EXAMPLES:

```
sage: from sage.schemes.hyperelliptic_curves.invariants import clebsch_invariants
sage: R.<x, y> = QQ[]
sage: clebsch_invariants(x^6 + y^6)
(2, 2/3, -2/9, 0)
sage: R.<x> = QQ[]
sage: clebsch_invariants(x^6 + x^5 + x^4 + x^2 + 2)
(62/15, 15434/5625, -236951/140625, 229930748/791015625)
sage: magma(x^6 + 1).ClebschInvariants() # optional - magma
[ 2, 2/3, -2/9, 0 ]
sage: magma(x^6 + x^5 + x^4 + x^2 + 2).ClebschInvariants() # optional - magma
[ 62/15, 15434/5625, -236951/140625, 229930748/791015625 ]
```

`sage.schemes.hyperelliptic_curves.invariants.clebsch_to_igusa(A, B, C, D)`

Convert Clebsch invariants $A, B, C, D$ to Igusa invariants $I_2, I_4, I_6, I_{10}$.

EXAMPLES:

```
sage: from sage.schemes.hyperelliptic_curves.invariants import clebsch_to_igusa, igusa_to_clebsch
sage: clebsch_to_igusa(2, 3, 4, 5)
(-240, 17370, 231120, -103098906)
sage: igusa_to_clebsch(*clebsch_to_igusa(2, 3, 4, 5))
(2, 3, 4, 5)
sage: Cs = tuple(map(GF(31), (2, 3, 4, 5))); Cs
(2, 3, 4, 5)
sage: clebsch_to_igusa(*Cs)
(8, 10, 15, 26)
sage: igusa_to_clebsch(*clebsch_to_igusa(*Cs))
(2, 3, 4, 5)
```

`sage.schemes.hyperelliptic_curves.invariants.differential_operator(f, g, k)`

Return the differential operator $(fg)_k$ symbolically in the polynomial ring in $dfdx$, $dfdy$, $dgdx$, $dgdy$.

This is defined by Mestre on p 315 [Mes1991]:

$$(fg)_k = \frac{(m-k)!(n-k)!}{m!n!} \left( \frac{\partial f}{\partial x} \frac{\partial g}{\partial y} - \frac{\partial f}{\partial y} \frac{\partial g}{\partial x} \right)^k.$$

EXAMPLES:
Elliptic curves, Release 9.7

```python
sage: from sage.schemes.hyperelliptic_curves.invariants import differential_operator
sage: R.<x, y> = QQ[]
1
sage: differential_operator(x, y, 1)
-dfdy*dgdx + dfdx*dgdy
sage: differential_operator(x*y, x*y, 2)
1/4*dfdy^2*dgdx^2 - 1/2*dfdx*dfdy*dgdx*dgdy + 1/4*dfdx^2*dgdy^2
sage: differential_operator(x^2, x^2, 2)
1/36*dfdy^4*dgdx^4 - 1/18*dfdx*dfdy^3*dgdx^3*dgdy + 1/96*dfdx^2*dfdy^2*dgdx^2*dgdy^2
sage: differential_operator(x^2*y, x*y^2, 2)
1/36*dfdy^4*dgdx^4 - 1/18*dfdx*dfdy^3*dgdx^3*dgdy + 1/96*dfdx^2*dfdy^2*dgdx^2*dgdy^2
```

**sage.schemes.hyperelliptic_curves.invariants.diffsym(U, f, g)**

Given a differential operator $U$ in $\text{dfdx}, \text{dfdy}, \text{dgdx}, \text{dgdy}$, represented symbolically by $U$, apply it to $f$, $g$.

**EXAMPLES:**

```python
sage: from sage.schemes.hyperelliptic_curves.invariants import diffsym
sage: R.<x, y> = QQ[]
```

```python
sage: S.<dfdx, dfdy, dgdx, dgdy> = QQ[]
```

```python
sage: [ diffsym(dd, x^2, y*0 + 1) for dd in S.gens() ]
[2*x, 0, 0, 0]
```

```python
sage: [ diffsym(dd, x*0 + 1, y^2) for dd in S.gens() ]
[0, 0, 0, 2*y]
```

```python
sage: [ diffsym(dd, x^2, y^2) for dd in S.gens() ]
[2*x*y^2, 0, 0, 2*x^2*y]
```

```python
sage: diffsym(dfdx + dfdy*dgdy, y*x^2, y^3)
2*x*y^4 + 3*x^2*y^2
```

**sage.schemes.hyperelliptic_curves.invariants.diffxy(f, xtimes, y, ytimes)**

Differentiate a polynomial $f$, $\times x$ with respect to $x$, and $\times y$ with respect to $y$.

**EXAMPLES:**

```python
sage: R.<u, v> = QQ[]
```

```python
sage: sage.schemes.hyperelliptic_curves.invariants.diffxy(u^2*v^3, u, 0, v, 0)
```

```python
sage: sage.schemes.hyperelliptic.curves.invariants.diffxy(u^2*v^3, u, 2, v, 1)
```

```python
sage: sage.schemes.hyperelliptic.curves.invariants.diffxy(u^2*v^3, u, 2, v, 2)
```

```python
sage: sage.schemes.hyperelliptic.curves.invariants.diffxy(u^2*v^3 + u^4*v^4, u, 2, v, 2)
```

```python
sage: sage.schemes.hyperelliptic.curves.invariants.diffxy(u^2*v^3 + u^4*v^4, u, 2, v, 2)
```

```python
sage: sage.schemes.hyperelliptic.curves.invariants.diffxy(u^2*v^3 + u^4*v^4, u, 2, v, 2)
```

```python
sage: sage.schemes.hyperelliptic.curves.invariants.diffxy(u^2*v^3 + u^4*v^4, u, 2, v, 2)
```

```python
sage: sage.schemes.hyperelliptic.curves.invariants.diffxy(u^2*v^3 + u^4*v^4, u, 2, v, 2)
```

**sage.schemes.hyperelliptic_curves.invariants.igusa_clebsch_invariants(f)**

Given a sextic form $f$, return the Igusa-Clebsch invariants $I_2, I_4, I_6, I_{10}$ of Igusa and Clebsch [IJ1960].

$f$ may be homogeneous in two variables or inhomogeneous in one.

**EXAMPLES:**

Elliptic curves, Release 9.7

sage: from sage.schemes.hyperelliptic_curves.invariants import igusa_clebsch_invariants

sage: R.<x, y> = QQ[]
sage: igusa_clebsch_invariants(x^6 + y^6)
(-240, 1620, -119880, -46656)
sage: R.<x> = QQ[]
sage: igusa_clebsch_invariants(x^6 + x^5 + x^4 + x^2 + 2)
(-496, 6220, -955932, -1111784)

sage: magma(x^6 + 1).IgusaClebschInvariants() # optional - magma
[ -240, 1620, -119880, -46656 ]

sage: magma(x^6 + x^5 + x^4 + x^2 + 2).IgusaClebschInvariants() # optional - magma
[ -496, 6220, -955932, -1111784 ]

sage.schemes.hyperelliptic_curves.invariants.igusa_to_clebsch(I2, I4, I6, I10)
Convert Igusa invariants $I_2, I_4, I_6, I_{10}$ to Clebsch invariants $A, B, C, D$.

EXAMPLES:

sage: from sage.schemes.hyperelliptic_curves.invariants import clebsch_to_igusa, igusa_to_clebsch
sage: igusa_to_clebsch(-2400, 173700, 23112000, -10309890600)
(20, 342/5, 2512/5, 43381012/1125)
sage: clebsch_to_igusa(*igusa_to_clebsch(-2400, 173700, 23112000, -10309890600))
(-2400, 173700, 23112000, -10309890600)

sage: Is = tuple(map(GF(31), (-2400, 173700, 23112000, -10309890600))); Is
(18, 7, 12, 27)
sage: igusa_to_clebsch(*Is)
(20, 25, 25, 12)
sage: clebsch_to_igusa(*igusa_to_clebsch(*Is))
(18, 7, 12, 27)

sage.schemes.hyperelliptic_curves.invariants.ubs(f)
Given a sextic form $f$, return a dictionary of the invariants of Mestre, p 317 [Mes1991].

$f$ may be homogeneous in two variables or inhomogeneous in one.

EXAMPLES:

sage: from sage.schemes.hyperelliptic_curves.invariants import ubs
sage: x = QQ['x'].0
sage: ubs(x^6 + 1)
{'A': 2, 'B': 2/3, 'C': -2/9, 'D': 0, 'Delta': -2/3*x^2*h^2, 'f': x^6 + h^6, 'i': 2*x^2*h^2, 'y1': 0, 'y2': 0, 'y3': 0}

(continues on next page)
16.15 Kummer surfaces over a general ring

```python
defines KummerSurfaces over a general ring
```

```python
class sage.schemes.hyperelliptic_curves.kummer_surface.KummerSurface(J)
Bases: sage.schemes.projective.projective_subscheme.AlgebraicScheme_subscheme_projective
```

```
EXAMPLES:

sage: R.<x> = QQ[]
sage: f = x^5 + x + 1
sage: X = HyperellipticCurve(f)
sage: J = Jacobian(X)
sage: K = KummerSurface(J)
Closed subscheme of Projective Space of dimension 3 over Rational Field defined by:
-3*X^4 + 4*X^0*X^1 + 3 + 4*X^0*X^1 + 2*X^2 + 2 + 2*X^0 + 2*X^2 + 2 + X^2 + 4 + 4*X^0 + 3 + X
-2*X^0 + 2*X^1 + X^3 + 2*X^1 + 2*X^3 + 2 + 2*X^0 + 2*X^2 + 2 + X^2 + 4 + 4*X^0 + 3 + X
```

16.15 Kummer surfaces over a general ring

class sage.schemes.hyperelliptic_curves.kummer_surface.KummerSurface(J)
Bases: sage.schemes.projective.projective_subscheme.AlgebraicScheme_subscheme_projective

EXAMPLES:

```python
sage: R.<x> = QQ[]
sage: f = x^5 + x + 1
sage: X = HyperellipticCurve(f)
sage: J = Jacobian(X)
sage: K = KummerSurface(J)
Closed subscheme of Projective Space of dimension 3 over Rational Field defined by:
```

16.16 Conductor and reduction types for genus 2 curves

AUTHORS:

- William Stein (2006-03-05): wrote Sage interface to genus2reduction
- Jeroen Demeyer (2014-09-17): replace genus2reduction program by PARI library call (trac ticket #15808)

ACKNOWLEDGMENT: (From Liu’s website:) Many thanks to Henri Cohen who started writing this program. After this program is available, many people pointed out to me (mathematical as well as programming) bugs: B. Poonen, E. Schaefer, C. Stahlke, M. Stoll, F. Villegas. So thanks to all of them. Thanks also go to Ph. Depouilly who help me to compile the program.

