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Calculus is done using symbolic expressions which consist of symbols and numeric objects linked by operators (functions).

**Note:** While polynomial manipulation can be done with expressions, it is more efficient to use polynomial ring elements.
CHAPTER ONE

USING CALCULUS

• Symbolic Computation
• Examples
  – Calculus examples
  – Calculus Tests and Examples
  – Further examples from Wester’s paper
• More about symbolic variables and functions
• Main operations on symbolic expressions
• Assumptions about symbols and functions
• Symbolic Equations and Inequalities
• Symbolic Series
• Symbolic Integration
• Solving ordinary differential equations
• Solving ODE numerically by GSL
• Numerical Integration
• Real Interpolation using GSL
• Transforms
  – Discrete Wavelet Transform
  – Discrete Fourier Transforms
  – Fast Fourier Transforms Using GSL
• Vector Calculus
• Riemann Mapping
• Other calculus functionality
• Complexity Measures
• Units of measurement
INTERNAL FUNCTIONALITY SUPPORTING CALCULUS

- The symbolic ring
- Subrings of the Symbolic Ring
- Operators
- Operands
- Classes for symbolic functions
- Functional notation support for common calculus methods
- Factory for symbolic functions
- Internals of Callable Symbolic Expressions
- Conversion of symbolic expressions to other types
- Substitution Maps
- Benchmarks
- Randomized tests of GiNaC / PyNaC
- Pynac interface
- Access to Maxima methods
- External integrators
- External interpolators

2.1 Symbolic Expressions

RELATIONAL EXPRESSIONS:

We create a relational expression:

```
sage: x = var('x')
sage: eqn = (x-1)^2 <= x^2 - 2*x + 3
sage: eqn.subs(x == 5)
16 <= 18
```

Notice that squaring the relation squares both sides.
This can transform a true relation into a false one:

```
sage: eqn = SR(-5) < SR(-3); eqn
-5 < -3
sage: bool(eqn)
True
sage: eqn^2
25 < 9
sage: bool(eqn^2)
False
```

We can do arithmetic with relations:

```
sage: e = x+1 <= x-2
sage: e + 2
x + 3 <= x
sage: e - 1
x <= x - 3
sage: e*(-1)
-x - 1 <= -x + 2
sage: (-2)*e
-2*x - 2 <= -2*x + 4
sage: e*5
5*x + 5 <= 5*x - 10
sage: e/5
1/5*x + 1/5 <= 1/5*x - 2/5
sage: 5/e
5/(x + 1) <= 5/(x - 2)
sage: e/(-2)
-1/2*x - 1/2 <= -1/2*x + 1
sage: -2/e
-2/(x + 1) <= -2/(x - 2)
```

We can even add together two relations, as long as the operators are the same:

```
sage: (x^3 + x <= x - 17) + (-x <= x - 10)
x^3 <= 2*x - 27
```

Here they are not:

```
sage: (x^3 + x <= x - 17) + (-x >= x - 10)
Traceback (most recent call last):
  ...
TypeError: incompatible relations
```

**ARBITRARY SAGE ELEMENTS:**

You can work symbolically with any Sage data type. This can lead to nonsense if the data type is strange, e.g., an element of a finite field (at present).

We mix Singular variables with symbolic variables:
```python
sage: R.<u,v> = QQ[]
sage: var('a,b,c')
(a, b, c)
sage: expand((u + v + a + b + c)^2)
```

\[
a^2 + 2*a*b + b^2 + 2*a*c + 2*b*c + c^2 + 2*a*u + 2*b*u + 2*c*u + u^2 + 2*a*v + 2*b*v \rightarrow + 2*c*v + 2*u*v + v^2
\]

```python
class sage.symbolic.expression.Expression
    Bases: sage.structure.element.CommutativeRingElement

    Nearly all expressions are created by calling new_Expression_from_*, but we need to make sure this at least does not leave self._gobj uninitialized and segfault.

    Order (hold=False)
    Return the order of the expression, as in big oh notation.

    OUTPUT:
    A symbolic expression.

    EXAMPLES:

    ```python
    sage: n = var('n')
sage: t = (17*n^3).Order(); t
    Order(n^3)
sage: t.derivative(n)
    Order(n^2)
    ```

    To prevent automatic evaluation use the hold argument:

    ```python
    sage: (17*n^3).Order(hold=True)
    Order(17*n^3)
    ```

    WZ_certificate (n, k)
    Return the Wilf-Zeilberger certificate for this hypergeometric summand in n, k.

    To prove the identity \( \sum_k F(n,k) = \text{const} \) it suffices to show that \( F(n+1,k) - F(n,k) = G(n,k+1) - G(n,k) \), with \( G = RF \) and \( R \) the WZ certificate.

    EXAMPLES:
    To show that \( \sum_k \binom{n}{k} = 2^n \) do:

    ```python
    sage: _ = var('k n')
sage: F(n,k) = binomial(n,k) / 2^n
sage: c = F(n,k).WZ_certificate(n,k); c
1/2*k/(k - n - 1)
sage: G(n,k) = c * F(n,k); G
(n, k) |--> 1/2*k*binomial(n, k)/(2^n*(k - n - 1))
sage: (F(n+1,k) - F(n,k) - G(n,k+1) + G(n,k)).simplify_full()
0
    ```

    abs (hold=False)
    Return the absolute value of this expression.

    EXAMPLES:

    ```python
    sage: var('x, y')
    (x, y)
    ```
```

2.1. Symbolic Expressions 7
Using the hold parameter it is possible to prevent automatic evaluation:

```
sage: SR(-5).abs(hold=True)
abs(-5)
```

To then evaluate again, we use unhold():

```
sage: a = SR(-5).abs(hold=True); a.unhold()
5
```

**add** (hold=False, *args)

Return the sum of the current expression and the given arguments.

To prevent automatic evaluation use the hold argument.

EXAMPLES:

```
sage: x.add(x)
2*x
sage: x.add(x, hold=True)
x + x
sage: x.add(x, (2+x), hold=True)
(x + 2) + x + x
sage: x.add(x, (2+x), x, hold=True)
(x + 2) + x + x + x

To then evaluate again, we use unhold():

```
sage: a = x.add(x, hold=True); a.unhold()
2*x
```

**add_to_both_sides** (x)

Return a relation obtained by adding x to both sides of this relation.

EXAMPLES:

```
sage: var('x y z')
(x, y, z)
sage: eqn = x^2 + y^2 + z^2 <= 1
sage: eqn.add_to_both_sides(-z^2)
x^2 + y^2 <= -z^2 + 1
sage: eqn.add_to_both_sides(1)
x^2 + y^2 + z^2 + 1 <= (1 + 1)
```

**arccos** (hold=False)

Return the arc cosine of self.

EXAMPLES:

```
sage: x.arccos()
arccos(x)
sage: SR(1).arccos()
```

(continues on next page)
sage: SR(1/2).arccos()
1/3*pi
sage: SR(0.4).arccos()
1.15927948072741
sage: plot(lambda x: SR(x).arccos(), -1,1)
Graphics object consisting of 1 graphics primitive

To prevent automatic evaluation use the `hold` argument:

```
sage: SR(1).arccos(hold=True)
arccos(1)
```

This also works using functional notation:

```
sage: arccos(1,hold=True)
arccosh(1)
sage: arccos(1)
0
```

To then evaluate again, we use `unhold()`:

```
sage: a = SR(1).arccos(hold=True); a.unhold()
0
```

**arccosh** *(hold=False)*

Return the inverse hyperbolic cosine of self.

**EXAMPLES:**

```
sage: x.arccosh()
arccosh(x)
sage: SR(0).arccosh()
1/2*I*pi
sage: SR(1/2).arccosh()
arccosh(1/2)
sage: SR(CDF(1/2)).arccosh() # rel tol 1e-15
1.0471975511965976*I
sage: maxima('acosh(0.5)')
1.04719755119659...*%i
```

To prevent automatic evaluation use the `hold` argument:

```
sage: SR(-1).arccosh()
I*pi
sage: SR(-1).arccosh(hold=True)
arccosh(-1)
```

This also works using functional notation:

```
sage: arccosh(-1,hold=True)
arccosh(-1)
sage: arccosh(-1)
I*pi
```

To then evaluate again, we use `unhold()`:
\begin{verbatim}
sage: a = SR(-1).arccosh(hold=True); a.unhold()
I*pi
\end{verbatim}

\textbf{arcsin} \textit{(hold=False)}

Return the arcsin of \(x\), i.e., the number \(y\) between -\(pi\) and \(pi\) such that \(\sin(y) = x\).

\textbf{EXAMPLES:}

\begin{verbatim}
sage: x.arcsin()
arcsin(x)
sage: SR(0.5).arcsin()
1/6*pi
sage: SR(0.999).arcsin()
1.52607123962616
sage: SR(1/3).arcsin()
arcsin(1/3)
sage: SR(-1/3).arcsin()
-arcsin(1/3)
sage: SR(0).arcsin()
0
sage: SR(0).arcsin(hold=True)
arcsin(0)
sage: arcsin(0,hold=True)
arcsin(0)
sage: arcsin(0)
0
\end{verbatim}

To prevent automatic evaluation use the \texttt{hold} argument:

\begin{verbatim}
sage: arcsin(0)
0
\end{verbatim}

This also works using functional notation:

\begin{verbatim}
sage: arcsin(0,hold=True)
arcsin(0)
sage: arcsin(0)
0
\end{verbatim}

To then evaluate again, we use \texttt{unhold()}:}

\begin{verbatim}
sage: a = SR(0).arcsin(hold=True); a.unhold()
0
\end{verbatim}

\textbf{arcsinh} \textit{(hold=False)}

Return the inverse hyperbolic sine of self.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: x.arcsinh()
arcsinh(x)
sage: SR(0).arcsinh()
0
sage: SR(1).arcsinh()
arcsinh(1)
sage: SR(1.0).arcsinh()
0.881373587019543
sage: maxima('asinh(2.0)')
1.4436354751788...
\end{verbatim}

Sage automatically applies certain identities:

\begin{verbatim}
sage: SR(3/2).arcsinh().cosh()
1/2*sqrt(13)
\end{verbatim}
To prevent automatic evaluation use the `hold` argument:

```python
sage: SR(-2).arcsinh()
-arcsinh(2)
sage: SR(-2).arcsinh(hold=True)
arcsinh(-2)
```

This also works using functional notation:

```python
sage: arcsinh(-2,hold=True)
arcsinh(-2)
sage: arcsinh(-2)
arcsinh(-2)
```

To then evaluate again, we use `unhold()`:

```python
sage: a = SR(-2).arcsinh(hold=True); a.unhold()
arcsinh(-2)
```

`arctan` (*hold=False*)

Return the arc tangent of self.

```python
sage: x = var('x')
sage: x.arctan()
arctan(x)
sage: SR(1).arctan()
1/4*pi
sage: SR(1/2).arctan()
arctan(1/2)
sage: SR(0.5).arctan()
0.463647609000806
sage: plot(lambda x: SR(x).arctan(), -20,20)
Graphics object consisting of 1 graphics primitive
```

To prevent automatic evaluation use the `hold` argument:

```python
sage: SR(1).arctan(hold=True)
arctan(1)
```

This also works using functional notation:

```python
sage: arctan(1,hold=True)
arctan(1)
sage: arctan(1)
1/4*pi
```

To then evaluate again, we use `unhold()`:

```python
sage: a = SR(1).arctan(hold=True); a.unhold()
1/4*pi
```

`arctan2` (*x, hold=False*)

Return the inverse of the 2-variable tan function on self and x.

```python
arctan2 (x, hold=False)
Return the inverse of the 2-variable tan function on self and x.

EXAMPLES:
```
```
sage: var('x,y')
(x, y)
sage: x.arctan2(y)
arctan2(x, y)
sage: SR(1/2).arctan2(1/2)
1/4*pi
sage: maxima.eval('atan2(1/2,1/2)')
'\%pi/4'
sage: SR(-0.7).arctan2(SR(-0.6))
-2.27942259892257
```

To prevent automatic evaluation use the `hold` argument:

```
sage: SR(1/2).arctan2(1/2, hold=True)
arctan2(1/2, 1/2)
```

This also works using functional notation:

```
sage: arctan2(1,2,hold=True)
arctan2(1, 2)
sage: arctan2(1,2)
arctan(1/2)
```

To then evaluate again, we use `unhold()`:

```
sage: a = SR(1/2).arctan2(1/2, hold=True); a.unhold()
1/4*pi
```

**arctanh** *(hold=False)*

Return the inverse hyperbolic tangent of self.

**EXAMPLES:**

```
sage: x.arctanh()
arctanh(x)
sage: SR(0).arctanh()
0
sage: SR(1/2).arctanh()
1/2*log(3)
sage: SR(0.5).arctanh()
0.549306144334055
sage: SR(0.5).arctanh().tanh()
0.500000000000000
sage: maxima('atanh(0.5)')  # abs tol 2e-16
0.5493061443340548
```

To prevent automatic evaluation use the `hold` argument:

```
sage: SR(-1/2).arctanh()
-1/2*log(3)
sage: SR(-1/2).arctanh(hold=True)
arctanh(-1/2)
```

This also works using functional notation:
To then evaluate again, we use `unhold()`:

```
sage: a = SR(-1/2).arctanh(hold=True); a.unhold()
-1/2*log(3)
```

**args()**

EXAMPLES:

```
sage: x, y = var('x, y')
sage: f = x + y
sage: f.arguments()
(x, y)
sage: g = f.function(x)
sage: g.arguments()
(x,)
```

**arguments()**

EXAMPLES:

```
sage: x, y = var('x, y')
sage: f = x + y
sage: f.arguments()
(x, y)
sage: g = f.function(x)
sage: g.arguments()
(x,)
```

**assume()**

Assume that this equation holds. This is relevant for symbolic integration, among other things.

EXAMPLES: We call the assume method to assume that \( x > 2 \):

```
sage: (x > 2).assume()
```

`Bool` returns `True` below if the inequality is definitely known to be `True`.

```
sage: bool(x > 0)
True
sage: bool(x < 0)
False
```

This may or may not be `True`, so `bool` returns `False`:

```
sage: bool(x > 3)
False
```

If you make inconsistent or meaningless assumptions, Sage will let you know:

```
sage: forget()
sage: assume(x<0)
```

(continues on next page)
\begin{verbatim}
sage: assume(x>0)
Traceback (most recent call last):
  ...
ValueError: Assumption is inconsistent
sage: assumptions()
[x < 0]
sage: forget()
\end{verbatim}

\textbf{binomial} \((k, \text{hold}=False)\)

Return binomial coefficient “self choose \(k\)”.

\textbf{OUTPUT:}

A symbolic expression.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: var('x, y')
(x, y)
sage: SR(5).binomial(SR(3))
10
sage: x.binomial(SR(3))
1/6*(x - 1)*(x - 2)*x
sage: x.binomial(y)
binomial(x, y)
\end{verbatim}

To prevent automatic evaluation use the \textit{hold} argument:

\begin{verbatim}
sage: x.binomial(3, \text{hold=True})
binomial(x, 3)
sage: SR(5).binomial(3, \text{hold=True})
binomial(5, 3)
\end{verbatim}

To then evaluate again, we use \textit{unhold()}:

\begin{verbatim}
sage: a = SR(5).binomial(3, \text{hold=True}); a.unhold()
10
\end{verbatim}

The \textit{hold} parameter is also supported in functional notation:

\begin{verbatim}
sage: binomial(5,3, \text{hold=True})
binomial(5, 3)
\end{verbatim}

\textbf{canonicalize_radical()}

Choose a canonical branch of the given expression. The square root, cube root, natural log, etc. functions are multi-valued. The \textit{canonicalize_radical()} method will choose \textit{one} of these values based on a heuristic.

For example, \texttt{sqrt(x^2)} has two values: \(x\), and \(-x\). The \textit{canonicalize_radical()} function will choose \textit{one} of them, consistently, based on the behavior of the expression as \(x\) tends to positive infinity. The solution chosen is the one which exhibits this same behavior. Since \texttt{sqrt(x^2)} approaches positive infinity as \(x\) does, the solution chosen is \(x\) (which also tends to positive infinity).

\textbf{Warning:} As shown in the examples below, a canonical form is not always returned, i.e., two mathematically identical expressions might be converted to different expressions.
Assumptions are not taken into account during the transformation. This may result in a branch choice inconsistent with your assumptions.

ALGORITHM:

This uses the Maxima `radcan()` command. From the Maxima documentation:

Simplifies an expression, which can contain logs, exponentials, and radicals, by converting it into a form which is canonical over a large class of expressions and a given ordering of variables; that is, all functionally equivalent forms are mapped into a unique form. For a somewhat larger class of expressions, `radcan` produces a regular form. Two equivalent expressions in this class do not necessarily have the same appearance, but their difference can be simplified by `radcan` to zero.

For some expressions `radcan` is quite time consuming. This is the cost of exploring certain relationships among the components of the expression for simplifications based on factoring and partial fraction expansions of exponents.

EXAMPLES:

`canonicalize_radical()` can perform some of the same manipulations as `log_expand()`:

```sage
canonicalize_radical()
```

```sage:
y = SR.symbol('y')
sage: f = log(x*y)
sage: f.log_expand()
log(x) + log(y)
sage: f.canonicalize_radical()
log(x) + log(y)
```

And also handles some exponential functions:

```sage
canonicalize_radical()
```

```sage:
f = (e^x-1)/(1+e^(x/2))
sage: f.canonicalize_radical()
e^(1/2*x) - 1
```

It can also be used to change the base of a logarithm when the arguments to `log()` are positive real numbers:

```sage
canonicalize_radical()
```

```sage:
f = log(8)/log(2)
sage: f.canonicalize_radical()
3
```

```sage:
a = SR.symbol('a')
sage: f = (log(x+x^2)-log(x))^a/log(1+x)^(a/2)
sage: f.canonicalize_radical()
log(x + 1)^(1/2*a)
```

The simplest example of counter-intuitive behavior is what happens when we take the square root of a square:

```sage
canonicalize_radical()
```

```sage:
sqrt(x^2).canonicalize_radical()
x
```

If you don’t want this kind of “simplification,” don’t use `canonicalize_radical()`.

This behavior can also be triggered when the expression under the radical is not given explicitly as a square:
Another place where this can become confusing is with logarithms of complex numbers. Suppose \( x \) is complex with \( x = r e^{i t} \) (\( r \) real). Then \( \log(x) = \log(r) + i(t + 2k\pi) \) for some integer \( k \).

Calling `canonicalize_radical()` will choose a branch, eliminating the solutions for all choices of \( k \) but one. Simplified by hand, the expression below is \((1/2)\log(2) + i\pi k\) for integer \( k \). However, `canonicalize_radical()` will take each log expression, and choose one particular solution, dropping the other. When the results are subtracted, we’re left with no imaginary part:

```
sage: f = (1/2)*log(2*x) + (1/2)*log(1/x)
sage: f.canonicalize_radical()
1/2*log(2)
```

Naturally the result is wrong for some choices of \( x \):

```
sage: f(x = -1)
i*pi + 1/2*log(2)
```

The example below shows two expressions \( e_1 \) and \( e_2 \) which are “simplified” to different expressions, while their difference is “simplified” to zero; thus `canonicalize_radical()` does not return a canonical form:

```
sage: e1 = 1/(sqrt(5)+sqrt(2))
sage: e2 = (sqrt(5)-sqrt(2))/3
sage: e1.canonicalize_radical()
1/(sqrt(5) + sqrt(2))
sage: e2.canonicalize_radical()
1/3*sqrt(5) - 1/3*sqrt(2)
sage: (e1-e2).canonicalize_radical()
0
```

The issue reported in trac ticket #3520 is a case where `canonicalize_radical()` causes a numerical integral to be calculated incorrectly:

```
sage: f1 = sqrt(25 - x) * sqrt(1 + 1/(4*(25-x)))
sage: f2 = f1.canonicalize_radical()
sage: numerical_integral(f1.real(), 0, 1)[0] # abs tol 1e-10
4.974852579915647
sage: numerical_integral(f2.real(), 0, 1)[0] # abs tol 1e-10
-4.974852579915647
```

`coefficient(s, n=1)`

Return the coefficient of \( s^n \) in this symbolic expression.

INPUT:

- \( s \) - expression
- \( n \) - expression, default 1

OUTPUT:

A symbolic expression. The coefficient of \( s^n \).

Sometimes it may be necessary to expand or factor first, since this is not done automatically.

EXAMPLES:
sage: var('x, y, a')
(x, y, a)
sage: f = 100 + a*x + x^3*sin(x*y) + x*y + x/y + 2*sin(x*y)/x; f
x^3*sin(x*y) + a*x + x*y + x/y + 2*sin(x*y)/x + 100
sage: f.collect(x)
x^3*sin(x*y) + (a + y + 1/y)*x + 2*sin(x*y)/x + 100
sage: f.coefficient(x,0)
100
sage: f.coefficient(x,-1)
2*sin(x*y)
sage: f.coefficient(x,1)
a + y + 1/y
sage: f.coefficient(x,2)
0
sage: f.coefficient(x,3)
sin(x*y)
sage: f.coefficient(x^3)
sin(x*y)
sage: f.coefficient(sin(x*y))
x^3 + 2/x
sage: f.collect(sin(x*y))
a*x + x*y + (x^3 + 2/x)*sin(x*y) + x/y + 100
sage: var('a, x, y, z')
(a, x, y, z)
sage: f = (a*sqrt(2))*x^2 + sin(y)*sqrt(x) + z^z
sage: f.coefficient(sin(y))
sqrt(x)
sage: f.coefficient(x^2)
sqrt(2)*a
sage: f.coefficient(x^(1/2))
sqrt(2)*a
sage: f.coefficient(1)
0
sage: f.coefficient(x, 0)
z^z

Any coefficient can be queried:

sage: (x^2 + 3*x^pi).coefficient(x, pi)
3
sage: (2^x + 5*x^x).coefficient(x, x)
5

coefficients (x=None, sparse=True)
Return the coefficients of this symbolic expression as a polynomial in x.

INPUT:

• x – optional variable.

OUTPUT:

Depending on the value of sparse,

• A list of pairs (expr, n), where expr is a symbolic expression and n is a power (sparse=True, default)

• A list of expressions where the n-th element is the coefficient of x^n when self is seen as polynomial in x (sparse=False).
EXAMPLES:

```
sage: var('x, y, a')
(x, y, a)
sage: p = x^3 - (x-3)*(x^2+x) + 1
sage: p.coefficients()
[[1, 0], [3, 1], [2, 2]]
sage: p.coefficients(sparse=False)
[1, 3, 2]
sage: p = x - x^3 + 5/7*x^5
sage: p.coefficients()
[[0, 1, 0, -1, 0, 5/7, 5]]
sage: p.coefficients(sparse=False)
[0, 1, 0, -1, 0, 5/7]
sage: p = expand((x-a*sqrt(2))^2 + x + 1); p
-x^3 + 2*a^2 + x + 1
sage: p.coefficients(a)
[[x^2 + x + 1, 0], [-2*a^2 + x, 1], [2, 2]]
sage: p.coefficients(a, sparse=False)
[x^2 + x + 1, -2*a + 1, 1]
sage: p.coefficients(x)
[[2*a^2 + 1, 0], [-2*a + 1, 1], [1, 2]]
sage: p.coefficients(x, sparse=False)
[2*a^2 + 1, -2*a + 1, 1]
```

```
collect(s)

Collect the coefficients of \( s \) into a group.

INPUT:

- \( s \) – the symbol whose coefficients will be collected.

OUTPUT:

A new expression, equivalent to the original one, with the coefficients of \( s \) grouped.

**Note:** The expression is not expanded or factored before the grouping takes place. For best results, call `expand()` on the expression before `collect()`.

EXAMPLES:

In the first term of \( f \), \( x \) has a coefficient of \( 4y \). In the second term, \( x \) has a coefficient of \( z \). Therefore, if we collect those coefficients, \( x \) will have a coefficient of \( 4y + z \):

```
sage: x, y, z = var('x, y, z')
sage: f = 4*x*y + x*z + 20*y^2 + 21*y*z + 4*z^2 + x^2*y^2*z^2
sage: f.collect(x)
x^2*y^2*z^2 + x*(4*y + z) + 20*y^2 + 21*y*z + 4*z^2
```

Here we do the same thing for \( y \) and \( z \); however, note that we do not factor the \( y^2 \) and \( z^2 \) terms before collecting coefficients:

```
sage: f.collect(y)
(4*x^2 + 20)*y^2 + (4*x + 21*z)*y + x*z + 4*z^2
sage: f.collect(z)
(x^2*y^2 + 4)*z^2 + 4*x*y + 20*y^2 + (x + 21*y)*z
```

The terms are collected, whether the expression is expanded or not:
```python
sage: f = (x + y)*(x - z)
sage: f.collect(x)
x^2 + x*(y - z) - y*z
sage: f.expand().collect(x)
x^2 + x*(y - z) - y*z
```

**collect_common_factors()**

This function does not perform a full factorization but only looks for factors which are already explicitly present.

Polynomials can often be brought into a more compact form by collecting common factors from the terms of sums. This is accomplished by this function.

**EXAMPLES:**

```python
sage: var('x')
x
sage: (x/(x^2 + x)).collect_common_factors()
1/(x + 1)
sage: var('a,b,c,x,y')
(a, b, c, x, y)
sage: (a*x+a*y).collect_common_factors()
a*(x + y)
sage: (a*x^2+2*a*x*y+a*y^2).collect_common_factors()
(a^2*x^2 + 2*a*x*y + a*y^2)*a
sage: (a*(b*(a+c)*x+b*(a+c)*y)*y)).collect_common_factors()
((x + y)*y + x)*(a + c)*a*b
```

**combine(deep=False)**

Return a simplified version of this symbolic expression by combining all toplevel terms with the same denominator into a single term.

Please use the keyword `deep=True` to apply the process recursively.

**EXAMPLES:**

```python
sage: var('x, y, a, b, c')
(x, y, a, b, c)
sage: f = x*(x-1)/(x^2 - 7) + y^2/(x^2-7) + 1/(x+1) + b/a + c/a; f
(x - 1)*x/(x^2 - 7) + y^2/(x^2 - 7) + b/a + c/a + 1/(x + 1)
sage: f.combine()
((x - 1)*x + y^2)/(x^2 - 7) + (b + c)/a + 1/(x + 1)
sage: (1/x + 1/x^2 + (x+1)/x).combine()
(1 + 2)/x + 1/x^2
sage: ex = 1/x + ((x + 1)/x - 1/x)/x^2 + (x+1)/x; ex
(x + 1)/x + 1/x + ((x + 1)/x - 1/x)/x^2
sage: ex.combine()
(x + 2)/x + (x + 1)/x - 1/x)/x^2
sage: ex combine(deep=True)
(x + 2)/x + 1/x^2
sage: (1+sin((x + 1)/x - 1/x)).combine(deep=True)
sin(1) + 1
```

**conjugate(hold=False)**

Return the complex conjugate of this symbolic expression.

**EXAMPLES:**
Using the hold parameter it is possible to prevent automatic evaluation:

```
sage: SR(I).conjugate(hold=True)
conjugate(I)
```

This also works in functional notation:

```
sage: conjugate(I)
-I
```

To then evaluate again, we use `unhold()`:

```
sage: a = SR(I).conjugate(hold=True); a.unhold()
-I
```

**content (s)**

Return the content of this expression when considered as a polynomial in $s$.

See also `unit()`, `primitive_part()`, and `unit_content_primitive()`.

**INPUT:**

- $s$ – a symbolic expression.

**OUTPUT:**

The content part of a polynomial as a symbolic expression. It is defined as the gcd of the coefficients.

**Warning:** The expression is considered to be a univariate polynomial in $s$. The output is different from the `content()` method provided by multivariate polynomial rings in Sage.

**EXAMPLES:**

```python
sage: (2*x+4).content(x)
2
sage: (2*x+1).content(x)
1
sage: (2*x+1/2).content(x)
1/2
sage: var('y')
y
sage: (2*x + 4*sin(y)).content(sin(y))
2
```

**contradicts (soln)**

Return `True` if this relation is violated by the given variable assignment(s).

**EXAMPLES:**

```python
sage: (x<3).contradicts(x==0)
False
sage: (x<3).contradicts(x==3)
True
sage: (x<=3).contradicts(x==3)
False
sage: y = var('y')
sage: (x<y).contradicts(x==30)
False
sage: (x<y).contradicts({x: 30, y: 20})
True
```

**convert (target=None)**

Call the convert function in the units package. For symbolic variables that are not units, this function just returns the variable.

**INPUT:**

- `self` – the symbolic expression converting from
- `target` – (default `None`) the symbolic expression converting to

**OUTPUT:**

A symbolic expression.

**EXAMPLES:**

```python
sage: units.length.foot.convert()
381/1250*meter
sage: units.mass.kilogram.convert(units.mass.pound)
100000000/45359237*pound
```

We do not get anything new by converting an ordinary symbolic variable:

```python
sage: a = var('a')
sage: a - a.convert()
0
```

Raises `ValueError` if `self` and `target` are not convertible:

```python
sage: units.mass.kilogram.convert(units.length.foot)
Traceback (most recent call last):
```

(continues on next page)
Recognizes derived unit relationships to base units and other derived units:

\[
\text{sage: (units.length.foot/units.time.second^2).convert(units.acceleration.}\to\text{galileo)}
\]
\[
762/25\text{galileo}
\]
\[
\text{sage: (units.mass.kilogram*units.length.meter/units.time.second^2).} \\
\to\text{convert(units.force.newton)}
\]
\[
\text{newton}
\]
\[
\text{sage: (units.length.foot^3).convert(units.area.acre*units.length.inch) }
\]
\[
1/3630\times(acre\text{in}ch)
\]
\[
\text{sage: (units.charge.coulomb).convert(units.current.ampere*units.time.second) } \\
\to\text{(ampere*second)}
\]
\[
\text{sage: (units.pressure.pascal*units.si_prefixes.kilo).convert(units.pressure.} \\
\to\text{pounds_per_square_inch)}
\]
\[
1290320000000/8896443230521\times\text{pounds_per_square_inch}
\]

For decimal answers multiply by 1.0:

\[
\text{sage: (units.pressure.pascal*units.si_prefixes.kilo).convert(units.pressure.} \\
\to\text{pounds_per_square_inch)}\times1.0
\]
\[
0.145037737730209\times\text{pounds_per_square_inch}
\]

Converting temperatures works as well:

\[
\text{sage: s = 68*units.temperature.fahrenheit}
\]
\[
\text{sage: s.convert(units.temperature.celsius)}
\]
\[
20\times\text{celsius}
\]
\[
\text{sage: s.convert()}
\]
\[
293.150000000000\times\text{kelvin}
\]

Trying to multiply temperatures by another unit then converting raises a ValueError:

\[
\text{sage: wrong = 50*units.temperature.celsius*units.length.foot}
\]
\[
\text{sage: wrong.convert()}
\]
\[
\text{Traceback (most recent call last):}
\]
\[
...\]
\[
\text{ValueError: Cannot convert}
\]

\textbf{cos (\textit{hold}=False)}

\textit{Return the cosine of self.}

\textbf{EXAMPLES:}

\[
\text{sage: var('x, y')}
\]
\[
(x, y)
\]
\[
\text{sage: cos(x^2 + y^2)}
\]
\[
\cos(x^2 + y^2)
\]
\[
\text{sage: cos(sage.symbolic.constants.pi)}
\]
\[
-1
\]
\[
\text{sage: cos(SR(1))}
\]
\[
\text{(continues on next page)}
\]
In order to get a numeric approximation use `.n()`:

```python
sage: SR(RR(1)).cos().n()
0.540302305868140
sage: SR(float(1)).cos().n()
0.540302305868140
```

To prevent automatic evaluation use the `hold` argument:

```python
sage: pi.cos()
-1
sage: pi.cos(hold=True)
cosh(pi)
```

This also works using functional notation:

```python
sage: cos(pi,hold=True)
cosh(pi)
```

To then evaluate again, we use `unhold()`:

```python
sage: a = pi.cos(hold=True); a.unhold()
-1
```

### `cosh` (hold=False)

Return cosh of self.

We have $\cosh(x) = (e^x + e^{-x})/2$.

**EXAMPLES:**

```python
sage: x.cosh()
cosh(x)
sage: SR(1).cosh()
cosh(1)
sage: SR(0).cosh()
1
sage: SR(1.0).cosh()
1.5430806348152425
sage: maxima('cosh(1.0)')
1.5430806348152425...
sage: SR(1.00000000000000000000000000).cosh()
1.543080634815242537784779056
sage: SR(RIF(1)).cosh()
1.5430806348152425?
```

To prevent automatic evaluation use the `hold` argument:

```python
sage: arcsinh(x).cosh()
sqrt(x^2 + 1)
sage: arcsinh(x).cosh(hold=True)
cosh(arcsinh(x))
```
This also works using functional notation:

```
sage: cosh(arcsinh(x), hold=True)
cosh(arcsinh(x))
sage: cosh(arcsinh(x))
sqrt(x^2 + 1)
```

To then evaluate again, we use `unhold()`:

```
sage: a = arcsinh(x).cosh(hold=True); a.unhold()
sqrt(x^2 + 1)
```

`sage` (hold=False)

Return the sign of self, which is -1 if self < 0, 0 if self == 0, and 1 if self > 0, or unevaluated when self is a nonconstant symbolic expression.

If self is not real, return the complex half-plane (left or right) in which the number lies. If self is pure imaginary, return the sign of the imaginary part of self.

**EXAMPLES:**

```
sage: x = var('x')
sage: SR(-2).csgn()
-1
sage: SR(0.0).csgn()
0
sage: SR(10).csgn()
1
sage: x.csgn()
csgn(x)
sage: SR(CDF.0).csgn()
1
sage: SR(I).csgn()
1
sage: SR(-I).csgn()
-1
sage: SR(1+I).csgn()
1
sage: SR(1-I).csgn()
1
sage: SR(-1+I).csgn()
-1
sage: SR(-1-I).csgn()
-1
```

Using the hold parameter it is possible to prevent automatic evaluation:

```
sage: SR(I).csgn(hold=True)
csgn(I)
```

`decl_assume` (decl)

`decl_forget` (decl)

`default_variable()`

Return the default variable, which is by definition the first variable in self, or `x` if there are no variables in self. The result is cached.

**EXAMPLES:**
sage: sqrt(2).default_variable()
x
sage: x, theta, a = var('x, theta, a')
sage: f = x^2 + theta^3 - a^x
sage: f.default_variable()
a
Note that this is the first variable, not the first argument:

sage: f(theta, a, x) = a + theta^3
sage: f.default_variable()
a
sage: f.variables()
(a, theta)
sage: f.arguments()
(theta, a, x)

default_variable()

Return the exponent of the highest nonnegative power of s in self.

OUTPUT:

An integer >= 0.

EXAMPLES:

sage: var('x,y,a')
(x, y, a)
sage: f = 100 + a*x + x^3*sin(x*y) + x*y + x/y^10 + 2*sin(x*y)/x; f
x^3*sin(x*y) + a*x + x*y + 2*sin(x*y)/x + x/y^10 + 100
sage: f.degree(x)
3
sage: f.degree(y)
1
sage: f.degree(sin(x*y))
1
sage: (x^-3+y).degree(x)
0

denominator(normalize=True)

Return the denominator of this symbolic expression

INPUT:

- **normalize** – (default: True) a boolean.

If **normalize** is True, the expression is first normalized to have it as a fraction before getting the denominator.

If **normalize** is False, the expression is kept and if it is not a quotient, then this will just return 1.

See also:

normalize(), numerator(), numerator_denominator(), combine()

EXAMPLES:

sage: x, y, z, theta = var('x, y, z, theta')
sage: f = (sqrt(x) + sqrt(y) + sqrt(z))/(x^10 - y^10 - sqrt(theta))
sage: f.numerator()
sqrt(x) + sqrt(y) + sqrt(z)
(continues on next page)
derivative(*args)
Return the derivative of this expression with respect to the variables supplied in args.