Also Liu has given me explicit permission to include genus2reduction with Sage and for people to modify the C source code however they want.

```python
class sage.interfaces.genus2reduction.Genus2reduction
    Bases: sage.structure.sage_object.SageObject

Conductor and Reduction Types for Genus 2 Curves.

Use \( R = \text{genus2reduction}(Q, P) \) to obtain reduction information about the Jacobian of the projective smooth curve defined by \( y^2 + Q(x)y = P(x) \). Type \( R? \) for further documentation and a description of how to interpret the local reduction data.

EXAMPLES:

```sage
sage: x = QQ['x'].0
sage: R = genus2reduction(x^3 - 2*x^2 - 2*x + 1, -5*x^5)
```

```sage
sage: R.conductor
1416875
```

```sage
sage: factor(R.conductor)
5^4 * 2267
```

This means that only the odd part of the conductor is known.

```sage
sage: R.prime_to_2_conductor_only
True
```

The discriminant is always minimal away from 2, but possibly not at 2.

```sage
sage: factor(R.minimal_disc)
2^3 * 5^5 * 2267
```

Printing \( R \) summarizes all the information computed about the curve

```sage
sage: R
Reduction data about this proper smooth genus 2 curve:
  y^2 + (x^3 - 2*x^2 - 2*x + 1)*y = -5*x^5
A Minimal Equation (away from 2):
  y^2 = x^6 - 240*x^4 - 2550*x^3 - 11400*x^2 - 24100*x - 19855
Minimal Discriminant (away from 2): 56675000
Conductor (away from 2): 1416875
Local Data:
  p=2
  (potential) stable reduction: (II), j=1
```

(continues on next page)
Here are some examples of curves with modular Jacobians:

**sage:** \( R = \text{genus2reduction}(x^3 + x + 1, -2x^5 - 3x^2 + 2x - 2) \)
\( \text{factor}(R.\text{conductor}) \)
\( 2^3 \cdot 2 \)
\( \text{factor}(\text{genus2reduction}(x^3 + 1, -x^5 - 3x^4 + 2x^3 + x^2 - x - 1).\text{conductor}) \)
\( 5^6 \)

**EXAMPLES:**

**sage:** \( \text{genus2reduction}(0, x^6 + 3x^3 + 63) \)
Reduction data about this proper smooth genus 2 curve:
\( y^2 = x^6 + 3x^3 + 63 \)
A Minimal Equation (away from 2):
\( y^2 = x^6 + 3x^3 + 63 \)
Minimal Discriminant (away from 2): 10628388316852992
Conductor (away from 2): 2893401
Local Data:
\( p=2 \)
(potential) stable reduction: (V), \( j_1+j_2=0, j_1\cdot j_2=0 \)
\( p=3 \)
(potential) stable reduction: (I)
reduction at p: [III{9}] page 184, (3)^2, \( f=10 \)
\( p=7 \)
(potential) stable reduction: (V), \( j_1+j_2=0, j_1\cdot j_2=0 \)
reduction at p: [I{0}-II-0] page 159, (1), \( f=2 \)

In the above example, Liu remarks that in fact at \( p = 2 \), the reduction is [II-II-0] page 163, (1), \( f = 8 \). So the conductor of \( J(C) \) is actually \( 2 \cdot 2893401 = 5786802 \).

**A MODULAR CURVE:**
Consider the modular curve \( X_1(13) \) defined by an equation
\[ y^2 + (x^3 - x^2 - 1)y = x^2 - x. \]
We have:

**sage:** \( \text{genus2reduction}(x^3-x^2-1, x^2 - x) \)
Reduction data about this proper smooth genus 2 curve:
\( y^2 + (x^3 - x^2 - 1)y = x^2 - x \)
A Minimal Equation (away from 2):
\( y^2 = x^6 + 58x^5 + 1401x^4 + 18038x^3 + 130546x^2 + 503516x + 808561 \)
Minimal Discriminant (away from 2): 169

(continues on next page)
Conductor: 169
Local Data:
\[ p = 13 \]
(potential) stable reduction: (V), \( j_1 + j_2 = 0 \), \( j_1 \cdot j_2 = 0 \)
reduction at \( p \): \([I\{0\}-II-0]\) page 159, (1), \( f = 2 \)

So the curve has good reduction at 2. At \( p = 13 \), the stable reduction is union of two elliptic curves, and both of them have 0 as modular invariant. The reduction at 13 is of type \([1_0-0-II-0]\) (see Namikawa-Ueno, page 159). It is an elliptic curve with a cuspidal nonsingular point. The group of connected components of the Neron model of \( J(C) \) is trivial, and the exponent of the conductor of \( J(C) \) at 13 is \( f = 2 \). (Note: It is a theorem of Conrad-Edixhoven-Stein that the component group of \( J(X_1(p)) \) is trivial for all primes \( p \).)

class sage.interfaces.genus2reduction.ReductionData(pari_result, P, Q, minimal_equation, minimal_disc, local_data, conductor, prime_to_2_conductor_only)

Bases: sage.structure.sage_object.SageObject

Reduction data for a genus 2 curve.

How to read local_data attribute, i.e., if this class is \( R \), then the following is the meaning of \( R \).

\( \text{local_data}[p] \).

For each prime number \( p \) dividing the discriminant of \( y^2 + Q(x) y = P(x) \), there are two lines.

The first line contains information about the stable reduction after field extension. Here are the meanings of the symbols of stable reduction:

(I) The stable reduction is smooth (i.e. the curve has potentially good reduction).

(II) The stable reduction is an elliptic curve \( E \) with an ordinary double point. \( j \mod p \) is the modular invariant of \( E \).

(III) The stable reduction is a projective line with two ordinary double points.

(IV) The stable reduction is two projective lines crossing transversally at three points.

(V) The stable reduction is the union of two elliptic curves \( E_1 \) and \( E_2 \) intersecting transversally at one point. Let \( j_1, j_2 \) be their modular invariants, then \( j_1 + j_2 \) and \( j_1 \cdot j_2 \) are computed (they are numbers mod \( p \)).

(VI) The stable reduction is the union of an elliptic curve \( E \) and a projective line which has an ordinary double point. These two components intersect transversally at one point. \( j \mod p \) is the modular invariant of \( E \).

(VII) The stable reduction is as above, but the two components are both singular.

In the cases (I) and (V), the Jacobian \( J(C) \) has potentially good reduction. In the cases (III), (IV) and (VII), \( J(C) \) has potentially multiplicative reduction. In the two remaining cases, the (potential) semi-abelian reduction of \( J(C) \) is extension of an elliptic curve (with modular invariant \( j \mod p \)) by a torus.

The second line contains three data concerning the reduction at \( p \) without any field extension.

1. The first symbol describes the REDUCTION AT \( p \) of \( C \). We use the symbols of Namikawa-Ueno for the type of the reduction (Namikawa, Ueno:”The complete classification of fibers in pencils of curves of genus two”, Manuscripta Math., vol. 9, (1973), pages 143-186.) The reduction symbol is followed by the corresponding page number (or just an indication) in the above article. The lower index is printed by , for instance, \([I_2-II-5]\) means \([I_2-II-5]\). Note that if \( K \) and \( K' \) are Kodaira symbols for singular fibers of elliptic curves, \([K-K'-m]\) and \([K'-K-m]\) are the same type. Finally, \([K-K'-1]\) (not the same as \([K-K'-1]\)) is \([K'-K-alpha]\) in the notation of Namikawa-Ueno. The figure \([2I_0-m]\) in Namikawa-Ueno, page 159 must be denoted by \([2I_0-(m+1)]\).
2. The second datum is the GROUP OF CONNECTED COMPONENTS (over an ALGEBRAIC CLOSURE (!) of $F_p$) of the Neron model of $J(C)$. The symbol $(n)$ means the cyclic group with $n$ elements. When $n=0$, $(0)$ is the trivial group $(1)$. $H_n$ is isomorphic to $(2)^{x(2)}$ if $n$ is even and to $(4)$ otherwise.

Note - The set of rational points of $\Phi$ can be computed using Theorem 1.17 in S. Bosch and Q. Liu “Rational points of the group of components of a Neron model”, Manuscripta Math. 98 (1999), 275-293.

3. Finally, $f$ is the exponent of the conductor of $J(C)$ at $p$.

**Warning:** Be careful regarding the formula:

$$\text{valuation of the naive minimal discriminant} = f + n - 1 + 11c(X).$$

(Q. Liu : “Conducteur et discriminant minimal de courbes de genre 2”, Compositio Math. 94 (1994) 51-79, Theoreme 2) is valid only if the residual field is algebraically closed as stated in the paper. So this equality does not hold in general over $\mathbb{Q}_p$. The fact is that the minimal discriminant may change after unramified extension. One can show however that, at worst, the change will stabilize after a quadratic unramified extension (Q. Liu : “Modèles entiers de courbes hyperelliptiques sur un corps de valuation discrète”, Trans. AMS 348 (1996), 4577-4610, Section 7.2, Proposition 4).

```
sage.interfaces.genus2reduction.divisors_to_string(divs)
```
Convert a list of numbers (representing the orders of cyclic groups in the factorization of a finite abelian group) to a string according to the format shown in the examples.

**INPUT:**
- `divs` – a (possibly empty) list of numbers

**OUTPUT:** a string representation of these numbers

**EXAMPLES:**

```
sage: from sage.interfaces.genus2reduction import divisors_to_string
sage: print(divisors_to_string([]))
(1)
sage: print(divisors_to_string([5]))
(5)
sage: print(divisors_to_string([5]*6))
(5)^6
sage: print(divisors_to_string([2,3,4]))
(2)x(3)x(4)
sage: print(divisors_to_string([6,2,2]))
(6)x(2)^2
```
CHAPTER
SEVENTEEN

INDICES AND TABLES

• Index
• Module Index
• Search Page
BIBLIOGRAPHY


sage.interfaces.genus2reduction, 686

S
sage.schemes.elliptic_curves.cm, 431
sage.schemes.elliptic_curves.constructor, 1
sage.schemes.elliptic_curves.descent_two_isogeny, 577
sage.schemes.elliptic_curves.ec_database, 310
sage.schemes.elliptic_curves.ell_curve_isogeny, 147
sage.schemes.elliptic_curves.ell_egros, 580
sage.schemes.elliptic_curves.ell_field, 87
sage.schemes.elliptic_curves.ell finite_field, 109
sage.schemes.elliptic_curves.ell_generic, 57
sage.schemes.elliptic_curves.ell_local_data, 441
sage.schemes.elliptic_curves.ell modular_symbols, 484
sage.schemes.elliptic_curves.ell_number_field, 311
sage.schemes.elliptic_curves.ell padic_field, 584
sage.schemes.elliptic_curves.ell_point, 23
sage.schemes.elliptic_curves.ell rational_field, 217
sage.schemes.elliptic_curves.ell tate_curve, 450
sage.schemes.elliptic_curves.ell torsion, 387
sage.schemes.elliptic_curves.ell wp, 455
sage.schemes.elliptic_curves.formal_group, 129
sage.schemes.elliptic_curves.gal reps, 391
sage.schemes.elliptic_curves.gal reps number_field, 403
sage.schemes.elliptic_curves.gp simon, 585
sage.schemes.elliptic_curves.heegner, 504
sage.schemes.elliptic_curves.height, 364
sage.schemes.elliptic_curves.hom, 135
sage.schemes.elliptic_curves.hom composite, 181
sage.schemes.elliptic_curves.hom_velusqrt, 173
sage.schemes.elliptic_curves.isogeny_class, 413
sage.schemes.elliptic_curves.isogeny small degree, 189
sage.schemes.elliptic_curves.jacobian, 19
sage.schemes.elliptic_curves.kodaira_symbol, 449
sage.schemes.elliptic_curves.lseries_ell, 495
sage.schemes.elliptic_curves.mod5family, 586
sage.schemes.elliptic_curves.mod sym num, 489
sage.schemes.elliptic_curves.modular parametrization, 482
sage.schemes.elliptic_curves.padic lseries, 561
sage.schemes.elliptic_curves.period lattice, 458
sage.schemes.elliptic_curves.period lattice region, 477
sage.schemes.elliptic_curves.Qcurves, 437
sage.schemes.elliptic_curves.saturation, 382
sage.schemes.elliptic_curves.sha tate, 420
sage.schemes.elliptic_curves.weierstrass morphism, 143
sage.schemes.elliptic_curves.weierstrass transform, 586
sage.schemes.hyperelliptic_curves.constructor, 591
sage.schemes.hyperelliptic_curves.hypellfrob, 666
sage.schemes.hyperelliptic_curves.hyperelliptic finite field, 601
sage.schemes.hyperelliptic_curves.hyperelliptic g2, 678
sage.schemes.hyperelliptic_curves.hyperelliptic generic, 593
sage.schemes.hyperelliptic_curves.hyperelliptic padic field, 616
sage.schemes.hyperelliptic_curves.hyperelliptic rational field, 633
sage.schemes.hyperelliptic_curves.invariants.
sage.schemes.hyperelliptic_curves.jacobian_g2,
672
sage.schemes.hyperelliptic_curves.jacobian_generic,
668
sage.schemes.hyperelliptic_curves.jacobian_homset,
673
sage.schemes.hyperelliptic_curves.jacobian_morphism,
674
sage.schemes.hyperelliptic_curves.kummer_surface,
685
sage.schemes.hyperelliptic_curves.mestre, 633
sage.schemes.hyperelliptic_curves.monsky_washnitzer, 636
INDEX

A

a1() (sage.schemes.elliptic_curves.ell_generic.EllipticCurve_generic.
  method), 58

ainvs() (sage.schemes.elliptic_curves.ell_generic.EllipticCurve_generic.
  method), 59

a2() (sage.schemes.elliptic_curves.ell_generic.EllipticCurve_generic.
  method), 58

a3() (sage.schemes.elliptic_curves.ell_generic.EllipticCurve_generic.
  method), 58

a4() (sage.schemes.elliptic_curves.ell_generic.EllipticCurve_generic.
  method), 58

a6() (sage.schemes.elliptic_curves.ell_generic.EllipticCurve_generic.
  method), 58

a_invariants() (sage.schemes.elliptic_curves.ell_generic.EllipticCurve_generic.
  method), 58

a_number() (sage.schemes.hyperelliptic_curves.hyperelliptic_finite_field.HyperellipticCurve_finite_field.
  method), 603

abelian_group() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field.
  method), 110

abelian_variety() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field.
  method), 222

absolute_degree() (sage.schemes.elliptic_curves.heegner.RingClassField.
  method), 545

absolute_igusa_invariants_kohel() (in module
  sage.schemes.hyperelliptic_curves.monsky_washnitzer), 656

absolute_igusa_invariants_kohel() (in module
  sage.schemes.hyperelliptic_curves.invariants), 681

absolute_igusa_invariants_kohel() (sage.schemes.hyperelliptic_curves.hyperelliptic_g2.HyperellipticCurve_g2.
  method), 678

absolute_igusa_invariants_wamelen() (in module
  sage.schemes.hyperelliptic_curves.invariants), 681

absolute_igusa_invariants_wamelen() (sage.schemes.hyperelliptic_curves.hyperelliptic_g2.HyperellipticCurve_g2.
  method), 679

add_reductions() (sage.schemes.elliptic_curves.saturation.EllipticCurveSaturator.
  method), 382

additive_order() (sage.schemes.elliptic_curves.ell_point.EllipticCurvePoint_field.
  method), 25

additive_order() (sage.schemes.elliptic_curves.ell_point.EllipticCurvePoint_finite_field.
  method), 38

additive_order() (sage.schemes.elliptic_curves.ell_point.EllipticCurvePoint_number_field.
  method), 42

adjusted_prec() (in module
  sage.schemes.elliptic_curves.constructor), 14

approximative_value() (sage.schemes.elliptic_curves.mod_sym_num.ModularSymbolNumerical.
  method), 492

archimedean_local_height() (sage.schemes.elliptic_curves.ell_point.EllipticCurvePoint_number_field.
  method), 43

are_projectively_equivalent() (in module
  sage.schemes.elliptic_curves.constructor), 14

alpha() (sage.schemes.elliptic_curves.heegner.GaloisAutomorphismQuadric.
  method), 507

alpha() (sage.schemes.elliptic_curves.height.EllipticCurveCanonicalHeight.
  method), 367

alpha() (sage.schemes.elliptic_curves.padic_lseries.pAdicLseries.
  method), 562

an() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field.
  method), 222

analytic_rank() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field.
  method), 222

analytic_rank_upper_bound() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field.
  method), 224

antilogarithm() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field.
  method), 226

antilogarithm() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field.
  method), 227

ap() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field.
  method), 227

ap() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field.
  method), 228

approximative_value() (sage.schemes.elliptic_curves.mod_sym_num.ModularSymbolNumerical.
  method), 492

are_projectively_equivalent() (in module
  sage.schemes.elliptic_curves.constructor), 14
as_morphism() (sage.schemes.elliptic_curves.ell_curve_isogeny.EllipticCurveIsogeny method), 153
beta() (sage.schemes.elliptic_curves.ellgeneric.EllipticCurveGeneric method), 538
bernardi_sigma_function() (sage.schemes.elliptic_curves.padic_lseries.pAdicLseries().method), 461
ate_pairing() (sage.schemes.elliptic_curves.ell_point. EllipticCurvePoint_ell.method), 26
atkin_lehner_act() (sage.schemes.elliptic_curves.heegner.HeegnerQuatAlgEmbedding method), 520
automorphisms() (sage.schemes.elliptic_curves.ell_generic. EllipticCurveGeneric method), 59
Billerey_B_bound() (in module sage.schemes.elliptic_curves.gal_rep_number_field), 403
Billerey_P_bound() (in module sage.schemes.elliptic_curves.gal_rep_number_field), 404
Billerey_P_L_bound() (in module sage.schemes.elliptic_curves.gal_rep_number_field), 405
Billerey_R_bound() (in module sage.schemes.elliptic_curves.gal_rep_number_field), 406
b_invariants() (sage.schemes.elliptic_curves.ell_generic. EllipticCurve_generic method), 60
bad_reduction_type() (sage.schemes.elliptic_curves.ell_local_data. EllipticCurveLocalData method), 443
base_extend() (sage.schemes.elliptic_curves.ell_generic. EllipticCurveGeneric method), 61
base_extend() (sage.schemes.elliptic_curves.ell_number_field. EllipticCurveNumberField method), 313
base_extend() (sage.schemes.elliptic_curves.ell_number_field. EllipticCurveNumberField method), 594