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

See also:
This is implemented in the _derivative method (see the source code).

EXAMPLES:

```
sage: var("x y")
(x, y)
sage: t = (x^2+y)^2
sage: t.derivative(x)
4*(x^2 + y)*x
sage: t.derivative(x, 2)
12*x^2 + 4*y
sage: t.derivative(x, 2, y)
4
sage: t.derivative(y)
2*x^2 + 2*y
```

If the function depends on only one variable, you may omit the variable. Giving just a number (for the
order of the derivative) also works:

```
sage: f(x) = x^3 + sin(x)
sage: f.derivative()
x |--> 3*x^2 + cos(x)
sage: f.derivative(2)
x |--> 6*x - sin(x)
```

Some expressions can’t be cleanly differentiated by the chain rule:

```
sage: _ = var('x', domain='real')
sage: _ = var('w z')
sage: (x^z).conjugate().diff(x)
conjugate(x^(z - 1))*conjugate(z)
sage: (w^z).conjugate().diff(w)
w^(z - 1)*z*D[0](conjugate)(w^z)
sage: atanh(x).real_part().diff(x)
```

(continues on next page)
(continued from previous page)
\[-1/(x^2 - 1)\]
sage: \text{atanh}(x).\text{imag\_part()}.\text{diff}(x)
0
sage: \text{atanh}(w).\text{real\_part()}.\text{diff}(w)
-D[0]\{(\text{real\_part})(\arctanh(w))/((w^2 - 1)\}
\begin{sagecell}
sage: \text{atanh}(w).\text{imag\_part()}.\text{diff}(w)
0
sage: \text{atanh}(w).\text{imag\_part()}.\text{diff}(w)
\text{abs}(\log(x)).\text{diff}(x)
1/2*(\text{conjugate}(\log(x))/x + \log(x)/x)/\text{abs}(\log(x))
\text{abs}(\log(z)).\text{diff}(z)
1/2*(\text{conjugate}(\log(z))/z + \log(z)/\text{conjugate}(z))/\text{abs}(\log(z))
sage: \text{forget()}\end{sagecell}
sage: t = \sin(x+y^2)\cdot\tan(x\cdot y)
sage: t.\text{derivative}(x)
(tan(x*y)^2 + 1)*y*sin(y^2 + x) + cos(y^2 + x)*tan(x*y)
sage: t.\text{derivative}(y)
(tan(x*y)^2 + 1)*x*sin(y^2 + x) + 2*y*cos(y^2 + x)*tan(x*y)
sage: h = \sin(x)/\cos(x)
sage: derivative(h, x, x, x)
8*sin(x)^2/cos(x)^2 + 6*sin(x)^4/cos(x)^4 + 2
sage: derivative(h, x, 3)
8*sin(x)^2/cos(x)^2 + 6*sin(x)^4/cos(x)^4 + 2
sage: \text{var('x, y')}
(x, y)
sage: u = (\sin(x) + \cos(y))\cdot(\cos(x) - \sin(y))
sage: derivative(u, x, y)
-cos(x)*\cos(y) + \sin(x)*\sin(y)
sage: f = ((x^2+1)/(x^2-1))^(1/4)
\text{g = derivative(f, x); g \# this is a complex expression}
-1/2*(((x^2 + 1)*x/(x^2 - 1))^2 - x/(x^2 - 1))/(((x^2 + 1)/(x^2 - 1))^3/4)
\begin{sagecell}
sage: g.\text{factor()}
-x/((x + 1)^2*(x - 1)^2*(x^2 + 1)/(x^2 - 1))^3/4\end{sagecell}
sage: y = \text{var('y')}
sage: f = y^(\sin(x))
sage: derivative(f, x)
y^sin(x)\cdot\cos(x)\cdot\log(y)
sage: g(x) = \sqrt{5-2*x}
sage: g_3 = derivative(g, x, 3); g_3(2)
-3
sage: f = x*e^(-x)
\text{g = derivative(f, 100)}
x*e^(-x) - 100*e^{-x}
sage: g = 1/(sqrt((x^2-1)*(x+5)^6))
\text{derivative(g, x)}
-((x + 5)^6*x + 3*(x^2 - 1)*(x + 5)^5)/((x^2 - 1)*(x + 5)^6)^3/2
\begin{sagecell}
\text{diff(*args)}
\end{sagecell}
Return the derivative of this expressions with respect to the variables supplied in args.

2.1. Symbolic Expressions 27
Multiple variables and iteration counts may be supplied; see documentation for the global derivative() function for more details.

See also:

This is implemented in the _derivative method (see the source code).

EXAMPLES:

```python
sage: var("x y")
(x, y)
sage: t = (x^2+y)^2
sage: t.derivative(x)
4*(x^2 + y)*x
sage: t.derivative(x, 2)
12*x^2 + 4*y
sage: t.derivative(x, 2, y)
4
sage: t.derivative(y)
2*x^2 + 2*y
```

If the function depends on only one variable, you may omit the variable. Giving just a number (for the order of the derivative) also works:

```python
sage: f(x) = x^3 + sin(x)
sage: f.derivative()
x |--> 3*x^2 + cos(x)
sage: f.derivative(2)
x |--> 6*x - sin(x)
```

Some expressions can’t be cleanly differentiated by the chain rule:

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sage: _ = var('x', domain='real')
sage: _ = var('w z')
sage: (x^z).conjugate().diff(x)
conjugate(x^(z - 1))*conjugate(z)
sage: (w^z).conjugate().diff(w)
w^(z - 1)*z*D[0](conjugate)(w^z)
sage: atanh(x).real_part().diff(x)
-1/(x^2 - 1)
sage: atanh(x).imag_part().diff(x)
0
sage: atanh(w).real_part().diff(w)
-D[0](real_part)(arctanh(w))/(w^2 - 1)
sage: atanh(w).imag_part().diff(w)
-D[0](imag_part)(arctanh(w))/(w^2 - 1)
sage: abs(log(x)).diff(x)
1/2*(conjugate(log(x))/x + log(x)/x)/abs(log(x))
sage: abs(log(z)).diff(z)
1/2*(conjugate(log(z))/z + log(z)/conjugate(z))/abs(log(z))
sage: forget()
sage: t = sin(x+y^2)*tan(x*y)
sage: t.derivative(x)
(tan(x*y)^2 + 1)*y*sin(y^2 + x) + cos(y^2 + x)*tan(x*y)
sage: t.derivative(y)
(tan(x*y)^2 + 1)*x*sin(y^2 + x) + 2*y*cos(y^2 + x)*tan(x*y)
```
sage: h = sin(x)/cos(x)
sage: derivative(h, x, x, x)
\frac{8\sin(x)^2}{\cos(x)^2} + \frac{6\sin(x)^4}{\cos(x)^4} + 2
sage: derivative(h, x, 3)
\frac{8\sin(x)^2}{\cos(x)^2} + \frac{6\sin(x)^4}{\cos(x)^4} + 2

sage: var(’x, y’)
(x, y)
sage: u = (sin(x) + cos(y))*(cos(x) - sin(y))
sage: derivative(u, x, y)
-\cos(x)\cos(y) + \sin(x)\sin(y)
sage: f = ((x^2+1)/(x^2-1))^(1/4)
sage: g = derivative(f, x); g
# this is a complex expression
-1/2*(x^2 + 1)*x/(x^2 - 1)^2 - x/(x^2 - 1))/((x^2 + 1)/(x^2 - 1))^(3/4)
sage: g.factor()
-\frac{x}{(x + 1)^2*(x - 1)^2*(x^2 + 1)/(x^2 - 1))^(3/4)}

sage: y = var(’y’)
sage: f = y^(sin(x))
sage: derivative(f, x)
y^\sin(x)\cos(x)*\log(y)

sage: g(x) = sqrt(5-2*x)
sage: g_3 = derivative(g, x, 3); g_3(2)
-3

sage: f = x*e^(-x)
sage: derivative(f, 100)
x*e^(-x) - 100*e^(-x)

sage: g = 1/(sqrt((x^2-1)*(x+5)^6))
sage: derivative(g, x)
-(x + 5)^6*x + 3*(x^2 - 1)*x + 5)^(5)/(x^2 - 1)*x + 5)^(3/2)

differentiate(*args)
Return the derivative of this expression with respect to the variables supplied in args.

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

See also:
This is implemented in the _derivative method (see the source code).

EXAMPLES:

sage: var("x y")
(x, y)
sage: t = (x^2+y)^2
tsage: t.derivative(x)
4*(x^2 + y)*x
tsage: t.derivative(x, 2)
12*x^2 + 4*y
tsage: t.derivative(x, 2, y)
4
tsage: t.derivative(y)
2*x^2 + 2*y
If the function depends on only one variable, you may omit the variable. Giving just a number (for the
degree of the derivative) also works:

```
sage: f(x) = x^3 + sin(x)
sage: f.derivative()
x |--> 3*x^2 + cos(x)
sage: f.derivative(2)
x |--> 6*x - sin(x)
```

Some expressions can’t be cleanly differentiated by the chain rule:

```
sage: _ = var('x', domain='real')
sage: _ = var('w z')
sage: (x^z).conjugate().diff(x)
conjugate(x^(z - 1))*conjugate(z)
sage: (w^z).conjugate().diff(w)
w^(z - 1)*z*D[0](conjugate)(w^z)
sage: atanh(x).real_part().diff(x)
-1/(x^2 - 1)
sage: atanh(x).imag_part().diff(x)
0
sage: atanh(w).real_part().diff(w)
-w*D[0](real_part)(arctanh(w))/(w^2 - 1)
sage: atanh(w).imag_part().diff(w)
-w*D[0](imag_part)(arctanh(w))/(w^2 - 1)
sage: abs(log(x)).diff(x)
1/2*(conjugate(log(x))/x + log(x)/x)/abs(log(x))
sage: abs(log(z)).diff(z)
1/2*(conjugate(log(z))/z + log(z)/conjugate(z))/abs(log(z))
sage: forget()
sage: t = sin(x*y^2)*tan(x*y)
sage: t.derivative(x)
(tan(x*y)^2 + 1)*y*sin(y^2 + x) + cos(y^2 + x)*tan(x*y)
sage: t.derivative(y)
(tan(x*y)^2 + 1)*x*sin(y^2 + x) + 2*y*cos(y^2 + x)*tan(x*y)
```

```
sage: h = sin(x)/cos(x)
sage: derivative(h, x, 3)
8*sin(x)^2/cos(x)^2 + 6*sin(x)^4/cos(x)^4 + 2
sage: derivative(h, x, 3)
8*sin(x)^2/cos(x)^2 + 6*sin(x)^4/cos(x)^4 + 2
```

```
sage: var('x, y')
(x, y)
sage: u = (sin(x) + cos(y))*cosh(x) - sinh(y)
sage: derivative(u, x, y)
-cos(x)*cos(y) + sinh(x)*sin(y)
sage: f = (x^2+1)/(x^2-1))^(1/4)
sage: g = derivative(f, x); g # this is a complex expression
-1/2*x/(x^2+1)*x/(x^2-1)^2 - x/(x^2-1))/(x^2+1)/(x^2-1))^(3/4)
sage: g.factor()
-x/(x + 1)^2*(x - 1)^2*(x^2 + 1)/(x^2 - 1))^(3/4)
```
\( \sin(x) \cdot \cos(x) \cdot \log(y) \)

```sage
sage: g(x) = sqrt(5-2*x)
sage: g_3 = derivative(g, x, 3); g_3(2)
-3
```

```sage
sage: f = x*e^(-x)
sage: derivative(f, 100)
x*e^(-x) - 100*e^(-x)
```

```sage
sage: g = 1/((x^2-1)*(x+5)^6)
sage: derivative(g, x)
-((x + 5)^6*x + 3*(x^2 - 1)*(x + 5)^5)/((x^2 - 1)*(x + 5)^6)^(3/2)
```

**distribute** (*recursive=True*)
Distribute some indexed operators over similar operators in order to allow further groupings or simplifications.

Implemented cases (so far):
- Symbolic sum of a sum ==> sum of symbolic sums
- Integral (definite or not) of a sum ==> sum of integrals.
- Symbolic product of a product ==> product of symbolic products.

**INPUT:**
- **recursive** – (default : True) the distribution proceeds along the subtrees of the expression.

**AUTHORS:**
- Emmanuel Charpentier, Ralf Stephan (05-2017)

**divide_both_sides** (*x, checksign=None*)
Return a relation obtained by dividing both sides of this relation by \( x \).

**Note:** The **checksign** keyword argument is currently ignored and is included for backward compatibility reasons only.

**EXAMPLES:**

```sage
sage: theta = var('theta')
sage: eqn = (x^3 + theta < sin(x*theta))
sage: eqn.divide_both_sides(theta, checksign=False)
(x^3 + theta)/theta < sin(theta*x)/theta
sage: eqn.theta
(x^3 + theta)/theta < sin(theta*x)/theta
```

**exp** (*hold=False*)
Return exponential function of self, i.e., \( e \) to the power of self.

**EXAMPLES:**
To prevent automatic evaluation use the `hold` argument:

```
sage: (pi*I).exp(hold=True)
e^(I*pi)
```

This also works using functional notation:

```
sage: exp(I*pi,hold=True)
e^(I*pi)
sage: exp(I*pi)
-1
```

To then evaluate again, we use `unhold()`:

```
sage: a = (pi*I).exp(hold=True); a.unhold()
-1
```

**expand** *(side=None)*

Expand this symbolic expression. Products of sums and exponentiated sums are multiplied out, numerators of rational expressions which are sums are split into their respective terms, and multiplications are distributed over addition at all levels.

**EXAMPLES:**

We expand the expression \((x - y)^5\) using both method and functional notation.

```
sage: x,y = var('x,y')
sage: a = (x-y)^5
sage: a.expand()
x^5 - 5*x^4*y + 10*x^3*y^2 - 10*x^2*y^3 + 5*x*y^4 - y^5
sage: expand(a)
x^5 - 5*x^4*y + 10*x^3*y^2 - 10*x^2*y^3 + 5*x*y^4 - y^5
```

We expand some other expressions:

```
sage: expand((x-1)^3/(y-1))
x^3/(y - 1) - 3*x^2/(y - 1) + 3*x/(y - 1) - 1/(y - 1)
sage: expand((x*sin((x+y)^2))^2)
x^2 + 2*x*sin(x^2 + 2*x*y + y^2) + sin(x^2 + 2*x*y + y^2)^2
```

Observe that `expand()` also expands function arguments:
We can expand individual sides of a relation:

\[
sage: \ a = (16x - 13)^2 == (3x + 5)^2/2
\]

\[
sage: \ a.expand()
256x^2 - 416x + 169 == 9/2x^2 + 15x + 25/2
\]

\[
sage: \ a.expand('left')
256x^2 - 416x + 169 == 1/2*(3x + 5)^2
\]

\[
sage: \ a.expand('right')
(16x - 13)^2 == 9/2x^2 + 15x + 25/2
\]

**expand_log (algorithm='products')**

Simplify symbolic expression, which can contain logs.

Expands logarithms of powers, logarithms of products and logarithms of quotients. The option `algorithm` specifies which expression types should be expanded.

**INPUT:**

- `self`: expression to be simplified
- `algorithm` (default: `products`) optional, governs which expression is expanded. Possible values are
  - `nothing` (no expansion),
  - `powers` (log(a^r) is expanded),
  - `products` (like `powers` and also log(a*b) are expanded),
  - `all` (all possible expansion).

See also examples below.

**DETAILS:** This uses the Maxima simplifier and sets `logexpand` option for this simplifier. From the Maxima documentation: “Logexpand:true causes log(a^b) to become b*log(a). If it is set to all, log(a*b) will also simplify to log(a)+log(b). If it is set to super, then log(a/b) will also simplify to log(a)-log(b) for rational numbers a/b, a≠1. (log(1/b), for integer b, always simplifies.) If it is set to false, all of these simplifications will be turned off.

**ALIAS:** `log_expand()` and `expand_log()` are the same

**EXAMPLES:**

By default powers and products (and quotients) are expanded, but not quotients of integers:

\[
sage: \ (\log(3/4*x^\pi)).log_expand()
pi*log(x) + log(3/4)
\]

To expand also log(3/4) use `algorithm='all'`:

\[
sage: \ (\log(3/4*x^\pi)).log Expand('all')
pi*log(x) + log(3) - 2*log(2)
\]

To expand only the power use `algorithm='powers'`:
sage: (log(x^6)).log_expand('powers')
6*log(x)

The expression \( \log((3x)^6) \) is not expanded with \texttt{algorithm='powers'}, since it is converted into product first:

sage: (log((3*x)^6)).log_expand('powers')
log(729*x^6)

This shows that the option \texttt{algorithm} from the previous call has no influence to future calls (we changed some default Maxima flag, and have to ensure that this flag has been restored):

sage: (log(3/4*x^pi)).log_expand()
pi*log(x) + log(3/4)
sage: (log(3/4*x^pi)).log_expand('all')
pi*log(x) + log(3) - 2*log(2)
sage: (log(3/4*x^pi)).log_expand()
pi*log(x) + log(3/4)

AUTHORS:
- Robert Marik (11-2009)

\texttt{expand_rational} \texttt{(side=None)}

Expand this symbolic expression. Products of sums and exponentiated sums are multiplied out, numerators of rational expressions which are sums are split into their respective terms, and multiplications are distributed over addition at all levels.

EXAMPLES:

We expand the expression \((x - y)^5\) using both method and functional notation.

sage: x,y = var('x,y')
sage: a = (x-y)^5
sage: a.expand()
x^5 - 5*x^4*y + 10*x^3*y^2 - 10*x^2*y^3 + 5*x*y^4 - y^5
sage: expand(a)
x^5 - 5*x^4*y + 10*x^3*y^2 - 10*x^2*y^3 + 5*x*y^4 - y^5

We expand some other expressions:

sage: expand((x-1)^3/(y-1))
x^3/(y - 1) - 3*x^2/(y - 1) + 3*x/(y - 1) - 1/(y - 1)
sage: expand((x+sin((x+y)^2))^2)
x^2 + 2*x*sin(x^2 + 2*x*y + y^2) + sin(x^2 + 2*x*y + y^2)^2

Observe that \texttt{expand()} also expands function arguments:

sage: f(x) = function('f')(x)
sage: fx = f(x*(x+1)); fx
f((x + 1)*x)
sage: fx.expand()
f(x^2 + x)

We can expand individual sides of a relation:
```python
sage: a = (16*x-13)^2 == (3*x+5)^2/2
sage: a.expand()
256*x^2 - 416*x + 169 == 9/2*x^2 + 15*x + 25/2
sage: a.expand('left')
256*x^2 - 416*x + 169 == 1/2*(3*x + 5)^2
sage: a.expand('right')
(16*x - 13)^2 == 9/2*x^2 + 15*x + 25/2
```

**expand_sum()**

For every symbolic sum in the given expression, try to expand it, symbolically or numerically.

While symbolic sum expressions with constant limits are evaluated immediately on the command line, unevaluated sums of this kind can result from, e.g., substitution of limit variables.

**INPUT:**

- `self` - symbolic expression

**EXAMPLES:**

```python
sage: (k,n) = var('k,n')
sage: ex = sum(abs(-k*k+n),k,1,n)(n=8); ex
sum(abs(-k^2 + 8), k, 1, 8)
sage: ex.expand_sum()
162
sage: f(x,k) = sum((2/n)*(sin(n*x)*(-1)^(n+1)), n, 1, k)
sage: f(x,2)
-2*sum((-1)^n*sin(n*x)/n, n, 1, 2)
sage: f(x,2).expand_sum()  
-sin(2*x) + 2*sin(x)
```

We can use this to do floating-point approximation as well:

```python
sage: (k,n) = var('k,n')
sage: f(n)=sum(sqrt(abs(-k*k+n)),k,1,n)
sage: f(8)
sum(sqrt(abs(-k^2 + 8)), k, 1, 8)
sage: f(8).expand_sum()
sqrt(41) + sqrt(17) + 2*sqrt(14) + 3*sqrt(7) + 2*sqrt(2) + 3
sage: f(8).expand_sum().n()
31.7752256945384
```

See trac ticket #9424 for making the following no longer raise an error:

```python
sage: f(8).n()
31.7752256945384
```

**expand_trig** *(full=False, half_angles=False, plus=True, times=True)*

Expand trigonometric and hyperbolic functions of sums of angles and of multiple angles occurring in self. For best results, self should already be expanded.

**INPUT:**

- `full` - (default: False) To enhance user control of simplification, this function expands only one level at a time by default, expanding sums of angles or multiple angles. To obtain full expansion into sines and cosines immediately, set the optional parameter full to True.
- `half_angles` - (default: False) If True, causes half-angles to be simplified away.
• **plus** - (default: True) Controls the sum rule; expansion of sums (e.g. ‘sin(x + y)’) will take place only if plus is True.

• **times** - (default: True) Controls the product rule, expansion of products (e.g. sin(2*x)) will take place only if times is True.

OUTPUT:

A symbolic expression.

EXAMPLES:

```sage
sage: sin(5*x).expand_trig()
sage: cos(2*x + var('y')).expand_trig()
sage: (x, k1, k2) = var('x, k1, k2')
sage: cos((k1-k2)*x).expand().expand_trig()
```

We illustrate various options to this function:

```sage
sage: f = sin(sin(3*cos(2*x))*x)
sage: f.expand_trig()  
sage: f.expand_trig(full=True)  
sage: sin(2*x).expand_trig(times=False)  
sage: sin(2*x).expand_trig(times=True)  
sage: sin(2 + x).expand_trig(plus=False)  
sage: sin(2 + x).expand_trig(plus=True)  
sage: sin(x/2).expand_trig(half_angles=False)  
sage: sin(x/2).expand_trig(half_angles=True)  
```

If the expression contains terms which are factored, we expand first:

```sage
(x, k1, k2) = var('x, k1, k2')
sage: cos((k1-k2)*x).expand().expand_trig()  
```

ALIASES:

```sage
trig_expand() and expand_trig() are the same
```

**factor (dontfactor=[])**

Factor the expression, containing any number of variables or functions, into factors irreducible over the integers.

**INPUT:**

• **self** - a symbolic expression

• **dontfactor** - list (default: []), a list of variables with respect to which factoring is not to occur.

  Factoring also will not take place with respect to any variables which are less important (using the variable ordering assumed for CRE form) than those on the ‘dontfactor’ list.

**EXAMPLES:**
\texttt{sage}: x,y,z = var('x, y, z')
\texttt{sage}: (x^3-y^3).factor()  
\texttt{(x^2 + x*y + y^2)*(x - y)}
\texttt{sage}: factor(-8*y - 4*x + z^2*(2*y + x))  
\texttt{(x + 2*y)*(z + 2)*(z - 2)}
\texttt{sage}: f = -1 - 2*x - x^2 + y^2 + 2*x*y^2 + x^2*y^2
\texttt{sage}: F = factor(f/(36*(1 + 2*y + y^2)), dontfactor=[x]); F  
\texttt{1/36*(x^2 + 2*x + 1)*(y - 1)/(y + 1)}

If you are factoring a polynomial with rational coefficients (and dontfactor is empty) the factorization is done using Singular instead of Maxima, so the following is very fast instead of dreadfully slow:

\texttt{sage}: var('x,y')  
\texttt{(x, y)}
\texttt{sage}: (x^99 + y^99).factor()  
\texttt{(x^60 + x^57*y^3 - x^51*y^9 - x^48*y^12 + x^42*y^18 + x^39*y^21 - x^33*y^27 - x^30*y^30 - x^27*y^33 + x^21*y^39 + x^18*y^42 - x^12*y^48 - x^9*y^51 + x^3*y^57 + y^60)*(x^20 + x^19*y - x^17*y^3 - x^16*y^4 + x^14*y^6 + x^13*y^7 - x^11*y^9 - x^10*y^10 - x^9*y^11 + x^7*y^13 + x^6*y^14 - x^4*y^16 - x^3*y^17 + x*y^19 + y^20)*(x^10 - x^9*y + x^8*y^2 - x^7*y^3 + x^6*y^4 - x^5*y^5 + x^4*y^6 - x^3*y^7 + x^2*y^8 - x*y^9 + y^10)*(x^6 - x^3*y^3 + y^6)*(x^2 - x*y + y^2)*(x + y)

\texttt{factor\_list (dontfactor=[])}

Return a list of the factors of self, as computed by the factor command.

INPUT:

- self - a symbolic expression
- dontfactor - see docs for \texttt{factor()}

\textbf{Note:} If you already have a factored expression and just want to get at the individual factors, use the \texttt{\_factor\_list} method instead.

\textbf{EXAMPLES:}

\texttt{sage}: var('x, y, z')  
\texttt{(x, y, z)}
\texttt{sage}: f = x^3-y^3
\texttt{sage}: f.factor()  
\texttt{(x^2 + x*y + y^2)*(x - y)}

Notice that the -1 factor is separated out:

\texttt{sage}: f.factor\_list()  
\texttt{[(x^2 + x*y + y^2, 1), (x - y, 1)]}

We factor a fairly straightforward expression:

\texttt{sage}: factor(-8*y - 4*x + z^2*(2*y + x)).factor\_list()  
\texttt{[(x + 2*y, 1), (z + 2, 1), (z - 2, 1)]}

A more complicated example:
sage: var('x, u, v')
(x, u, v)
sage: f = expand((2*u*v^2-v^2-4*u^3)^2) * (-u)^3 * (x-sin(x))^3
sage: f.factor() 
-(4*u^3 - 2*u*v^2 + v^2)^2*u^3*(x - sin(x))^3
sage: g = f.factor_list(); g
[(4*u^3 - 2*u*v^2 + v^2, 2), (u, 3), (x - sin(x), 3), (-1, 1)]

This function also works for quotients:

sage: f = -1 - 2*x - x^2 + y^2 + 2*x*y^2 + x^2*y^2
sage: g = f/(36*(1 + 2*y + y^2)); g
1/36*(x^2*y^2 + 2*x*y^2 - x^2 + y^2 - 2*x - 1)/(y^2 + 2*y + 1)
sage: g.factor(dontfactor=[x])
1/36*(x^2 + 2*x + 1)*(y - 1)/(y + 1)
sage: g.factor_list(dontfactor=[x])
[(x^2 + 2*x + 1, 1), (y + 1, -1), (y - 1, 1), (1/36, 1)]

This example also illustrates that the exponents do not have to be integers:

sage: f = x^(2*sin(x)) * (x-1)^(sqrt(2)*x); f
(x - 1)^(sqrt(2)*x)*x^(2*sin(x))
sage: f.factor_list()
[(x - 1, sqrt(2)*x), (x, 2*sin(x))]

factorial (hold=False)
Return the factorial of self.

OUTPUT:
A symbolic expression.

EXAMPLES:

sage: var('x, y')
(x, y)
sage: SR(5).factorial()  
120
sage: x.factorial()  
factorial(x)
sage: (x^2+y^3).factorial()  
factorial(y^3 + x^2)

To prevent automatic evaluation use the hold argument:

sage: SR(5).factorial(hold=True)
factorial(5)

This also works using functional notation:

sage: factorial(5,hold=True)  
factorial(5)
sage: factorial(5)  
120

To then evaluate again, we use unhold():

sage: a = SR(5).factorial(hold=True); a.unhold()  
120
factorial_simplify()  
Simplify by combining expressions with factorials, and by expanding binomials into factorials.  
**ALIAS:** factorial_simplify and simplify_factorial are the same

**EXAMPLES:**

Some examples are relatively clear:

```
sage: var('n,k')
(n, k)
sage: f = factorial(n+1)/factorial(n); f
factorial(n + 1)/factorial(n)
sage: f.simplify_factorial()
n + 1
```

```
sage: f = factorial(n)*(n+1); f
(n + 1)*factorial(n)
sage: simplify(f)
(n + 1)*factorial(n)
sage: f.simplify_factorial()
factorial(n + 1)
```

```
sage: f = binomial(n, k)*factorial(k)*factorial(n-k); f
binomial(n, k)*factorial(k)*factorial(-k + n)
sage: f.simplify_factorial()
factorial(n)
```

A more complicated example, which needs further processing:

```
sage: f = factorial(x)/factorial(x-2)/2 + factorial(x+1)/factorial(x)/2; f
1/2*factorial(x + 1)/factorial(x) + 1/2*factorial(x)/factorial(x - 2)
sage: g = f.simplify_factorial(); g
1/2*(x - 1)*x + 1/2*x + 1/2
sage: g.simplify_rational()
1/2*x^2 + 1/2
```

find(pattern)

Find all occurrences of the given pattern in this expression.  
Note that once a subexpression matches the pattern, the search does not extend to subexpressions of it.

**EXAMPLES:**

```
sage: var('x,y,z,a,b')
(x, y, z, a, b)
sage: w0 = SR.wild(0); w1 = SR.wild(1)
sage: (sin(x)*sin(y)).find(sin(w0))
[sin(y), sin(x)]
sage: ((sin(x)+sin(y))*(a+b)).expand().find(sin(w0))
[sin(y), sin(x)]
sage: (1+x+x^2+x^3).find(x)
[x]
sage: (1+x+x^2+x^3).find(x^w0)
[x^2, x^3]
```

(continues on next page)
sage: (1+x+x^2+x^3).find(y)
[]
# subexpressions of a match are not listed
sage: ((x^y)^z).find(w0^w1)
[(x^y)^z]

**find_local_maximum** *(a, b, var=None, tol=1.48e-08, maxfun=500)*

Numerically find a local maximum of the expression self on the interval [a,b] (or [b,a]) along with the point at which the maximum is attained.

See the documentation for `find_local_minimum()` for more details.

**EXAMPLES:**

```python
sage: f = x*cos(x)
sage: f.find_local_maximum(0,5)
(0.5610963381910451, 0.8603335890...)
sage: f.find_local_maximum(0,5, tol=0.1, maxfun=10)
(0.561090323458081..., 0.857926501456...)
```

**find_local_minimum** *(a, b, var=None, tol=1.48e-08, maxfun=500)*

Numerically find a local minimum of the expression self on the interval [a,b] (or [b,a]) and the point at which it attains that minimum. Note that self must be a function of (at most) one variable.

**INPUT:**

- **var** - variable (default: first variable in self)
- **a, b** - endpoints of interval on which to minimize self.
- **tol** - the convergence tolerance
- **maxfun** - maximum function evaluations

**OUTPUT:**

A tuple `(minval, x)`, where

- **minval** – float. The minimum value that self takes on in the interval [a,b].
- **x** – float. The point at which self takes on the minimum value.

**EXAMPLES:**

```python
sage: f = x*cos(x)
sage: f.find_local_minimum(1, 5)
(-3.288371395590..., 3.4256184695...)
sage: f.find_local_minimum(1, 5, tol=1e-3)
(-3.288370845983..., 3.4250840220...)
sage: show(f.plot(0, 20))
sage: f.find_local_minimum(1, 15)
(-9.477294259479..., 9.5293344109...)
```

**ALGORITHM:**

Uses `sage.numerical.optimize.find_local_minimum()`.

**AUTHORS:**
find_root \((a, b, \text{var}=\text{None}, \text{xtol}=1e-12, \text{rtol}=8.881784197001252e-16, \text{maxiter}=100, \text{full_output}=\text{False})\)

Numerically find a root of self on the closed interval \([a,b]\) (or \([b,a]\)) if possible, where self is a function in the one variable. Note: this function only works in fixed (machine) precision, it is not possible to get arbitrary precision approximations with it.

**INPUT:**

- \(a, b\) - endpoints of the interval
- \(\text{var}\) - optional variable
- \(\text{xtol}, \text{rtol}\) - the routine converges when a root is known to lie within xtol of the value return. Should be \(\geq 0\). The routine modifies this to take into account the relative precision of doubles.
- \(\text{maxiter}\) - integer; if convergence is not achieved in maxiter iterations, an error is raised. Must be \(\geq 0\).
- \(\text{full_output}\) - bool (default: False), if True, also return object that contains information about convergence.

**EXAMPLES:**

Note that in this example both \(f(-2)\) and \(f(3)\) are positive, yet we still find a root in that interval:

```
sage: f = x^2 - 1
sage: f.find_root(-2, 3)
1.0
sage: f.find_root(-2, 3, x)
1.0
sage: z, result = f.find_root(-2, 3, full_output=True)
sage: result.converged
True
sage: result.flag
'converged'
sage: result.function_calls
11
sage: result.iterations
10
sage: result.root
1.0
```

More examples:

```
sage: (sin(x) + exp(x)).find_root(-10, 10)
-0.588532743981862...
sage: sin(x).find_root(-1,1)
0.0
```

This example was fixed along with trac ticket #4942 - there was an error in the example pi is a root for \(tan(x)\), but an asymptote to \(1/tan(x)\) added an example to show handling of both cases:

```
sage: (tan(x)).find_root(3,3.5)
3.1415926535...
sage: (1/tan(x)).find_root(3, 3.5)
Traceback (most recent call last):
  ... NotImplementedError: Brent's method failed to find a zero for f on the...
  ... interval
```
An example with a square root:

```python
sage: f = 1 + x + sqrt(x+2); f.find_root(-2,10)
-1.618033988749895
```

Some examples that Ted Kosan came up with:

```python
sage: t = var('t')
sage: v = 0.004*(9600*e^(-(1200*t)) - 2400*e^(-(300*t)))
sage: v.find_root(0, 0.002)
0.001540327067911417...
```

With this expression, we can see there is a zero very close to the origin:

```python
sage: a = .004*(8*e^(-(300*t)) - 8*e^(-(1200*t)))*(720000*e^(-(300*t)) - ...)
-11520000*e^(-(1200*t)) + .004*(9600*e^(-(1200*t)) - 2400*e^(-(300*t))))^2
sage: show(plot(a, 0, .002), xmin=0, xmax=.002)
```

It is easy to approximate with `find_root`:

```python
sage: a.find_root(0,0.002)
0.0004110514049349...
```

Using `solve` takes more effort, and even then gives only a solution with free (integer) variables:

```python
sage: a.solve(t)
[]
sage: b = a.canonicalize_radical(); b
(46080.0*e^(1800*t) - 576000.0*e^(900*t) + 737280.0)*e^(-2400*t)
sage: b.solve(t)
[]
sage: b.solve(t, to_poly_solve=True)
[t == 1/450*I*pi*z... + 1/900*log(-3/4*sqrt(41) + 25/4),
 t == 1/450*I*pi*z... + 1/900*log(3/4*sqrt(41) + 25/4)]
sage: n(1/900*log(-3/4*sqrt(41) + 25/4))
0.000411051404934985
```

We illustrate that root finding is only implemented in one dimension:

```python
sage: x, y = var('x,y')
sage: (x-y).find_root(-2,2)
Traceback (most recent call last):
  ...
NotImplementedError: root finding currently only implemented in 1 dimension.
```

```python
forget()
```

Forget the given constraint.

EXAMPLES:

```python
sage: var('x,y')
(x, y)
sage: forget()
sage: assume(x>0, y < 2)
sage: assumptions()
[x > 0, y < 2]
sage: forget(y < 2)
sage: assumptions()
[x > 0]
```
fraction *(base_ring)*

Return this expression as element of the algebraic fraction field over the base ring given.

**EXAMPLES:**

```python
sage: fr = (1/x).fraction(ZZ); fr
1/x
sage: parent(fr)
Fraction Field of Univariate Polynomial Ring in x over Integer Ring
sage: parent((pi+sqrt(2))/x).fraction(SR))
Fraction Field of Univariate Polynomial Ring in x over Symbolic Ring
sage: parent((pi+sqrt(2))/x).fraction(SR))
Fraction Field of Univariate Polynomial Ring in x over Symbolic Ring
sage: y=var('y')

```

```python
sage: fr=((3*x^5 - 5*y^5)^7/(x*y)).fraction(GF(7)); fr
(3*x^35 + 2*y^35)/(x*y)
```

free_variables()

Return sorted tuple of unbound variables that occur in this expression.

**EXAMPLES:**