base_extend() (sage.schemes.hyperelliptic_curves.jacobian_morphism. JacobianHomset_divisor_classes method), 673
base_extend() (sage.schemes.hyperelliptic_curves.monsky_washnitzer. MonskyWashnitzerDifferentialRing method), 642
base_extend() (sage.schemes.hyperelliptic_curves.monsky_washnitzer. MonskyWashnitzerQuotientRing method), 653
base_field() (sage.schemes.elliptic_curves.ell_field. EllipticCurve_field method), 87
base_field() (sage.schemes.elliptic_curves.heegner.GaloisGroup method), 509
base_field() (sage.schemes.elliptic_curves.heegner.HeegnerPoints_level_disc_cond method), 674
cantor_composition() (in module sage.schemes.hyperelliptic_curves.jacobian_morphism), 676
cantor_composition_simple() (in module sage.schemes.hyperelliptic_curves.jacobian_morphism), 676
cantor_reduction() (in module sage.schemes.hyperelliptic_curves.jacobian_morphism), 677
cantor_reduction_simple() (in module sage.schemes.hyperelliptic_curves.jacobian_morphism), 678
basis() (sage.schemes.elliptic_curves.ell_curve_isogeny. EllipticCurveIsogeny method), 461
b8() (sage.schemes.elliptic_curves.ell_generic. EllipticCurveGeneric method), 60
b4() (sage.schemes.elliptic_curves.ell_generic. EllipticCurveGeneric method), 60
b6() (sage.schemes.elliptic_curves.ell_generic. EllipticCurveGeneric method), 60
b2() (sage.schemes.elliptic_curves.ell_generic. EllipticCurveGeneric method), 60
Billerey_B() (in module sage.schemes.elliptic_curves.gal_rep_number_field), 403
Billerey_P() (in module sage.schemes.elliptic_curves.gal_rep_number_field), 404
Billerey_P_L() (in module sage.schemes.elliptic_curves.gal_rep_number_field), 405
Billerey_R() (in module sage.schemes.elliptic_curves.gal_rep_number_field), 406
cardinality() (sage.schemes.elliptic_curves.ell_finite_field.EllipticCurve_finite_field method), 111
cardinality() (sage.schemes.elliptic_curves.heegner.GaloisGroup method), 228
cardinality() (sage.schemes.hyperelliptic_curves.hyperelliptic_finite_field.HyperellipticCurve_finite_field method), 603
cardinality_bsgs() (sage.schemes.elliptic_curves.ell_finite_field.EllipticCurves_finite_field method), 113
cardinality_exhaustive() (sage.schemes.elliptic_curves.ell_finite_field.EllipticCurves_finite_field method), 114
cardinality_exhaustive() (sage.schemes.hyperelliptic_curves.hyperelliptic_finite_field.HyperellipticCurve_finite_field method), 604
cardinality() (sage.schemes.hyperelliptic_curves.hyperelliptic_finite_field.HyperellipticCurve_finite_field method), 604
cardinality() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field method), 15
change_ring() (sage.schemes.elliptic_curves.ell_finite_field.EllipticCurve_finite_field method), 619
ccheck_prime() (sage.schemes.elliptic_curves.ell_finite_field.EllipticCurve_finite_field method), 448
cchord_and_tangent() (in module sage.schemes.elliptic_curves.constructor), 15
class_number() (in module sage.schemes.elliptic_curves.heegner), 548
clear_cache() (sage.schemes.elliptic_curves.mod_sym_num.ModularSymbolNumerical method), 493
clebsch_invariants() (in module sage.schemes.hyperelliptic_curves.invariants), 682
clebsch_invariants() (sage.schemes.hyperelliptic_curves.hyperelliptic_field.EllipticCurve_field method), 679
clebsch_to_igusa() (in module sage.schemes.hyperelliptic_curves.invariants), 682
cm_discriminant() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field method), 151
Elliptic curves, Release 9.7

compute_codomain_formula() (in module sage.schemes.elliptic_curves.ell_curve_isogeny), 161
compute_codomain_kohel() (in module sage.schemes.elliptic_curves.ell_curve_isogeny), 161
compute_intermediate_curves() (in module sage.schemes.elliptic_curves.ell_curve_isogeny), 162
compute_isogeny_kernel_polynomial() (in module sage.schemes.elliptic_curves.ell_curve_isogeny), 163
calculate() (sage.schemes.elliptic_curves.heegner.HeegnerQuatAlgEmbedding method), 538
conjugate() (sage.schemes.elliptic_curves.heegner.HeegnerQuatAlgEmbedding method), 538
calculate_over_K() (sage.schemes.elliptic_curves.heegner.HeegnerQuatAlgEmbedding method), 513
compute() (sage.schemes.elliptic_curves.period_lattice.RegionPeriodicRegion method), 478
calculate() (sage.schemes.elliptic_curves.period_lattice.RegionPeriodicRegion method), 462
calculate() (sage.schemes.elliptic_curves.isogeny_class.IsogenyClass_EC_NonsupERS method), 417
calculate() (sage.schemes.elliptic_curves.isogeny_class.IsogenyClass_EC_Rational method), 417
count_points() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field method), 108
count_points() (sage.schemes.hyperelliptic_curves.hyperelliptic_field.EllipticCurve_brillhart_tate method), 108
create_object() (sage.schemes.elliptic_curves.constructor.EllipticCurveFactory method), 4
create_object() (sage.schemes.hyperelliptic_curves.constructor.EllipticCurveFactory method), 5
calculate() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field method), 228
calculate() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field method), 511
conductors() (sage.schemes.elliptic_curves.ell_local_data.EllipticCurveLseries method), 443
calculate() (sage.schemes.elliptic_curves.ell_tate_curve.TateCurve method), 451
calculate() (sage.schemes.elliptic_curves.ell_torsion.EllipticCurveTorsionSubgroup method), 389
conjugacy_test() (in module sage.schemes.elliptic_curves.formal_group.EllipticCurveFormalGroup method), 389

700 Index
Elliptic curves, Release 9.7

Index

...
Elliptic curves, Release 9.7

domain_gen() (sage.schemes.elliptic_curves.heegner.HeegnerQuatAlg method), 539
Dp_valued_height() (sage.schemes.elliptic_curves.padic_lseries.pAdicLseries method), 571
Dp_valued_regulator() (sage.schemes.elliptic_curves.padic_lseries.pAdicLseries method), 571
Dp_valued_series() (sage.schemes.elliptic_curves.padic_lseries.pAdicLseries method), 493
ds() (sage.schemes.elliptic_curves.period_lattice_region.PeriodicRegion method), 479
dual() (sage.schemes.elliptic_curves.ell_curve_isogeny.EllipticCurveIsogeny method), 153
dual() (sage.schemes.elliptic_curves.hom.EllipticCurveHom method), 136
dual() (sage.schemes.elliptic_curves.hom_composite.EllipticCurveHom_composite method), 183
dual() (sage.schemes.elliptic_curves.weierstrass_morphism.WeierstrassIsomorphism method), 143
e2() (sage.schemes.elliptic_curves.ell_tate_curve.TateCurve method), 453
e_log_RC() (sage.schemes.elliptic_curves.period_lattice.RegionPeriodLattice method), 463
e_p() (sage.schemes.elliptic_curves.height.EllipticCurveCanonicalHeight method), 369
egros_from_j() (in module sage.schemes.elliptic_curves.ell_egros), 581
egros_from_j_0() (in module sage.schemes.elliptic_curves.ell_egros), 582
egros_from_j_1728() (in module sage.schemes.elliptic_curves.ell_egros), 582
egros_from_jlist() (in module sage.schemes.elliptic_curves.ell_egros), 583
egros_get_j() (in module sage.schemes.elliptic_curves.ell_egros), 583
ei() (sage.schemes.elliptic_curves.period_lattice.RegionPeriodLattice_ell method), 465
Element (sage.schemes.hyperelliptic_curves.monsky_washnitzer.SpecialHyperellipticQuotientRing attribute), 642
Element (sage.schemes.hyperelliptic_curves.monsky_washnitzer.SpecialHyperellipticQuotientRing attribute), 647
Element (sage.schemes.hyperelliptic_curves.monsky_washnitzer.SpecialHyperellipticQuotientRing attribute), 652
e1() (sage.schemes.elliptic_curves.heegner.HeegnerQuatAlg method), 528
e1_heegner_discriminants() (in module sage.schemes.elliptic_curves.heegner), 548
e1_heegner_discriminants_list() (in module sage.schemes.elliptic_curves.heegner), 549
e1_heegner_point() (in module sage.schemes.elliptic_curves.heegner), 549
e1() (sage.schemes.elliptic_curves.ell_egros), 581
egros_from_j_0() (in module sage.schemes.elliptic_curves.ell_egros), 582
egros_from_j_1728() (in module sage.schemes.elliptic_curves.ell_egros), 582
egros_from_jlist() (in module sage.schemes.elliptic_curves.ell_egros), 583
egros_get_j() (in module sage.schemes.elliptic_curves.ell_egros), 583
ei() (sage.schemes.elliptic_curves.period_lattice.RegionPeriodLattice_ell method), 465
Element (sage.schemes.hyperelliptic_curves.monsky_washnitzer.SpecialHyperellipticQuotientRing attribute), 642
Element (sage.schemes.hyperelliptic_curves.monsky_washnitzer.SpecialHyperellipticQuotientRing attribute), 647
Element (sage.schemes.hyperelliptic_curves.monsky_washnitzer.SpecialHyperellipticQuotientRing attribute), 652
e1() (sage.schemes.elliptic_curves.heegner.HeegnerQuatAlg method), 528
e1_heegner_discriminants() (in module sage.schemes.elliptic_curves.heegner), 548