```python
sage: (x,y,z) = var('x,y,z')

```

```python
sage: (x+y).free_variables()
(x, y)
```

```python
sage: (2*x).free_variables()
(x,)
```

```python
sage: (x^y).free_variables()
(x, y)
```

```python
sage: sin(x+y^z).free_variables()
(x, y, z)
```

full_simplify()

Apply `simplify_factorial()`, `simplify_rectform()`, `simplify_trig()`, `simplify_rational()`, and then `expand_sum()` to self (in that order).

**ALIAS:** `simplify_full` and `full_simplify` are the same.

**EXAMPLES:**

```python
sage: f = sin(x)^2 + cos(x)^2
sage: f.simplify_full()
1
```

```python
sage: f = sin(x)/(x^2 + x)
sage: f.simplify_full()
sin(1/(x + 1))
```

```python
sage: var('n,k')
(n, k)
```

(continues on next page)
```python
sage: f = binomial(n,k)*factorial(k)*factorial(n-k)
sage: f.simplify_full()
factorial(n)
```

**function(*args)**

Return a callable symbolic expression with the given variables.

**EXAMPLES:**

We will use several symbolic variables in the examples below:

```python
sage: var('x, y, z, t, a, w, n')
(x, y, z, t, a, w, n)
```

```python
sage: u = sin(x) + x*cos(y)
sage: g = u.function(x,y)
sage: g(x,y)
x*cos(y) + sin(x)
sage: g(t,z)
t*cos(z) + sin(t)
sage: g(x^2, x*y)
x^2*cos(x*y) + sin(x^2)
```

```python
sage: f = (x^2 + sin(a*w)).function(a,x,w); f
(a, x, w) |--> x^2 + sin(a*w)
sage: f(1,2,3)
sin(3) + 4
```

Using the `function()` method we can obtain the above function \( f \), but viewed as a function of different variables:

```python
sage: h = f.function(w,a); h
(w, a) |--> x^2 + sin(a*w)
```

This notation also works:

```python
sage: h(w,a) = f
sage: h
(w, a) |--> x^2 + sin(a*w)
```

You can even make a symbolic expression \( f \) into a function by writing \( f(x,y) = f \):

```python
sage: f = x^n + y^n; f
x^n + y^n
sage: f(x,y) = f
sage: f
(x, y) |--> x^n + y^n
sage: f(2,3)
3^n + 2^n
```

**gamma(hold=False)**

Return the Gamma function evaluated at self.

**EXAMPLES:**

- sage: gamma(3)
  2
- sage: gamma(3/2)
  sqrt(pi)
- sage: gamma(-0.5)
  NaN
- sage: gamma(1-0.5)
  1.7724538509055159
- sage: gamma(0.5)
  1.7724538509055159
- sage: gamma(-1j)
  0.15483339452034547 + 0.7938196078193652j
- sage: gamma(-1j*pi)
  0.15483339452034547 + 0.7938196078193652j
- sage: gamma(pi/2j)
  -0.15483339452034547 - 0.7938196078193652j
- sage: gamma((1,2))
  ValueError: Gamma function only accepts a single noncomplex argument
We plot the familiar plot of this log-convex function:

```
sage: plot(gamma(x), -6,4).show(ymin=-3,ymax=3)
```

To prevent automatic evaluation use the `hold` argument:

```
sage: SR(1/2).gamma()
sqrt(pi)
sage: SR(1/2).gamma(hold=True)
gamma(1/2)
```

This also works using functional notation:

```
sage: gamma(1/2,hold=True)
gamma(1/2)
sage: gamma(1/2)
sqrt(pi)
```

To then evaluate again, we use `unhold()`:

```
sage: a = SR(1/2).gamma(hold=True); a.unhold()
sqrt(pi)
```

### gamma_normalize()

Return the expression with any gamma functions that have a common base converted to that base. Additionally the expression is normalized so any fractions can be simplified through cancellation.

**EXAMPLES:**

```
sage: m,n = var('m n', domain='integer')
sage: (gamma(n+2)/gamma(n)).gamma_normalize()
(n + 1)*n
sage: (gamma(n+2)*gamma(n)).gamma_normalize()
(n + 1)*n*gamma(n)^2
sage: (gamma(n+2)*gamma(m-1)/gamma(n)/gamma(m+1)).gamma_normalize()
(n + 1)*n/((m - 1)*m)
```

Check that trac ticket #22826 is fixed:
sage: _ = var('n')
sage: (n-1).gcd(n+1)
1
sage: ex = (n-1)^2*gamma(2*n+5)/gamma(n+3) + gamma(2*n+3)/gamma(n+1)
sage: ex.gamma_normalize()
(4*n^3 - 2*n^2 - 7*n + 7)*gamma(2*n + 3)/((n + 1)*gamma(n + 1))

**gcd**

Return the symbolic gcd of self and b.

Note that the polynomial GCD is unique up to the multiplication by an invertible constant. The following examples make sure all results are caught.

**EXAMPLES:**

```sage
sage: var('x,y')
(x, y)
sage: SR(10).gcd(SR(15))
5
sage: (x^3 - 1).gcd(x-1) / (x-1) in QQ
True
sage: (x^3 - 1).gcd(x^2+x+1) / (x^2+x+1) in QQ
True
sage: (x^3 - x^2*pi + x^2 - pi^2).gcd(x-pi) / (x-pi) in QQ
True
sage: gcd(sin(x)^2 + sin(x), sin(x)^2 - 1) / (sin(x) + 1) in QQ
True
sage: gcd(x^3 - y^3, x-y) / (x-y) in QQ
True
sage: gcd(x^100-y^100, x^10-y^10) / (x^10-y^10) in QQ
True
sage: r = gcd(expand( (x^2+17*x+3/7*y)*(x^5 - 17*y + 2/3) ), expand((x^13+17*x^3/7*y)*(x^5 - 17*y + 2/3)) )
sage: r / (x^5 - 17*y + 2/3) in QQ
True
```

Embedded Sage objects of all kinds get basic support. Note that full algebraic GCD is not implemented yet:

```sage
sage: gcd(I - I*x, x^2 - 1)
x - 1
sage: gcd(I + I*x, x^2 - 1)
x + 1
sage: alg = SR(QQbar(sqrt(2) + I*sqrt(3)))
sage: gcd(alg + alg*x, x^2 - 1) # known bug (trac #28489)
x + 1
sage: alg - alg*x, x^2 - 1) # known bug (trac #28489)
x - 1
sage: sqrt2 = SR(QQbar(sqrt(2)))
sage: gcd(sqrt2 + x, x^2 - 2) # known bug
1
```

**gosper_sum** (*args*)

Return the summation of this hypergeometric expression using Gosper’s algorithm.

**INPUT:**

- a symbolic expression that may contain rational functions, powers, factorials, gamma function terms, binomial coefficients, and Pochhammer symbols that are rational-linear in their arguments
• the main variable and, optionally, summation limits

EXAMPLES:

```python
sage: a, b, k, m, n = var('a b k m n')
sage: SR(1).gosper_sum(n)
n
sage: SR(1).gosper_sum(n, 5, 8)
4
sage: n.gosper_sum(n)
1/2*(n - 1)*n
sage: n.gosper_sum(n, 0, 5)
15
sage: n.gosper_sum(n, 0, m)
1/2*(m + 1)*m
sage: n.gosper_sum(n, a, b)
-1/2*(a + b)*(a - b - 1)
sage: (factorial(m + n)/factorial(n)).gosper_sum(n)
n*factorial(m + n)/((m + 1)*factorial(n))
sage: (binomial(m + n, n)).gosper_sum(n)
(n + m + 1)*binomial(a + m, a)/(m + 1)
sage: (binomial(m + n, n)).gosper_sum(n, 0, a)
(a + m + 1)*binomial(a + m, a)/(m + 1)
sage: (binomial(m + n, n)).gosper_sum(n, 0, 5)
1/120*(m + 6)*(m + 5)*(m + 4)*(m + 3)*(m + 2)
sage: (rising_factorial(a, n)/rising_factorial(b, n)).gosper_sum(n)
(b + n - 1)*gamma(a + n)*gamma(b)/((a - b + 1)*gamma(a)*gamma(b + n))
sage: factorial(n).gosper_term(n)
Traceback (most recent call last):...
ValueError: expression not Gosper-summable
```

**gosper_term**(n)

Return Gosper’s hypergeometric term for self.

Suppose \( f = \text{self} \) is a hypergeometric term such that:

\[
s_n = \sum_{k=0}^{n-1} f_k
\]

and \( f_k \) doesn’t depend on \( n \). Return a hypergeometric term \( g_n \) such that \( g_{n+1} - g_n = f_n \).

EXAMPLES:

```python
sage: _ = var('n')
sage: SR(1).gosper_term(n)
n
sage: n.gosper_term(n)
1/2*(n^2 - n)/n
sage: (n*factorial(n)).gosper_term(n)
1/n
sage: factorial(n).gosper_term(n)
Traceback (most recent call last):...
ValueError: expression not Gosper-summable
```

**gradient**(variables=None)

Compute the gradient of a symbolic function.
This function returns a vector whose components are the derivatives of the original function with respect to the arguments of the original function. Alternatively, you can specify the variables as a list.

EXAMPLES:

```
sage: x, y = var('x y')
sage: f = x^2+y^2
sage: f.gradient()
(2*x, 2*y)
sage: g(x,y) = x^2+y^2
sage: g.gradient()
(x, y) |--> (2*x, 2*y)
sage: n = var('n')
sage: f(x,y) = x^n+y^n
sage: f.gradient()
(x, y) |--> (n*x^(n - 1), n*y^(n - 1))
sage: f.gradient([y,x])
(x, y) |--> (n*y^(n - 1), n*x^(n - 1))
```

See also:

`gradient()` of scalar fields on Euclidean spaces (and more generally pseudo-Riemannian manifolds), in particular for computing the gradient in curvilinear coordinates.

`has(pattern)`

EXAMPLES:

```
sage: var('x,y,a'); w0 = SR.wild(); w1 = SR.wild()
(x, y, a)
sage: (x*sin(x + y + 2*a)).has(y)
True
```

Here “x+y” is not a subexpression of “x+y+2*a” (which has the subexpressions “x”, “y” and “2*a”):

```
sage: (x*sin(x + y + 2*a)).has(x+y)
False
sage: (x*sin(x + y + 2*a)).has(x + y + w0)
True
```

The following fails because “2*(x+y)” automatically gets converted to “2*x+2*y” of which “x+y” is not a subexpression:

```
sage: (x*sin(2*(x+y) + 2*a)).has(x+y)
False
```

Although x^1==x and x^0==1, neither “x” nor “1” are actually of the form “x^something”:

```
sage: (x+1).has(x^w0)
False
```

Here is another possible pitfall, where the first expression matches because the term “-x” has the form “(-1)*x” in GiNaC. To check whether a polynomial contains a linear term you should use the coeff() function instead.

```
sage: (4*x^2 - x + 3).has(w0*x)
True
sage: (4*x^2 + x + 3).has(w0*x)
False
```

(continues on next page)
sage: (4*x^2 + x + 3).has(x)
True
sage: (4*x^2 - x + 3).coefficient(x,1)
-1
sage: (4*x^2 + x + 3).coefficient(x,1)
1

\texttt{has\_wild()}

Return \texttt{True} if this expression contains a wildcard.

\textbf{EXAMPLES:}

sage: (1 + x^2).has_wild()
False
sage: (SR.wild(0) + x^2).has_wild()
True
sage: SR.wild(0).has_wild()
True

\texttt{hessian()}

Compute the hessian of a function. This returns a matrix components are the 2nd partial derivatives of the original function.

\textbf{EXAMPLES:}

sage: x, y = var('x y')
sage: f = x^2+y^2
sage: f.hessian()
\[
\begin{bmatrix}
2 & 0 \\
0 & 2 \\
\end{bmatrix}
\]
sage: g(x,y) = x^2+y^2
sage: g.hessian()
\[
\begin{bmatrix}
(x, y) |--> 2 & (x, y) |--> 0 \\
(x, y) |--> 0 & (x, y) |--> 2 \\
\end{bmatrix}
\]

\texttt{horner(x)}

Rewrite this expression as a polynomial in Horner form in \(x\).

\textbf{EXAMPLES:}

sage: add((i+1)*x^i for i in range(5)).horner(x)
(((5*x + 4)*x + 3)*x + 2)*x + 1
sage: x, y, z = SR.var('x,y,z')
sage: (x^5 + y*cos(x) + z^3 + (x + y)^2 + y^x).horner(x)
z^3 + ((x^3 + 1)*x + 2*y)*x + y^2 + y*cos(x) + y^x
sage: expr = sin(5*x).expand_trig(); expr
5*cos(x)^4*sin(x) - 10*cos(x)^2*sin(x)^3 + sin(x)^5
sage: expr.horner(sin(x))
(5*cos(x)^4 - (10*cos(x)^2 - sin(x)^2)*sin(x)^2)*sin(x)
sage: expr.horner(cos(x))
sin(x)^5 + 5*(cos(x)^2*sin(x) - 2*sin(x)^3)*cos(x)^2

\texttt{hypergeometric\_simplify(algorithm='maxima')}

Simplify an expression containing hypergeometric or confluent hypergeometric functions.

\textbf{INPUT:}
• **algorithm**—(default: 'maxima') the algorithm to use for for simplification. Implemented are
  'maxima', which uses Maxima's `hgfred` function, and 'sage', which uses an algorithm imple-
  mented in the hypergeometric module

**ALIAS:** `hypergeometric_simplify()` and `simplify_hypergeometric()` are the same

**EXAMPLES:**

```python
sage: hypergeometric((5, 4), (4, 1, 2, 3),
...: x).simplify_hypergeometric()
1/144*x^2*hypergeometric(((), (3, 4), x) +
1/3*x*hypergeometric(((), (2, 3), x) + hypergeometric(((), (1, 2), x)
sage: (2*hypergeometric(((), (x), x)).simplify_hypergeometric()
2*e^x
sage: (nest(lambda y: hypergeometric([y], [1], x), 3, 1)
...: .simplify_hypergeometric())
laguerre(-laguerre(-e^x, x), x)
sage: (nest(lambda y: hypergeometric([y], [1], x), 3, 1)
...: .simplify_hypergeometric(algorithm='sage'))
hypergeometric(hypergeometric((e^x,), (1,), x), (1,), x)
sage: hypergeometric_M(1, 3, x).simplify_hypergeometric()
-2*((x + 1)*e^(-x) - 1)*e^x/x^2
sage: (2 * hypergeometric_U(1, 3, x)).simplify_hypergeometric()
2*(x + 1)/x^2
```

**imag** *(hold=False)*

Return the imaginary part of this symbolic expression.

**EXAMPLES:**

```python
sage: sqrt(-2).imag_part()
sqrt(2)
```

We simplify \( \ln(\exp(z)) \) to \( z \). This should only be for \(-\pi < \Im(z) <= \pi \), but Maxima does not have a
symbolic imaginary part function, so we cannot use `assume` to assume that first:

```python
sage: z = var('z')
sage: f = log(exp(z))
sage: f
\log(e^z)
sage: f.simplify()
z
sage: forget()
```

A more symbolic example:

```python
sage: var('a, b')
(a, b)
sage: f = log(a + b*I)
sage: f.imag_part()
\arctan2(\text{imag_part}(a) + \text{real_part}(b), -\text{imag_part}(b) + \text{real_part}(a))
```

Using the `hold` parameter it is possible to prevent automatic evaluation:

```python
sage: I.imag_part()
1
sage: I.imag_part(hold=True)
\text{imag_part}(I)
```
This also works using functional notation:

```
sage: imag_part(I, hold=True)
imag_part(I)
sage: imag_part(I)
1
```

To then evaluate again, we use `unhold()`:

```
sage: a = I.imag_part(hold=True); a.unhold()
1
```

`imag_part (hold=False)`
Return the imaginary part of this symbolic expression.

**EXAMPLES:**

```
sage: sqrt(-2).imag_part()
sqrt(2)
```

We simplify \(\ln(\exp(z))\) to \(z\). This should only be for \(-\pi < \text{Im}(z) \leq \pi\), but Maxima does not have a symbolic imaginary part function, so we cannot use `assume` to assume that first:

```
sage: z = var('z')
sage: f = log(exp(z))
sage: f
log(e^z)
sage: f.simplify()
z
sage: forget()
```

A more symbolic example:

```
sage: var('a, b')
(a, b)
sage: f = log(a + b*I)
sage: f.imag_part()
arctan2(imag_part(a) + real_part(b), -imag_part(b) + real_part(a))
```

Using the `hold` parameter it is possible to prevent automatic evaluation:

```
sage: I.imag_part()
1
sage: I.imag_part(hold=True)
imag_part(I)
```

This also works using functional notation:

```
sage: imag_part(I, hold=True)
imag_part(I)
sage: imag_part(I)
1
```

To then evaluate again, we use `unhold()`:

```
sage: a = I.imag_part(hold=True); a.unhold()
1
```

2.1. Symbolic Expressions
**implicit_derivative**\((Y, X, n=1)\)

Return the \(n\)'th derivative of \(Y\) with respect to \(X\) given implicitly by this expression.

**INPUT:**

- \(Y\) - The dependent variable of the implicit expression.
- \(X\) - The independent variable with respect to which the derivative is taken.
- \(n\) - (default: 1) the order of the derivative.

**EXAMPLES:**

```python
sage: var('x, y')
(x, y)

sage: f = cos(x)*sin(y)
sage: f.implicit_derivative(y, x)
sin(x)*sin(y)/(cos(x)*cos(y))

sage: g = x*y^2
sage: g.implicit_derivative(y, x, 3)
-1/4*(y + 2*y/x)/x^2 + 1/4*(2*y^2/x - y^2/x^2)/(x*y) - 3/4*y/x^3
```

It is an error to not include an independent variable term in the expression:

```python
sage: (cos(x)*sin(x)).implicit_derivative(y, x)
Traceback (most recent call last):
 ...
ValueError: Expression cos(x)*sin(x) contains no y terms
```

**integral**\((*\text{args}, **\text{kwds})\)

Compute the integral of self. Please see `sage.symbolic.integration.integral.integrate()` for more details.

**EXAMPLES:**

```python
sage: sin(x).integral(x,0,3)
-cos(3) + 1

sage: sin(x).integral(x)
-cos(x)
```

**integrate**\((*\text{args}, **\text{kwds})\)

Compute the integral of self. Please see `sage.symbolic.integration.integral.integrate()` for more details.

**EXAMPLES:**

```python
sage: sin(x).integral(x,0,3)
-cos(3) + 1

sage: sin(x).integral(x)
-cos(x)
```

**inverse_laplace**\((t, s)\)

Return inverse Laplace transform of self. See `sage.calculus.calculus.inverse_laplace`.

**EXAMPLES:**

```python
sage: var('w, m')
(w, m)

sage: f = (1/(w^2+10)).inverse_laplace(w, m); f
1/10*sqrt(10)*sin(sqrt(10)*m)
```
**is_algebraic()**

Return True if this expression is known to be algebraic.

**EXAMPLES:**

```python
sage: sqrt(2).is_algebraic()
True
sage: (5*sqrt(2)).is_algebraic()
True
sage: (sqrt(2) + 2^(1/3) - 1).is_algebraic()
True
sage: (I*golden_ratio + sqrt(2)).is_algebraic()
True
sage: (sqrt(2) + pi).is_algebraic()
False
sage: SR(QQ(2/3)).is_algebraic()
True
sage: SR(1.2).is_algebraic()
False
```

**is_constant()**

Return whether this symbolic expression is a constant.

A symbolic expression is constant if it does not contain any variables.

**EXAMPLES:**

```python
sage: pi.is_constant()
True
sage: SR(1).is_constant()
True
sage: SR(2).is_constant()
True
sage: log(2).is_constant()
True
sage: I.is_constant()
True
sage: x.is_constant()
False
```

**is_exact()**

Return True if this expression only contains exact numerical coefficients.

**EXAMPLES:**

```python
sage: x, y = var('x, y')
sage: (x+y-1).is_exact()
True
sage: (x+y-1.9).is_exact()
False
sage: x.is_exact()
True
sage: pi.is_exact()
True
sage: (sqrt(x-y) - 2*x + 1).is_exact()
True
sage: ((x-y)^0.5 - 2*x + 1).is_exact()
False
```
**is_infinity()**

Return True if self is an infinite expression.

**EXAMPLES:**

```
sage: SR(oo).is_infinity()
True
sage: x.is_infinity()
False
```

**is_integer()**

Return True if this expression is known to be an integer.

**EXAMPLES:**

```
sage: SR(5).is_integer()
True
```

**is_negative()**

Return True if this expression is known to be negative.

**EXAMPLES:**

```
sage: SR(-5).is_negative()
True
```

Check if we can correctly deduce negativity of mul objects:

```
sage: t0 = SR.symbol("t0", domain='positive')
sage: t0.is_negative()
False
sage: (-t0).is_negative()
True
sage: (-pi).is_negative()
True
```

Assumptions on symbols are handled correctly:

```
sage: y = var('y')
sage: assume(y < 0)
sage: y.is_positive()
False
sage: y.is_negative()
True
sage: forget()
```

**is_negative_infinity()**

Return True if self is a negative infinite expression.

**EXAMPLES:**

```
sage: SR(oo).is_negative_infinity()
False
sage: SR(-oo).is_negative_infinity()
True
sage: x.is_negative_infinity()
False
```
is_numeric()  
A Pynac numeric is an object you can do arithmetic with that is not a symbolic variable, function, or constant. Return True if this expression only consists of a numeric object.

EXAMPLES:

```python
sage: SR(1).is_numeric()
True
sage: x.is_numeric()
False
sage: pi.is_numeric()
False
sage: sin(x).is_numeric()
False
```

is_polynomial(var)  
Return True if self is a polynomial in the given variable.

EXAMPLES:

```python
sage: var('x,y,z')
(x, y, z)
sage: t = x^2 + y; t
x^2 + y
sage: t.is_polynomial(x)
True
sage: t.is_polynomial(y)
True
sage: t.is_polynomial(z)
True
sage: t = sin(x) + y; t
y + sin(x)
sage: t.is_polynomial(x)
False
sage: t.is_polynomial(y)
True
sage: t.is_polynomial(sin(x))
True
```

is_positive()  
Return True if this expression is known to be positive.

EXAMPLES:

```python
sage: t0 = SR.symbol("t0", domain='positive')
sage: t0.is_positive()
True
sage: t0.is_negative()
False
sage: t0.is_real()
True
sage: t1 = SR.symbol("t1", domain='positive')
sage: (t0*t1).is_positive()
True
sage: (t0 + t1).is_positive()
True
sage: (t0*x).is_positive()
False
```
sage: forget()
sage: assume(x>0)
sage: x.is_positive()
True
sage: cosh(x).is_positive()
True
sage: f = function('f')(x)
sage: assume(f>0)
sage: f.is_positive()
True
sage: forget()

is_positive_infinity()
Return True if self is a positive infinite expression.

EXAMPLES:

sage: SR(oo).is_positive_infinity()
True
sage: SR(-oo).is_positive_infinity()
False
sage: x.is_infinity()
False

is_rational_expression()
Return True if this expression if a rational expression, i.e., a quotient of polynomials.

EXAMPLES:

sage: var('x y z')
(x, y, z)
sage: ((x + y + z)/(1 + x^2)).is_rational_expression()
True
sage: ((1 + x + y)^10).is_rational_expression()
True
sage: ((1/x + z)^5 - 1).is_rational_expression()
True
sage: (1/(x + y)).is_rational_expression()
True
sage: (exp(x) + 1).is_rational_expression()
False
sage: (sin(x*y) + z^3).is_rational_expression()
False
sage: (exp(x) + exp(-x)).is_rational_expression()
False

is_real()
Return True if this expression is known to be a real number.

EXAMPLES:

sage: t0 = SR.symbol("t0", domain='real')
sage: t0.is_real()
True
sage: t0.is_positive()
False
sage: t1 = SR.symbol("t1", domain='positive')
sage: (t0+t1).is_real()
True
sage: (t0+x).is_real()
False
sage: (t0*t1).is_real()
True
sage: t2 = SR.symbol("t2", domain='positive')
sage: (t1**t2).is_real()
True
sage: (t0*x).is_real()
False
sage: (t0^t1).is_real()
False
sage: (t1^t2).is_real()
True
sage: gamma(pi).is_real()
True
sage: cosh(-3).is_real()
True
sage: cos(exp(-3) + log(2)).is_real()
True
sage: gamma(t1).is_real()
True
sage: (x*pi).is_real()
False
sage: (cos(exp(t0) + log(t1))^8).is_real()
True
sage: cos(I + 1).is_real()
False
sage: sin(2 - I).is_real()
False
sage: (2^t0).is_real()
True

The following is real, but we cannot deduce that.:

sage: (x*x.conjugate()).is_real()
False

Assumption of real has the same effect as setting the domain:

sage: forget()
sage: assume(x, 'real')
sage: x.is_real()
True
sage: cosh(x).is_real()
True
sage: forget()

The real domain is also set with the integer domain:

sage: SR.var('x', domain='integer').is_real()
True

is_relational()
Return True if self is a relational expression.

EXAMPLES:
sage: x = var('x')
sage: eqn = (x-1)^2 == x^2 - 2*x + 3
sage: eqn.is_relational()
True
sage: sin(x).is_relational()
False

is_square()  
Returns True if self is a perfect square.

EXAMPLES:

sage: f(n,m) = n*2 + m
sage: f(2,1).is_square()
False
sage: f(3,3).is_square()
True
sage: f(n,m).is_square()
Traceback (most recent call last):
  ...
NotImplementedError: is_square() not implemented for non numeric elements of Symbolic Ring
sage: SR(42).is_square()
False
sage: SR(4).is_square()
True

is_symbol()  
Return True if this symbolic expression consists of only a symbol, i.e., a symbolic variable.

EXAMPLES:

sage: x.is_symbol()
True
sage: var('y')
y
sage: y.is_symbol()
True
sage: (x*y).is_symbol()
False
sage: pi.is_symbol()
False
sage: ((x+y)/y).is_symbol()
True
sage: (x^y).is_symbol()
False

is_terminating_series()  
Return True if self is a series without order term.

A series is terminating if it can be represented exactly, without requiring an order term. You can explicitly request terminating series by setting the order to positive infinity.

OUTPUT:
Boolean. Whether self was constructed by series() and has no order term.

EXAMPLES:
```python
sage: (x^5+x^2+1).series(x, +oo)
1 + 1*x^2 + 1*x^5
sage: (x^5+x^2+1).series(x,+oo).is_terminating_series()
True
sage: SR(5).is_terminating_series()
False
sage: var('x')
x
sage: x.is_terminating_series()
False
sage: exp(x).series(x,10).is_terminating_series()
False
```

**is_trivial_zero()**

Check if this expression is trivially equal to zero without any simplification.

This method is intended to be used in library code where trying to obtain a mathematically correct result by applying potentially expensive rewrite rules is not desirable.

**EXAMPLES:**

```python
sage: SR(0).is_trivial_zero()
True
sage: SR(0.0).is_trivial_zero()
True
sage: SR(float(0.0)).is_trivial_zero()
True
sage: (SR(1)/2^1000).is_trivial_zero()
False
sage: SR(1./2^10000).is_trivial_zero()
False
```

The **is_zero()** method is more capable:

```python
sage: t = pi + (pi - 1)*pi - pi^2
sage: t.is_trivial_zero()
False
sage: t.is_zero()
True
sage: t = pi + x*pi + (pi - 1 - x)*pi - pi^2
sage: t.is_zero()
True
sage: u = sin(x)^2 + cos(x)^2 - 1
sage: u.is_trivial_zero()
False
sage: u.is_zero()
True
```

**is_trivially_equal(other)**

Check if this expression is trivially equal to the argument expression, without any simplification.

Note that the expressions may still be subject to immediate evaluation.

This method is intended to be used in library code where trying to obtain a mathematically correct result by applying potentially expensive rewrite rules is not desirable.

**EXAMPLES:**
sage: (x^2).is_trivially_equal(x^2)
True
sage: ((x+1)^2 - 2*x - 1).is_trivially_equal(x^2)
False
sage: (x*(x+1)).is_trivially_equal((x+1)*x)
True
sage: (x^2 + x).is_trivially_equal((x+1)*x)
False
sage: ((x+1)*(x+1)).is_trivially_equal((x+1)^2)
True
sage: (x^2 + 2*x + 1).is_trivially_equal((x+1)^2)
False
sage: (x^-1).is_trivially_equal(1/x)
True
sage: (x/x^2).is_trivially_equal(1/x)
True
sage: ((x^2+x) / (x+1)).is_trivially_equal(1/x)
False

is_unit()
Return True if this expression is a unit of the symbolic ring.
Note that a proof may be attempted to get the result. To avoid this use (ex-1).is_trivial_zero().
EXAMPLES:

sage: SR(1).is_unit()
True
sage: SR(-1).is_unit()
True
sage: SR(0).is_unit()
False

iterator()
Return an iterator over the operands of this expression.
EXAMPLES:

sage: x,y,z = var('x,y,z')
sage: list((x+y+z).iterator())
[x, y, z]
sage: list((x*y*z).iterator())
[x, y, z]
sage: list((x^-y*z*(x+y)).iterator())
[x + y, x^-y, z]
Note that symbols, constants and numeric objects do not have operands, so the iterator function raises an
error in these cases:

sage: x.iterator()
Traceback (most recent call last):
  ... ValueError: expressions containing only a numeric coefficient, constant or symbol have no operands
sage: pi.iterator()
Traceback (most recent call last):
  ... ValueError: expressions containing only a numeric coefficient, constant or symbol have no operands

(continues on next page)
laplace\,(t,\,s)
Return Laplace transform of self. See sage.calculus.calculus.laplace

EXAMPLES:

```
sage: var('x,s,z')
(x, s, z)
sage: (z + exp(x)).laplace(x, s)
z/s + 1/(s - 1)
```

laurent_polynomial\,(base\_ring=None,\,ring=None)
Return this symbolic expression as a Laurent polynomial over the given base ring, if possible.

INPUT:

- base\_ring - (optional) the base ring for the polynomial
- ring - (optional) the parent for the polynomial

You can specify either the base ring (base\_ring) you want the output Laurent polynomial to be over, or you can specify the full laurent polynomial ring (ring) you want the output laurent polynomial to be an element of.

EXAMPLES:

```
sage: f = x^2 -2/3/x + 1
sage: f.laurent_polynomial(QQ)
-2/3*x^-1 + 1 + x^2
sage: f.laurent_polynomial(GF(19))
12*x^-1 + 1 + x^2
```

lcm\,(b)
Return the lcm of self and b.

The lcm is computed from the gcd of self and b implicitly from the relation self * b = gcd(self, b) * lcm(self, b).

**Note:** In agreement with the convention in use for integers, if self * b == 0, then gcd(self, b) == max(self, b) and lcm(self, b) == 0.

**Note:** Since the polynomial lcm is computed from the gcd, and the polynomial gcd is unique up to a constant factor (which can be negative), the polynomial lcm is unique up to a factor of -1.

EXAMPLES:

```
sage: var('x,y')
(x, y)
sage: SR(10).lcm(SR(15))
30
```

(continues on next page)
sage: (x^3 - 1).lcm(x-1)
x^3 - 1
sage: (x^3 - 1).lcm(x^2+x+1)
x^3 - 1
sage: (x^3 - sage.symbolic.constants.pi).lcm(x-sage.symbolic.constants.pi)
(pi - x^3)*(pi - x)
sage: lcm(x^3 - y^3, x-y) / (x^3 - y^3) in [1,-1]
True
sage: lcm(x^100-y^100, x^10-y^10) / (x^100 - y^100) in [1,-1]
True
sage: a = expand( (x^2+17*x+3/7*y)*(x^5 - 17*y + 2/3) )
sage: b = expand((x^13+17*x+3/7*y)*(x^5 - 17*y + 2/3) )
sage: gcd(a,b) * lcm(a,b) / (a * b) in [1,-1]
True

The result is not automatically simplified:

sage: ex = lcm(sin(x)^2 - 1, sin(x)^2 + sin(x)); ex
(sin(x)^2 + sin(x))*(sin(x)^2 - 1)/(sin(x) + 1)
sage: ex.simplify_full()
sin(x)^3 - sin(x)

leading_coeff(s)
Return the leading coefficient of s in self.

EXAMPLES:

sage: var('x,y,a')
(x, y, a)
sage: f = 100 + a*x + x^3*sin(x*y) + x*y + x/y + 2*sin(x*y)/x; f
x^3*sin(x*y) + a*x + x*y + x/y + 2*sin(x*y)/x + 100
sage: f.leading_coefficient(x)
sin(x*y)
sage: f.leading_coefficient(y)
x
sage: f.leading_coefficient(sin(x*y))
x^3 + 2/x

leading_coefficient(s)
Return the leading coefficient of s in self.

EXAMPLES:

sage: var('x,y,a')
(x, y, a)
sage: f = 100 + a*x + x^3*sin(x*y) + x*y + x/y + 2*sin(x*y)/x; f
x^3*sin(x*y) + a*x + x*y + x/y + 2*sin(x*y)/x + 100
sage: f.leading_coefficient(x)
sin(x*y)
sage: f.leading_coefficient(y)
x
sage: f.leading_coefficient(sin(x*y))
x^3 + 2/x

left()
If self is a relational expression, return the left hand side of the relation. Otherwise, raise a ValueError.

EXAMPLES:
```
sage: x = var('x')
sage: eqn = (x-1)^2 == x^2 - 2*x + 3
sage: eqn.left_hand_side()
(x - 1)^2
sage: eqn.lhs()
(x - 1)^2
sage: eqn.left()
(x - 1)^2
```

### `left_hand_side()`

If self is a relational expression, return the left hand side of the relation. Otherwise, raise a `ValueError`.

**EXAMPLES:**

```
sage: x = var('x')
sage: eqn = (x-1)^2 == x^2 - 2*x + 3
sage: eqn.left_hand_side()
(x - 1)^2
sage: eqn.lhs()
(x - 1)^2
sage: eqn.left()
(x - 1)^2
```

### `lhs()`

If self is a relational expression, return the left hand side of the relation. Otherwise, raise a `ValueError`.

**EXAMPLES:**

```
sage: x = var('x')
sage: eqn = (x-1)^2 == x^2 - 2*x + 3
sage: eqn.left_hand_side()
(x - 1)^2
sage: eqn.lhs()
(x - 1)^2
sage: eqn.left()
(x - 1)^2
```

### `limit(*args, **kwds)`

Return a symbolic limit. See `sage.calculus.calculus.limit`.

**EXAMPLES:**

```
sage: (sin(x)/x).limit(x=0)
1
```

### `list(x=None)`

Return the coefficients of this symbolic expression as a polynomial in x.

**INPUT:**

- x – optional variable.

**OUTPUT:**

A list of expressions where the n-th element is the coefficient of x^n when self is seen as polynomial in x.

**EXAMPLES:**

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\texttt{sage}: \texttt{var('x, y, a')}
\texttt{(x, y, a)}
\texttt{sage}: \texttt{(x^5).list()}
\texttt{[0, 0, 0, 0, 1]}  
\texttt{sage}: \texttt{p = x - x^3 + 5/7*x^5}
\texttt{sage}: \texttt{p.list()}
\texttt{[0, 1, 0, -1, 0, 5/7]}  
\texttt{sage}: \texttt{p = expand((x-a*sqrt(2))^2 + x + 1); p}
\texttt{-2*sqrt(2)*a*x + 2*a^2 + x^2 + x + 1}  
\texttt{sage}: \texttt{p.list(a)}
\texttt{[x^2 + x + 1, -2*sqrt(2)*x, 2]}  
\texttt{sage}: \texttt{s=(1/(1-x)).series(x,6); s}
\texttt{1 + x + 1*x^2 + 1*x^3 + 1*x^4 + 1*x^5 + Order(x^6)}  
\texttt{sage}: \texttt{s.list()}  
\texttt{[1, 1, 1, 1, 1, 1]}

\texttt{log}(b=None, \texttt{hold}=False)  
Return the logarithm of self.

\textbf{EXAMPLES:}

\texttt{sage}: \texttt{x, y = var('x, y')}  
\texttt{sage}: \texttt{x.log()}
\texttt{log(x)}  
\texttt{sage}: \texttt{(x\^{}y + y\^{}x).log()}
\texttt{log(x^y + y^x)}  
\texttt{sage}: \texttt{SR(0).log()}
\texttt{-Infinity}  
\texttt{sage}: \texttt{SR(-1).log()}
\texttt{I*pi}  
\texttt{sage}: \texttt{SR(1).log()}
\texttt{0}  
\texttt{sage}: \texttt{SR(1/2).log()}
\texttt{log(1/2)}  
\texttt{sage}: \texttt{SR(0.5).log()}
\texttt{-0.693147180559945}  
\texttt{sage}: \texttt{SR(0.5).log().exp()}
\texttt{0.500000000000000}  
\texttt{sage}: \texttt{math.log(0.5)}
\texttt{-0.6931471805599453}  
\texttt{sage}: \texttt{plot(\texttt{lambda x: SR(x).log()}, 0.1,10)}
\texttt{Graphics object consisting of 1 graphics primitive}

To prevent automatic evaluation use the \texttt{hold} argument:

\texttt{sage}: \texttt{I.log()}
\texttt{1/2*I*pi}  
\texttt{sage}: \texttt{I.log(hold=True)}
\texttt{log(I)}

To then evaluate again, we use \texttt{unhold()}:  

\texttt{sage}: \texttt{a = I.log(hold=True); a.unhold()}
\texttt{1/2*I*pi}

The \texttt{hold} parameter also works in functional notation:
**log Expand** *(algorithm='products')*
Simplify symbolic expression, which can contain logs.

Expands logarithms of powers, logarithms of products and logarithms of quotients. The option **algorithm** specifies which expression types should be expanded.

**INPUT:**

- **self** - expression to be simplified
- **algorithm** - (default: 'products') optional, governs which expression is expanded. Possible values are
  - 'nothing' (no expansion),
  - 'powers' (log(a^r) is expanded),
  - 'products' (like 'powers' and also log(a*b) are expanded),
  - 'all' (all possible expansion).

See also examples below.

**DETAILS:** This uses the Maxima simplifier and sets logexpand option for this simplifier. From the Maxima documentation: “Logexpand: true causes log(a^b) to become b*log(a). If it is set to all, log(a^b) will also simplify to log(a)+log(b). If it is set to super, then log(a/b) will also simplify to log(a)-log(b) for rational numbers a/b, a#1. (log(1/b), for integer b, always simplifies.) If it is set to false, all of these simplifications will be turned off.”

**ALIAS:** log_expand() and expand_log() are the same

**EXAMPLES:**

By default powers and products (and quotients) are expanded, but not quotients of integers:

```python
sage: (log(3/4*x^pi)).log_expand()
pi*log(x) + log(3/4)
```

To expand also log(3/4) use **algorithm='all'**:  
```python
sage: (log(3/4*x^pi)).log_expand('all')
pi*log(x) + log(3) - 2*log(2)
```

To expand only the power use **algorithm='powers'**:  
```python
sage: (log(x^6)).log_expand('powers')
6*log(x)
```

The expression log((3*x)^6) is not expanded with **algorithm='powers'**, since it is converted into product first:

```python
sage: (log((3*x)^6)).log_expand('powers')
log(729*x^6)
```

This shows that the option **algorithm** from the previous call has no influence to future calls (we changed some default Maxima flag, and have to ensure that this flag has been restored):
AUTHORS:

- Robert Marik (11-2009)

**log_gamma** *(hold=False)*

Return the log gamma function evaluated at self. This is the logarithm of gamma of self, where gamma is a complex function such that $\gamma(n)$ equals $\text{factorial}(n-1)$.

**EXAMPLES:**

```python
sage: x = var('x')
sage: x.log_gamma()
log_gamma(x)
sage: SR(2).log_gamma()
0
sage: SR(5).log_gamma()
log(24)
sage: a = SR(5).log_gamma(); a.n()
3.17805383034795
```

To prevent automatic evaluation use the `hold` argument:

```python
sage: SR(5).log_gamma(hold=True)
log_gamma(5)
```

To evaluate again, currently we must use numerical evaluation via `n()`:

```python
sage: a = SR(5).log_gamma(hold=True); a.n()
3.17805383034795
```

**log_simplify** *(algorithm=None)*

Simplify a (real) symbolic expression that contains logarithms.

The given expression is scanned recursively, transforming subexpressions of the form $a \log(b) + c \log(d)$ into $\log(b^a d^c)$ before simplifying within the $\log()$.

The user can specify conditions that $a$ and $c$ must satisfy before this transformation will be performed using the optional parameter `algorithm`. 
**Warning:** This is only safe to call if every variable in the given expression is assumed to be real. The simplification it performs is in general not valid over the complex numbers. For example:

```python
sage: x, y = SR.var('x, y')
sage: f = log(x*y) - (log(x) + log(y))
sage: f(x=-i, y=i)
-2*I*pi
sage: f.simplify_log()
0
```

**INPUT:**

- `self` - expression to be simplified
- `algorithm` - (default: None) optional, governs the condition on \(a\) and \(c\) which must be satisfied to contract expression \(a \log(b) + c \log(d)\). Values are
  - `None` (use Maxima default, integers),
  - `'one'` (1 and -1),
  - `'ratios'` (rational numbers),
  - `'constants'` (constants),
  - `'all'` (all expressions).

**ALGORITHM:**

This uses the Maxima `logcontract()` command.

**ALIAS:**

`log_simplify()` and `simplify_log()` are the same.

**EXAMPLES:**

```python
sage: x, y, t = var('x y t')
```

Only two first terms are contracted in the following example; the logarithm with coefficient \(\frac{1}{2}\) is not contracted:

```python
sage: f = log(x) + 2*log(y) + 1/2*log(t)
sage: f.simplify_log()
log(x*y^2) + 1/2*log(t)
```

To contract all terms in the previous example, we use the `'ratios'` algorithm:

```python
sage: f.simplify_log(algorithm='ratios')
log(sqrt(t)*x*y^2)
```

To contract terms with no coefficient (more precisely, with coefficients 1 and -1), we use the `'one'` algorithm:

```python
sage: f = log(x) + 2*log(y) - log(t)
sage: f.simplify_log('one')
2*log(y) + log(x/t)
```
\begin{deluxetable}{|l|l|
\hline
\texttt{sage}: & f = \log(x)+\log(y)-1/3\log((x+1)) \\
\texttt{sage}: & f.simplify_log() \\
& \log(x*y) - 1/3\log(x + 1) \\
\texttt{sage}: & f.simplify_log('ratios') \\
& \log(x*y/(x + 1)^{1/3}) \\
\hline
\end{deluxetable}

\(\pi\) is an irrational number; to contract logarithms in the following example we have to set \texttt{algorithm} to 'constants' or 'all':

\begin{deluxetable}{|l|l|
\hline
\texttt{sage}: & f = \log(x)+\log(y)-\pi\log((x+1)) \\
\texttt{sage}: & f.simplify_log('constants') \\
& \log(x*y/(x + 1)^{\pi}) \\
\hline
\end{deluxetable}

\(x*\log(9)\) is contracted only if \texttt{algorithm} is 'all':

\begin{deluxetable}{|l|l|
\hline
\texttt{sage}: & (x*\log(9)).simplify_log() \\
& 2*x*\log(3) \\
\texttt{sage}: & (x*\log(9)).simplify_log('all') \\
& \log(3^{(2*x)}) \\
\hline
\end{deluxetable}

\textbf{AUTHORS:}

- Robert Marik (11-2009)

\textbf{low\_degree}(s)

Return the exponent of the lowest nonpositive power of s in self.

\textbf{OUTPUT:}

An integer \(\leq 0\).

\textbf{EXAMPLES:}

\begin{deluxetable}{|l|l|
\hline
\texttt{sage}: & \texttt{var}(\'x,y,a\') \\
& (x, y, a) \\
\texttt{sage}: & f = 100 + a*x + x^3*\sin(x*y) + x*y + x/y^{10} + 2*\sin(x*y)/x; f \\
& x^3*\sin(x*y) + a*x + x*y + 2*\sin(x*y)/x + x/y^{10} + 100 \\
\texttt{sage}: & f.low\_degree(x) \\
& -1 \\
\texttt{sage}: & f.low\_degree(y) \\
& -10 \\
\texttt{sage}: & f.low\_degree(\sin(x*y)) \\
& 0 \\
\texttt{sage}: & (x^3+y).low\_degree(x) \\
& 0 \\
\hline
\end{deluxetable}

\textbf{match}(\textit{pattern})

Check if self matches the given pattern.

\textbf{INPUT:}

- \textit{pattern} – a symbolic expression, possibly containing wildcards to match for

\textbf{OUTPUT:}

One of

None if there is no match, or a dictionary mapping the wildcards to the matching values if a match was found. Note that the dictionary is empty if there were no wildcards in the given pattern.

See also \url{http://www.ginac.de/tutorial/Pattern-matching-and-advanced-substitutions.html}
EXAMPLES:

```
sage: var('x,y,z,a,b,c,d,f,g')
(x, y, z, a, b, c, d, f, g)
sage: w0 = SR.wild(0); w1 = SR.wild(1); w2 = SR.wild(2)
sage: ((x+y)^a).match((x+y)^a)  # no wildcards, so empty dict
{}
sage: print(((x+y)^a).match((x+y)^b))
None
sage: t = ((x+y)^a).match(w0^w1)
sage: t[w0], t[w1]
(x + y, a)
sage: print(((x+y)^a).match(w0^w0))
None
sage: ((x+y)^a)(x+y).match(w0^w0)
{w0: x + y}
sage: t = ((a+b)*(a+c)).match((a+w0)*(a+w1))
sage: set([t[w0], t[w1]]) == set([b, c])
True
sage: ((a+b)*(a+c)).match((w0+b)*(w0+c))
{w0: a}
sage: t = ((a+b)*(a+c)).match((w0+w1)*(w0+w2))
sage: t[w0]
a
sage: set([t[w1], t[w2]]) == set([b, c])
True
sage: t = ((a+b)*(a+c)).match((w0+w1)*(w1+w2))
sage: t[w1]
a
sage: set([t[w0], t[w2]]) == set([b, c])
True
sage: t = (a*(x+y)+a*z+b).match(a*w0+w1)
sage: s = set([t[w0], t[w1]])
sage: s == set([x+y, a*z+b]) or s == set([z, a*(x+y)+b])
True
sage: print((a+b+c+d+f+g).match(c))
None
sage: (a+b+c+d+f+g).has(c)
True
sage: (a+b+c+d+f+g).match(c+w0)
{w0: a + b + d + f + g}
sage: (a+b+c+d+f+g).match(c+g+w0)
{w0: a + b + d + f}
sage: (a+b).match(a+b+w0)  # known bug
{w0: 0}
sage: print((a+b^2).match(a^w0+b^w1))
None
sage: (a+b^2).match(a+b^w1)
{w1: 2}
sage: (x+x.arctan2(x^2)).match(w0*w0.arctan2(w0^2))
{w0: x}
```

Beware that behind-the-scenes simplification can lead to surprising results in matching:

```
sage: print((x+x).match(w0+w1))
None
sage: t = x+x; t
2*x
(continues on next page)
```
Since asking to match w0+w1 looks for an addition operator, there is no match.

**maxima_methods()**
Provide easy access to maxima methods, converting the result to a Sage expression automatically.

**EXAMPLES:**

```plaintext
sage: t = log(sqrt(2) - 1) + log(sqrt(2) + 1); t
log(sqrt(2) + 1) + log(sqrt(2) - 1)
sage: res = t.maxima_methods().logcontract(); res
log((sqrt(2) + 1)*(sqrt(2) - 1))
sage: type(res)
<type 'sage.symbolic.expression.Expression'>
```

**minpoly(*args, **kwds)**
Return the minimal polynomial of this symbolic expression.

**EXAMPLES:**

```plaintext
sage: golden_ratio.minpoly()
x^2 - x - 1
```

**mul(**hold=False, **args)**
Return the product of the current expression and the given arguments.

To prevent automatic evaluation use the hold argument.

**EXAMPLES:**

```plaintext
sage: x.mul(x)
x^2
sage: x.mul(x, hold=True)
x*x
sage: x.mul(x, (2+x), hold=True)
(x + 2)*x*x
sage: x.mul(x, (2+x), x, hold=True)
(x + 2)*x*x*x
sage: x.mul(x, (2+x), x, 2*x, hold=True)
(2*x)*(x + 2)*x*x*x
```

To then evaluate again, we use unhold():

```plaintext
sage: a = x.mul(x, hold=True); a.unhold()
x^2
```

**multiply_both_sides** (**x, checksign=None**)
Return a relation obtained by multiplying both sides of this relation by x.

**Note:** The checksign keyword argument is currently ignored and is included for backward compatibility reasons only.

**EXAMPLES:**
Since the direction of the inequality never changes when doing arithmetic with equations, you can multiply or divide the equation by a quantity with unknown sign:

| sage: f*(1+I) |
| (I + 1)*x + 3*I + 3 < (I + 1)*y - 2*I - 2 |
| sage: f = sqrt(2) + x == y^3 |
| sage: f.multiply_both_sides(I) |
| I*x + I*sqrt(2) == I*y^3 |
| sage: f.multiply_both_sides(-1) |
| -x - sqrt(2) == -y^3 |

Note that the direction of the following inequalities is not reversed:

| sage: (x^3 + 1 > 2*sqrt(3)) * (-1) |
| -x^3 - 1 > -2*sqrt(3) |
| sage: (x^3 + 1 >= 2*sqrt(3)) * (-1) |
| -x^3 - 1 >= -2*sqrt(3) |
| sage: (x^3 + 1 <= 2*sqrt(3)) * (-1) |
| -x^3 - 1 <= -2*sqrt(3) |

**negation()**

Return the negated version of self, that is the relation that is False iff self is True.

**EXAMPLES:**

| sage: (x < 5).negation() |
| x >= 5 |
| sage: (x == sin(3)).negation() |
| x != sin(3) |
| sage: (2*x >= sqrt(2)).negation() |
| 2*x < sqrt(2) |

**nintegral(*args, **kwds)**

Compute the numerical integral of self. Please see `sage.calculus.calculus.nintegral` for more details.

**EXAMPLES:**

| sage: sin(x).nintegral(x, 0, 3) |
| (1.989992496600..., 2.209335488557...e-14, 21, 0) |

**nintegrate(*args, **kwds)**

Compute the numerical integral of self. Please see `sage.calculus.calculus.nintegral` for more details.

**EXAMPLES:**
sage: sin(x).nintegral(x, 0, 3)
(1.989992496600..., 2.209335488557...e-14, 21, 0)

\section*{\texttt{nops} ()}

Return the number of arguments of this expression.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: var('a,b,c,x,y')
(a, b, c, x, y)
sage: a.n(number_of_operands())
0
sage: (a^2 + b^2 + (x+y)^2).number_of_operands()
3
sage: (a^2).number_of_operands()
2
sage: (a+b^2*c).number_of_operands()
3
\end{verbatim}

\section*{\texttt{norm} ()}

Return the complex norm of this symbolic expression, i.e., the expression times its complex conjugate. If \( c = a + bi \) is a complex number, then the norm of \( c \) is defined as the product of \( c \) and its complex conjugate

\[
\text{norm}(c) = \text{norm}(a + bi) = c \cdot \bar{c} = a^2 + b^2.
\]

The norm of a complex number is different from its absolute value. The absolute value of a complex number is defined to be the square root of its norm. A typical use of the complex norm is in the integral domain \( \mathbb{Z}[i] \) of Gaussian integers, where the norm of each Gaussian integer \( c = a + bi \) is defined as its complex norm.

\textbf{See also:}

\texttt{sage.misc.functional.norm()}

\textbf{EXAMPLES:}

\begin{verbatim}
sage: a = 1 + 2*I
sage: a.norm()
5
sage: a = sqrt(2) + 3^(1/3)*I; a
sqrt(2) + I*3^(1/3)
sage: a.norm()
3^(2/3) + 2
sage: CDF(a).norm()
4.080083823051...
sage: CDF(a.norm())
4.080083823051904
\end{verbatim}

\section*{\texttt{normalize} ()}

Return this expression normalized as a fraction

\textbf{See also:}

\texttt{numerator()}, \texttt{denominator()}, \texttt{numerator_denominator()}, \texttt{combine()}

\textbf{EXAMPLES:}

\begin{verbatim}
sage: var('x, y, a, b, c')
(x, y, a, b, c)
\end{verbatim}
\begin{verbatim}
 sage: g = x + y/(x + 2)
sage: g.normalize()
(x^2 + 2*x + y)/(x + 2)

 sage: f = x*(x-1)/(x^2 - 7) + y^2/(x^2-7) + 1/(x+1) + b/a + c/a
 sage: f.normalize()
(a*x^3 + b*x^3 + c*x^3 + a*x*y^2 + a*x^2 + b*x^2 + c*x^2 +
 a*y^2 - a*x - 7*b*x - 7*c*x - 7*a - 7*b - 7*c)/((x^2 - 7)*a*(x + 1))
\end{verbatim}

**ALGORITHM:** Uses GiNaC.

\textbf{number\_of\_arguments} ()

**EXAMPLES:**

\begin{verbatim}
 sage: x, y = var('x,y')
sage: f = x + y
 sage: f.number_of_arguments()
2

 sage: g = f.function(x)
sage: g.number_of_arguments()
1

 sage: x, y, z = var('x,y,z')
sage: (x+y).number_of_arguments()
2
 sage: (x+1).number_of_arguments()
1
 sage: (sin(x)+1).number_of_arguments()
1
 sage: (sin(z)+x+y).number_of_arguments()
3
 sage: (sin(x+y)).number_of_arguments()
2
\end{verbatim}

\begin{verbatim}
 sage: ( 2^(8/9) - 2^(1/9) )(x-1)
Traceback (most recent call last):
 ... 
ValueError: the number of arguments must be less than or equal to 0
\end{verbatim}

\textbf{number\_of\_operands} ()

**Return the number of arguments of this expression.**

**EXAMPLES:**

\begin{verbatim}
 sage: var('a,b,c,x,y')
(a, b, c, x, y)
sage: a.number_of_operands()
0
 sage: (a^2 + b^2 + (x+y)^2).number_of_operands()
3
 sage: (a^2).number_of_operands()
2
 sage: (a*b^2*c).number_of_operands()
3
\end{verbatim}
\textbf{numerator} \textit{(normalize=True)}

Return the numerator of this symbolic expression

INPUT:

- \texttt{normalize} – (default: True) a boolean.

If \texttt{normalize} is True, the expression is first normalized to have it as a fraction before getting the numerator.

If \texttt{normalize} is False, the expression is kept and if it is not a quotient, then this will return the expression itself.

See also:

\texttt{normalize()}, \texttt{denominator()}, \texttt{numerator_denominator()}, \texttt{combine()}

\textbf{EXAMPLES:}

\begin{verbatim}
sage: a, x, y = var('a,x,y')
sage: f = x*(x-a)/((x^2 - y)*(x-a)); f
x/(x^2 - y)
sage: f.numerator()
x
sage: f.denominator()
x^2 - y
sage: f.numerator(normalize=False)
x
sage: f.denominator(normalize=False)
x^2 - y
sage: y = var('y')
sage: g = x + y/(x + 2); g
x + y/(x + 2)
sage: g.numerator()
x^2 + 2*x + y
sage: g.denominator()
x + 2
sage: g.numerator(normalize=False)
x + y/(x + 2)
sage: g.denominator(normalize=False)
1
\end{verbatim}

\textbf{numerator_denominator} \textit{(normalize=True)}

Return the numerator and the denominator of this symbolic expression

INPUT:

- \texttt{normalize} – (default: True) a boolean.

If \texttt{normalize} is True, the expression is first normalized to have it as a fraction before getting the numerator and denominator.

If \texttt{normalize} is False, the expression is kept and if it is not a quotient, then this will return the expression itself together with 1.

See also:

\texttt{normalize()}, \texttt{numerator()}, \texttt{denominator()}, \texttt{combine()}

\textbf{EXAMPLES:}

\begin{verbatim}
sage: a, x, y = var('a,x,y')
sage: f = x*(x-a)/((x^2 - y)*(x-a)); f
x/(x^2 - y)
sage: f.numerator()
x
sage: f.denominator()
x^2 - y
sage: f.numerator(normalize=False)
x
sage: f.denominator(normalize=False)
x^2 - y
sage: y = var('y')
sage: g = x + y/(x + 2); g
x + y/(x + 2)
sage: g.numerator()
x^2 + 2*x + y
sage: g.denominator()
x + 2
sage: g.numerator(normalize=False)
x + y/(x + 2)
sage: g.denominator(normalize=False)
1
\end{verbatim}
sage: x, y, a = var("x y a")
sage: ((x+y)^2/(x-y)^3*x^3).numerator_denominator()
((x + y)^2*x^3, (x - y)^3)
sage: ((x+y)^2/(x-y)^3*x^3).numerator_denominator(False)
((x + y)^2*x^3, (x - y)^3)
sage: g = x + y/(x + 2)
sage: g.numerator_denominator()
(x^2 + 2*x + y, x + 2)
sage: g.numerator_denominator(normalize=False)
(x + y/(x + 2), 1)
sage: g = x^2*(x + 2)
sage: g.numerator_denominator()
((x + 2)*x^2, 1)
sage: g.numerator_denominator(normalize=False)
((x + 2)*x^2, 1)

numerical_approx(prec=None, digits=None, algorithm=None)

Return a numerical approximation of self with prec bits (or decimal digits) of precision.

No guarantee is made about the accuracy of the result.

INPUT:

• prec – precision in bits
• digits – precision in decimal digits (only used if prec is not given)
• algorithm – which algorithm to use to compute this approximation

If neither prec nor digits is given, the default precision is 53 bits (roughly 16 digits).

EXAMPLES:

sage: sin(x).subs(x=5).n()
-0.958924274663138
sage: sin(x).subs(x=5).n(100)
-0.95892427466313846889315440616
sage: sin(x).subs(x=5).n(digits=50)
-0.9589242746631384688931544061559397335246154396460
sage: zeta(x).subs(x=2).numerical_approx(digits=50)
1.6449340668482264364724151666460251892189499012068
sage: cos(3).numerical_approx(200)
-0.98999249660044545727157279473126130239367909661558832881409
sage: numerical_approx(cos(3), 200)
-0.98999249660044545727157279473126130239367909661558832881409
sage: numerical_approx(cos(3), digits=10)
-0.9899924966
sage: (i + 1).numerical_approx(32)
1.00000000 + 1.00000000*I
sage: (pi + e + sqrt(2)).numerical_approx(100)
7.2740880444219335226246195788

op

Provide access to the operands of an expression through a property.

EXAMPLES:
sage: t = 1+x+x^2
sage: t.op
Operands of x^2 + x + 1
sage: x.op
Traceback (most recent call last):
  ...TypeError: expressions containing only a numeric coefficient, constant or
  →symbol have no operands
sage: t.op[0]
x^2

Indexing directly with \mathtt{t[1]} causes problems with numpy types.

sage: t[1] Traceback (most recent call last): ...TypeError: 'sage.symbolic.expression.Expression' object ...

\texttt{operands}()

Return a list containing the operands of this expression.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: var('a,b,c,x,y')
(a, b, c, x, y)
sage: (a^2 + b^2 + (x+y)^2).operands()
[a^2, b^2, (x + y)^2]
sage: (a^2).operands()
[a, 2]
sage: (a*b^2*c).operands()
[a, b^2, c]
\end{verbatim}

\texttt{operator}()

Return the topmost operator in this expression.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: x,y,z = var('x,y,z')
sage: (x+y).operator()
<function add_vararg ...>
sage: (x^y).operator()
<built-in function pow>
sage: (x^y * z).operator()
<function mul_vararg ...>
sage: (x < y).operator()
<built-in function lt>
sage: abs(x).operator()
abs
sage: r = gamma(x).operator(); type(r)
<class 'sage.functions.gamma.Function_gamma'>
sage: psi = function('psi', nargs=1)
sage: psi(x).operator()
psi
sage: r = psi(x).operator()
sage: r == psi
True
\end{verbatim}
sage: f = function('f', nargs=1, conjugate_func=lambda self, x: 2*x)
sage: nf = f(x).operator()
sage: nf(x).conjugate()
2*x

sage: f = function('f')
sage: a = f(x).diff(x); a; diff(f(x), x)
diff(f(x), x)

partial_fraction(var=None)
Return the partial fraction expansion of self with respect to the given variable.

INPUT:
• var – variable name or string (default: first variable)

OUTPUT:
A symbolic expression

See also:
partial_fraction_decomposition()

EXAMPLES:

sage: f = x^2/(x+1)^3
sage: f.partial_fraction()
l/(x + 1) - 2/(x + 1)^2 + 1/(x + 1)^3

Notice that the first variable in the expression is used by default:

sage: y = var('y')
sage: f = y^2/(y+1)^3
sage: f.partial_fraction()
l/(y + 1) - 2/(y + 1)^2 + 1/(y + 1)^3
sage: f = y^2/(y+1)^3 + x/(x-1)^3
sage: f.partial_fraction()
y^2/(y^3 + 3*y^2 + 3*y + 1) + 1/(x - 1)^2 + 1/(x - 1)^3

You can explicitly specify which variable is used:

sage: f.partial_fraction(y)
x/(x^3 - 3*x^2 + 3*x - 1) + 1/(y + 1) - 2/(y + 1)^2 + 1/(y + 1)^3

partial_fraction_decomposition(var=None)
Return the partial fraction decomposition of self with respect to the given variable.

INPUT:
• var – variable name or string (default: first variable)

OUTPUT:
A list of symbolic expressions

See also:
partial_fraction()
EXAMPLES:

```
sage: f = x^2/(x+1)^3
sage: f.partial_fraction_decomposition()
[1/(x + 1), -2/(x + 1)^2, (x + 1)^(-3)]
sage: (4+f).partial_fraction_decomposition()
[1/(x + 1), -2/(x + 1)^2, (x + 1)^(-3), 4]
```

Notice that the first variable in the expression is used by default:

```
sage: y = var('y')
sage: f = y^2/(y+1)^3
sage: f.partial_fraction_decomposition()
[1/(y + 1), -2/(y + 1)^2, (y + 1)^(-3)]
```

You can explicitly specify which variable is used:

```
sage: f.partial_fraction_decomposition(y)
[1/(y + 1), -2/(y + 1)^2, (y + 1)^(-3), x/(x^3 - 3*x^2 + 3*x - 1)]
```

```
plot(*args, **kwds)
Plot a symbolic expression. All arguments are passed onto the standard plot command.
```

EXAMPLES:

This displays a straight line:

```
sage: sin(2).plot((x,0,3))
```

This draws a red oscillatory curve:

```
sage: sin(x^2).plot((x,0,2*pi), rgbcolor=(1,0,0))
```

Another plot using the variable theta:

```
sage: var('theta')
theta
sage: (cos(theta) - erf(theta)).plot((theta,-2*pi,2*pi))
```

A very thick green plot with a frame:

```
sage: sin(x).plot((x,-4*pi, 4*pi), thickness=20, rgbcolor=(0,0.7,0)).show(frame=True)
```

You can embed 2d plots in 3d space as follows:

```
sage: plot(sin(x^2), (x,-pi, pi), thickness=2).plot3d(z = 1)  # long time
```

A more complicated family:
A plot involving the floor function:

```sage
g = plot(1.0 - x * floor(1/x), (x,0.00001,1.0))
Graphics object consisting of 1 graphics primitive
```

Sage used to allow symbolic functions with “no arguments”; this no longer works:

```sage
g = plot(2*sin, -4, 4)
Traceback (most recent call last):
  ...TypeError: unsupported operand parent(s) for *: 'Integer Ring' and '<class 'sage.functions.trig.Function_sin'>'
```

You should evaluate the function first:

```sage
g = plot(2*sin(x), -4, 4)
Graphics object consisting of 1 graphics primitive
```

**poly** *(x=None)*

Express this symbolic expression as a polynomial in \(x\). If this is not a polynomial in \(x\), then some coefficients may be functions of \(x\).

**Warning:** This is different from **polynomial()** which returns a Sage polynomial over a given base ring.

**EXAMPLES:**

```sage
def poly(x):
    p = (x-a*sqrt(2))^2 + x + 1
    return p
```

```sage
g = poly(a)
g = poly(x)
g = poly(y)
```

**polynomial** *(base_ring=None, ring=None)*

Return this symbolic expression as an algebraic polynomial over the given base ring, if possible.

The point of this function is that it converts purely symbolic polynomials into optimised algebraic polynomials over a given base ring.

You can specify either the base ring (\(base\_ring\)) you want the output polynomial to be over, or you can specify the full polynomial ring (\(ring\)) you want the output polynomial to be an element of.

**INPUT:**

- **base_ring** *(optional)* the base ring for the polynomial
- **ring** *(optional)* the parent for the polynomial
Warning: This is different from `poly()` which is used to rewrite self as a polynomial in terms of one of the variables.

EXAMPLES:

```
sage: f = x^2 -2/3*x + 1
sage: f.polynomial(QQ)
x^2 - 2/3*x + 1
sage: f.polynomial(GF(19))
x^2 + 12*x + 1
```

Polynomials can be useful for getting the coefficients of an expression:

```
sage: g = 6*x^2 - 5
sage: g.coefficients()
[(2, 1), (5, 0)]
sage: g.polynomial(QQ).list()
[0, 5, 6]
sage: g.polynomial(QQ).dict()
{0: 0, 2: 5}
```

```
sage: f = x^2*e + x + pi/e
sage: f.polynomial(RDF)  # abs tol 5e-16
2.718281828459045*x^2 + x + 1.1557273497909217
sage: g = f.polynomial(RR); g
2.71828182845905*x^2 + x + 1.15572734979092
sage: g.parent()
Univariate Polynomial Ring in x over Real Field with 53 bits of precision
sage: f.polynomial(ComplexField(100))
2.7182818284590452354*x^2 + x + 1.155727349790920178
```

We coerce a multivariate polynomial with complex symbolic coefficients:

```
sage: x, y, n = var('x, y, n')
sage: f = pi^3*x - y^2*e - I; f
pi^3*x - y^2*e - I
sage: f.polynomial(CDF)  # abs tol 5e-16
(-2.718281828459045)*y^2 + 31.0062766802874714*x^2 + x + 1.155727349790921717910093183
```

Another polynomial:

```
sage: f = sum((e*I)^n*x^n for n in range(5)); f
x^4*e^4 - I*x^3*e^3 - x^2*e^2 + I*x*e + 1
sage: f.polynomial(CDF)  # abs tol 5e-16
54.598150033144236*x^4 - 20.085536923187668*I*x^3 - 7.38905609893065*x^2 + 2.
```

(continues on next page)
A multivariate polynomial over a finite field:

```python
sage: f = (3*x^5 - 5*y^5)^7; f
(3*x^5 - 5*y^5)^7
sage: g = f.polynomial(GF(7)); g
3*x^35 + 2*y^35
sage: parent(g)
Multivariate Polynomial Ring in x, y over Finite Field of size 7
```

We check to make sure constants are converted appropriately:

```python
sage: (pi*x).polynomial(SR)
pi*x
```

Using the `ring` parameter, you can also create polynomials rings over the symbolic ring where only certain variables are considered generators of the polynomial ring and the others are considered “constants”:

```python
sage: a, x, y = var('a,x,y')
sage: f = a*x^10*y+3*x
sage: B = f.polynomial(ring=SR['x,y'])
sage: B.coefficients()
[a, 3]
```

**power** *(exp, hold=False)*

Return the current expression to the power `exp`.

To prevent automatic evaluation use the `hold` argument.

**EXAMPLES:**

```python
sage: (x^2).power(2)
x^4
sage: (x^2).power(2, hold=True)
(x^2)^2
```

To then evaluate again, we use `unhold()`:

```python
sage: a = (x^2).power(2, hold=True); a.unhold()
x^4
```

**power_series**(base_ring)

Return algebraic power series associated to this symbolic expression, which must be a polynomial in one variable, with coefficients coercible to the base ring.

The power series is truncated one more than the degree.

**EXAMPLES:**

```python
sage: theta = var('theta')
sage: f = theta^3 + (1/3)*theta - 17/3
sage: g = f.power_series(QQ); g
-17/3 + 1/3*theta + theta^3 + O(theta^4)
sage: g^3
-4913/27 + 289/9*theta - 17/9*theta^2 + 2602/27*theta^3 + O(theta^4)
```
**primitive_part** (s)
Return the primitive polynomial of this expression when considered as a polynomial in s.

See also unit(), content(), and unit_content_primitive().

**INPUT:**

• s – a symbolic expression.

**OUTPUT:**

The primitive polynomial as a symbolic expression. It is defined as the quotient by the unit() and content() parts (with respect to the variable s).

**EXAMPLES:**

```sage```
(2*x+4).primitive_part(x)
```
x + 2
```

```sage```
(2*x+1).primitive_part(x)
```
2*x + 1
```

```sage```
(2*x+1/2).primitive_part(x)
```
\( \frac{4}{\pi}x + 1 \)

```sage```
var('y')
y
```sage```
(2*x + 4*sin(y)).primitive_part(sin(y))
```
x + 2*sin(y)
```

**prod** (*args, **kwds)
Return the symbolic product \( \prod_{v=a}^{b} expression \) with respect to the variable \( v \) with endpoints \( a \) and \( b \).

**INPUT:**

• expression - a symbolic expression
• v - a variable or variable name
• a - lower endpoint of the product
• b - upper endpoint of the product
• algorithm - (default: 'maxima') one of
  – 'maxima' - use Maxima (the default)
  – 'giac' - (optional) use Giac
  – 'sympy' - use SymPy
• hold - (default: False) if True don’t evaluate

**pyobject** ()
Get the underlying Python object.

**OUTPUT:**

The Python object corresponding to this expression, assuming this expression is a single numerical value or an infinity representable in Python. Otherwise, a TypeError is raised.

**EXAMPLES:**
Integers and Rationals are converted internally though, so you won’t get back the same object:

```
sage: b = -17/3
sage: a = SR(b)
sage: a.pyobject()
-17/3
sage: a.pyobject() is b
False
```

**rational_expand** *(side=None)*

Expand this symbolic expression. Products of sums and exponentiated sums are multiplied out, numerators of rational expressions which are sums are split into their respective terms, and multiplications are distributed over addition at all levels.

**EXAMPLES:**

We expand the expression \((x - y)^5\) using both method and functional notation.