e1_heegner_discriminants_list() (in module sage.schemes.elliptic_curves.heegner), 549
e1_heegner_point() (in module sage.schemes.elliptic_curves.heegner), 549
e1() (sage.schemes.elliptic_curves.ell_egros), 581
egros_from_j_0() (in module sage.schemes.elliptic_curves.ell_egros), 582
egros_from_j_1728() (in module sage.schemes.elliptic_curves.ell_egros), 582
egros_from_jlist() (in module sage.schemes.elliptic_curves.ell_egros), 583
egros_get_j() (in module sage.schemes.elliptic_curves.ell_egros), 583
ei() (sage.schemes.elliptic_curves.period_lattice.RegionPeriodLattice_ell method), 465
Element (sage.schemes.hyperelliptic_curves.monsky_washnitzer.SpecialHyperellipticQuotientRing attribute), 642
Element (sage.schemes.hyperelliptic_curves.monsky_washnitzer.SpecialHyperellipticQuotientRing attribute), 647
Element (sage.schemes.hyperelliptic_curves.monsky_washnitzer.SpecialHyperellipticQuotientRing attribute), 652
e1() (sage.schemes.elliptic_curves.heegner.HeegnerQuatAlg method), 528
e1_heegner_discriminants() (in module sage.schemes.elliptic_curves.heegner), 548
e1_heegner_discriminants_list() (in module sage.schemes.elliptic_curves.heegner), 549
e1_heegner_point() (in module sage.schemes.elliptic_curves.heegner), 549
e1() (sage.schemes.elliptic_curves.ell_egros), 581
egros_from_j_0() (in module sage.schemes.elliptic_curves.ell_egros), 582
egros_from_j_1728() (in module sage.schemes.elliptic_curves.ell_egros), 582
egros_from_jlist() (in module sage.schemes.elliptic_curves.ell_egros), 583
egros_get_j() (in module sage.schemes.elliptic_curves.ell_egros), 583
ei() (sage.schemes.elliptic_curves.period_lattice.RegionPeriodLattice_ell method), 465
Element (sage.schemes.hyperelliptic_curves.monsky_washnitzer.SpecialHyperellipticQuotientRing attribute), 642
Element (sage.schemes.hyperelliptic_curves.monsky_washnitzer.SpecialHyperellipticQuotientRing attribute), 647
Element (sage.schemes.hyperelliptic_curves.monsky_washnitzer.SpecialHyperellipticQuotientRing attribute), 652
e1() (sage.schemes.elliptic_curves.heegner.HeegnerQuatAlg method), 528
e1_heegner_discriminants() (in module sage.schemes.elliptic_curves.heegner), 548
e1_heegner_discriminants_list() (in module sage.schemes.elliptic_curves.heegner), 549
e1_heegner_point() (in module sage.schemes.elliptic_curves.heegner), 549

Elliptic curves, Release 9.7

frobenius() (sage.schemes.elliptic_curves.padic_lseries.pAdicLseries method), 572
frobenius() (sage.schemes.hyperelliptic_curves.hyperelliptic_padic_field method), 625
frobenius_expansion_by_newton() (in module sage.schemes.hyperelliptic_curves.monsky_washnitzer), 656
frobenius_expansion_by_series() (in module sage.schemes.hyperelliptic_curves.monsky_washnitzer), 657
frobenius_matrix() (in module sage.schemes.elliptic_curves.gal_reps_number_field), 608
frobenius_matrix_hypellfrob() (in module sage.schemes.elliptic_curves.gal_reps_number_field), 609
frobenius_order() (in module sage.schemes.elliptic_curves.gal_reps_number_field), 115
frobenius_polynomial() (in module sage.schemes.elliptic_curves.gal_reps_number_field), 611
frobenius_polynomial() (in module sage.schemes.elliptic_curves.gal_reps_number_field), 612
frobenius_polynomial() (in module sage.schemes.elliptic_curves.gal_reps_number_field), 610
frobenius_polynomial_cardinalities() (in module sage.schemes.elliptic_curves.gal_reps_number_field), 611
frobenius_polynomial_matrix() (in module sage.schemes.elliptic_curves.gal_reps_number_field), 610
frobenius_polynomial_pari() (in module sage.schemes.elliptic_curves.gal_reps_number_field), 613
from_factors() (in module sage.schemes.elliptic_curves.hom_composite), 184
full() (in module sage.schemes.elliptic_curves.period_lattice_region), 480
full_p_saturation() (in module sage.schemes.elliptic_curves.saturation), 384

G

galois_group() (in module sage.schemes.elliptic_curves.heegner), 547

galois_group_over_hilbert_class_field() (in module sage.schemes.elliptic_curves.jacobian_generic), 528

galois_group_over_quadratic_field() (in module sage.schemes.elliptic_curves.jacobian_generic), 528

galois_orbit_over_K() (in module sage.schemes.elliptic_curves.heegner), 528

galois_representation() (in module sage.schemes.elliptic_curves.gal_reps_number_field), 314

galois_representation() (in module sage.schemes.elliptic_curves.gal_reps_number_field), 506

galois_representation() (in module sage.schemes.elliptic_curves.gal_reps_number_field), 406

galois_representation() (in module sage.schemes.elliptic_curves.gal_reps_number_field), 508

galois_representation() (in module sage.schemes.elliptic_curves.gal_reps_number_field), 508

galois_representation() (in module sage.schemes.elliptic_curves.gal_reps_number_field), 392

galois_representation() (in module sage.schemes.elliptic_curves.gal_reps_number_field), 407

G

galois_group() (in module sage.schemes.elliptic_curves.heegner), 547

galois_group_over_hilbert_class_field() (in module sage.schemes.elliptic_curves.jacobian_generic), 528

galois_group_over_quadratic_field() (in module sage.schemes.elliptic_curves.jacobian_generic), 528

galois_orbit_over_K() (in module sage.schemes.elliptic_curves.heegner), 528

galois_representation() (in module sage.schemes.elliptic_curves.gal_reps_number_field), 314

galois_representation() (in module sage.schemes.elliptic_curves.gal_reps_number_field), 506

galois_representation() (in module sage.schemes.elliptic_curves.gal_reps_number_field), 406

galois_representation() (in module sage.schemes.elliptic_curves.gal_reps_number_field), 508

galois_representation() (in module sage.schemes.elliptic_curves.gal_reps_number_field), 392

galois_representation() (in module sage.schemes.elliptic_curves.gal_reps_number_field), 407
<table>
<thead>
<tr>
<th>Function/Method</th>
<th>Module</th>
<th>Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>igusa_clebsch_invariants()</td>
<td>in module <code>&lt;module&gt;</code></td>
<td>683</td>
</tr>
<tr>
<td>inverse()</td>
<td>in module <code>&lt;module&gt;</code></td>
<td>589</td>
</tr>
<tr>
<td>igusa_clebsch_invariants()</td>
<td>in module <code>&lt;module&gt;</code></td>
<td>436</td>
</tr>
<tr>
<td>image_classes()</td>
<td>in module <code>&lt;module&gt;</code></td>
<td>393</td>
</tr>
<tr>
<td>image_type()</td>
<td>in module <code>&lt;module&gt;</code></td>
<td>394</td>
</tr>
<tr>
<td>index()</td>
<td>in module <code>&lt;module&gt;</code></td>
<td>541</td>
</tr>
<tr>
<td>index()</td>
<td>in module <code>&lt;module&gt;</code></td>
<td>480</td>
</tr>
<tr>
<td>inf_max_abs()</td>
<td>in module <code>&lt;module&gt;</code></td>
<td>380</td>
</tr>
<tr>
<td>init()</td>
<td>in module <code>&lt;module&gt;</code></td>
<td>85</td>
</tr>
<tr>
<td>integral_model()</td>
<td>in module <code>&lt;module&gt;</code></td>
<td>327</td>
</tr>
<tr>
<td>integral_model()</td>
<td>in module <code>&lt;module&gt;</code></td>
<td>330</td>
</tr>
<tr>
<td>integral_model()</td>
<td>in module <code>&lt;module&gt;</code></td>
<td>527</td>
</tr>
<tr>
<td>integral_model()</td>
<td>in module <code>&lt;module&gt;</code></td>
<td>244</td>
</tr>
<tr>
<td>integral_points()</td>
<td>in module <code>&lt;module&gt;</code></td>
<td>244</td>
</tr>
<tr>
<td>integral_points()</td>
<td>in module <code>&lt;module&gt;</code></td>
<td>311</td>
</tr>
<tr>
<td>integral_points_with_bounded_mw_coeffs()</td>
<td>in module <code>&lt;module&gt;</code></td>
<td>136</td>
</tr>
<tr>
<td>integrate()</td>
<td>in module <code>&lt;module&gt;</code></td>
<td>556</td>
</tr>
<tr>
<td>intersection()</td>
<td>in module <code>&lt;module&gt;</code></td>
<td>185</td>
</tr>
<tr>
<td>interval_products()</td>
<td>in module <code>&lt;module&gt;</code></td>
<td>145</td>
</tr>
<tr>
<td>intervals()</td>
<td>in module <code>&lt;module&gt;</code></td>
<td>130</td>
</tr>
<tr>
<td>invariant_differential()</td>
<td>in module <code>&lt;module&gt;</code></td>
<td>117</td>
</tr>
<tr>
<td>inverse()</td>
<td>in module <code>&lt;module&gt;</code></td>
<td>130</td>
</tr>
</tbody>
</table>

**Index**
Elliptic curves, Release 9.7

method), 331
is_Q_curve()
(in
module
is_isogenous() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field
sage.schemes.elliptic_curves.Qcurves), 438
method), 247
is_Q_curve() (sage.schemes.elliptic_curves.ell_number_field.EllipticCurv
is_isomorphic() (sage.schemes.elliptic_curves.ell_generic.EllipticCurve_generic
method), 328
method), 69
is_quadratic_twist()
is_j_supersingular()
(in
module
(sage.schemes.elliptic_curves.ell_field.EllipticCurve_field
sage.schemes.elliptic_curves.ell_finite_field),