```
sage: x, y = var('x, y')
sage: a = (x-y)^5
sage: a.expand()
x^5 - 5*x^4*y + 10*x^3*y^2 - 10*x^2*y^3 + 5*x*y^4 - y^5
sage: expand(a)
x^5 - 5*x^4*y + 10*x^3*y^2 - 10*x^2*y^3 + 5*x*y^4 - y^5
```

We expand some other expressions:

```
sage: expand((x-1)^3/(y-1))
x^3/(y - 1) - 3*x^2/(y - 1) + 3*x/(y - 1) - 1/(y - 1)
sage: expand((x+sin((x+y)^2))^2)
x^2 + 2*x*sin(x^2 + 2*x*y + y^2) + sin(x^2 + 2*x*y + y^2)^2
```

Observe that **expand()** also expands function arguments:

```
sage: f(x) = function('f')(x)
sage: fx = f(x*(x+1)); fx
f((x + 1)*x)
sage: fx.expand()
f(x^2 + x)
```

We can expand individual sides of a relation:

```
sage: a = (16*x-13)^2 == (3*x+5)^2/2
sage: a.expand()
256*x^2 - 416*x + 169 == 9/2*x^2 + 15*x + 25/2
sage: a.expand('left')
256*x^2 - 416*x + 169 == 1/2*(3*x + 5)^2
sage: a.expand('right')
(16*x - 13)^2 == 9/2*x^2 + 15*x + 25/2
```
rational_simplify\(\texttt{(algorithm='full', map=False)}\)
Simplify rational expressions.

INPUT:

- **self** - symbolic expression
- **algorithm** - (default: ‘full’) string which switches the algorithm for simplifications. Possible values are
  - ‘simple’ (simplify rational functions into quotient of two polynomials),
  - ‘full’ (apply repeatedly, if necessary)
  - ‘noexpand’ (convert to common denominator and add)
- **map** - (default: False) if True, the result is an expression whose leading operator is the same as that of the expression self but whose subparts are the results of applying simplification rules to the corresponding subparts of the expressions.

ALIAS: rational_simplify() and simplify_rational() are the same

DETAILS: We call Maxima functions ratsimp, fullratsimp and xthru. If each part of the expression has to be simplified separately, we use Maxima function map.

EXAMPLES:

```python
sage: f = sin(x/(x^2 + x))
sage: f
sin(x/(x^2 + x))
sage: f.simplify_rational()
sin(1/(x + 1))
```

```python
sage: f = ((x - 1)^(3/2) - (x + 1)*sqrt(x - 1))/sqrt((x - 1)*(x + 1)); f
-((x + 1)*sqrt(x - 1) - (x - 1)^(3/2))/sqrt((x + 1)*(x - 1))
sage: f.simplify_rational()
-2*sqrt(x - 1)/sqrt(x^2 - 1)
```

With map=True each term in a sum is simplified separately and thus the resuls are shorter for functions which are combination of rational and nonrational functions. In the following example, we use this option if we want not to combine logarithm and the rational function into one fraction:

```python
sage: f = (x^2-1)/(x+1)-ln(x)/(x+2)
sage: f.simplify_rational()
(x^2 + x - log(x) - 2)/(x + 2)
sage: f.simplify_rational(map=True)
x - log(x)/(x + 2) - 1
```

Here is an example from the Maxima documentation of where algorithm='simple' produces an (possibly useful) intermediate step:

```python
sage: y = var('y')
sage: g = (x^(y/2) + 1)^2*(x^(y/2) - 1)^2/(x^y - 1)
sage: g.simplify_rational(algorithm='simple')(x^2*y - 2*x^y + 1)/(x^y - 1)
sage: g.simplify_rational()
x^y - 1
```

With option algorithm='noexpand' we only convert to common denominators and add. No expansion of products is performed:
\texttt{sage} f=1/(x+1)+x/(x+2)^2
\texttt{sage} f.simplify_rational()
\frac{(2+5x+x^3+5x^2+8x+4)}{x^3+5x^2+8x+4}
\texttt{sage} f.simplify_rational(algorithm='noexpand')
\frac{(x+2)^2+(x+1)x}{(x+2)^2(x+1)}

\texttt{real} (\texttt{hold}=False)

Return the real part of this symbolic expression.

EXAMPLES:

\texttt{sage} x = var('x')
\texttt{sage} x.real_part()
real_part(x)
\texttt{sage} SR(2+3*I).real_part()
2
\texttt{sage} SR(CDF(2,3)).real_part()
2.0
\texttt{sage} SR(CC(2,3)).real_part()
2.00000000000000
\texttt{sage} f = log(x)
\texttt{sage} f.real_part()
\log(abs(x))

Using the \texttt{hold} parameter it is possible to prevent automatic evaluation:

\texttt{sage} SR(2).real_part()
2
\texttt{sage} SR(2).real_part(hold=True)
real_part(2)

This also works using functional notation:

\texttt{sage} real_part(I,hold=True)
real_part(I)
\texttt{sage} real_part(I)
0

To then evaluate again, we use \texttt{unhold():}

\texttt{sage} a = SR(2).real_part(hold=True); a.unhold()
2

\texttt{real_part} (\texttt{hold}=False)

Return the real part of this symbolic expression.

EXAMPLES:

\texttt{sage} x = var('x')
\texttt{sage} x.real_part()
real_part(x)
\texttt{sage} SR(2+3*I).real_part()
2
\texttt{sage} SR(CDF(2,3)).real_part()
2.0
\texttt{sage} SR(CC(2,3)).real_part()
2.00000000000000

(continues on next page)
sage: f = log(x)
sage: f.real_part()
log(abs(x))

Using the \texttt{hold} parameter it is possible to prevent automatic evaluation:

sage: SR(2).real_part()
2
sage: SR(2).real_part(hold=True)
real_part(2)

This also works using functional notation:

sage: real_part(I, hold=True)
real_part(I)
sage: real_part(I)
0

To then evaluate again, we use \texttt{unhold()}:

sage: a = SR(2).real_part(hold=True); a.unhold()
2

\texttt{rectform()}
Convert this symbolic expression to rectangular form; that is, the form $a + bi$ where $a$ and $b$ are real numbers and $i$ is the imaginary unit.

\textbf{Note:} The name “rectangular” comes from the fact that, in the complex plane, $a$ and $bi$ are perpendicular.

\textbf{INPUT:}

- \texttt{self} – the expression to convert.

\textbf{OUTPUT:}

A new expression, equivalent to the original, but expressed in the form $a + bi$.

\textbf{ALGORITHM:}

We call Maxima’s \texttt{rectform()} and return the result unmodified.

\textbf{EXAMPLES:}

The exponential form of $\sin(x)$:

sage: f = (e^(I*x) - e^(-I*x)) / (2*I)
sage: f.rectform()
sin(x)

And $\cos(x)$:

sage: f = (e^(I*x) + e^(-I*x)) / 2
sage: f.rectform()
\cos(x)

In some cases, this will simplify the given expression. For example, here, $e^{ik\pi}$, $\sin(k\pi) = 0$ should cancel leaving only $\cos(k\pi)$ which can then be simplified:
sage: k = var('k')
sage: assume(k, 'integer')
sage: f = e^(I*pi*k)
sage: f.rectform()
(-1)^k

However, in general, the resulting expression may be more complicated than the original:

sage: f = e^(I*x)
sage: f.rectform()
\cos(x) + I\sin(x)

**reduce_trig** (var=None)

Combine products and powers of trigonometric and hyperbolic sin’s and cos’s of x into those of multiples of x. It also tries to eliminate these functions when they occur in denominators.

**INPUT:**

- `self` - a symbolic expression
- `var` - (default: None) the variable which is used for these transformations. If not specified, all variables are used.

**OUTPUT:**

A symbolic expression.

**EXAMPLES:**

sage: y=var('y')
sage: f=sin(x)*cos(x)^3+sin(y)^2

sage: f.reduce_trig()
-1/2*cos(2*y) + 1/8*sin(4*x) + 1/4*sin(2*x) + 1/2

To reduce only the expressions involving x we use optional parameter:

sage: f.reduce_trig(x)
sin(y)^2 + 1/8*sin(4*x) + 1/4*sin(2*x)

**ALIASES:** `trig_reduce()` and `reduce_trig()` are the same

**residue** (symbol)

Calculate the residue of `self` with respect to `symbol`.

**INPUT:**

- `symbol` - a symbolic variable or symbolic equality such as `x == 5`. If an equality is given, the expansion is around the value on the right hand side of the equality, otherwise at 0.

**OUTPUT:**

The residue of `self`.

Say, `symbol` is `x == a`, then this function calculates the residue of `self` at `x = a`, i.e., the coefficient of `1/(x - a)` of the series expansion of `self` around `a`.

**EXAMPLES:**

sage: (1/x).residue(x == 0)
1
sage: (1/x).residue(x == oo)
(continues on next page)
We can also compute the residue at more general places, given that the pole is recognized:

```
sage: k = var('k', domain='integer')
sage: (gamma(1+x)/(1 - exp(-x))).residue(x==2*I*pi*k)
gamma(2*I*pi*k + 1)
sage: csc(x).residue(x==2*pi*k)
1
```

resultant (other, var)

Compute the resultant of this polynomial expression and the first argument with respect to the variable given as the second argument.

EXAMPLES:

```
sage: _ = var('a b n k u x y')
sage: x.resultant(y, x)
y
sage: (x+y).resultant(x-y, x)
-2*y
sage: r = (x^4*y^2+x^2*y-y).resultant(x*y-y*a-x*b+a*b+u,x)
sage: r.coefficient(a^4)
b^4*y^2 - 4*b^3*y^3 + 6*b^2*y^4 - 4*b*y^5 + y^6
sage: x.resultant(sin(x), x)
Traceback (most recent call last):
  ... runtimeerror: resultant(): arguments must be polynomials
```

rhs ()

If self is a relational expression, return the right hand side of the relation. Otherwise, raise a ValueError.

EXAMPLES:

```
sage: x = var('x')
sage: eqn = (x-1)^2 <= x^2 - 2*x + 3
sage: eqn.right_hand_side()
x^2 - 2*x + 3
sage: eqn.rhs()
x^2 - 2*x + 3
sage: eqn.right()
x^2 - 2*x + 3
```

right ()

If self is a relational expression, return the right hand side of the relation. Otherwise, raise a ValueError.
EXAMPLES:

```sage
cell: x = var('x')
sage: eqn = (x-1)^2 <= x^2 - 2*x + 3
eqn.right_hand_side()
x^2 - 2*x + 3
eqn.rhs()
x^2 - 2*x + 3
eqn.right()
x^2 - 2*x + 3
```

`right_hand_side()`
If self is a relational expression, return the right hand side of the relation. Otherwise, raise a ValueError.

```sage
cell: x = var('x')
sage: eqn = (x-1)^2 <= x^2 - 2*x + 3
eqn.right_hand_side()
x^2 - 2*x + 3
eqn.rhs()
x^2 - 2*x + 3
eqn.right()
x^2 - 2*x + 3
```

`roots(x=None, explicit_solutions=True, multiplicities=True, ring=None)`
Return roots of `self` that can be found exactly, possibly with multiplicities. Not all roots are guaranteed to be found.

**Warning:** This is *not* a numerical solver - use `find_root` to solve for `self == 0` numerically on an interval.

**INPUT:**
- `x` - variable to view the function in terms of (use default variable if not given)
- `explicit_solutions` - bool (default True); require that roots be explicit rather than implicit
- `multiplicities` - bool (default True); when True, return multiplicities
- `ring` - a ring (default None): if not None, convert `self` to a polynomial over `ring` and find roots over `ring`

**OUTPUT:**
A list of pairs `(root, multiplicity)` or list of roots.
If there are infinitely many roots, e.g., a function like `sin(x)`, only one is returned.

**EXAMPLES:**

```sage
cell: x, a = var('x, a')
(s, a)
```

A simple example:

```sage
cell: ((x^2-1)^2).roots() 
[(-1, 2), (1, 2)]
cell: ((x^2-1)^2).roots(multiplicities=False)
[-1, 1]
```
A complicated example:

```
sage: f = expand((x^2 - 1)^3*(x^2 + 1)*(x-a)); f
-a*x^8 + x^9 + 2*a*x^6 - 2*x^7 - 2*a*x^2 + 2*x^3 + a - x
```

The default variable is $a$, since it is the first in alphabetical order:

```
sage: f.roots()
[(x, 1)]
```

As a polynomial in $a$, $x$ is indeed a root:

```
sage: f.poly(a)
x^9 - 2*x^7 + 2*x^3 - (x^8 - 2*x^6 + 2*x^2 - 1)*a - x
sage: f(a=x)
0
```

The roots in terms of $x$ are what we expect:

```
sage: f.roots(x)
[(a, 1), (-I, 1), (I, 1), (1, 3), (-1, 3)]
```

Only one root of $\sin(x) = 0$ is given:

```
sage: f = sin(x)
sage: f.roots(x)
[(0, 1)]
```

**Note:** It is possible to solve a greater variety of equations using `solve()` and the keyword `to_poly_solve`, but only at the price of possibly encountering approximate solutions. See documentation for `f.solve` for more details.

We derive the roots of a general quadratic polynomial:

```
sage: var('a,b,c,x')
(a, b, c, x)
sage: (a*x^2 + b*x + c).roots(x)
[(-1/2*(b + sqrt(b^2 - 4*a*c))/a, 1), (-1/2*(b - sqrt(b^2 - 4*a*c))/a, 1)]
```

By default, all the roots are required to be explicit rather than implicit. To get implicit roots, pass `explicit_solutions=False` to `.roots()`

```
sage: var('x')
x
sage: f = x^(1/9) + (2^(8/9) - 2^(1/9))*(x - 1) - x^(8/9)
sage: f.roots()
Traceback (most recent call last):
...
RuntimeError: no explicit roots found
sage: f.roots(explicit_solutions=False)
[[(2^(8/9) + x^(8/9) - 2^(1/9) - x^(1/9))/(2^(8/9) - 2^(1/9)), 1]]
```

Another example, but involving a degree 5 poly whose roots do not get computed explicitly:

```
sage: f = x^5 + x^3 + 17*x + 1
sage: f.roots()
(continues on next page)
```
Traceback (most recent call last):
... 
RuntimeError: no explicit roots found

```
sage: f.roots(explicit_solutions=False)
[(x^5 + x^3 + 17*x + 1, 1)]
sage: f.roots(explicit_solutions=False, multiplicities=False)
[x^5 + x^3 + 17*x + 1]
```

Now let us find some roots over different rings:

```
sage: f.roots(ring=CC)
[(-0.0588115223184..., 1), (-1.33109917875... - 1.52241655183732*I, 1), (-1.
 →31099917875... + 1.52241655183732*I, 1), (1.36050567903502 - 1.
 →5180872209965*I, 1), (1.36050567903502 + 1.51880872209965*I, 1)]
sage: (2.5*f).roots(ring=RR)
[(-0.058811522318449..., 1)]
sage: f.roots(ring=CC, multiplicities=False)
[-0.05881152231844944?, -1.33109917875796? - 1.522416551837318?*I, -1.
 →51808722099650?*I, 1.360505679035020? + 1.518808722099650?*I]
```

Root finding over finite fields:

```
sage: f.roots(ring=GF(7^2, 'a'))
[(3, 1), (4*a + 6, 2), (3*a + 3, 2)]
```

**round()**

Round this expression to the nearest integer.

**EXAMPLES:**

```
sage: u = sqrt(43203735824841025516773866131535024)
sage: u.round()
207855083711803945
sage: t = sqrt(Integer('1'*1000)).round(); print(str(t)[-10:]);
3333333333
sage: (-sqrt(110)).round()
-10
sage: (-sqrt(115)).round()
-11
sage: (sqrt(-3)).round()
Traceback (most recent call last):
... 
ValueError: could not convert sqrt(-3) to a real number
```

**series(symbol, order=None)**

Return the power series expansion of self in terms of the given variable to the given order.

**INPUT:**

- symbol - a symbolic variable or symbolic equality such as $x == 5$; if an equality is given, the expansion is around the value on the right hand side of the equality

---

2.1. Symbolic Expressions
• order - an integer; if nothing given, it is set to the global default (20), which can be changed using set_series_precision()

OUTPUT:
A power series.
To truncate the power series and obtain a normal expression, use the truncate() command.

EXAMPLES:
We expand a polynomial in \( x \) about 0, about 1, and also truncate it back to a polynomial:

\[
sage: \text{var}(\text{\texttt{\textbackslash \textquoteleft x, y}})\\
(x, y)\\
sage: f = (x^3 - \sin(y) \times x^2 - 5 \times x + 3); f\\
x^3 - x^2 \sin(y) - 5x + 3\\
sage: g = f.series(x, 4); g\\
3 + (-5) \times x + (-\sin(y)) \times x^2 + 1 \times x^3 + \text{Order}(x^4)\\
sage: g.truncate()\\
x^3 - x^2 \sin(y) - 5x + 3\\
sage: g = f.series(x==1, 4); g\\
(-\sin(y) - 1) + (-2 \times \sin(y) - 2) \times (x - 1) + (-\sin(y) + 3) \times (x - 1)^2 + 1 \times (x - 1)^3 + \text{Order}((x - 1)^4)\\
sage: h = g.truncate(); h\\
(x - 1)^3 - (x - 1)^2 \times (\sin(y) - 3) - 2 \times (x - 1) \times (\sin(y) + 1) - \sin(y) - 1\\
sage: h.expand()\\
x^3 - x^2 \sin(y) - 5x + 3
\]

We computer another series expansion of an analytic function:

\[
sage: f = \sin(x)/x^2\\
sage: f.series(x,7)\\
1 \times x^(-1) + (-1/6) \times x + 1/120 \times x^3 + (-1/5040) \times x^5 + \text{Order}(x^7)\\
sage: f.series(x)\\
1 \times x^(-1) + (-1/6) \times x + \ldots + \text{Order}(x^{20})\\
sage: f.series(x==1,3)\\
(\sin(1)) + (\cos(1) - 2 \times \sin(1)) \times (x - 1) + (-2 \times \cos(1) + 5/2 \times \sin(1)) \times (x - 1)^2 + \ldots + \text{Order}((x - 1)^3)\\
sage: f.series(x==1,3).truncate().expand()\\
-2 \times x^2 \times \cos(1) + 5/2 \times x^2 \times \sin(1) + 5 \times x \times \cos(1) - 7 \times x \times \sin(1) - 3 \times \cos(1) + 11/2 \times \sin(1)\\
\]

Expressions formed by combining series can be expanded by applying series again:

\[
sage: (1/(1-x)).series(x, 3)+(1/(1+x)).series(x,3)\\
(1 + 1 \times x + 1 \times x^2 + \text{Order}(x^3)) + (1 + (-1) \times x + 1 \times x^2 + \text{Order}(x^3))\\
sage: _.series(x,3)\\
2 + 2 \times x^2 + \text{Order}(x^3)\\
sage: (1/(1-x)).series(x, 3)*(1/(1+x)).series(x,3)\\
(1 + 1 \times x + 1 \times x^2 + \text{Order}(x^3)) \times (1 + (-1) \times x + 1 \times x^2 + \text{Order}(x^3))\\
sage: _.series(x,3)\\
1 + 1 \times x^2 + \text{Order}(x^3)
\]

Following the GiNaC tutorial, we use John Machin’s amazing formula \( \pi = 16 \tan^{-1}(1/5) - 4 \tan^{-1}(1/239) \) to compute digits of \( \pi \). We expand the arc tangent around 0 and insert the fractions 1/5 and 1/239.
sage: x = var('x')
sage: f = atan(x).series(x, 10); f
1*x + (-1/3)*x^3 + 1/5*x^5 + (-1/7)*x^7 + 1/9*x^9 + Order(x^10)
sage: float(16*f.subs(x==1/5) - 4*f.subs(x==1/239))
3.1415926824043994

\textbf{show()}

Pretty-Print this symbolic expression

This typeset it nicely and prints it immediately.

\textbf{OUTPUT:}

This method does not return anything. Like \texttt{print}, output is sent directly to the screen.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: (x^2 + 1).show()
<html><script type="math/tex">
\newcommand{\Bold}[1]{\mathbf{#1}}
x^{2} + 1
</script></html>
\end{verbatim}

\textbf{simplify()}\texttt{()}

Return a simplified version of this symbolic expression.

\textbf{Note:} Currently, this just sends the expression to Maxima and converts it back to Sage.

\textbf{See also:}
simplify_full(), \texttt{simplify_trig()}, \texttt{simplify_rational()}, simplify_rectform(), simplify_factorial(), simplify_log(), simplify_real(), simplify_hypergeometric(), canonicalize_radical()

\textbf{EXAMPLES:}

\begin{verbatim}
sage: a = var('a'); f = x*sin(2)/(x^a); f
x*sin(2)/x^a
sage: f.simplify()
x^(-a + 1)*sin(2)
\end{verbatim}

\textbf{simplify_factorial(\texttt{) (})}

Simplify by combining expressions with factorials, and by expanding binomials into factorials.

\textbf{ALIAS:} factorial_simplify and simplify_factorial are the same

\textbf{EXAMPLES:}

\begin{verbatim}
sage: a = var('a'); f = factorial(n+1)/factorial(n); f
factorial(n + 1)/factorial(n)
sage: f.simplify_factorial()
n + 1
sage: f = factorial(n)*(n+1); f
(n + 1)*factorial(n)
sage: simplify(f)
(continues on next page)
\end{verbatim}
(n + 1) * factorial(n)
sage: f.simplify_factorial()
factorial(n + 1)

A more complicated example, which needs further processing:

```sage
f = factorial(x)/factorial(x-2)/2 + factorial(x+1)/factorial(x)/2; f
g = f.simplify_factorial(); g
```

simplify_full()

Apply `simplify_factorial()`, `simplify_rectform()`, `simplify_trig()`, `simplify_rational()`, and then `expand_sum()` to self (in that order).

ALIAS: `simplify_full` and `full_simplify` are the same.

EXAMPLES:

```sage
f = sin(x)^2 + cos(x)^2
f.simplify_full()
1
```

```sage
f = sin(x/(x^2 + x))
f.simplify_full()
sin(1/(x + 1))
```

simplify_hypergeometric(algorithm='maxima')

Simplify an expression containing hypergeometric or confluent hypergeometric functions.

INPUT:

- `algorithm` – (default: 'maxima') the algorithm to use for for simplification. Implemented are 'maxima', which uses Maxima's hgfred function, and 'sage', which uses an algorithm implemented in the hypergeometric module

ALIAS: `hypergeometric_simplify()` and `simplify_hypergeometric()` are the same

EXAMPLES:

```sage
hypergeometric((5, 4), (4, 1, 2, 3), x).simplify_hypergeometric()
1/144*x^2*hypergeometric((), (3, 4), x) +...
1/3*x*hypergeometric((), (2, 3), x) + hypergeometric((), (1, 2), x)
```
sage: (2*hypergeometric((,), (), x)).simplify_hypergeometric()
2*e^x

sage: (nest(lambda y: hypergeometric([y], [1], x), 3, 1)....: .simplify_hypergeometric())
laguerre(-laguerre(-e^x, x), x)
sage: (nest(lambda y: hypergeometric([y], [1], x), 3, 1)....: .simplify_hypergeometric(algorithm='sage'))
hypergeometric(hypergeometric((e^x,), (1,), x), (1,), x)
sage: hypergeometric_M(1, 3, x).simplify_hypergeometric()
-2*((x + 1)*e^(-x) - 1)*e^x/x^2
sage: (2 * hypergeometric_U(1, 3, x)).simplify_hypergeometric()
2*(x + 1)/x^2

**simplify_log**(algorithm=None)
Simplify a (real) symbolic expression that contains logarithms.

The given expression is scanned recursively, transforming subexpressions of the form $a \log(b) + c \log(d)$ into $\log(b^a d^c)$ before simplifying within the $\log()$.

The user can specify conditions that $a$ and $c$ must satisfy before this transformation will be performed using the optional parameter parameter algorithm.

**Warning:** This is only safe to call if every variable in the given expression is assumed to be real. The simplification it performs is in general not valid over the complex numbers. For example:

```
sage: x,y = SR.var('x,y')
sage: f = log(x*y) - (log(x) + log(y))
sage: f(x=-1, y=i)
-2*I*pi
sage: f.simplify_log()
0
```

**INPUT:**
- **self** - expression to be simplified
- **algorithm** - (default: None) optional, governs the condition on $a$ and $c$ which must be satisfied to contract expression $a \log(b) + c \log(d)$. Values are
  - None (use Maxima default, integers),
  - 'one' (1 and -1),
  - 'ratios' (rational numbers),
  - 'constants' (constants),
  - 'all' (all expressions).

**ALGORITHM:**
This uses the Maxima logcontract() command.

**ALIAS:**
log_simplify() and simplify_log() are the same.

**EXAMPLES:**
sage: x,y,t=var('x y t')

Only two first terms are contracted in the following example; the logarithm with coefficient \(\frac{1}{2}\) is not contracted:

sage: f = log(x)+2*log(y)+1/2*log(t)
sage: f.simplify_log()
log(x*y^2) + 1/2*log(t)

To contract all terms in the previous example, we use the 'ratios' algorithm:

sage: f.simplify_log(algorithm='ratios')
log(sqrt(t)*x*y^2)

To contract terms with no coefficient (more precisely, with coefficients 1 and -1), we use the 'one' algorithm:

sage: f = log(x)+2*log(y)-log(t)
sage: f.simplify_log('one')
2*log(y) + log(x/t)

\(\pi\) is an irrational number; to contract logarithms in the following example we have to set algorithm to 'constants' or 'all':

sage: f = log(x)+log(y)-pi*log((x+1))
sage: f.simplify_log('constants')
log(x*y/(x + 1)^pi)

\(x\log(9)\) is contracted only if algorithm is 'all':

sage: (x*log(9)).simplify_log()  
2*x*log(3)
sage: (x*log(9)).simplify_log('all')  
log(3^(2*x))

AUTHORS:

• Robert Marik (11-2009)

simplify_rational (algorithm='full', map=False)
Simplify rational expressions.

INPUT:

• self - symbolic expression
• algorithm - (default: ‘full’) string which switches the algorithm for simplifications. Possible values are
  – ‘simple’ (simplify rational functions into quotient of two polynomials),
  – ‘full’ (apply repeatedly, if necessary)
– ‘noexpand’ (convert to common denominator and add)

  • map - (default: False) if True, the result is an expression whose leading operator is the same as that of the expression self but whose subparts are the results of applying simplification rules to the corresponding subparts of the expressions.

ALIAS: rational_simplify() and simplify_rational() are the same

DETAILS: We call Maxima functions ratsimp, fullratsimp and xthru. If each part of the expression has to be simplified separately, we use Maxima function map.

EXAMPLES:

```python
sage: f = sin(x/(x^2 + x))
sage: f
sin(x/(x^2 + x))
sage: f.simplify_rational()
sin(1/(x + 1))

sage: f = ((x - 1)^(3/2) - (x + 1)*sqrt(x - 1))/sqrt((x - 1)*(x + 1)); f
-((x + 1)*sqrt(x - 1) - (x - 1)^(3/2))/sqrt((x + 1)*(x - 1))
sage: f.simplify_rational()
-2*sqrt(x - 1)/sqrt(x^2 - 1)
```

With map=True each term in a sum is simplified separately and thus the results are shorter for functions which are combination of rational and nonrational functions. In the following example, we use this option if we want not to combine logarithm and the rational function into one fraction:

```python
sage: f=(x^2-1)/(x+1)-ln(x)/(x+2)
sage: f.simplify_rational()
x - log(x)/(x + 2) - 1
sage: f.simplify_rational(map=True)
x - log(x)/(x + 2) - 1
```

Here is an example from the Maxima documentation of where algorithm='simple' produces an (possibly useful) intermediate step:

```python
sage: y = var('y')
sage: g = (x^(y/2) + 1)^2*(x^(y/2) - 1)^2/(x^y - 1)
sage: g.simplify_rational(algorithm='simple')
(x^(2*y) - 2*x^y + 1)/(x^y - 1)
sage: g.simplify_rational()
x^y - 1
```

With option algorithm='noexpand' we only convert to common denominators and add. No expansion of products is performed:

```python
sage: f=1/(x+1)+x/(x+2)^2
sage: f.simplify_rational()
(2*x^2 + 5*x + 4)/(x^3 + 5*x^2 + 8*x + 4)
sage: f.simplify_rational(algorithm='noexpand')
((x + 2)^2 + (x + 1)*x)/((x + 2)^2*(x + 1))
```

simplify_real()
Simplify the given expression over the real numbers. This allows the simplification of \(\sqrt{x^2}\) into \(|x|\) and the contraction of \(\log(x) + \log(y)\) into \(\log(xy)\).

INPUT:

  • self – the expression to convert.

2.1. Symbolic Expressions
A new expression, equivalent to the original one under the assumption that the variables involved are real.

**EXAMPLES:**

```python
sage: f = sqrt(x^2)
sage: f.simplify_real()
abs(x)
```

```python
sage: y = SR.var('y')
sage: f = log(x) + 2*log(y)
sage: f.simplify_real()
log(x*y^2)
```

## simplify_rectform

**complexity_measure='string_length'**

Attempt to simplify this expression by expressing it in the form $a + bi$ where both $a$ and $b$ are real. This transformation is generally not a simplification, so we use the given complexity_measure to discard non-simplifications.

**INPUT:**

- `self` – the expression to simplify.
- `complexity_measure` – (default: `sage.symbolic.complexity_measures.string_length`) a function taking a symbolic expression as an argument and returning a measure of that expressions complexity. If `None` is supplied, the simplification will be performed regardless of the result.

**OUTPUT:**

If the transformation produces a simpler expression (according to `complexity_measure`) then that simpler expression is returned. Otherwise, the original expression is returned.

**ALGORITHM:**

We first call `rectform()` on the given expression. Then, the supplied complexity measure is used to determine whether or not the result is simpler than the original expression.

**EXAMPLES:**

The exponential form of $\tan(x)$:

```python
sage: f = ( e^(I*x) - e^(-I*x) ) / ( I*e^(I*x) + I*e^(-I*x) )
sage: f.simplify_rectform()
sin(x)/cos(x)
```

This should not be expanded with Euler’s formula since the resulting expression is longer when considered as a string, and the default complexity_measure uses string length to determine which expression is simpler:

```python
sage: f = e^(I*x)
sage: f.simplify_rectform()
e^(I*x)
```

However, if we pass `None` as our complexity measure, it is:

```python
sage: f = e^(I*x)
sage: f.simplify_rectform(complexity_measure = None)
cos(x) + I*sin(x)
```
**simplify_trig** *(expand=True)*

Optionally expand and then employ identities such as \( \sin^2(x) + \cos^2(x) = 1 \), \( \cosh^2(x) - \sinh^2(x) = 1 \), \( \sin(x) \csc(x) = 1 \), or \( \tanh(x) = \sinh(x)/\cosh(x) \) to simplify expressions containing tan, sec, etc., to sin, cos, sinh, cosh.

**INPUT:**

- `self` - symbolic expression
- `expand` - (default: True) if True, expands trigonometric and hyperbolic functions of sums of angles and of multiple angles occurring in `self` first. For best results, `self` should be expanded. See also `expand_trig()` to get more controls on this expansion.

**ALIAS:** `trig_simplify()` and `simplify_trig()` are the same

**EXAMPLES:**

```python
sage: f = sin(x)^2 + cos(x)^2; f
\cos(x)^2 + \sin(x)^2
sage: f.simplify()
\cos(x)^2 + \sin(x)^2
sage: f.simplify_trig()
1
sage: h = sin(x)*csc(x)
\sin(x)*\csc(x)
```

In some cases we do not want to expand:

```python
sage: f=tan(3*x)
sage: f.simplify_trig()
-(4*\cos(x)^2 - 1)*\sin(x)/(4*\cos(x)*\sin(x)^2 - \cos(x))
sage: f.simplify_trig(False)
\sin(3*x)/\cos(3*x)
```

**sin** *(hold=False)*

**EXAMPLES:**

```python
sage: var('x, y')
(x, y)
sage: sin(x^2 + y^2)
\sin(x^2 + y^2)
sage: sin(sage.symbolic.constants.pi)
0
sage: sin(SR(1))
\sin(1)
sage: sin(SR(RealField(150)(1)))
0.84147098480789650665250232163029899962256306
```

Using the `hold` parameter it is possible to prevent automatic evaluation:

```python
sage: SR(0).sin()
0
sage: SR(0).sin(hold=True)
\sin(0)
```

This also works using functional notation:
sage: sin(0,hold=True)
sin(0)
sage: sin(0)
0

To then evaluate again, we use \texttt{unhold()}:
sage: a = SR(0).sin(hold=True); a.unhold()
0

\texttt{sinh}(\texttt{hold}=False)

Return \texttt{sinh} of self.

We have \texttt{sinh}(x) = (e^x - e^{-x})/2.

EXAMPLES:

sage: x.sinh()
sinh(x)
sage: SR(1).sinh()
sinh(1)
sage: SR(0).sinh()
0
sage: SR(1.0).sinh()
1.17520119364380
sage: maxima('sinh(1.0)')
1.17520119364380...

\texttt{sinh}(1.0000000000000000000000000)
sage: SR(1).sinh().n(90)
1.1752011936438014568823819
sage: SR(RIF(1)).sinh()
1.175201193643802?

To prevent automatic evaluation use the \texttt{hold} argument:
sage: arccosh(x).sinh()
sqrt(x + 1)*sqrt(x - 1)
sage: arccosh(x).sinh(hold=True)
sinh(arccosh(x))

This also works using functional notation:
sage: sinh(arccosh(x),hold=True)
sinh(arccosh(x))
sage: sinh(arccosh(x))
sqrt(x + 1)*sqrt(x - 1)

To then evaluate again, we use \texttt{unhold()}:
sage: a = arccosh(x).sinh(hold=True); a.simplify()
sqrt(x + 1)*sqrt(x - 1)

\texttt{solve}(x, \texttt{multiplicities}=False, \texttt{solution_dict}=False, \texttt{explicit_solutions}=False, \texttt{to_poly_solve}=False, \texttt{algorithm}=None, \texttt{domain}=None)

Analytically solve the equation \texttt{self} == 0 or a univariate inequality for the variable \texttt{x}. 
Warning: This is not a numerical solver - use find_root to solve for self == 0 numerically on an interval.

INPUT:
- `x` - variable(s) to solve for
- `multiplicities` - bool (default: False); if True, return corresponding multiplicities. This keyword is incompatible with to_poly_solve=True and does not make any sense when solving an inequality.
- `solution_dict` - bool (default: False); if True or non-zero, return a list of dictionaries containing solutions. Not used when solving an inequality.
- `explicit_solutions` - bool (default: False); require that all roots be explicit rather than implicit. Not used when solving an inequality.
- `to_poly_solve` - bool (default: False) or string; use Maxima’s to_poly_solver package to search for more possible solutions, but possibly encounter approximate solutions. This keyword is incompatible with multiplicities=True and is not used when solving an inequality. Setting to_poly_solve to 'force' omits Maxima’s solve command (useful when some solutions of trigonometric equations are lost).

EXAMPLES:

```python
sage: z = var('z')
sage: (z^5 - 1).solve(z)
[[z == 1/4*sqrt(5) + 1/4*I*sqrt(2*sqrt(5) + 10) - 1/4, z == -1/4*sqrt(5) + 1/4*I*sqrt(-2*sqrt(5) + 10) - 1/4, z == -1/4*sqrt(5) - 1/4*I*sqrt(-2*sqrt(5) + 10) - 1/4, z == 1/4*sqrt(5) - 1/4*I*sqrt(2*sqrt(5) + 10) - 1/4, z == 1]]
```

```python
sage: solve((z^3-1)^3, z, multiplicities=True)
([z == 1/2*I*sqrt(3) - 1/2, z == -1/2*I*sqrt(3) - 1/2, z == 1], [3, 3, 3])
```

**solve_diophantine** (x=None, solution_dict=False)
Solve a polynomial equation in the integers (a so called Diophantine).

If the argument is just a polynomial expression, equate to zero. If `solution_dict=True` return a list of dictionaries instead of a list of tuples.

EXAMPLES:

```python
sage: x, y = var('x, y')
sage: solve_diophantine(3*x == 4)
[]
sage: solve_diophantine(x^2 - 9)
[-3, 3]
sage: sorted(solve_diophantine(x^2 + y^2 == 25))
[(-5, 0), (-4, -3), (-4, 3), (-3, -4), (-3, 4), (0, -5),...]
```

The function is used when solve() is called with all variables assumed integer:

```python
sage: assume(x, 'integer')
sage: assume(y, 'integer')
sage: sorted(solve(x*y == 1, (x,y)))
[[-1, -1], [1, 1]]
```

You can also pick specific variables, and get the solution as a dictionary.
sage: solve_diophantine(x*y == 10, x)
[-10, -5, -2, -1, 1, 2, 5, 10]
sage: sorted(solve_diophantine(x*y - y == 10, (x,y)))
[(-9, -1), (-4, -2), (-1, -5), (0, -10), (2, 10), (3, 5), (6, 2), (11, 1)]
sage: res = solve_diophantine(x*y - y == 10, solution_dict=True)
sage: sol = [{y: -5, x: -1}, {y: -10, x: 0}, {y: -1, x: -9}, {y: -2, x: -4}, 
{y: 10, x: 2}, {y: 1, x: 11}, {y: 2, x: 6}, {y: 5, x: 3}]
sage: all(solution in res for solution in sol) and bool(len(res) == len(sol))
True

If the solution is parametrized the parameter(s) are not defined, but you can substitute them with specific integer values:

sage: x,y,z = var('x,y,z')
sage: sol=solve_diophantine(x^2-y==0); sol
(t, t^2)
sage: [(sol[0].subs(t=t),sol[1].subs(t=t)) for t in range(-3,4)]
[(-3, 9), (-2, 4), (-1, 1), (0, 0), (1, 1), (2, 4), (3, 9)]
sage: sol = solve_diophantine(x^2 + y^2 == z^2); sol
(2*p*q, p^2 - q^2, p^2 + q^2)
sage: [(sol[0].subs(p=p,q=q),sol[1].subs(p=p,q=q),sol[2].subs(p=p,q=q)) for p,q in range(1,4),
for p,q in range(1,4)]
[(2, 0, 2), (4, -3, 5), (6, -8, 10), (4, 3, 5), (8, 0, 8), (12, -5, 13), (6,
8, 10), (12, 5, 13), (18, 0, 18)]

Solve Brahmagupta-Pell equations:

sage: sol = sorted(solve_diophantine(x^2 - 2*y^2 == 1), key=str)
sage: sol
[(1, 0), (3, -2), (17, -12), (99, -70), (577, -408), (3363, -2378)]

See also:
http://docs.sympy.org/latest/modules/solvers/diophantine.html

sqrt (hold=False)

Return the square root of this expression

EXAMPLES:

sage: var('x, y')
(x, y)
sage: SR(2).sqrt()
sqrt(2)
sage: (x^2+y^2).sqrt()
sqrt(x^2 + y^2)
sage: (x^2).sqrt()
sqrt(x^2)

Immediate simplifications are applied:

sage: sqrt(x^2)
sqrt(x^2)
sage: x = SR.symbol('x', domain='real')
Using the `hold` parameter it is possible to prevent automatic evaluation:

```sage
sage: SR(4).sqrt()
sage: SR(4).sqrt(hold=True)
```

To then evaluate again, we use `unhold()`:

```sage
sage: a = SR(4).sqrt(hold=True); a.unhold()
```

To use this parameter in functional notation, you must coerce to the symbolic ring:

```sage
sage: sqrt(SR(4),hold=True)
sage: sqrt(4,hold=True)
```

### step (hold=False)

Return the value of the unit step function, which is 0 for negative x, 1 for 0, and 1 for positive x.

**See also:**

`sage.functions.generalized.FunctionUnitStep`

**EXAMPLES:**

```sage
sage: x = var('x')
sage: SR(1.5).step() 1
sage: SR(0).step() 1
```
Using the `hold` parameter it is possible to prevent automatic evaluation:

```python
sage: SR(2).step()
1
sage: SR(2).step(hold=True)
unit_step(2)
```

**subs (**`*args`, **`kwds`)**

Substitute the given subexpressions in this expression.

**EXAMPLES:**

```python
sage: var('x,y,z,a,b,c,d,f,g')
(x, y, z, a, b, c, d, f, g)
sage: w0 = SR.wild(0); w1 = SR.wild(1)
sage: t = a^2 + b^2 + (x+y)^3
sage: t.subs(a=c)
(x + y)^3 + b^2 + c^2
sage: t.subs(b=19, x=z)
(y + z)^3 + a^2 + 361
sage: t.subs({a^2: c})
(x + y)^3 + b^2 + c
sage: t.subs({w0^2: w0^3})
a^3 + b^3 + (x + y)^3
sage: t.subs(w0^2 == w0^3)
a^3 + b^3 + (x + y)^3
sage: t.subs(a == b, b == c)
(x + y)^3 + b^2 + c^2
```

Any number of arguments is accepted:

```python
sage: t.subs(a=b, b=c)
(x + y)^3 + b^2 + c^2
sage: t.subs({a:b}, b=c)
(x + y)^3 + b^2 + c^2
```
It can even accept lists of lists:

```python
sage: eqn1 = (a*x + b*y == 0)
sage: eqn2 = (1 + y == 0)
sage: soln = solve([eqn1, eqn2], [x, y])
sage: soln
[[x == b/a, y == -1]]
sage: f = x + y
sage: f.subs(soln)
b/a - 1
```

Duplicate assignments will throw an error:

```python
sage: t.subs({a:b}, a=c)
Traceback (most recent call last):
  ...  ValueError: duplicate substitution for a, got values b and c
sage: t.subs([x == 1], a = 1, b = 2, x = 2)
Traceback (most recent call last):
  ...  ValueError: duplicate substitution for x, got values 1 and 2
```

All substitutions are performed at the same time:

```python
sage: t.subs({a:b, b:c})
(x + y)^3 + b^2 + c^2
```

Substitutions are done term by term, in other words Sage is not able to identify partial sums in a substitution (see trac ticket #18396):

```python
sage: f = x + x^2 + x^4
sage: f.subs(x = y)
y^4 + y^2 + y
sage: f.subs(x^2 == y)
x^4 + x + y
sage: f.subs(x + x^2 == y)  # partial sum does not work
x^4 + x^2 + x
sage: f.subs(x + x^2 + x^4 == y)  # whole sum is fine
y
```

Note that it is the very same behavior as in Maxima:

```python
sage: E = 'x^4 + x^2 + x'
sage: subs = [('x','y'), ('x^2','y'), ('x^2+x','y'), ('x^4+x^2+x^4','y')]
sage: cmd = '()'  # empty substitution
sage: for s1,s2 in subs:
.....:  maxima.eval(cmd.format(E, s1, s2))
y^4+y^2+y
'y+x^4+x'
x^4+x^2+x^4
'y'
```

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Or as in Maple:

```python
sage: cmd = 'subs({}={}, {})' # optional - maple
sage: for s1, s2 in subs: # optional - maple
....:    maple.eval(cmd.format(s1, s2, E)) # optional - maple
'y^4+y^2+y'
'x^4+x+y'
'x^4+x^2+x'
'y'
```

But Mathematica does something different on the third example:

```python
sage: cmd = '{} /. {} -> {}' # optional - mathematica
sage: for s1, s2 in subs: # optional - mathematica
....:    mathematica.eval(cmd.format(E, s1, s2)) # optional - mathematica
2 4
y + y^2 + y
4
x + x + y
4
x + y
y
```

The same, with formatting more suitable for cut and paste:

```python
sage: for s1, s2 in subs: # optional - mathematica
....:    mathematica(cmd.format(E, s1, s2)) # optional - mathematica
y + y^2 + y^4
x + x^4 + y
x^4 + y
y
```

**substitute** (*args, **kwds*)

Substitute the given subexpressions in this expression.

**EXAMPLES:**

```python
sage: var('x,y,z,a,b,c,d,f,g')
(x, y, z, a, b, c, d, f, g)
sage: w0 = SR.wild(0); w1 = SR.wild(1)
sage: t = a^2 + b^2 + (x+y)^3
Substitute with keyword arguments (works only with symbols):

```python
sage: t.subs(a=c)
(x + y)^3 + b^2 + c^2
sage: t.subs(b=19, x=z)
(y + z)^3 + a^2 + 361
```

Substitute with a dictionary argument:

```python
sage: t.subs({a^2: c})
(x + y)^3 + b^2 + c
```

Substitute with one or more relational expressions:
sage: t.subs(w0^2 == w0^3)
  a^3 + b^3 + (x + y)^3

sage: t.subs(w0 == w0^2)
  a^8 + b^8 + (x^2 + y^2)^6

sage: t.subs(a == b, b == c)
  (x + y)^3 + b^2 + c^2

Any number of arguments is accepted:

sage: t.subs({a:b}, b=c)
  (x + y)^3 + b^2 + c^2

sage: t.subs({x == 3, y == 2}, a == 2, {b:3})
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It can even accept lists of lists:

sage: eqn1 = (a*x + b*y == 0)
sage: eqn2 = (1 + y == 0)
sage: soln = solve([eqn1, eqn2], [x, y])
sage: soln
  [[x == b/a, y == -1]]

sage: f = x + y
sage: f.subs(soln)
  b/a - 1

Duplicate assignments will throw an error:

sage: t.subs({a:b}, a=c)
  Traceback (most recent call last):
    ...
    ValueError: duplicate substitution for a, got values b and c

sage: t.subs([x == 1], a = 1, b = 2, x = 2)
  Traceback (most recent call last):
    ...
    ValueError: duplicate substitution for x, got values 1 and 2

All substitutions are performed at the same time:

sage: t.subs({a:b, b:c})
  (x + y)^3 + b^2 + c^2

Substitutions are done term by term, in other words Sage is not able to identify partial sums in a substitution (see trac ticket #18396):

sage: f = x + x^2 + x^4
sage: f.subs(x = y)
  y^4 + y^2 + y
sage: f.subs(x^2 == y)  # one term is fine
  x^4 + x + y
sage: f.subs(x + x^2 == y)  # partial sum does not work

(continues on next page)

```
x^4 + x^2 + x
sage: f.subs(x + x^2 + x^4 == y)  # whole sum is fine
y
```

Note that it is the very same behavior as in Maxima:

```
sage: E = 'x^4 + x^2 + x'
sage: subs = [('x','y'), ('x^2','y'), ('x^2+x','y'), ('x^4+x^2+x','y')]
sage: cmd = '{}, {}={}'
sage: for s1,s2 in subs:
        maxima.eval(cmd.format(E, s1, s2))
'y^4+y^2+y'
'y+x^4+x'
'x^4+x^2+x'
'y'
```

Or as in Maple:

```
sage: cmd = 'subs({}, {}={})'  # optional - maple
sage: for s1,s2 in subs:
        maple.eval(cmd.format(s1,s2, E))  # optional - maple
'y^4+y^2+y'
'x^4+x+y'
'x^4+x^2+x'
'y'
```

But Mathematica does something different on the third example:

```
sage: cmd = '{} /. {} -> {}'  # optional - mathematica
sage: for s1,s2 in subs:
        mathematica.eval(cmd.format(E,s1,s2))  # optional - mathematica
2 4
y + y^2 + y^4
4
x + x + y^4
4
x + y
y
```

The same, with formatting more suitable for cut and paste:

```
sage: for s1,s2 in subs:  # optional - mathematica
    mathematica(cmd.format(E,s1,s2))  # optional - mathematica
y + y^2 + y^4
x + x^4 + y
x^4 + y
y
```

**substitute_function**(original, new)

Return this symbolic expressions all occurrences of the function original replaced with the function new.

**EXAMPLES:**

```
sage: x,y = var('x,y')
sage: foo = function('foo'); bar = function('bar')
sage: f = foo(x) + 1/foo(pi+y)
```

(continues on next page)
substitution_delayed(pattern, replacement)

Replace all occurrences of pattern by the result of replacement.

In contrast to subs(), the pattern may contain wildcards and the replacement can depend on the particular term matched by the pattern.

INPUT:

• pattern – an Expression, usually containing wildcards.

• replacement – a function. Its argument is a dictionary mapping the wildcard occurring in pattern to the actual values. If it returns None, this occurrence of pattern is not replaced. Otherwise, it is replaced by the output of replacement.

OUTPUT:

An Expression.

EXAMPLES:

sage: var('x y')
(x, y)
sage: w0 = SR.wild(0)
sage: sqrt(1 + 2*x + x^2).substitution_delayed(
    ....:   sqrt(w0), lambda d: sqrt(factor(d[w0])))
    ....:
    sqrt((x + 1)^2)
sage: def r(d):
    ....:   if x not in d[w0].variables():
    ....:       return cos(d[w0])
sage: (sin(x^2 + x) + sin(y^2 + y)).substitution_delayed(sin(w0), r)
cos(y^2 + y) + sin(x^2 + x)

See also:

match()
• **b** - upper endpoint of the sum

• **algorithm** - (default: 'maxima') one of
  – 'maxima' - use Maxima (the default)
  – 'maple' - (optional) use Maple
  – 'mathematica' - (optional) use Mathematica
  – 'giac' - (optional) use Giac
  – 'sympy' - use SymPy

**EXAMPLES:**

```python
sage: k, n = var('k,n')
sage: k.sum(k, 1, n).factor()
1/2*(n + 1)*n
```

```python
sage: (1/k^4).sum(k, 1, oo)
1/90*pi^4
```

```python
sage: (1/k^5).sum(k, 1, oo)
zeta(5)
```

A well known binomial identity:

```python
sage: assume(n>=0)
sage: binomial(n,k).sum(k, 0, n)
2^n
```

And some truncations thereof:

```python
sage: binomial(n,k).sum(k,1,n)
2^n - 1
sage: binomial(n,k).sum(k,2,n)
2^n - n - 1
sage: binomial(n,k).sum(k,0,n-1)
2^n - 1
sage: binomial(n,k).sum(k,1,n-1)
2^n - 2
```

The binomial theorem:

```python
sage: x, y = var('x, y')
sage: (binomial(n,k) * x^k * y^(n-k)).sum(k, 0, n)
(x + y)^n
```

```python
sage: (k * binomial(n, k)).sum(k, 1, n)
2^(n - 1)*n
```

```python
sage: ((-1)^k*binomial(n,k)).sum(k, 0, n)
0
```

```python
sage: (2^(-k)/(k*(k+1))).sum(k, 1, oo)
-log(2) + 1
```

Summing a hypergeometric term:
We check a well known identity:

```
sage: bool((k^3).sum(k, 1, n) == k.sum(k, 1, n)^2)
True
```

A geometric sum:

```
sage: a, q = var('a, q')
sage: (a*q^k).sum(k, 0, n)
(a*q^(n + 1) - a)/(q - 1)
```

The geometric series:

```
sage: assume(abs(q) < 1)
sage: (a*q^k).sum(k, 0, oo)
-a/(q - 1)
```

A divergent geometric series. Do not forget to `forget` your assumptions:

```
sage: forget()
sage: assume(q > 1)
sage: (a*q^k).sum(k, 0, oo)
Traceback (most recent call last):
  ...
ValueError: Sum is divergent.
```

This summation only Mathematica can perform:

```
sage: (1/(1+k^2)).sum(k, -oo, oo, algorithm = 'mathematica')  # optional - mathematica
pi*coth(pi)
```

Use Giac to perform this summation:

```
sage: (sum(1/(1+k^2), k, -oo, oo, algorithm = 'giac')).factor()
pi*(e^(2*pi) + 1)/((e^pi + 1)*(e^pi - 1))
```

Use Maple as a backend for summation:

```
sage: (binomial(n,k)*x^k).sum(k, 0, n, algorithm = 'maple')  # optional - maple
(x + 1)^n
```

Note:

1. Sage can currently only understand a subset of the output of Maxima, Maple and Mathematica, so even if the chosen backend can perform the summation the result might not be convertible into a usable Sage expression.

```
tan(hold=False)
```

EXAMPLES:
sage: var('x, y')
(x, y)
sage: tan(x^2 + y^2)
tan(x^2 + y^2)
sage: tan(sage.symbolic.constants.pi/2)
Infinity
sage: tan(SR(1))
tan(1)
sage: tan(SR(RealField(150)(1)))
1.5574077246549022305069748074583601730872508

To prevent automatic evaluation use the hold argument:

sage: (pi/12).tan()
-sqrt(3) + 2
sage: (pi/12).tan(hold=True)
tan(1/12*pi)

This also works using functional notation:

sage: tan(pi/12,hold=True)
tan(1/12*pi)
sage: tan(pi/12)
-sqrt(3) + 2

To then evaluate again, we use unhold():

sage: a = (pi/12).tan(hold=True); a.unhold()
-sqrt(3) + 2

tanh (hold=False)
Return tanh of self.
We have tanh(x) = sinh(x)/cosh(x).

EXAMPLES:

sage: x.tanh()
tanh(x)
sage: SR(1).tanh()
tanh(1)
sage: SR(0).tanh()
0
sage: SR(1.0).tanh()
0.76159415555765
sage: maxima('tanh(1.0)')
0.761594155557649
sage: plot(lambda x: SR(x).tanh(), -1, 1)
Graphics object consisting of 1 graphics primitive

To prevent automatic evaluation use the hold argument:

sage: arcsinh(x).tanh()
x/sqrt(x^2 + 1)
sage: arcsinh(x).tanh(hold=True)
tanh(arcsinh(x))

This also works using functional notation:
To then evaluate again, we use \texttt{unhold()}:

\begin{verbatim}
sage: a = arcsinh(x).tanh(hold=True); a.unhold()
\end{verbatim}

\texttt{taylor(*args)}

Expand this symbolic expression in a truncated Taylor or Laurent series in the variable \( v \) around the point \( a \), containing terms through \( (x - a)^n \). Functions in more variables is also supported.

INPUT:

- \texttt{*args} - the following notation is supported
  - \( x, a, n \) - variable, point, degree
  - \((x, a), (y, b), n\) - variables with points, degree of polynomial

EXAMPLES:

\begin{verbatim}
sage: var('a, x, z')
(a, x, z)
sage: taylor(a*log(z), z, 2, 3)
\end{verbatim}

1/24*a*(z - 2)^3 - 1/8*a*(z - 2)^2 + 1/2*a*(z - 2) + a*log(2)

\begin{verbatim}
sage: taylor(sqrt (sin(x) + a*x + 1), x, 0, 3)
\end{verbatim}

1/48*(3*a^3 + 9*a^2 + 9*a - 1)*x^3 - 1/8*(a^2 + 2*a + 1)*x^2 + 1/2*(a + 1)*x → 1

\begin{verbatim}
sage: taylor (sqrt (x + 1), x, 0, 5)
\end{verbatim}

7/256*x^5 - 5/128*x^4 + 1/16*x^3 - 1/8*x^2 + 1/2*x + 1

\begin{verbatim}
sage: taylor (1/log (x + 1), x, 0, 3)
\end{verbatim}

-19/720*x^3 + 1/24*x^2 - 1/12*x + 1/x + 1/2

\begin{verbatim}
sage: taylor (cos(x) - sec(x), x, 0, 5)
\end{verbatim}

-1/6*x^4 - x^2

\begin{verbatim}
sage: taylor ((cos(x) - sec(x))^3, x, 0, 9)
\end{verbatim}

-1/2*x^8 - x^6

\begin{verbatim}
sage: taylor (1/(cos(x) - sec(x))^3, x, 0, 5)
\end{verbatim}

-15377/7983360*x^4 - 6767/604800*x^2 + 11/120/x^2 + 1/2/x^4 - 1/x^6 - 347/15120
→ 15120

\texttt{test_relation(ntests=20, domain=None, proof=True)}

Test this relation at several random values, attempting to find a contradiction. If this relation has no variables, it will also test this relation after casting into the domain.

Because the interval fields never return false positives, we can be assured that if True or False is returned (and proof is False) then the answer is correct.

INPUT:
• `ntests` – (default 20) the number of iterations to run
• `domain` – (optional) the domain from which to draw the random values defaults to CIF for equality testing and RIF for order testing
• `proof` – (default True) if False and the domain is an interval field, regard overlapping (potentially equal) intervals as equal, and return True if all tests succeeded.

OUTPUT:
Boolean or `NotImplemented`, meaning
• True – this relation holds in the domain and has no variables.
• False – a contradiction was found.
• `NotImplemented` – no contradiction found.

EXAMPLES:

```python
sage: (3 < pi).test_relation()
True
sage: (0 >= pi).test_relation()
False
sage: (exp(pi) - pi).n()
19.9999999999999
sage: (exp(pi) - pi == 20).test_relation()
False
sage: (sin(x)^2 + cos(x)^2 == 1).test_relation()
NotImplemented
sage: (sin(x)^2 + cos(x)^2 == 1).test_relation(proof=False)
True
sage: var('x,y')
(x, y)
sage: (x < y).test_relation()
False
```

`to_gamma()`
Convert factorial, binomial, and Pochhammer symbol expressions to their gamma function equivalents.

EXAMPLES:

```python
sage: m,n = var('m n', domain='integer')
sage: factorial(n).to_gamma()
gamma(n + 1)
sage: binomial(m,n).to_gamma()
gamma(m + 1)/(gamma(m - n + 1)*gamma(n + 1))
```

`trailing_coeff(s)`
Return the trailing coefficient of s in self, i.e., the coefficient of the smallest power of s in self.

EXAMPLES:

```python
sage: var('x,y,a')
(x, y, a)
sage: f = 100 + a*x + x^3*sin(x*y) + x*y + x/y + 2*sin(x*y)/x; f
x^3*sin(x*y) + a*x + x*y + x/y + 2*sin(x*y)/x + 100
sage: f.trailing_coefficient(x)
2*sin(x*y)
```
```python
sage: f.trailing_coefficient(y)
x
sage: f.trailing_coefficient(sin(x*y))
a*x + x*y + x/y + 100
```

**trailing_coefficient** *(s)*

Return the trailing coefficient of s in self, i.e., the coefficient of the smallest power of s in self.

**EXAMPLES:**

```python
sage: var('x,y,a')
(x, y, a)
sage: f = 100 + a*x + x^3*sin(x*y) + x*y + x/y + 2*sin(x*y)/x; f
x^3*sin(x*y) + a*x + x*y + x/y + 2*sin(x*y)/x + 100
sage: f.trailing_coefficient(x)
2*sin(x*y)
sage: f.trailing_coefficient(y)
x
sage: f.trailing_coefficient(sin(x*y))
a*x + x*y + x/y + 100
```

**trig_expand** *(full=False, half_angles=False, plus=True, times=True)*

Expand trigonometric and hyperbolic functions of sums of angles and of multiple angles occurring in self.

For best results, self should already be expanded.

**INPUT:**

- **full** *(default: False)*: To enhance user control of simplification, this function expands only one level at a time by default, expanding sums of angles or multiple angles. To obtain full expansion into sines and cosines immediately, set the optional parameter full to True.

- **half_angles** *(default: False)*: If True, causes half-angles to be simplified away.

- **plus** *(default: True)*: Controls the sum rule; expansion of sums (e.g. sin(x + y)) will take place only if plus is True.

- **times** *(default: True)*: Controls the product rule, expansion of products (e.g. sin(2*x)) will take place only if times is True.

**OUTPUT:**

A symbolic expression.

**EXAMPLES:**

```python
sage: sin(5*x).expand_trig()
5*cos(x)^4*sin(x) - 10*cos(x)^2*sin(x)^3 + sin(x)^5
sage: cos(2*x + var('y')).expand_trig()
cos(2*x)*cos(y) - sin(2*x)*sin(y)
```

We illustrate various options to this function:

```python
sage: f = sin(sin(3*cos(2*x))*x)
sage: f.expand_trig() # default
sin((3*cos(cos(2*x)) + 2*sin(cos(2*x)) - sin(cos(2*x)) + 3)*x)
sage: f.expand_trig(full=True)
sin((3*cos(cos(2*x)) + 2*sin(cos(2*x)) - sin(cos(2*x)) + 3)*x)
sage: f.expand_trig(full=True)
sin((3*cos(cos(2*x)) + 2*sin(cos(2*x)) - sin(cos(2*x)) + 3)*x)
```

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\texttt{sage}: \sin(2\times x).\texttt{expand\_trig(times=False)}
\sin(2\times x)
\texttt{sage}: \sin(2\times x).\texttt{expand\_trig(times=True)}
2\times \cos(x)\times \sin(x)
\texttt{sage}: \sin(2 + x).\texttt{expand\_trig(plus=False)}
\sin(x + 2)
\texttt{sage}: \sin(2 + x).\texttt{expand\_trig(plus=True)}
\cos(x)\times \sin(2) + \cos(2)\times \sin(x)
\texttt{sage}: \sin(x/2).\texttt{expand\_trig(half\_angles=False)}
\sin(1/2\times x)
\texttt{sage}: \sin(x/2).\texttt{expand\_trig(half\_angles=True)}
(-1)^{\text{floor}(1/2\times x/\pi)}\times \sqrt{-1/2\times \cos(x) + 1/2)

If the expression contains terms which are factored, we expand first:
\texttt{sage}: (x, k1, k2) = \texttt{var}('x, k1, k2')
\texttt{sage}: \cos((k1-k2)*x).\texttt{expand().expand\_trig()}
\cos(k1\times x)\times \cos(k2\times x) + \sin(k1\times x)\times \sin(k2\times x)

\textbf{ALIASES:}
\texttt{trig\_expand()} and \texttt{expand\_trig()} are the same

\textbf{trig\_reduce (var=None)}
Combine products and powers of trigonometric and hyperbolic sin’s and cos’s of x into those of multiples
of x. It also tries to eliminate these functions when they occur in denominators.

\textbf{INPUT:}
• \texttt{self} - a symbolic expression
• \texttt{var} - (default: None) the variable which is used for these transformations. If not specified, all
variables are used.

\textbf{OUTPUT:}
A symbolic expression.

\textbf{EXAMPLES:}
\texttt{sage}: y=\texttt{var}('y')
\texttt{sage}: f=\sin(x)\times \cos(x)\times 3\times \sin(y)^2
\texttt{sage}: f.\texttt{reduce\_trig()}
-1/2\times \cos(2\times y) + 1/8\times \sin(4\times x) + 1/4\times \sin(2\times x) + 1/2

To reduce only the expressions involving x we use optional parameter:
\texttt{sage}: f.\texttt{reduce\_trig(x)}
\sin(y)^2 + 1/8\times \sin(4\times x) + 1/4\times \sin(2\times x)

\textbf{ALIASES:} \texttt{trig\_reduce()} and \texttt{reduce\_trig()} are the same

\textbf{trig\_simplify (expand=True)}
Optionally expand and then employ identities such as \sin(x)^2 + \cos(x)^2 = 1, \cosh(x)^2 - \sinh(x)^2 = 1,
\sin(x)\csc(x) = 1, or \tanh(x) = \sinh(x)/\cosh(x) to simplify expressions containing tan, sec, etc., to
sin, cos, sinh, cosh.

\textbf{INPUT:}
• \texttt{self} - symbolic expression
• expand - (default: True) if True, expands trigonometric and hyperbolic functions of sums of angles and of multiple angles occurring in self first. For best results, self should be expanded. See also `expand_trig()` to get more controls on this expansion.

ALIAS: `trig_simplify()` and `simplify_trig()` are the same

EXAMPLES:

```python
sage: f = sin(x)^2 + cos(x)^2; f
cos(x)^2 + sin(x)^2
sage: f.simplify()
1
sage: h = sin(x)*csc(x)
sage: h.simplify_trig()
1
sage: k = tanh(x)*cosh(2*x)
sage: k.simplify_trig()
(2*sinh(x)^3 + sinh(x))/cosh(x)
```

In some cases we do not want to expand:

```python
sage: f=tan(3*x)
sage: f.simplify_trig()
-(4*cos(x)^2 - 1)*sin(x)/(4*cos(x)*sin(x)^2 - cos(x))
sage: f.simplify_trig(False)
sin(3*x)/cos(3*x)
```

`truncate()`

Given a power series or expression, return the corresponding expression without the big oh.

INPUT:

• self – a series as output by the `series()` command.

OUTPUT:

A symbolic expression.

EXAMPLES:

```python
sage: f = sin(x)/x^2
sage: f.truncate()
sin(x)/x^2
sage: f.series(x,7)
1*x^(-1) + (-1/6)*x + 1/120*x^3 + (-1/5040)*x^5 + Order(x^7)
sage: f.series(x==1,3).truncate().expand()
-2*x^2*cos(1) + 5/2*x^2*sin(1) + 5*x*cos(1) - 7*x*sin(1) - 3*cos(1) + 11/
˓→2*sin(1)
```

`unhold()` (exclude=None)

Evaluates any held operations (with the `hold` keyword) in the expression

INPUT:

• self – an expression with held operations

• exclude – (default: None) a list of operators to exclude from evaluation. Excluding arithmetic operators does not yet work (see trac ticket #10169).
OUTPUT:

A new expression with held operations, except those in `exclude`, evaluated

EXAMPLES:

```python
sage: a = exp(I * pi, hold=True)
sage: a
e^(I*pi)
sage: a.unhold()
-1
sage: b = x.add(x, hold=True)
sage: b
x + x
sage: b.unhold()
2*x
sage: (a + b).unhold()
2*x - 1
sage: c = (x.mul(x, hold=True)).add(x.mul(x, hold=True), hold=True)
sage: c
x*x + x*x
sage: c.unhold()
2*x^2
sage: sin(tan(0, hold=True), hold=True).unhold()
0
sage: sin(tan(0, hold=True), hold=True).unhold(exclude=[sin])
sin(0)
sage: (e^sgn(0, hold=True)).unhold()
e^0
sage: log(3).unhold()
log(3)
```

`unit(s)`

Return the unit of this expression when considered as a polynomial in `s`.

See also `content()`, `primitive_part()`, and `unit_content_primitive()`.

INPUT:

- `s` – a symbolic expression.

OUTPUT:

The unit part of a polynomial as a symbolic expression. It is defined as the sign of the leading coefficient.

EXAMPLES:

```python
sage: (2*x+4).unit(x)
1
sage: (-2*x+1).unit(x)
-1
sage: (2*x+1/2).unit(x)
1
sage: var('y')
y
sage: (2*x - 4*sin(y)).unit(sin(y))
-1
```
unit_content_primitive(s)
Return the factorization into unit, content, and primitive part.

INPUT:

- s – a symbolic expression, usually a symbolic variable. The whole symbolic expression self will be considered as a univariate polynomial in s.

OUTPUT:

A triple (unit, content, primitive polynomial) containing the unit, content, and primitive polynomial. Their product equals self.

EXAMPLES:

```
sage: var('x,y')
(x, y)
sage: ex = 9*x^3*y+3*y
sage: ex.unit_content_primitive(x)
(1, 3*y, 3*x^3 + 1)
sage: ex.unit_content_primitive(y)
(1, 9*x^3 + 3, y)
```

variables()
Return sorted tuple of variables that occur in this expression.

EXAMPLES:

```
sage: (x,y,z) = var('x,y,z')
sage: (x+y).variables()
(x, y)
sage: (2*x).variables()
(x,)
sage: (x^y).variables()
(x, y)
sage: sin(x+y^z).variables()
(x, y, z)
```

zeta (hold=False)

EXAMPLES:

```
sage: x, y = var('x, y')
sage: (x/y).zeta()
zeta(x/y)
sage: SR(2).zeta()
1/6*pi^2
sage: SR(3).zeta()
zeta(3)
sage: SR(CDF(0,1)).zeta()  # abs tol le-16
0.003300223685324103 - 0.4181554491413217*I
sage: CDF(0,1).zeta()  # abs tol le-16
0.003300223685324103 - 0.4181554491413217*I
sage: plot(lambda x: SR(x).zeta(), -10,10).show(ymin=-3,ymax=3)
```

To prevent automatic evaluation use the hold argument:

```
sage: SR(2).zeta(hold=True)
zeta(2)
```

This also works using functional notation:
To then evaluate again, we use \texttt{unhold()}:

\begin{verbatim}
sage: a = SR(2).zeta(hold=True); a.unhold()
1/6*pi^2
\end{verbatim}

\begin{class}
\verbatim
class sage.symbolic.expression.ExpressionIterator
    Bases: object

class sage.symbolic.expression.hold_class
    Bases: object

    Instances of this class can be used with Python \textit{with}.EXAMPLES:
\end{verbatim}

\begin{verbatim}
sage: with hold:
....:  tan(1/12*pi)
....:
tan(1/12*pi)
sage: tan(1/12*pi)
-sqrt(3) + 2
sage: with hold:
....:  2^5
....:
32
sage: with hold:
....:  SR(2)^5
....:
2^5
sage: with hold:
....:  t=tan(1/12*pi)
....:
sage: t
\end{verbatim}

\begin{verbatim}
tan(1/12*pi)
sage: t.unhold()
-sqrt(3) + 2
\end{verbatim}

\begin{method}
\verbatim
start()
    Start a hold context.

    EXAMPLES:
\end{verbatim}

\begin{verbatim}
sage: hold.start()
sage: SR(2)^5
2^5
sage: hold.stop()
sage: SR(2)^5
32
\end{verbatim}

\begin{method}
\verbatim
stop()
    Stop any hold context.

    EXAMPLES:
\end{verbatim}
```python
sage: hold.start()
sage: SR(2)^5
2^5
sage: hold.stop()
sage: SR(2)^5
32
```

**sage.symbolic.expression.is**Expression***(x)*

Return True if \( x \) is a symbolic Expression.

**EXAMPLES:**
```
sage: from sage.symbolic.expression import is_Expression
sage: is_Expression(x)
True
sage: is_Expression(2)
False
sage: is_Expression(SR(2))
True
```

**sage.symbolic.expression.is**SymbolicEquation***(x)*

Return True if \( x \) is a symbolic equation.

**EXAMPLES:**
```
The following two examples are symbolic equations:

sage: from sage.symbolic.expression import is_SymbolicEquation
sage: is_SymbolicEquation(sin(x) == x)
True
sage: is_SymbolicEquation(sin(x) < x)
True
sage: is_SymbolicEquation(x)
False
```

This is not, since \( 2 == 3 \) evaluates to the boolean \( False \):
```
sage: is_SymbolicEquation(2 == 3)
False
```

However here since both 2 and 3 are coerced to be symbolic, we obtain a symbolic equation:
```
sage: is_SymbolicEquation(SR(2) == SR(3))
True
```

**sage.symbolic.expression.solve_diophantine**(*f, **args, **kwds)*

Solve a Diophantine equation.

The argument, if not given as symbolic equation, is set equal to zero. It can be given in any form that can be converted to symbolic. Please see \( \text{Expression.solve_diophantine()} \) for a detailed synopsis.