method), 93
127
is_quartic_twist() (sage.schemes.elliptic_curves.ell_field.EllipticCurve
is_kernel_polynomial()
(in
module
method), 94
sage.schemes.elliptic_curves.isogeny_small_degree),
is_quasi_unipotent()
190
(sage.schemes.elliptic_curves.gal_reps.GaloisRepresentation
is_kolyvagin() (sage.schemes.elliptic_curves.heegner.GaloisGroupmethod), 398
method), 510
is_ramified()
(in
module
is_kolyvagin_conductor()
(in
module
sage.schemes.elliptic_curves.heegner), 556
sage.schemes.elliptic_curves.heegner), 555
is_real() (sage.schemes.elliptic_curves.period_lattice.PeriodLattice_ell
is_local_integral_model()
method), 471
(sage.schemes.elliptic_curves.ell_number_field.EllipticCurve_number_field
is_rectangular() (sage.schemes.elliptic_curves.period_lattice.PeriodLat
method), 333
method), 471
is_local_integral_model()
is_reducible() (sage.schemes.elliptic_curves.gal_reps.GaloisRepresenta
(sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field
method), 399
method), 248
is_same_disc() (sage.schemes.hyperelliptic_curves.hyperelliptic_padic_fi
is_minimal() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field
method), 627
method), 248
is_semistable() (sage.schemes.elliptic_curves.ell_rational_field.EllipticC
is_normalized() (sage.schemes.elliptic_curves.hom.EllipticCurveHom
method), 249
method), 137
is_semistable() (sage.schemes.elliptic_curves.gal_reps.GaloisRepresent
is_odd_degree() (sage.schemes.hyperelliptic_curves.hyperelliptic_g2.HyperellipticCurve_g2
method), 399
method), 680
is_separable() (sage.schemes.elliptic_curves.hom.EllipticCurveHom
is_on_curve() (sage.schemes.elliptic_curves.ell_generic.EllipticCurve_generic
method), 138
method), 69
is_separable() (sage.schemes.elliptic_curves.hom_composite.EllipticCur
is_on_identity_component()
method), 185
(sage.schemes.elliptic_curves.ell_point.EllipticCurvePoint_number_field
is_sextic_twist() (sage.schemes.elliptic_curves.ell_field.EllipticCurve_
method), 52
method), 95
is_ordinary() (sage.schemes.elliptic_curves.ell_finite_field.EllipticCurve_finite_field
is_singular() (sage.schemes.hyperelliptic_curves.hyperelliptic_generic.H
method), 119
method), 595
is_ordinary() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field
is_smooth() (sage.schemes.hyperelliptic_curves.hyperelliptic_generic.Hyp
method), 248
method), 596
is_ordinary() (sage.schemes.elliptic_curves.gal_reps.GaloisRepresentation
is_split()
(in
module
method), 397
sage.schemes.elliptic_curves.heegner), 556
is_ordinary() (sage.schemes.elliptic_curves.padic_lseries.pAdicLseriesOrdinary
is_split() (sage.schemes.elliptic_curves.ell_tate_curve.TateCurve
method), 566
method), 452
is_ordinary() (sage.schemes.elliptic_curves.padic_lseries.pAdicLseriesSupersingular
is_subfield() (sage.schemes.elliptic_curves.heegner.RingClassField
method), 572
method), 547
is_p_integral() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field
is_supersingular() (sage.schemes.elliptic_curves.ell_finite_field.Elliptic
method), 249
method), 119
is_p_minimal() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field
is_supersingular() (sage.schemes.elliptic_curves.ell_rational_field.Elli
method), 249
method), 250
is_possible_j()
(in
module is_supersingular() (sage.schemes.elliptic_curves.padic_lseries.pAdicLs
sage.schemes.elliptic_curves.ell_egros), 584
method), 566
is_potentially_crystalline()
is_supersingular() (sage.schemes.elliptic_curves.padic_lseries.pAdicLs
(sage.schemes.elliptic_curves.gal_reps.GaloisRepresentationmethod), 573
method), 398
is_surjective() (sage.schemes.elliptic_curves.gal_reps.GaloisRepresent
is_potentially_semistable()
method), 400
(sage.schemes.elliptic_curves.gal_reps.GaloisRepresentation
is_surjective() (sage.schemes.elliptic_curves.gal_reps_number_field.G
method), 398
method), 408
708

Index


Elliptic curves, Release 9.7

is_surjective() (sage.schemes.elliptic_curves.hom.EllipticCurveHom, 139
method), 139

is_unipotent() (sage.schemes.elliptic_curves.gal_reps.GaloisRepresentation, 401
method), 401

is_unramified() (sage.schemes.elliptic_curves.gal_reps.GaloisRepresentation, 401
method), 401

is_x_coord() (sage.schemes.elliptic_curves.ell_generic.EllipticCurve_generic, 69
method), 69

is_zero() (sage.schemes.elliptic_curves.hom.EllipticCurveHom, 213
method), 213

isogenies_13() (in module sage.schemes.elliptic_curves.isogeny_small_degree, 192
method), 192

isogenies_13_0() (in module isogeny() (sage.schemes.elliptic_curves.ell_field.EllipticCurve_field, 100
sage.schemes.elliptic_curves.isogeny_small_degree), 192
method), 192

isogenies_13_1728() (in module isogeny_class() (sage.schemes.elliptic_curves.ell_number_field.EllipticCurve_number_field, 334
method), 334
method), 334

isogenies_2() (in module isogeny_class() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_field, 251
method), 251
method), 251

isogenies_3() (in module isogeny_domain_from_kernel() (in module sage.schemes.elliptic_curves.ell_curve_isogeny, 169
sage.schemes.elliptic_curves.isogeny_small_degree), 196
method), 196

isogenies_5() (in module isogeny_degree() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_field, 340
method), 340
method), 340

isogenies_5_0() (in module isogeny_class() (sage.schemes.elliptic_curves.ell_number_field.EllipticCurve_number_field, 334
method), 334
method), 334

isogenies_5_1728() (in module isogeny_degrees_cm() (sage.schemes.elliptic_curves.isogeny_class.isogeny_class, 417
sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_field, 254
method), 254
method), 254

isogenies_7() (in module isogeny_class_EC (class in sage.schemes.elliptic_curves.isogeny_small_degree), 417
method), 417

isogenies_7_0() (in module isogeny_class_EC (class in sage.schemes.elliptic_curves.isogeny_class), 417
method), 417

isogenies_7_1728() (in module isogeny_class_EC (class in sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_field, 102
method), 102
method), 102

isogenies_prime_degree() (in module sage.schemes.elliptic_curves.isogeny_small_degree), 146

isogenies_prime_degree() (sage.schemes.elliptic_curves.ell_field.EllipticCurve_field, 95
method), 95

isogenies_prime_degree() (sage.schemes.elliptic_curves.ell_field.EllipticCurve_field, 95
method), 95

isogenies_prime_degree() (sage.schemes.elliptic_curves.ell_number_field.EllipticCurve_number_field, 333
method), 333

isogenies_prime_degree() (class in sage.schemes.elliptic_curves.isogeny_class.isogeny_class, 417
method), 417

isogenies_prime_degree_general() (in module isomorphisms() (in module sage.schemes.elliptic_curves.isogeny_class.isogeny_class, 70
sage.schemes.elliptic_curves.weierstrass_morphism), 146
method), 146

isogenies_prime_degree_genus_0() (in module isomorphisms() (sage.schemes.elliptic_curves.ell_field.EllipticCurve_field, 250
method), 250

Index 709
Elliptic curves, Release 9.7

method), 71

j_invariant() (sage.schemes.elliptic_curves.ell_generic.EllipticCurve_generic
 method), 72

J

Jacobian() (in module sage.schemes.elliptic_curves.jacobian), 19

jacobian() (sage.schemes.elliptic_curves.jacobian.EllipticCurveJacobian
 method), 20

Jacobian_of_curve() (in module sage.schemes.elliptic_curves.jacobian), 20

Jacobian_of_equation() (in module sage.schemes.elliptic_curves.jacobian), 20

JacobianHomset_divisor_classes (class in sage.schemes.elliptic_curves.jacobian_homset), 673

JacobianMorphism_divisor_class_field (class in sage.schemes.elliptic_curves.jacobian_morphism), 675

join() (sage.schemes.elliptic_curves.height.JoinOfIntervals
 static method), 379

K

kernel_polynomial() (sage.schemes.elliptic_curves.ell_curve_isogeny.EllipticCurveIsogeny
 method), 156

kernel_polynomial() (sage.schemes.elliptic_curves.hom.EllipticCurveHom
 method), 139

kernel_polynomial() (sage.schemes.elliptic_curves.hom_composite.EllipticCurveHom_composite
 method), 185

kernel_polynomial() (sage.schemes.elliptic_curves.weierstrass_morphism.EllipticCurveEndomorphism
 method), 143

kodaira_symbol() (sage.schemes.elliptic_curves.ell_number_field.EllipticCurveNumberField
 method), 341

kodaira_type() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurveRationalField
 method), 256

kodaira_type_old() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurveRationalField
 method), 257

KodairaSymbol() (in module sage.schemes.elliptic_curves.kodaira_symbol), 449

KodairaSymbol_class (class in sage.schemes.elliptic_curves.kodaira_symbol), 450

kolyvagin_cohomology_class() (sage.schemes.elliptic_curves.heegner.HeegnerPointOnEllipticCur
 method), 514