**EXAMPLES:**
```
sage: R.<a,b> = PolynomialRing(ZZ); R
Multivariate Polynomial Ring in a, b over Integer Ring
sage: solve_diophantine(a^2-3*b^2+1)
[]
sage: sorted(solve_diophantine(a^2-3*b^2+2), key=str)
[(-1/2*sqrt(3)*(sqrt(3) + 2)^t + 1/2*sqrt(3)*(-sqrt(3) + 2)^t - 1/2*(sqrt(3) + 2)^t - 1/2*(-sqrt(3) + 2)^t, ...
```

(continues on next page)
\[ \frac{-1}{6}\sqrt{3}(\sqrt{3} + 2)^t + \frac{1}{6}\sqrt{3}(-\sqrt{3} + 2)^t - \frac{1}{2}(\sqrt{3} + 2)^t \]
\[ \rightarrow \]
\[ \frac{1}{2}\sqrt{3}(\sqrt{3} + 2)^t - \frac{1}{2}\sqrt{3}(-\sqrt{3} + 2)^t + \frac{1}{2}(\sqrt{3} + 2)^t \]
\[ + \frac{1}{2}(-\sqrt{3} + 2)^t, \]
\[ \frac{1}{6}\sqrt{3}(\sqrt{3} + 2)^t - \frac{1}{6}\sqrt{3}(-\sqrt{3} + 2)^t + \frac{1}{2}(\sqrt{3} + 2)^t \]
\[ \rightarrow \]
\[ \frac{1}{2}\sqrt{3}(\sqrt{3} + 2)^t - \frac{1}{2}\sqrt{3}(-\sqrt{3} + 2)^t + \frac{1}{2}(\sqrt{3} + 2)^t + \frac{1}{2}(-\sqrt{3} + 2)^t \]

### 2.2 Callable Symbolic Expressions

**EXAMPLES:**

When you do arithmetic with:

```python
sage: f(x, y, z) = sin(x+y+z)
sage: g(x, y) = y + 2*x
sage: f + g
(x, y, z) |--> 2*x + y + sin(x + y + z)
```

```python
sage: f(x, y, z) = sin(x+y+z)
sage: g(w, t) = cos(w - t)
sage: f + g
(t, w, x, y, z) |--> cos(-t + w) + sin(x + y + z)
```

```python
sage: f(x, y, t) = y*(x^2-t)
sage: g(x, y, w) = x + y - cos(w)
sage: f*g
(x, y, t, w) |--> (x^2 - t)*(x + y - cos(w))*y
```

```python
sage: f(x,y, t) = x+y
sage: g(x, y, w) = w + t
sage: f + g
(x, y, t, w) |--> t + w + x + y
```

```python
class sage.symbolic.callable.CallableSymbolicExpressionFunctor(\texttt{arguments})
Bases: sage.categories.pushout.ConstructionFunctor

A functor which produces a CallableSymbolicExpressionRing from the SymbolicRing.

**EXAMPLES:**

```python
sage: from sage.symbolic.callable import CallableSymbolicExpressionFunctor
sage: x,y = var('x,y')
sage: f = CallableSymbolicExpressionFunctor((x,y)); f
CallableSymbolicExpressionFunctor(x, y)
sage: f(SR)
Callable function ring with arguments (x, y)
sage: loads(dumps(f))
CallableSymbolicExpressionFunctor(x, y)
```

```python
arguments()
EXAMPLES:
```
sage: from sage.symbolic.callable import CallableSymbolicExpressionFunctor
sage: x,y = var('x,y')
sage: a = CallableSymbolicExpressionFunctor((x,y))
sage: a.arguments()
(x, y)

merge(other)
EXAMPLES:

sage: from sage.symbolic.callable import CallableSymbolicExpressionFunctor
sage: x,y = var('x,y')
sage: a = CallableSymbolicExpressionFunctor((x,))
sage: b = CallableSymbolicExpressionFunctor((y,))
sage: a.merge(b)
CallableSymbolicExpressionFunctor(x, y)

unify_arguments(x)
Takes the variable list from another CallableSymbolicExpression object and compares it with
the current CallableSymbolicExpression object’s variable list, combining them according to the
following rules:

Let a be self’s variable list, let b be y’s variable list.

1. If a == b, then the variable lists are identical, so return that variable list.
2. If a != b, then check if the first n items in a are the first n items in b, or vice versa. If so, return a list
with these n items, followed by the remaining items in a and b sorted together in alphabetical order.

Note: When used for arithmetic between CallableSymbolicExpression’s, these rules ensure that
the set of CallableSymbolicExpression’s will have certain properties. In particular, it ensures that
the set is a commutative ring, i.e., the order of the input variables is the same no matter in which order
arithmetic is done.

INPUT:
- x - A CallableSymbolicExpression

OUTPUT: A tuple of variables.

EXAMPLES:

sage: from sage.symbolic.callable import CallableSymbolicExpressionFunctor
sage: x,y = var('x,y')
sage: a = CallableSymbolicExpressionFunctor((x,))
sage: b = CallableSymbolicExpressionFunctor((y,))
sage: a.unify_arguments(b)
(x, y)

AUTHORS:
- Bobby Moretti: thanks to William Stein for the rules

class sage.symbolic.callable.CallableSymbolicExpressionRingFactory
Bases: sage.structure.factory.UniqueFactory
create_key(args, check=True)
EXAMPLES:
sage: x, y = var('x, y')
sage: CallableSymbolicExpressionRing.create_key((x, y))
(x, y)

create_object\n\textit{(version, key, **extra_args)}
Returns a CallableSymbolicExpressionRing given a version and a key.

\textbf{EXAMPLES:}

sage: x, y = var('x, y')
sage: CallableSymbolicExpressionRing.create_object(0, (x, y))
Callable function ring with arguments (x, y)

class \texttt{sage.symbolic.callable.CallableSymbolicExpressionRing_class}(arguments)
Bases: \texttt{sage.symbolic.ring.SymbolicRing}

\textbf{EXAMPLES:}

We verify that coercion works in the case where \(x\) is not an instance of SymbolicExpression, but its parent is still the SymbolicRing:

sage: f(x) = 1
sage: f*e
x |--> e

\texttt{args()}\n
Returns the arguments of \texttt{self}. The order that the variables appear in \texttt{self.arguments()} is the order that is used in evaluating the elements of \texttt{self}.

\textbf{EXAMPLES:}

sage: x, y = var('x, y')
sage: f(x, y) = 2*x + y
sage: f.parent().arguments()
(x, y)
sage: f(y, x) = 2*x + y
sage: f.parent().arguments()
(y, x)

\texttt{arguments()}\n
Returns the arguments of \texttt{self}. The order that the variables appear in \texttt{self.arguments()} is the order that is used in evaluating the elements of \texttt{self}.

\textbf{EXAMPLES:}

sage: x, y = var('x, y')
sage: f(x, y) = 2*x + y
sage: f.parent().arguments()
(x, y)
sage: f(y, x) = 2*x + y
sage: f.parent().arguments()
(y, x)

\texttt{construction()}\n
\textbf{EXAMPLES:}

sage: f(x, y) = x^2 + y
sage: f.parent().construction()
(CallableSymbolicExpressionFunctor(x, y), Symbolic Ring)
sage.symbolic.callable.is_CallableSymbolicExpression(x)
Returns True if x is a callable symbolic expression.

EXAMPLES:

```
sage: from sage.symbolic.callable import is_CallableSymbolicExpression
sage: var('a x y z')
(a, x, y, z)
sage: f(x,y) = a + 2*x + 3*y + z
sage: is_CallableSymbolicExpression(f)
True
sage: is_CallableSymbolicExpression(a+2*x)
False
sage: def foo(n):
...    return n^2
...
... 2.3 Assumptions
... 2.3. Assumptions
...
```

sage.symbolic.callable.is_CallableSymbolicExpressionRing(x)
Returns True if x is a callable symbolic expression ring.

INPUT:
- x - object

OUTPUT: bool

EXAMPLES:

```
sage: from sage.symbolic.callable import is_CallableSymbolicExpressionRing
sage: is_CallableSymbolicExpressionRing(QQ)
False
sage: var('x,y,z')
(x, y, z)
sage: is_CallableSymbolicExpressionRing(CallableSymbolicExpressionRing((x,y,z)))
True
```

2.3 Assumptions

The GenericDeclaration class provides assumptions about a symbol or function in verbal form. Such assumptions can be made using the assume() function in this module, which also can take any relation of symbolic expressions as argument. Use forget() to clear all assumptions. Creating a variable with a specific domain is equivalent with making an assumption about it.

There is only rudimentary support for consistency and satisfiability checking in Sage. Assumptions are used both in Maxima and Pynac to support or refine some computations. In the following we show how to make and query assumptions. Please see the respective modules for more practical examples.

In addition to the global assumptions() database, assuming() creates reusable, stackable context managers allowing for temporary updates of the database for evaluation of a (block of) statements.

EXAMPLES:
The default domain of a symbolic variable is the complex plane:

```
sage: var('x')
x
sage: x.is_real()
```
False
sage: assume(x, 'real')
sage: x.is_real()
True
sage: forget()
sage: x.is_real()
False

Here is the list of acceptable features:

```
sage: maxima('features')
(integer, noninteger, even, odd, rational, irrational, real, imaginary, complex, analytic,
→ increasing, decreasing, oddfun, evenfun, posfun, constant, commutative, lassociative,
→ rassociative, symmetric, antisymmetric, integervalued]
```

Set positive domain using a relation:

```
sage: assume(x>0)
sage: x.is_positive()
True
sage: x.is_real()
True
sage: assumptions()
[x > 0]
```

Assumptions also affect operations that do not use Maxima:

```
sage: forget()
sage: assume(x, 'even')
sage: assume(x, 'real')
sage: (-1)^x
1
sage: (-gamma(pi))^x
gamma(pi)^x
sage: binomial(2*x, x).is_integer()
True
```

Assumptions are added and in some cases checked for consistency:

```
sage: assume(x>0)
sage: assume(x<0)
Traceback (most recent call last):
...
ValueError: Assumption is inconsistent
sage: forget()
```

```class sage.symbolic.assumptions.GenericDeclaration(var, assumption)
Bases: sage.structure.unique_representation.UniqueRepresentation

This class represents generic assumptions, such as a variable being an integer or a function being increasing. It passes such information to Maxima’s declare (wrapped in a context so it is able to forget) and to Pynac.

INPUT:

- var – the variable about which assumptions are being made
- assumption – a string containing a Maxima feature, either user defined or in the list given by maxima('features')```
EXAMPLES:

```python
code
sage: from sage.symbolic.assumptions import GenericDeclaration
sage: decl = GenericDeclaration(x, 'integer')
sage: decl.assume()
sage: sin(x*pi)
0
sage: decl.forget()
sage: sin(x*pi)
sin(pi*x)
sage: sin(x*pi).simplify()
sin(pi*x)
```

Here is the list of acceptable features:

```python
code
sage: maxima('features')
[integer, noninteger, even, odd, rational, irrational, real, imaginary, complex, analytic,
increasing, decreasing, oddfun, evenfun, posfun, constant, commutative, lassociative,
→rassociative, symmetric, antisymmetric, integervalued]
```

Test unique representation behavior:

```python
code
sage: GenericDeclaration(x, 'integer') is GenericDeclaration(SR.var("x"), 'integer')
True
```

**assume()**

Make this assumption.

**contradicts(soln)**

Return True if this assumption is violated by the given variable assignment(s).

**INPUT:**

- soln – Either a dictionary with variables as keys or a symbolic relation with a variable on the left hand side.

**EXAMPLES:**

```python
code
sage: from sage.symbolic.assumptions import GenericDeclaration
sage: GenericDeclaration(x, 'integer').contradicts(x==4)
False
sage: GenericDeclaration(x, 'integer').contradicts(x==4.0)
False
sage: GenericDeclaration(x, 'integer').contradicts(x==4.5)
True
sage: GenericDeclaration(x, 'integer').contradicts(x==sqrt(17))
True
sage: GenericDeclaration(x, 'noninteger').contradicts(x==sqrt(17))
False
sage: GenericDeclaration(x, 'noninteger').contradicts(x==17)
True
sage: GenericDeclaration(x, 'even').contradicts(x==3)
True
sage: GenericDeclaration(x, 'complex').contradicts(x==3)
False
sage: GenericDeclaration(x, 'imaginary').contradicts(x==3)
True
sage: GenericDeclaration(x, 'imaginary').contradicts(x==I)
```

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sage: var('y,z')
(y, z)
sage: GenericDeclaration(x, 'imaginary').contradicts(x==y+z)
False
sage: GenericDeclaration(x, 'rational').contradicts(y==pi)
False
sage: GenericDeclaration(x, 'rational').contradicts(x==pi)
True
sage: GenericDeclaration(x, 'irrational').contradicts(x!=pi)
False
sage: GenericDeclaration(x, 'rational').contradicts({x: pi, y: pi})
True
sage: GenericDeclaration(x, 'rational').contradicts({z: pi, y: pi})
False

forget()
Forget this assumption.

has(arg)
Check if this assumption contains the argument arg.

EXAMPLES:

sage: from sage.symbolic.assumptions import GenericDeclaration as GDecl
sage: var('y')
y
sage: d = GDecl(x, 'integer')
sage: d.has(x)
True
sage: d.has(y)
False

sage.symbolic.assumptions.assume(*args)
Make the given assumptions.

INPUT:

• *args – a variable-length sequence of assumptions, each consisting of:
  – any number of symbolic inequalities, like 0 < x, x < 1
  – a subsequence of variable names, followed by some property that should be assumed for those variables; for example, x, y, z, 'integer' would assume that each of x, y, and z are integer variables, and x, 'odd' would assume that x is odd (as opposed to even).

The two types can be combined, but a symbolic inequality cannot appear in the middle of a list of variables.

OUTPUT:
If everything goes as planned, there is no output.
If you assume something that is not one of the two forms above, then an AttributeError is raised as we try to call its assume method.
If you make inconsistent assumptions (for example, that x is both even and odd), then a ValueError is raised.
Warning: Do not use Python’s chained comparison notation in assumptions. Python literally translates the expression $0 < x < 1$ to $(0 < x) \land (x < 1)$, but the value of \texttt{bool}(0 < x) is \texttt{False} when $x$ is a symbolic variable. Therefore, by the definition of Python’s logical “and” operator, the entire expression is equal to $0 < x$.

EXEMPLARY:

Assumptions are typically used to ensure certain relations are evaluated as true that are not true in general.

Here, we verify that for $x > 0$, $\sqrt{x^2} = x$:

```python
sage: assume(x > 0)
sage: bool(sqrt(x^2) == x)
True
```

This will be assumed in the current Sage session until forgotten:

```python
sage: bool(sqrt(x^2) == x)
True
sage: forget()
sage: bool(sqrt(x^2) == x)
False
```

Another major use case is in taking certain integrals and limits where the answers may depend on some sign condition:

```python
sage: var('x, n')
(x, n)
sage: assume(n+1>0)
sage: integral(x^n,x)
x^(n + 1)/(n + 1)
sage: forget()
sage: var('q, a, k')
(q, a, k)
sage: assume(q > 1)
sage: sum(a*q^k, k, 0, oo)
Traceback (most recent call last):
  ... ValueError: Sum is divergent.
sage: forget()
sage: assume(abs(q) < 1)
sage: sum(a*q^k, k, 0, oo)
-a/(q - 1)
sage: forget()
```

An integer constraint:

```python
sage: n,P,r,r2 = SR.var('n, P, r, r2')
sage: assume(n, 'integer')
sage: c = P*e^(r*n)
sage: d = P*(1+r2)^n
sage: solve(c==d,r2)
[r2 == e^r - 1]
sage: forget()
```

Simplifying certain well-known identities works as well:

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Instead of using chained comparison notation, each relationship should be passed as a separate assumption:

```python
sage: x = SR.var('x')
sage: assume(0 < x, x < 1) # instead of assume(0 < x < 1)
sage: assumptions()
[0 < x, x < 1]
sage: forget()
```

If you make inconsistent or meaningless assumptions, Sage will let you know:

```python
sage: assume(x<0)
sage: assume(x>0)
Traceback (most recent call last):
  ... ValueError: Assumption is inconsistent
sage: assume(x<1)
Traceback (most recent call last):
  ... ValueError: Assumption is redundant
sage: assumptions()
[x < 0]
sage: forget()
sage: assume(x,'even')
sage: assume(x,'odd')
Traceback (most recent call last):
  ... ValueError: Assumption is inconsistent
sage: forget()
```

You can also use assumptions to evaluate simple truth values:

```python
sage: x, y, z = var('x, y, z')
sage: assume(x==y,y==z,z==x)
sage: bool(x==z)
True
sage: bool(z<x)
False
sage: bool(z>y)
False
sage: bool(y==z)
True
sage: forget()
sage: assume(x>=1,x<=1)
sage: bool(x==1)
True
sage: bool(x>1)
False
sage: forget()
```

```python
class sage.symbolic.assumptions.assuming(*args, **kwds)
```
Bases: object

Temporarily modify assumptions.

Create a context manager in which temporary assumptions are added (or substituted) to the current assumptions set.

The set of possible assumptions and declarations is the same as for `assume()`.

This can be useful in interactive mode to discover the assumptions necessary to a given integration, or the exact solution to a system of equations.

It can also be used to explore the branches of a `cases()` expression.

As with `assume()`, it is an error to add an assumption either redundant or inconsistent with the current assumption set (unless `replace=True` is used). See examples.

INPUT:

- `*args` – assumptions (same format as for `assume()`).
- `replace` – a boolean (default `[False]`). Specifies whether the new assumptions are added to (default) or replace (if `replace=True`) the current assumption set.

OUTPUT:

A context manager useable in a `with` statement (see examples).

EXAMPLES:

Basic functionality: inside a `with assuming:()` block, Sage uses the updated assumptions database. After exit, the original database is restored.

```
sage: var("x")
x
sage: forget(assumptions())
sage: solve(x^2 == 4,x)
[x == -2, x == 2]
sage: with assuming(x > 0):
....: solve(x^2 == 4,x)
....: [x == 2]
sage: assumptions()
[]
```

The local assumptions can be stacked. We can use this functionality to discover incrementally the assumptions necessary to a given calculation (and by the way, to check that Sage’s default integrator (Maxima’s, that is), sometimes nitpicks for naught).

```
sage: var("y,k,theta")
(y, k, theta)
sage: dgamma(y,k,theta)=y^(k-1)*e^(-y/theta)/(theta^k*gamma(k))
sage: integrate(dgamma(y,k,theta),y,0,oo)
Traceback (most recent call last):
...
ValueError: Computation failed since Maxima requested additional constraints;
→ using the 'assume' command before evaluation *may* help (example of legal
→ syntax is 'assume(theta>0)', see `assume?' for more details)
Is theta positive or negative?
sage: al=assuming(theta>0)
sage: with al:integrate(dgamma(y,k,theta),y,0,oo)
Traceback (most recent call last):
```

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ValueError: Computation failed since Maxima requested additional constraints; →
→using the 'assume' command before evaluation *may* help (example of legal
→syntax is 'assume(k>0)', see `assume?' for more details)
Is k positive, negative or zero?

```python
sage: a2=assuming(k>0)
sage: with a1,a2:integrate(dgamma(y,k,theta),y,0,oo)
```

Traceback (most recent call last):
...
ValueError: Computation failed since Maxima requested additional constraints; →
→using the 'assume' command before evaluation *may* help (example of legal
→syntax is 'assume(k>0)', see `assume?' for more details)
Is k an integer?

```python
sage: a3=assuming(k,"noninteger")
sage: with a1,a2,a3:integrate(dgamma(y,k,theta),y,0,oo)
```

1

```python
sage: a4=assuming(k,"integer")
sage: with a1,a2,a4:integrate(dgamma(y,k,theta),y,0,oo)
```

1

As mentioned above, it is an error to try to introduce redundant or inconsistent assumptions.

```python
sage: assume(x > 0)
sage: with assuming(x > -1): "I won't see this"
Traceback (most recent call last):
...
ValueError: Assumption is redundant

sage: with assuming(x < -1): "I won't see this"
Traceback (most recent call last):
...
ValueError: Assumption is inconsistent
```

```
sage.symbolic.assumptions.assumptions(*args)
```

List all current symbolic assumptions.

**INPUT:**

- args – list of variables which can be empty.

**OUTPUT:**

- list of assumptions on variables. If args is empty it returns all assumptions

**EXAMPLES:**

```python
sage: var('x, y, z, w')
(x, y, z, w)
sage: forget()
sage: assume(x^2+y^2 > 0)
sage: assumptions()
[x^2 + y^2 > 0]
sage: forget(x^2+y^2 > 0)
sage: assumptions()
[]
sage: assume(x > y)
sage: assume(z > w)
sage: sorted(assumptions(), key=lambda x: str(x))
```

(continues on next page)
It is also possible to query for assumptions on a variable independently:

```
sage: x, y, z = var('x y z')
sage: assume(x, 'integer')
sage: assume(y > 0)
sage: assume(y**2 + z**2 == 1)
sage: assume(x < 0)
sage: assumptions()
[x is integer, y > 0, y^2 + z^2 == 1, x < 0]
sage: assumptions(x)
[x is integer, x < 0]
sage: assumptions(x, y)
[x is integer, x < 0, y > 0, y^2 + z^2 == 1]
sage: assumptions(z)
[y^2 + z^2 == 1]
```

`sage.symbolic.assumptions.forget(*args)`

Forget the given assumption, or call with no arguments to forget all assumptions.

Here an assumption is some sort of symbolic constraint.

**INPUT:**

- *args – assumptions (default: forget all assumptions)

**EXAMPLES:**

We define and forget multiple assumptions:

```
sage: var('x,y,z')
(x, y, z)
sage: assume(x>0, y>0, z == 1, y>0)
sage: sorted(assumptions(key=lambda x:str(x)))
[x > 0, y > 0, z == 1]
sage: forget(x>0, z==1)
sage: assumptions()
[y > 0]
sage: assume(y, 'even', z, 'complex')
sage: assumptions()
[y > 0, y is even, z is complex]
sage: cos(y*pi).simplify()
1
sage: forget(y, 'even')
sage: cos(y*pi).simplify()

cos(pi*y)
sage: assumptions()
[y > 0, z is complex]
sage: forget()
sage: assumptions()
[]
```

`sage.symbolic.assumptions.preprocess_assumptions(args)`

Turn a list of the form (var1, var2, ..., 'property') into a sequence of declarations (var1 is
property), (var2 is property), ...

EXAMPLES:

```python
sage: from sage.symbolic.assumptions import preprocess_assumptions
sage: preprocess_assumptions([x, 'integer', x > 4])
[x is integer, x > 4]
sage: var('x, y')
(x, y)
sage: preprocess_assumptions([x, y, 'integer', x > 4, y, 'even'])
[x is integer, y is integer, x > 4, y is even]
```

### 2.4 Symbolic Equations and Inequalities

Sage can solve symbolic equations and inequalities. For example, we derive the quadratic formula as follows:

```python
sage: a, b, c = var('a, b, c')
sage: qe = (a*x^2 + b*x + c == 0)
sage: qe
a*x^2 + b*x + c == 0
sage: print(solve(qe, x))
[x == -1/2*(b + sqrt(b^2 - 4*a*c))/a, x == -1/2*(b - sqrt(b^2 - 4*a*c))/a]
```

#### 2.4.1 The operator, left hand side, and right hand side

Operators:

```python
sage: eqn = x^3 + 2/3 >= x - pi
sage: eqn.operator()
<built-in function ge>
sage: (x^3 + 2/3 < x - pi).operator()
<built-in function lt>
sage: (x^3 + 2/3 == x - pi).operator()
<built-in function eq>
```

Left hand side:

```python
sage: eqn = x^3 + 2/3 >= x - pi
sage: eqn.lhs()
x^3 + 2/3
sage: eqn.left()
x^3 + 2/3
sage: eqn.left_hand_side()
x^3 + 2/3
```

Right hand side:

```python
sage: eqn = x + sqrt(2) >= sqrt(3) + 5/2
sage: eqn.right()
sqrt(3) + 5/2
```

(continues on next page)
2.4.2 Arithmetic

Add two symbolic equations:

```
sage: var('a,b')
(a, b)
sage: m = 144 == -10 * a + b
sage: n = 136 == 10 * a + b
sage: m + n
280 == 2*b
sage: int(-144) + m
0 == -10*a + b - 144
```

Subtract two symbolic equations:

```
sage: var('a,b')
(a, b)
sage: m = 144 == 20 * a + b
sage: n = 136 == 10 * a + b
sage: m - n
8 == 10*a
sage: int(144) - m
0 == -20*a - b + 144
```

Multiply two symbolic equations:

```
sage: x = var('x')
sage: n = sin(x) == sin(x+2*pi, hold=True)
sage: m = x == 5*x + 1
sage: m * n
x*sin(x) == (5*x + 1)*sin(2*pi + x)
sage: m = 2*x == 3*x^2 - 5
sage: int(-1) * m
-2*x == -3*x^2 + 5
```

Divide two symbolic equations:

```
sage: x = var('x')
sage: n = sin(x) == sin(x+2*pi, hold=True)
sage: m = x != 5*x + 1
sage: n = sin(x) != sin(x+2*pi, hold=True)
sage: m/n
x/sin(x) != (5*x + 1)/sin(2*pi + x)
```

2.4. Symbolic Equations and Inequalities
2.4.3 Substitution

Substitution into relations:

```python
sage: x, a = var('x, a')
sage: eq = (x^3 + a == sin(x/a)); eq
x^3 + a == sin(x/a)
sage: eq.substitute(x=5*x)
125*x^3 + a == sin(5*x/a)
sage: eq.substitute(a=1)
x^3 + 1 == sin(x)
sage: eq.substitute(a=x)
x^3 + x == sin(1)
sage: eq.substitute(a=x, x=1)
x + 1 == sin(1/x)
sage: eq.substitute({a:x, x:1})
x + 1 == sin(1/x)
```

You can even substitute multivariable and matrix expressions:

```python
sage: x,y = var('x, y')
sage: M = Matrix([[x+1,y],[x^2,y^3]]); M
[x + 1  y]
[x^2  y^3]
sage: M.substitute({x:0,y:1})
[1 1]
[0 1]
```

2.4.4 Solving

We can solve equations:

```python
sage: x = var('x')
sage: S = solve(x^3 - 1 == 0, x)
sage: S
[x == 1/2*I*sqrt(3) - 1/2, x == -1/2*I*sqrt(3) - 1/2, x == 1]
sage: S[0]
x == 1/2*I*sqrt(3) - 1/2
sage: S[0].right()
1/2*I*sqrt(3) - 1/2
sage: S = solve(x^3 - 1 == 0, x, solution_dict=True)
sage: S
[{x: 1/2*I*sqrt(3) - 1/2}, {x: -1/2*I*sqrt(3) - 1/2}, {x: 1}]
sage: z = 5
sage: solve(z^2 == sqrt(3),z)
Traceback (most recent call last):
  ... TypeError: 5 is not a valid variable.
```

We can also solve equations involving matrices. The following example defines a multivariable function $f(x,y)$, then solves for where the partial derivatives with respect to $x$ and $y$ are zero. Then it substitutes one of the solutions into the Hessian matrix $H$ for $f$:

```python
sage: f(x,y) = x^2*y+y^2+y
sage: solutions = solve(list(f.diff()),[x,y],solution_dict=True)
sage: solutions == [{x: -I, y: 0}, {x: I, y: 0}, {x: 0, y: -1/2}]
```
True

```
sage: H = f.diff(2) # Hessian matrix
sage: H.subs(solutions[2])
[(x, y) |--> -1 (x, y) |--> 0]
[(x, y) |--> 0 (x, y) |--> 2]
sage: H(x,y).subs(solutions[2])
[-1 0]
[ 0 2]
```

We illustrate finding multiplicities of solutions:

```
sage: f = (x-1)^5*(x^2+1)
sage: solve(f == 0, x)
[x == -I, x == I, x == 1]
sage: solve(f == 0, x, multiplicities=True)
([x == -I, x == I, x == 1], [1, 1, 5])
```

We can also solve many inequalities:

```
sage: solve(1/(x-1)<=8,x)
[[x < 1], [x >= (9/8)]]
```

We can numerically find roots of equations:

```
sage: (x == sin(x)).find_root(-2,2)
0.0
sage: (x^5 + 3*x + 2 == 0).find_root(-2,2,x)
-0.6328345202421523
sage: (cos(x) == sin(x)).find_root(10,20)
19.634954084936208
```

We illustrate some valid error conditions:

```
sage: (cos(x) != sin(x)).find_root(10,20)
Traceback (most recent call last):
  ... ValueError: Symbolic equation must be an equality.
sage: (SR(3)==SR(2)).find_root(-1,1)
Traceback (most recent call last):
  ... RuntimeError: no zero in the interval, since constant expression is not 0.
```

There must be at most one variable:

```
sage: x, y = var('x,y')
sage: (x == y).find_root(-2,2)
Traceback (most recent call last):
  ... NotImplementedError: root finding currently only implemented in 1 dimension.
```
### 2.4.5 Assumptions

Forgetting assumptions:

```python
sage: var('x,y')
(x, y)
sage: forget() # Clear assumptions
sage: assume(x>0, y < 2)
sage: assumptions()
[x > 0, y < 2]
sage: (y < 2).forget()
sage: assumptions()
[x > 0]
sage: forget()
sage: assumptions()
[]
```

### 2.4.6 Miscellaneous

#### Conversion to Maxima:

```python
sage: x = var('x')
sage: eq = (x^(3/5) >= pi^2 + e^i)
sage: eq._maxima_init_()
'(_SAGE_VAR_x)^(3/5) >= ((%pi)^(2))+(exp(0+%i*1))'
sage: el = x^3 + x == sin(2*x)
sage: z = el._maxima_()
sage: z.parent() is sage.calculus.calculus.maxima
True
sage: z = el._maxima_(maxima)
sage: z.parent() is maxima
True
sage: z = maxima(el)
sage: z.parent() is maxima
True
```

#### Conversion to Maple:

```python
sage: x = var('x')
sage: eq = (x == 2)
sage: eq._maple_init_()
'x = 2'
```

#### Comparison:

```python
sage: x = var('x')
sage: (x>0) == (x>0)
True
sage: (x>0) == (x>1)
False
sage: (x>0) != (x>1)
True
```

#### Variables appearing in the relation:
\textbf{2.4. Symbolic Equations and Inequalities}

\begin{verbatim}
\texttt{sage: var('x,y,z,w')}
(x, y, z, w)
\texttt{sage: f = (x+y+w) == (x^2 - y^2 - z^3); f}
w + x + y == -z^3 + x^2 - y^2
\texttt{sage: f.variables()}
(w, x, y, z)
\end{verbatim}

LaTeX output:
\begin{verbatim}
\texttt{sage: latex(x^(3/5) >= pi)}
x^{\frac{3}{5}} \geq \pi
\end{verbatim}

When working with the symbolic complex number $I$, notice that comparisons do not automatically simplify even in trivial situations:

\begin{verbatim}
\texttt{sage: I^2 == -1}
-1 == -1
\texttt{sage: I^2 < 0}
-1 < 0
\texttt{sage: (I+1)^4 > 0}
-4 > 0
\end{verbatim}

Nevertheless, if you force the comparison, you get the right answer (trac ticket #7160):

\begin{verbatim}
\texttt{sage: bool(I^2 == -1)}
True
\texttt{sage: bool(I^2 < 0)}
True
\texttt{sage: bool((I+1)^4 > 0)}
False
\end{verbatim}

\textbf{2.4.7 More Examples}

\begin{verbatim}
\texttt{sage: x,y,a = var('x,y,a')}
\texttt{sage: f = x^2 + y^2 == 1}
\texttt{sage: f.solve(x)}
[x == -sqrt(-y^2 + 1), x == sqrt(-y^2 + 1)]
\texttt{sage: f = x^5 + a}
\texttt{sage: solve(f==0,x)}
[x == 1/4*(-a)^(1/5)*(sqrt(5) + I*sqrt(2*sqrt(5) + 10) - 1), x == -1/4*(-a)^(1/5)*(-sqrt(5) - I*sqrt(2*sqrt(5) + 10) + 1), x == -1/4*(-a)^(1/5)*(sqrt(5) + I*sqrt(-2*sqrt(5) + 10) + 1), x == 1/4*(-a)^(1/5)*(sqrt(5) - I*sqrt(2*sqrt(5) + 10) - 1), x == (-a)^(1/5)]
\end{verbatim}

You can also do arithmetic with inequalities, as illustrated below:

\begin{verbatim}
\texttt{sage: var('x y')}
(x, y)
\texttt{sage: f = x + 3 == y - 2}
\texttt{sage: f}
x + 3 == y - 2
\texttt{sage: g = f - 3; g}
x == y - 5
\texttt{sage: h = x^3 + sqrt(2) == x*y*sin(x)}
\end{verbatim}

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AUTHORS:

- Bobby Moretti: initial version (based on a trick that Robert Bradshaw suggested).
- William Stein: second version
- William Stein (2007-07-16): added arithmetic with symbolic equations

`sage.symbolic.relation.solve(f, *args, **kwds)`

Algebraically solve an equation or system of equations (over the complex numbers) for given variables. Inequalities and systems of inequalities are also supported.

**INPUT:**

- `f` - equation or system of equations (given by a list or tuple)
- `*args` - variables to solve for.
- `solution_dict` - bool (default: False); if True or non-zero, return a list of dictionaries containing the solutions. If there are no solutions, return an empty list (rather than a list containing an empty dictionary). Likewise, if there’s only a single solution, return a list containing one dictionary with that solution.

There are a few optional keywords if you are trying to solve a single equation. They may only be used in that context.

- `multiplicities` - bool (default: False); if True, return corresponding multiplicities. This keyword is incompatible with `to_poly_solve=True` and does not make any sense when solving inequalities.
- `explicit_solutions` - bool (default: False); require that all roots be explicit rather than implicit. Not used when solving inequalities.
- `to_poly_solve` - bool (default: False) or string; use Maxima’s `to_poly_solver` package to search for more possible solutions, but possibly encounter approximate solutions. This keyword is incompatible with `multiplicities=True` and is not used when solving inequalities. Setting `to_poly_solve` to ‘force’ (string) omits Maxima’s solve command (useful when some solutions of trigonometric equations are lost).
- `algorithm` - string (default: ‘maxima’); to use SymPy’s solvers set this to ‘sympy’. Note that SymPy is always used for diophantine equations.
- `domain` - string (default: ‘complex’); setting this to ‘real’ changes the way SymPy solves single equations; inequalities are always solved in the real domain.