kolyvagin_conductors() (sage.schemes.elliptic_curves.heegner.HeegnerPoints_level_disc
 method), 524

kolyvagin_generator() (sage.schemes.elliptic_curves.heegner.HeegnerQuatAlg
 method), 530

kolyvagin_generators() (sage.schemes.elliptic_curves.heegner.GaloisGroup
 method), 510

kolyvagin_point() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurveRationalField
 method), 257

kolyvagin sigma operator() (sage.schemes.elliptic_curves.heegner.HeegnerQuatAlg
 method), 532

KolyvaginCohomologyClass (class in sage.schemes.elliptic_curves.heegner), 539

KolyvaginCohomologyClassEn (class in sage.schemes.elliptic_curves.heegner), 540

KolyvaginPoint (class in sage.schemes.elliptic_curves.heegner), 540

KummerMorphism() (sage.schemes.hyperelliptic_curves.hyperelliptic_g2.HyperellipticCurve_g2
 method), 680

KummerSurface() (sage.schemes.hyperelliptic_curves.jacobian_g2.HyperellipticJacobian_g2
 method), 672

KummerSurface (class in sage.schemes.hyperelliptic_curves.kummer_surface), 685

L

L1_vanishes() (sage.schemes.elliptic_curves.lseries_ell.Lseries_ell
 method), 495
Elliptic curves, Release 9.7

max_pow_y() (sage.schemes.hyperelliptic_curves.monsky_washnitzer.SpecialHyperellipticQuotientElement method), 652

measure() (sage.schemes.elliptic_curves.padic_lseries.pAdicLseries method), 563

Mestre_conic() (in module sage.schemes.hyperelliptic_curves.mestre), 635

min() (sage.schemes.elliptic_curves.height.EllipticCurveCanonicalHeight method), 370

min_gr() (sage.schemes.elliptic_curves.height.EllipticCurveCanonicalHeight method), 371

minimal_discriminant_ideal() (sage.schemes.elliptic_curves.ell_number_field.EllipticCurve_number_field method), 346

minimal_model() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field method), 261

minimal_quadratic_twist() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field method), 261

mod() (sage.schemes.elliptic_curves.heegner.KolyvaginPoint method), 542

mod5family() (in module sage.schemes.elliptic_curves.mod5family), 586

mod5family() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field method), 262

modp_dual_elliptic_curve_factor() (sage.schemes.elliptic_curves.heegner.HeegnerQuatAlg method), 534

modp_splitting_data() (sage.schemes.elliptic_curves.heegner.HeegnerQuatAlg method), 534

modp_splitting_map() (sage.schemes.elliptic_curves.heegner.HeegnerQuatAlg method), 535

modular_degree() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field method), 262

modular_form() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field method), 264

modular_parametrization() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field method), 264

modular_symbol() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field method), 265
Elliptic curves, Release 9.7

mult_by_n() (sage.schemes.elliptic_curves.formal_group.EllipticCurveFormalGroup method), 131
multiplication_by_m() (sage.schemes.elliptic_curves.ell_generic.EllipticCurveGeneric method), 77
multiplication_by_m_isogeny() (sage.schemes.elliptic_curves.ell_generic.EllipticCurveGeneric method), 78
mwrank() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurveRationalField method), 269
mwrank_curve() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurveRationalField method), 270

N
n() (sage.schemes.elliptic_curves.heegner.KolyvaginCohomologyClass method), 540
nearby_rational_poly() (in module sage.schemes.elliptic_curves.heegner), 559
newform() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurveRationalField method), 270
newton_sqrt() (sage.schemes.hyperelliptic_curves.hyperelliptic_padic_field.HyperellipticCurvePadicField method), 629
ngens() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurveRationalField method), 271
non_archimedean_local_height() (sage.schemes.elliptic_curves.ell_point.EllipticCurvePointNumberField method), 53
non_minimal_primes() (sage.schemes.elliptic_curves.ell_number_field.EllipticCurveNumberField method), 346
non_surjective() (sage.schemes.elliptic_curves.gal_rep.GaloisRepresentation method), 402
non_surjective() (sage.schemes.elliptic_curves.gal_rep.GaloisRepresentation method), 410
nonneg_region() (in module sage.schemes.elliptic_curves.height), 381
normalise_periods() (in module sage.schemes.elliptic_curves.saturation), 386
normalised_basis() (sage.schemes.elliptic_curves.period_lattice.EllipticCurvePeriodLattice method), 472
Np() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurveRationalField method), 219
numerical_approx() (sage.schemes.elliptic_curves.heegner.HeegnerQuatAlg method), 508
numerical_approx() (sage.schemes.elliptic_curves.ell_point.EllipticCurvePointNumberField method), 542

O
odd_degree_model() (sage.schemes.hyperelliptic_curves.hyperelliptic_padic_field.HyperellipticCurveGeneric method), 599
omega() (sage.schemes.elliptic_curves.period_lattice.EllipticCurvePeriodLattice method), 472
padic_height() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field, method), 275

padic_height() (sage.schemes.elliptic_curves.ell_tate_curve.TateCurve, method), 452

padic_height_pairing_matrix() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field, method), 277

padic_height_via_multiply() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field, method), 278

padic_lseries() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field, method), 279

padic_regulator() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field, method), 281

padic_regulator() (sage.schemes.elliptic_curves.ell_tate_curve.TateCurve, method), 526

padic_sigma() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field, method), 282

padic_sigma_truncated() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field, method), 284

pAdicLseries (class in sage.schemes.elliptic_curves.padic_lseries, 561

pAdicLseriesOrdinary (class in sage.schemes.elliptic_curves.padic_lseries, 566

pAdicLseriesSupersingular (class in sage.schemes.elliptic_curves.padic_lseries, 571

parameter() (sage.schemes.elliptic_curves.ell_tate_curve.TateCurve, method), 389

parametrisation_onto_original_curve() (sage.schemes.elliptic_curves.ell_tate_curve.TateCurve, method), 453

parametrisation_onto_tate_curve() (sage.schemes.elliptic_curves.ell_tate_curve.TateCurve, method), 454

parent() (sage.schemes.elliptic_curves.ell_torsion.EllipticCurveTorsionSubgroup, method), 506

pari_curve() (sage.schemes.elliptic_curves.ell_generic.EllipticCurve_generic, method), 79

pari_curve() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field, method), 285

pari_mincurve() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field, method), 286

period_lattice() (sage.schemes.elliptic_curves.ell_number_field.EllipticCurve_number_field, method), 347

period_lattice() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field, method), 526

PeriodicRegion (class in sage.schemes.elliptic_curves.period_lattice_region, 477

PeriodicLattice (class in sage.schemes.elliptic_curves.period_lattice, 477
reduce() (sage.schemes.elliptic_curves.period_lattice.PeriodLatticeRegion method), 474
reduce() (sage.schemes.elliptic_curves.period_lattice.PeriodLatticeRegion method), 474
reduce_all() (sage.schemes.elliptic_curves.monsky_washnitzer.monsky_washnitzer.Differential method), 639
reduce() (sage.schemes.elliptic_curves.monsky_washnitzer.monsky_washnitzer.Differential method), 639
reduce_fast() (sage.schemes.elliptic_curves.monsky_washnitzer.monsky_washnitzer.Differential method), 640
reduce_mod() (sage.schemes.elliptic_curves.monsky_washnitzer.monsky_washnitzer.Differential method), 523
reduce_mod() (sage.schemes.elliptic_curves.monsky_washnitzer.monsky_washnitzer.Differential method), 523
reduce_neg_y() (sage.schemes.elliptic_curves.monsky_washnitzer.monsky_washnitzer.Differential method), 640
reduce_neg_y() (sage.schemes.elliptic_curves.monsky_washnitzer.monsky_washnitzer.Differential method), 640
reduce_neg_y_fast() (sage.schemes.elliptic_curves.monsky_washnitzer.monsky_washnitzer.Differential method), 640
reduce_neg_y_faster() (sage.schemes.elliptic_curves.monsky_washnitzer.monsky_washnitzer.Differential method), 641
reduce_negative() (in module sage.schemes.elliptic_curves.monsky_washnitzer.monsky_washnitzer.Differential method), 643
reduce_pos_y() (sage.schemes.elliptic_curves.monsky_washnitzer.monsky_washnitzer.Differential method), 641
reduce_pos_y() (sage.schemes.elliptic_curves.monsky_washnitzer.monsky_washnitzer.Differential method), 641
reduce_pos_y_fast() (sage.schemes.elliptic_curves.monsky_washnitzer.monsky_washnitzer.Differential method), 641
reduce_pos_y_faster() (sage.schemes.elliptic_curves.monsky_washnitzer.monsky_washnitzer.Differential method), 641
reduce_positive() (in module sage.schemes.elliptic_curves.monsky_washnitzer.monsky_washnitzer.Differential method), 664
reduce_tau() (in module sage.schemes.elliptic_curves.monsky_washnitzer.monsky_washnitzer.Differential method), 477
reduce_zero() (in module sage.schemes.elliptic_curves.monsky_washnitzer.monsky_washnitzer.Differential method), 665
reduced_quadratic_form() (in module sage.schemes.elliptic_curves.monsky_washnitzer.monsky_washnitzer.Differential method), 521
reducible_primes() (sage.schemes.elliptic_curves.ell_number_field.EllipticCurve_number_field method), 351
reducible_primes() (sage.schemes.elliptic_curves.ell_number_field.EllipticCurve_number_field method), 351
reducible_primes() (sage.schemes.elliptic_curves.gal_reps_number_field.EllipticCurve_number_field method), 402
reducible_primes() (sage.schemes.elliptic_curves.gal_reps_number_field.EllipticCurve_number_field method), 410
reducible_primes_Billerey() (in module sage.schemes.elliptic_curves.gal_reps_number_field.EllipticCurve_number_field method), 412
reducible_primes_naive() (in module sage.schemes.elliptic_curves.gal_reps_number_field.EllipticCurve_number_field method), 413

S
S() (sage.schemes.elliptic_curves.ell_curve_isogeny.Isogeny_class method), 359
S_integral_points() (sage.schemes.elliptic_curves.ell_curve_isogeny.Isogeny_class method), 359
S_integral_points() (sage.schemes.elliptic_curves.ell_curve_isogeny.Isogeny_class method), 359
S_to_Q() (in module sage.schemes.elliptic_curves.ell_curve_isogeny.Isogeny_class method), 431

Index
sage.schemes.elliptic_curves.ell_egros module, 580
sage.schemes.elliptic_curves.ell_field module, 87
sage.schemes.elliptic_curves.ell_finite_field module, 109
sage.schemes.elliptic_curves.ell_generic module, 57
sage.schemes.elliptic_curves.ell_local_data module, 441
sage.schemes.elliptic_curves.ell_modular_symbol module, 484
sage.schemes.elliptic_curves.ell_number_field module, 311
sage.schemes.elliptic_curves.ell_padic_field module, 584
sage.schemes.elliptic_curves.ell_point module, 23
sage.schemes.elliptic_curves.ell_rational_field module, 217
sage.schemes.elliptic_curves.ell_tate_curve module, 450
sage.schemes.elliptic_curves.ell_torsion module, 387
sage.schemes.elliptic_curves.ell_wp module, 455
sage.schemes.elliptic_curves.formal_group module, 129
sage.schemes.elliptic_curves.gal_reps module, 391
sage.schemes.elliptic_curves.gal_reps_number field module, 403
sage.schemes.elliptic_curves.gp_simon module, 585
sage.schemes.elliptic_curves.heegner module, 504
sage.schemes.elliptic_curves.height module, 364
sage.schemes.elliptic_curves.hom module, 135
sage.schemes.elliptic_curves.hom_composite module, 181
sage.schemes.elliptic_curves.hom_velusqrt module, 173
sage.schemes.elliptic_curves.isogeny_class module, 413
sage.schemes.elliptic_curves.isogeny_small_degree module, 189
sage.schemes.elliptic_curves.jacobian module, 19
sage.schemes.elliptic_curves.jacobian module, 19
sage.schemes.elliptic_curves.kodaira_symbol module, 449
sage.schemes.elliptic_curves.lseries_ell module, 495
sage.schemes.elliptic_curves.lseries_ell module, 495
sage.schemes.elliptic_curves.mod5family module, 586
sage.schemes.elliptic_curves.mod_sym_num module, 489
sage.schemes.elliptic_curves.modular_parametrization module, 482
sage.schemes.elliptic_curves.padic_lseries module, 561
sage.schemes.elliptic_curves.period_lattice module, 458
sage.schemes.elliptic_curves.period_lattice_region module, 477
sage.schemes.elliptic_curves.Qcurves module, 437
sage.schemes.elliptic_curves.saturation module, 382
sage.schemes.elliptic_curves.sha_tate module, 420
sage.schemes.elliptic_curves.weierstrass_morphism module, 143
sage.schemes.elliptic_curves.weierstrass_transform module, 586
sage.schemes.elliptic_curves.saturation module, 382
sage.schemes.elliptic_curves.sha_tate module, 420
sage.schemes.elliptic_curves.weierstrass_morphism module, 143
sage.schemes.elliptic_curves.weierstrass_transform module, 586
sage.schemes.hyperelliptic_curves.constructor module, 591
sage.schemes.hyperelliptic_curves.hypellfrob module, 666
sage.schemes.hyperelliptic_curves.hyperelliptic_finite_field module, 616
sage.schemes.hyperelliptic_curves.hyperelliptic_g2 module, 678
sage.schemes.hyperelliptic_curves.hyperelliptic_generic module, 593
sage.schemes.hyperelliptic_curves.hyperelliptic_padic_field module, 616
sage.schemes.hyperelliptic_curves.hyperelliptic_rational_field module, 633
sage.schemes.hyperelliptic_curves.hyperelliptic_rational_field module, 633
sage.schemes.hyperelliptic_curves.invartains module, 680
sage.schemes.hyperelliptic_curves.jacobian_g2 module, 672
sage.schemes.hyperelliptic_curves.jacobian_g2 module, 672
sage.schemes.hyperelliptic_curves.jacobian_homset module, 673
sage.schemes.hyperelliptic_curves.jacobian_morphism module, 674
sage.schemes.hyperelliptic_curves.kummer_surface module, 685
sage.schemes.hyperelliptic_curves.mestre module, 633
sage.schemes.hyperelliptic_curves.monsky_washnitzer module, 636
sage.schemes.hyperelliptic_curves.sha_tate module, 560

satisfies_heegner_hypothesis() (in module sage.schemes.elliptic_curves.heegner), 560
satisfies_heegner_hypothesis()
satisfies_heegner_hypothesis()
satisfies_kolyvagin_hypothesis()
satisfies_kolyvagin_hypothesis()
satisfies_kolyvagin_hypothesis()
satisfies_kolyvagin_hypothesis()
satisfies_kolyvagin_hypothesis()
satisfies_weak_heegner_hypothesis()
Elliptic curves, Release 9.7

sage.schemes.elliptic_curves.Qcurves), 437
supersingular_j_polynomial() (in module sage.schemes.elliptic_curves.ell_rational_field), 128
supersingular_primes() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field, method), 300
switch_sign() (sage.schemes.elliptic_curves.ell_curve_isogeny.EllipticCurveIsogeny, method), 159
sympow() (sage.schemes.elliptic_curves.isogeny.EllipticCurveIsogeny, method), 500
sympow_derivs() (sage.schemes.elliptic_curves.isogeny.EllipticCurveIsogeny, method), 500
tamagawa_number() (sage.schemes.elliptic_curves.ell_curve_isogeny.EllipticCurveIsogeny, method), 159
tamagawa_number() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field, method), 159
tamagawa_product() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field, method), 302
tamagawa_product() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field, method), 302
tamagawa_product_bsd() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field, method), 306	
tangent_at_smooth_point() (in module sage.schemes.elliptic_curves.constructor), 16
tate_curve() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field, method), 302
tate_pairing() (sage.schemes.elliptic_curves.ell_point.EllipticCurvePoint_field, method), 35
TateCurve (class in sage.schemes.elliptic_curves.ell_tate_curve), 450
tau() (sage.schemes.elliptic_curves.heegner.HeegnerPointOnEllipticCurve, method), 518
tau() (sage.schemes.elliptic_curves.height.EllipticCurveCanonicalHeight, method), 522
trace_of_frobenius() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field, method), 305
trace_of_frobenius() (sage.schemes.elliptic_curves.ell_rational_field.EllipticCurve_rational_field, method), 305
Elliptic curves, Release 9.7

x_rational_map() (sage.schemes.elliptic_curves.ell_curve_isogeny.EllipticCurveIsogeny method), 160
x_rational_map() (sage.schemes.elliptic_curves.hom.EllipticCurveHom method), 140
x_rational_map() (sage.schemes.elliptic_curves.hom_composite.EllipticCurveHom_composite method), 187
x_rational_map() (sage.schemes.elliptic_curves.weierstrass_morphism.WeierstrassIsomorphism method), 144
x_to_p() (sage.schemes.hyperelliptic_curves.monsky_washnitzer.MonskyWashnitzerDifferentialRing method), 646
xy() (sage.schemes.elliptic_curves.ell_point.EllipticCurvePoint_field method), 38

Y
y() (sage.schemes.elliptic_curves.formal_group.EllipticCurveFormalGroup method), 134
y() (sage.schemes.hyperelliptic_curves.monsky_washnitzer.SpecialHyperellipticQuotientRing method), 655

Z
zero() (sage.schemes.hyperelliptic_curves.monsky_washnitzer.SpecialHyperellipticQuotientRing method), 656
zero_sums() (sage.schemes.elliptic_curves.lseries_ell.Lseries_ell method), 503
zeros() (sage.schemes.elliptic_curves.lseries_ell.Lseries_ell method), 503
zeros_in_interval()
  (sage.schemes.elliptic_curves.lseries_ell.Lseries_ell method), 504
zeta_function() (sage.schemes.hyperelliptic_curves.hyperelliptic_finite_field.HyperellipticCurve_finite_field method), 615