**EXAMPLES:**
```python
sage: x, y = var('x, y')
sage: solve([x+y==6, x-y==4], x, y)
[[x == 5, y == 1]]

sage: solve([x^2+y^2 == 1, x^3 + x + 1], x, y)

sage: solve([sqrt(x) + sqrt(y) == 5, x + y == 10], x, y)

sage: solutions=solve([x^2+y^2 == 1, y^2 == x^3 + x + 1], x, y, solution_dict=True)
sage: for solution in solutions:
    print("{} , {}").format(solution[x].n(digits=3), solution[y].n(digits=3))
-0.500 - 0.866*I , -1.27 + 0.341*I
-0.500 - 0.866*I , 1.27 - 0.341*I
-0.500 + 0.866*I , -1.27 - 0.341*I
-0.500 + 0.866*I , 1.27 + 0.341*I
0.000 , -1.00
0.000 , 1.00
```

Whenever possible, answers will be symbolic, but with systems of equations, at times approximations will be given by Maxima, due to the underlying algorithm:

```python
sage: sols = solve([x^3==y,y^2==x], [x,y]); sols[-1], sols[0]
([x == 0, y == 0], [x == (0.3090169943749475 + 0.9510565162951535*I), y == (-0.8090169943749475 - 0.5877852522924731*I)])
```

Here we demonstrate very basic use of the optional keywords:

```python
sage: ((x^2-1)^2).solve(x)
[x == -1, x == 1]

sage: ((x^2-1)^2).solve(x,multiplicities=True)
([x == -1, x == 1], [2, 2])

sage: solve(sin(x)==x,x)

sage: solve(sin(x)==x,x,explicit_solutions=True)
[]

sage: solve(abs(1-abs(1-x)) == 10, x)
[abs(abs(x - 1) - 1) == 10]

sage: solve(abs(1-abs(1-x)) == 10, x, to_poly_solve=True)
```

(continues on next page)
We must solve with respect to actual variables:

```python
sage: z = 5
sage: solve([8*z + y == 3, -z + 7*y == 0], y, z)
Traceback (most recent call last):
...
TypeError: 5 is not a valid variable.
```

If we ask for dictionaries containing the solutions, we get them:

```python
sage: solve([x^2-1], x, solution_dict=True)
[{x: -1}, {x: 1}]
sage: solve([x^2-4*x+4], x, solution_dict=True)
[{x: 2}]
sage: res = solve([x^2 == y, y == 4], x, y, solution_dict=True)
sage: for soln in res:
    print("x: %s, y: %s" % (soln[x], soln[y]))
x: 2, y: 4
x: -2, y: 4
```

If there is a parameter in the answer, that will show up as a new variable. In the following example, \( r_1 \) is an arbitrary constant (because of the \( r \)):

```python
sage: forget()
sage: x, y = var('x,y')
sage: solve([x+y == 3, 2*x+2*y == 6], x, y)
[[x == -r1 + 3, y == r1]]
sage: var('b, c')
(b, c)
sage: solve((b-1)*(c-1), [b,c])
[[b == 1, c == r...], [b == r..., c == 1]]
```

Especially with trigonometric functions, the dummy variable may be implicitly an integer (hence the \( z \)):

```python
sage: solve(sin(x)==cos(x), x, to_poly_solve=True)
[x == 1/4*pi + pi*z...]
sage: solve([cos(x)*sin(x) == 1/2, x+y == 0], x, y)
[[x == 1/4*pi + pi*z..., y == -1/4*pi - pi*z...]]
```

Expressions which are not equations are assumed to be set equal to zero, as with \( x \) in the following example:

```python
sage: solve([x, y == 2], x, y)
[[x == 0, y == 2]]
```

If \( True \) appears in the list of equations it is ignored, and if \( False \) appears in the list then no solutions are returned. E.g., note that the first \( 3==3 \) evaluates to \( True \), not to a symbolic equation.

```python
sage: solve([3==3, 1.00000000000000*x^3 == 0], x)
[x == 0]
sage: solve([1.00000000000000*x^3 == 0], x)
[x == 0]
```
Here, the first equation evaluates to False, so there are no solutions:

```
sage: solve([1==3, 1.00000000000000*x^3 == 0], x)
[]
```

Completely symbolic solutions are supported:

```
sage: var('s,j,b,m,g')
(s, j, b, m, g)
sage: sys = [ m*(1-s) - b*s*j, b*s*j-g*j ]
sage: solve(sys,s,j)
[[s == 1, j == 0], [s == g/b, j == (b - g)*m/(b*g)]]
sage: solve(sys,(s,j))
[[s == 1, j == 0], [s == g/b, j == (b - g)*m/(b*g)]]
sage: solve(sys,[s,j])
[[s == 1, j == 0], [s == g/b, j == (b - g)*m/(b*g)]]
sage: z = var('z')
sage: solve((x-z)^2==2, x)
[x == z - sqrt(2), x == z + sqrt(2)]
```

Inequalities can be also solved:

```
sage: solve(x^2>8,x)
[[x < -2*sqrt(2)], [x > 2*sqrt(2)]]
sage: x,y=var('x,y'); (ln(x)-ln(y)>0).solve(x)
[[log(x) - log(y) > 0]]
sage: x,y=var('x,y'); (ln(x)>ln(y)).solve(x)  # random
[[0 < y, y < x, 0 < x], [y < x, 0 < y]]
```

A simple example to show the use of the keyword multiplicities:

```
sage: (x^2-1)^2).solve(x)
[x == -1, x == 1]
sage: (x^2-1)^2).solve(x,multiplicities=True)
([x == -1, x == 1], [2, 2])
sage: (x^2-1)^2).solve(x,multiplicities=True,to_poly_solve=True)
Traceback (most recent call last):
  ... Not ImplementedError: to_poly_solve does not return multiplicities
```

Here is how the explicit_solutions keyword functions:

```
sage: solve(sin(x)==x,x)
[x == sin(x)]
sage: solve(sin(x)==x,x,explicit_solutions=True)
[]
sage: solve(x*sin(x)==x^2,x)
[x == 0, x == sin(x)]
sage: solve(x*sin(x)==x^2,x,explicit_solutions=True)
[x == 0]
```

The following examples show the use of the keyword to_poly_solve:

```
sage: solve(abs(1-abs(1-x)) == 10, x)
[abs(abs(x - 1) - 1) == 10]
sage: solve(abs(1-abs(1-x)) == 10, x, to_poly_solve=True)
(continues on next page)
```
The following example is a regression in Maxima 5.39.0. It used to be possible to get one more solution here, namely \(1/\sqrt{\sqrt{2} + 1}\), see https://sourceforge.net/p/maxima/bugs/3276/:

\[
\text{sage: solve}(Q*\sqrt{Q^2 + 2} - 1, Q, \text{to_poly_solve=True})
\]
\[
[Q == -\sqrt{-\sqrt{2} - 1}, Q == \sqrt{\sqrt{2} + 1}*(\sqrt{2} - 1)]
\]

An effort is made to only return solutions that satisfy the current assumptions:

\[
\text{sage: solve}(x^2==4, x)
\]
\[
[x == -2, x == 2]
\]
\[
\text{sage: assume}(x<0)
\]
\[
\text{sage: solve}(x^2==4, x)
\]
\[
[x == -2]
\]

In some cases it may be worthwhile to directly use \texttt{to_poly_solve} if one suspects some answers are being missed:

\[
\text{sage: forget()}
\]
\[
\text{sage: solve}(\cos(x)==0, x)
\]
\[
[x == 1/2*pi]
\]
\[
\text{sage: solve}(\cos(x)==0, x, \text{to_poly_solve=True})
\]
\[
[x == 1/2*pi]
\]
\[
\text{sage: solve}(\cos(x)==0, x, \text{to_poly_solve='force'}
\]
\[
[x == 1/2*pi + pi*z...]
\]

The same may also apply if a returned unsolved expression has a denominator, but the original one did not:

\[
\text{sage: solve}(\cos(x) \times \sin(x) == 1/2, x, \text{to_poly_solve=True})
\]
\[
[\sin(x) == 1/2/\cos(x)]
\]
\[
\text{sage: solve}(\cos(x) \times \sin(x) == 1/2, x, \text{to_poly_solve=True, explicit_}
\]
\[
\text{→solutions=True}
\]
\[
[x == 1/4*pi + pi*z...]
\]
\[
\text{sage: solve}(\cos(x) \times \sin(x) == 1/2, x, \text{to_poly_solve='force'}
\]
\[
[x == 1/4*pi + pi*z...]
\]

We use \texttt{use_grobner} in Maxima if no solution is obtained from Maxima’s \texttt{to_poly_solve}:

\[
\text{sage: x,y=var('x y'); c1(x,y)=(x-5)^2+y^2-16; c2(x,y)=(y-3)^2+x^2-9
\]
\[
\text{sage: solve([c1(x,y),c2(x,y)],[x,y])}
\]

(continues on next page)
We use SymPy for Diophantine equations, see Expression.solve_diophantine:

\[
\begin{align*}
&x = -9/68 \times \sqrt{55} + 135/68, \\
&y = -15/68 \times \sqrt{55} + 123/68,
\end{align*}
\]

The following shows some more of SymPy’s capabilities that cannot be handled by Maxima:

\[
\begin{align*}
sage: &\ x = \text{solve}(x^2 - y^2/exp(x), y-1), \\
&sage: (r[0][x], r[0][y]) \\
&sage: (2*lambert_w(-1/2), 1)
\end{align*}
\]

\[
\begin{align*}
sage: &\ x = \text{solve}((x-z)^2==2, x) \\
&sage: []
\end{align*}
\]

\[
\begin{align*}
sage: &\ \text{assume}(x, 'integer') \\
&sage: &\ \text{assume}(z, 'integer') \\
&sage: &\ \text{solve}((x-z)^2==2, x)
\end{align*}
\]

\[
\begin{align*}
sage: &\ \text{return()}
\end{align*}
\]

\[
\begin{align*}
sage: &\ x = -8, x == 2
\end{align*}
\]

\[
\begin{align*}
&sage: &\ x = \text{solve}((x+y+z+t, -z-t), x, y, z, t, \text{algorithm='sympy'}) \\
&sage: (r[0][x], r[0][y]) \\
&sage: (-y, -t)
\end{align*}
\]

\[
\begin{align*}
&sage: &\ x = \text{solve}(\sinh(x) - 2*cosh(x), x, \text{algorithm='sympy'}) \\
&sage: \text{ImageSet}(\text{Lambda}(_n, 2*_n*pi + pi/2 + log(sqrt(3))), \text{Integers}), \\
&sage: \text{ImageSet}(\text{Lambda}(_n, 2*_n*pi - pi/2 + log(sqrt(3))), \text{Integers})]
\end{align*}
\]

\[
\begin{align*}
&sage: &\ x = \text{solve}(2*\sin(x) - 2*\sin(2*x), x, \text{algorithm='sympy'}) \\
&sage: \text{ImageSet}(\text{Lambda}(_n, 2*_n*pi), \text{Integers}), \\
&sage: \text{ImageSet}(\text{Lambda}(_n, 2*_n*pi + pi), \text{Integers}), \\
&sage: \text{ImageSet}(\text{Lambda}(_n, 2*_n*pi + 5*pi/3), \text{Integers}), \\
&sage: \text{ImageSet}(\text{Lambda}(_n, 2*_n*pi + pi/3), \text{Integers})]
\end{align*}
\]

\[
\begin{align*}
&sage: &\ x = \text{solve}(x^5 + 3*x^3 + 7, x, \text{algorithm='sympy'})[0] \ # \text{known bug} \\
&sage: &\ \text{complex_root_of}(x^5 + 3*x^3 + 7, 0)
\end{align*}
\]

\[
\begin{align*}
&sage\symbolic\relation\text{solve_ineq}(\text{ineq, vars=\text{None}}) \\
&Solves inequalities and systems of inequalities using Maxima. Switches between rational inequalities (sage\symbolic\relation\text{solve_ineq\_rational}) and Fourier elimination (sage\symbolic\relation\text{solve_ineq\_fouriered}). See the documentation of these functions for more details.
\end{align*}
\]

\[
\begin{align*}
&\text{INPUT:} \\
&\ \bullet \ \text{ineq - one inequality or a list of inequalities}
\end{align*}
\]

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Case 1: If \( \text{ineq} \) is one equality, then it should be a rational expression in one variable. This input is passed to \( \text{sage.symbolic.relation.solve_ineq_univar} \) function.

Case 2: If \( \text{ineq} \) is a list involving one or more inequalities, then the input is passed to \( \text{sage.symbolic.relation.solve_ineq_fourier} \) function. This function can be used for system of linear inequalities and for some types of nonlinear inequalities. See [http://maxima.cvs.sourceforge.net/viewvc/maxima/maxima/share/contrib/fourier_elim/rtest_fourier_elim.mac](http://maxima.cvs.sourceforge.net/viewvc/maxima/maxima/share/contrib/fourier_elim/rtest_fourier_elim.mac) for a big gallery of problems covered by this algorithm.

- \( \text{vars} \) - optional parameter with list of variables. This list is used only if Fourier elimination is used. If omitted or if rational inequality is solved, then variables are determined automatically.

### OUTPUT:

- \( \text{list} \) – output is list of solutions as a list of simple inequalities. Output \([A,B,C]\) means \((A \text{ or } B \text{ or } C)\) each \(A, B, C\) is again a list and if \(A=[a,b]\), then \(A\) means \((a \text{ and } b)\).

### EXAMPLES:

```
sage: from sage.symbolic.relation import solve_ineq
```

Inequalities in one variable. The variable is detected automatically:

```
sage: solve_ineq(x^2-1>3)
[[x < -2], [x > 2]]
sage: solve_ineq(1/(x-1)<=8)
[[x < 1], [x >= (9/8)]]
```

System of inequalities with automatically detected inequalities:

```
sage: y=var('y')
sage: solve_ineq([x-y<0,x+y-3<0],[y,x])
[[x < y, y < -x + 3, x < (3/2)]]
sage: solve_ineq([x-y<0,x+y-3<0],[x,y])
[[x < min(-y + 3, y)]]
```

Note that although Sage will detect the variables automatically, the order it puts them in may depend on the system, so the following command is only guaranteed to give you one of the above answers:

```
sage: solve_ineq([x-y<0,x+y-3<0])  # random
[[x < y, y < -x + 3, x < (3/2)]]
```

### ALGORITHM:

Calls \( \text{solve_ineq_fourier} \) if inequalities are list and \( \text{solve_ineq_univar} \) of the inequality is symbolic expression. See the description of these commands for more details related to the set of inequalities which can be solved. The list is empty if there is no solution.

### AUTHORS:

- Robert Marik (01-2010)

\( \text{sage.symbolic.relation.solve_ineq_fourier} \) \( \text{(ineq, vars=None)} \)

Solves system of inequalities using Maxima and Fourier elimination.

Can be used for system of linear inequalities and for some types of nonlinear inequalities. For examples, see the example section below and [http://maxima.cvs.sourceforge.net/viewvc/maxima/maxima/share/contrib/fourier_elim/rtest_fourier_elim.mac](http://maxima.cvs.sourceforge.net/viewvc/maxima/maxima/share/contrib/fourier_elim/rtest_fourier_elim.mac)
• \texttt{ineq} - list with system of inequalities
• \texttt{vars} - optionally list with variables for Fourier elimination.

\textbf{OUTPUT:}

• \texttt{list} - output is list of solutions as a list of simple inequalities output [A,B,C] means (A or B or C) each A, B, C is again a list and if A=[a,b], then A means (a and b). The list is empty if there is no solution.

\textbf{EXAMPLES:}

```sage
from sage.symbolic.relation import solve_ineq_fourier
sage: solve_ineq_fourier([x+y<9,x-y>4],[x,y])
[[y + 4 < x, x < -y + 9, y < (5/2)]
 sage: solve_ineq_fourier([x+y<9,x-y>4],[y,x])
[[y < min(x - 4, -x + 9)]]
 sagesolve_ineq_fourier([x^2>=0])
[[x < +Infinity]]
 sagesolve_ineq_fourier([log(x)>log(y)], [x,y])
[[y < x, 0 < y]]
 sagesolve_ineq_fourier([log(x)>log(y)], [y,x])
[[0 < y, y < x, 0 < x]]
```

Note that different systems will find default variables in different orders, so the following is not tested:

```sage
solve_ineq_fourier([log(x)>log(y)])  # random (one of the following appears)
[[0 < y, y < x, 0 < x]]
[[y < x, 0 < y]]
```

\textbf{ALGORITHM:}

Calls Maxima command \texttt{fourier_elim}

\textbf{AUTHORS:}

• Robert Marik (01-2010)

\texttt{sage.symbolic.relation.solve_ineq_univar(ineq)}

Function solves rational inequality in one variable.

\textbf{INPUT:}

• \texttt{ineq} - inequality in one variable

\textbf{OUTPUT:}

• \texttt{list} – output is list of solutions as a list of simple inequalities output [A,B,C] means (A or B or C) each A, B, C is again a list and if A=[a,b], then A means (a and b). The list is empty if there is no solution.

\textbf{EXAMPLES:}

```sage
from sage.symbolic.relation import solve_ineq_univar
sage: solve_ineq_univar(x-1/x>0)
[[x > -1, x < 0], [x > 1]]
 sage: solve_ineq_univar(x^2-1/x>0)
[[x < 0], [x > 1]]
 sagesolve_ineq_univar((x^3-1)*x<=0)
[[x >= 0, x <= 1]]
```

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ALGORITHM:
Calls Maxima command solve_rat_ineq

AUTHORS:
• Robert Marik (01-2010)

sage.symbolic.relation.solve_mod(eqns, modulus, solution_dict=False)
Return all solutions to an equation or list of equations modulo the given integer modulus. Each equation must involve only polynomials in 1 or many variables.

By default the solutions are returned as n-tuples, where n is the number of variables appearing anywhere in the given equations. The variables are in alphabetical order.

INPUT:
• eqns - equation or list of equations
• modulus - an integer
• solution_dict - bool (default: False); if True or non-zero, return a list of dictionaries containing the solutions. If there are no solutions, return an empty list (rather than a list containing an empty dictionary). Likewise, if there’s only a single solution, return a list containing one dictionary with that solution.

EXAMPLES:

```python
sage: var('x,y')
(x, y)
sage: solve_mod([x^2 + 2 == x, x^2 + y == y^2], 14)
[(4, 2), (4, 6), (4, 9), (4, 13)]
sage: solve_mod([x^2 == 1, 4*x == 11], 15)
[(14,)]
```

Fermat’s equation modulo 3 with exponent 5:

```python
sage: var('x,y,z')
(x, y, z)
sage: solve_mod([x^5 + y^5 == z^5], 3)
[(0, 0, 0), (0, 1, 1), (0, 2, 2), (1, 0, 1), (1, 1, 2), (1, 2, 0), (2, 0, 2), (2, -1, 0), (2, 2, 1)]
```

We can solve with respect to a bigger modulus if it consists only of small prime factors:

```python
sage: [d] = solve_mod([5*x + y == 3, 2*x - 3*y == 9], 3*5*7*11*19*23*29, solution_dict=True)
sage: d[x]
12915279
sage: d[y]
8610183
```

For cases where there are relatively few solutions and the prime factors are small, this can be efficient even if the modulus itself is large:

```python
sage: sorted(solve_mod([x^2 == 41], 10^20))
[(4538602480526452429,), (11445932736758703821,), (38554067263241296179,),
(45461397519473547571,), (54538602480526452429,), (61445932736758703821,),
(88554067263241296179,), (95461397519473547571,)]
```

We solve a simple equation modulo 2:
Warning: The current implementation splits the modulus into prime powers, then naively enumerates all possible solutions (starting modulo primes and then working up through prime powers), and finally combines the solution using the Chinese Remainder Theorem. The interface is good, but the algorithm is very inefficient if the modulus has some larger prime factors! Sage does have the ability to do something much faster in certain cases at least by using Groebner basis, linear algebra techniques, etc. But for a lot of toy problems this function as is might be useful. At least it establishes an interface.

sage.symbolic.relation.string_to_list_of_solutions(s)
Used internally by the symbolic solve command to convert the output of Maxima’s solve command to a list of solutions in Sage’s symbolic package.

EXAMPLES:
We derive the (monic) quadratic formula:

```
sage: var('x,a,b')
(x, a, b)
sage: solve(x^2 + a*x + b == 0, x)
[x == -1/2*a - 1/2*sqrt(a^2 - 4*b), x == -1/2*a + 1/2*sqrt(a^2 - 4*b)]
```

Behind the scenes when the above is evaluated the function string_to_list_of_solutions() is called with input the string s below:

```
sage: s = '[x=-(sqrt(a^2-4*b)+a)/2,x=(sqrt(a^2-4*b)-a)/2]'
sage: sage.symbolic.relation.string_to_list_of_solutions(s)
[x == -1/2*a - 1/2*sqrt(a^2 - 4*b), x == -1/2*a + 1/2*sqrt(a^2 - 4*b)]
```

sage.symbolic.relation.test_relation_maxima(relation)
Return True if this (in)equality is definitely true. Return False if it is false or the algorithm for testing (in)equality is inconclusive.

EXAMPLES:

```
sage: from sage.symbolic.relation import test_relation_maxima
sage: k = var('k')
sage: pol = 1/(k-1) - 1/k -1/k/(k-1)
sage: test_relation_maxima(pol == 0)
True
sage: f = sin(x)^2 + cos(x)^2 - 1
sage: test_relation_maxima(f == 0)
True
sage: test_relation_maxima( x == x )
True
sage: test_relation_maxima( x != x )
False
sage: test_relation_maxima( x > x )
False
sage: test_relation_maxima( x^2 > x )
False
sage: test_relation_maxima( x + 2 > x )
True
```

(continues on next page)
Here are some examples involving assumptions:

```
sage: x, y, z = var('x, y, z')
sage: assume(x>=y,y>=z,z>=x)
sage: test_relation_maxima(x==z)
True
sage: test_relation_maxima(z<x)
False
sage: test_relation_maxima(z>y)
False
sage: test_relation_maxima(y==z)
True
sage: forget()
sage: assume(x>=1,x<=1)
sage: test_relation_maxima(x==1)
True
sage: test_relation_maxima(x>1)
False
sage: test_relation_maxima(x>=1)
True
sage: test_relation_maxima(x!=1)
False
sage: forget()
sage: assume(x>0)
sage: test_relation_maxima(x==0)
False
sage: test_relation_maxima(x>-1)
True
sage: test_relation_maxima(x!=0)
True
sage: test_relation_maxima(x!=1)
False
sage: forget()
```

2.5 Symbolic Computation

AUTHORS:

- Bobby Moretti and William Stein (2006-2007)
- Robert Bradshaw (2007-10): minpoly(), numerical algorithm
- Robert Bradshaw (2008-10): minpoly(), algebraic algorithm
- Golam Mortuza Hossain (2009-06-22): _laplace_latex(), _inverse_laplace_latex()
- Tom Coates (2010-06-11): fixed trac ticket #9217

EXAMPLES:

The basic units of the calculus package are symbolic expressions which are elements of the symbolic expression ring (SR). To create a symbolic variable object in Sage, use the `var()` function, whose argument is the text of that variable. Note that Sage is intelligent about LaTeXing variable names.
Sage predefines $x$ to be a global indeterminate. Thus the following works:

```python
sage: x^2
x^2
sage: type(x)
<type 'sage.symbolic.expression.Expression'>
```

More complicated expressions in Sage can be built up using ordinary arithmetic. The following are valid, and follow the rules of Python arithmetic: (The `=` operator represents assignment, and not equality)

```python
sage: var('x,y,z')
(x, y, z)
sage: f = x + y + z/(2*sin(y*z/55))
sage: g = f^f; g
(x + y + 1/2*z/sin(1/55*y*z))^(x + y + 1/2*z/sin(1/55*y*z))
```

Differentiation and integration are available, but behind the scenes through Maxima:

```python
sage: f = sin(x)/cos(2*y)
sage: f.derivative(y)
2*sin(x)*sin(2*y)/cos(2*y)^2
sage: g = f.integral(x); g
-cos(x)/cos(2*y)
```

Note that these methods usually require an explicit variable name. If none is given, Sage will try to find one for you.

```python
sage: f = sin(x); f.derivative()
cos(x)
```

If the expression is a callable symbolic expression (i.e., the variable order is specified), then Sage can calculate the matrix derivative (i.e., the gradient, Jacobian matrix, etc.) if no variables are specified. In the example below, we use the second derivative test to determine that there is a saddle point at (0,-1/2).

```python
sage: f(x,y)=x^2*y+y^2+y
sage: f.diff() # gradient
(x, y) |--> (2*x*y, x^2 + 2*y + 1)
sage: solve(list(f.diff()),[x,y])
[[x == -I, y == 0], [x == I, y == 0], [x == 0, y == (-1/2)]]
sage: H=f.diff(2); H # Hessian matrix
[(x, y) |--> 2*y (x, y) |--> 2*x]
[(x, y) |--> 2*x (x, y) |--> 2]
sage: H(x=0,y=-1/2)
[-1 0]
[ 0 2]
sage: H(x=0,y=-1/2).eigenvalues()
[-1, 2]
```

Here we calculate the Jacobian for the polar coordinate transformation:

2.5. Symbolic Computation
When the order of variables is ambiguous, Sage will raise an exception when differentiating:

```python
sage: f = sin(x+y); f.derivative()
Traceback (most recent call last):
... ValueError: No differentiation variable specified.
```

Simplifying symbolic sums is also possible, using the sum command, which also uses Maxima in the background:

```python
sage: k, m = var('k, m')
sage: sum(1/k^4, k, 1, oo)
1/90*pi^4
sage: sum(binomial(m,k), k, 0, m)
2^m
```

Symbolic matrices can be used as well in various ways, including exponentiation:

```python
sage: M = matrix([[x,x^2],[1/x,x]])
sage: M^2
[x^2 + x 2*x^3]
[ 2 x^2 + x]
sage: e^M
[[ 1/2*(e^(2*sqrt(x)) + 1)*e^(x - sqrt(x)) 1/2*(x*e^(2*sqrt(x)) - 1)*e^(x - sqrt(x))]
[ 1/2*(e^(2*sqrt(x)) - 1)*e^(x - sqrt(x))/x^(3/2) 1/2*(e^(2*sqrt(x)) + e^(-sqrt(x)))]
```

And complex exponentiation works now:

```python
sage: M = i*matrix([[pi]])
sage: e^M
[ -1]
sage: M = i*matrix([[pi,0],[0,2*pi]])
sage: e^M
[ -1 0]
[ 0 1]
sage: M = matrix([[0,pi],[-pi,0]])
sage: e^M
[ -1 0]
[ 0 -1]
```

Substitution works similarly. We can substitute with a python dict:

```python
sage: f = sin(x+y - z)
sage: f({x: var('t')}, y: z)
sin(t*z - z)
```
Also we can substitute with keywords:

```
sage: f = sin(x*y - z)
sage: f(x = t, y = z)
sin(t*z - z)
```

It was formerly the case that if there was no ambiguity of variable names, we didn’t have to specify them; that still
works for the moment, but the behavior is deprecated:

```
sage: f = sin(x)
sage: f(y)
doctest:...: DeprecationWarning: Substitution using function-call syntax and unnamed arguments is deprecated and will be removed from a future release of Sage; you can use named arguments instead, like EXPR(x=..., y=...)
See http://trac.sagemath.org/5930 for details.
sin(y)
sage: f(pi)
0
```

However if there is ambiguity, we should explicitly state what variables we’re substituting for:

```
sage: f = sin(2*pi*x/y)
sage: f(x=4)
sin(8*pi/y)
```

We can also make a `CallableSymbolicExpression`, which is a `SymbolicExpression` that is a function
of specified variables in a fixed order. Each `SymbolicExpression` has a `function(...)` method that is used
to create a `CallableSymbolicExpression`, as illustrated below:

```
sage: u = log((2-x)/(y+5))
sage: f = u.function(x, y); f
(x, y) |--> log(-(x - 2)/(y + 5))
```

There is an easier way of creating a `CallableSymbolicExpression`, which relies on the Sage preparser.

```
sage: f(x,y) = log(x)*cos(y); f
(x, y) |--> cos(y)*log(x)
```

Then we have fixed an order of variables and there is no ambiguity substituting or evaluating:

```
sage: f(x,y) = log((2-x)/(y+5))
sage: f(7,t)
log(-5/(t + 5))
```

Some further examples:

```
sage: f = 5*sin(x)
sage: f
5*sin(x)
sage: f(x=2)
5*sin(2)
sage: f(x=pi)
0
sage: float(f(x=pi))
0.0
```

Another example:
We compute the length of the parabola from 0 to 2:

```python
sage: x = var('x')
sage: y = x^2
sage: dy = derivative(y,x)
sage: z = integral(sqrt(1 + dy^2), x, 0, 2)
sage: z
sqrt(17) + 1/4*arcsinh(4)
sage: n(z,200)
4.6467837624329358733826155674904591885104869874232887508703
sage: float(z)
4.646783762432936
```

We test pickling:

```python
sage: x, y = var('x,y')
sage: f = -sqrt(pi)*(x^3 + sin(x/cos(y)))
sage: bool(loads(dumps(f)) == f)
True
```

Coercion examples:

We coerce various symbolic expressions into the complex numbers:

```python
sage: CC(I)
1.00000000000000*I
sage: CC(2*I)
2.00000000000000*I
sage: ComplexField(200)(2*I)
2.0000000000000000000000000000000000000000000000000000000000*I
sage: ComplexField(200)(sin(I))
1.1752011936438014568823818505956008151557179813340958702296*I
sage: f = sin(I) + cos(I/2); f
cosh(1/2) + I*sinh(1)
sage: CC(f)
1.12762596520638 + 1.1752011936438014568823818505956008151557179813340958702296*I
sage: ComplexField(100)(f)
1.1276259652063807852262251614026720125478471180986674836290 + 1.1752011936438014568823818505956008151557179813340958702296*I
```

We illustrate construction of an inverse sum where each denominator has a new variable name:

```python
sage: f = sum(1/var('n%s%i' %i)^i for i in range(10))
sage: f
1/n1 + 1/n2^2 + 1/n3^3 + 1/n4^4 + 1/n5^5 + 1/n6^6 + 1/n7^7 + 1/n8^8 + 1/n9^9 + 1
```

Note that after calling var, the variables are immediately available for use:
We can, of course, substitute:

```sage
f(n9=9,n7=n6)
```

1/n1 + 1/n2^2 + 1/n3^3 + 1/n4^4 + 1/n5^5 + 1/n6^6 + 1/n6^7 + 1/n8^8 + 387420490/
→ 387420489

sage.calculus.calculus.at(ex, *args, **kwds)

Parses at formulations from other systems, such as Maxima. Replaces evaluation ‘at’ a point with substitution method of a symbolic expression.

**EXAMPLES:**

We do not import `at` at the top level, but we can use it as a synonym for substitution if we import it:

```sage
g = x^3-3
g = x^3-3
```

```sage
f = function('f')(t)
```

```sage
var('s,t')
(s, t)
```

```sage
f.diff(t,2)
diff(f(t), t, t)
```

```sage
s^2*laplace(f(t), t, s) - s*f(0) - D[0](f)(0)
```

We can also accept a non-keyword list of expression substitutions, like Maxima does (trac ticket #12796):

```sage
from sage.calculus.calculus import at
```

```sage
f(x), [x == 1])
f(l)
```

sage.calculus.calculus.dummy_diff(*args)

This function is called when `diff` appears in a Maxima string.

**EXAMPLES:**

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Here the function is used implicitly:

```python
sage: a = var('a')
sage: f = function('cr')(a)
sage: g = f.diff(a); g
diff(cr(a), a)
```

**sage.calculus.calculus.dummy_integrate(**args)**

This function is called to create formal wrappers of integrals that Maxima can’t compute:

**EXAMPLES:**

```python
sage: from sage.calculus.calculus import dummy_integrate
sage: f = function('f')
sage: dummy_integrate(f(x), x)
integrate(f(x), x)
sage: a, b = var('a,b')
sage: dummy_integrate(f(x), x, a, b)
integrate(f(x), x, a, b)
```

**sage.calculus.calculus.dummy_inverse_laplace(**args)**

This function is called to create formal wrappers of inverse laplace transforms that Maxima can’t compute:

**EXAMPLES:**

```python
sage: from sage.calculus.calculus import dummy_inverse_laplace
sage: s,t = var('s,t')
sage: F = function('F')
sage: dummy_inverse_laplace(F(s), s, t)
ilt(F(s), s, t)
```

**sage.calculus.calculus.dummy_laplace(**args)**

This function is called to create formal wrappers of laplace transforms that Maxima can’t compute:

**EXAMPLES:**

```python
sage: from sage.calculus.calculus import dummy_laplace
sage: s,t = var('s,t')
sage: f = function('f')
sage: dummy_laplace(f(t), t, s)
laplace(f(t), t, s)
```

**sage.calculus.calculus.inverse_laplace(ex, s, t, algorithm='maxima')**

Return the inverse Laplace transform with respect to the variable \( t \) and transform parameter \( s \), if possible.

If this function cannot find a solution, a formal function is returned. The function that is returned may be viewed as a function of \( t \).

**DEFINITION:**

The inverse Laplace transform of a function \( F(s) \) is the function \( f(t) \), defined by

\[
F(s) = \frac{1}{2\pi i} \int_{\gamma-i\infty}^{\gamma+i\infty} e^{st} F(s) dt,
\]
where \( \gamma \) is chosen so that the contour path of integration is in the region of convergence of \( F(s) \).

**INPUT:**
- \( \text{ex} \) - a symbolic expression
- \( s \) - transform parameter
- \( t \) - independent variable
- \( \text{algorithm} \) - (default: 'maxima') one of
  - 'maxima' - use Maxima (the default)
  - 'sympy' - use SymPy
  - 'giac' - use Giac

**See also:**
- laplace()

**EXAMPLES:**

```python
sage: var('w, m')
(w, m)
sage: f = (1/(w^2+10)).inverse_laplace(w, m); f
1/10*sqrt(10)*sin(sqrt(10)*m)
sage: laplace(f, m, w)
1/(w^2 + 10)
sage: f(t) = t*cos(t)
sage: s = var('s')
sage: L = laplace(f, t, s); L
|--> 2*s^2/(s^2 + 1)^2 - 1/(s^2 + 1)
sage: inverse_laplace(L, s, t)
|--> t*cos(t)
sage: inverse_laplace(1/(s^3+1), s, t)
1/3*(sqrt(3)*sin(1/2*sqrt(3)*t) - cos(1/2*sqrt(3)*t))*e^(1/2*t) + 1/3*e^(-t)
```

No explicit inverse Laplace transform, so one is returned formally a function \( \text{ilt} \):

```python
sage: inverse_laplace(cos(s), s, t)
ilt(cos(s), s, t)
```

Transform an expression involving a time-shift, via SymPy:

```python
sage: inverse_laplace(1/s^2*exp(-s), s, t, algorithm='sympy')
-(log(e^(-t)) + 1)*heaviside(t - 1)
```

The same instance with Giac:

```python
sage: inverse_laplace(1/s^2*exp(-s), s, t, algorithm='giac')
(t - 1)*heaviside(t - 1)
```

Transform a rational expression:

```python
sage: inverse_laplace((2*s^2*exp(-2*s) - exp(-s))/(s^3+1), s, t, algorithm='giac')
-1/3*(sqrt(3)*e^(1/2*t - 1/2)*sin(1/2*sqrt(3)*(t - 1)) - cos(1/2*sqrt(3)*(t -
\rightarrow 1)))*e^(1/2*t - 1/2) + e^(-t + 1))*heaviside(t - 1) + 2/3*(2*cos(1/2*sqrt(3)*(t - 2))*e^(1/2*t - 1) + e^(-t + 2))*heaviside(t - 2)
```
Dirac delta function can also be handled:

```
sage: inverse_laplace(1, s, t, algorithm='giac')
dirac_delta(t)
```

```
sage.calculus.calculus.laplace(ex, t, s, algorithm='maxima')
```

Return the Laplace transform with respect to the variable \( t \) and transform parameter \( s \), if possible.

If this function cannot find a solution, a formal function is returned. The function that is returned may be viewed as a function of \( s \).

**DEFINITION:**

The Laplace transform of a function \( f(t) \), defined for all real numbers \( t \geq 0 \), is the function \( F(s) \) defined by

\[
F(s) = \int_{0}^{\infty} e^{-st} f(t) dt.
\]

**INPUT:**

- \( ex \) - a symbolic expression
- \( t \) - independent variable
- \( s \) - transform parameter
- \( algorithm \) - (default: 'maxima') one of
  - 'maxima' - use Maxima (the default)
  - 'sympy' - use SymPy
  - 'giac' - use Giac

**Note:** The 'sympy' algorithm returns the tuple \((F, a, \text{cond})\) where \( F \) is the Laplace transform of \( f(t) \), \( \text{Re}(s) > a \) is the half-plane of convergence, and \( \text{cond} \) are auxiliary convergence conditions.

See also:

```
inverse_laplace()
```

**EXAMPLES:**

We compute a few Laplace transforms:

```
sage: var('x, s, z, t, t0')
(x, s, z, t, t0)
sage: sin(x).laplace(x, s)
1/(s^2 + 1)
sage: (z + exp(x)).laplace(x, s)
z/s + 1/(s - 1)
sage: log(t/t0).laplace(t, s)
-(euler_gamma + log(s) + log(t0))/s
```

We do a formal calculation:

```
sage: f = function('f')(x)
sage: g = f.diff(x); g
diff(f(x), x)
sage: g.laplace(x, s)
s*laplace(f(x), x, s) - f(0)
```
A BATTLE BETWEEN the X-women and the Y-men (by David Joyner): Solve

\[ x' = -16y, \quad x(0) = 270, \quad y' = -x + 1, \quad y(0) = 90. \]

This models a fight between two sides, the “X-women” and the “Y-men”, where the X-women have 270 initially and the Y-men have 90, but the Y-men are better at fighting, because of the higher factor of “-16” vs “-1”, and also get an occasional reinforcement, because of the “+1” term.

\[
\begin{align*}
\text{sage: } & \quad \text{var(’t’)} \\
\text{sage: } & \quad t \\
\text{sage: } & \quad x = \text{function(’x’) (t)} \\
\text{sage: } & \quad y = \text{function(’y’) (t)} \\
\text{sage: } & \quad \text{de1} = x.\text{diff}(t) + 16*y \\
\text{sage: } & \quad \text{de2} = y.\text{diff}(t) + x - 1 \\
\text{sage: } & \quad \text{de1}\text{.laplace}(t, s) \\
& \quad \quad = s*\text{laplace}(x(t), t, s) + 16*\text{laplace}(y(t), t, s) - x(0) \\
\text{sage: } & \quad \text{de2}\text{.laplace}(t, s) \\
& \quad \quad = s*\text{laplace}(y(t), t, s) - 1/s + \text{laplace}(x(t), t, s) - y(0)
\end{align*}
\]

Next we form the augmented matrix of the above system:

\[
\begin{align*}
\text{sage: } & \quad \text{A} = \text{matrix}([[s, 16, 270], [1, s, 90+1/s]]) \\
\text{sage: } & \quad \text{E} = \text{A.echelon_form()} \\
\text{sage: } & \quad \text{xt} = \text{E}[0,2].\text{inverse_laplace}(s,t) \\
\text{sage: } & \quad \text{yt} = \text{E}[1,2].\text{inverse_laplace}(s,t) \\
\text{sage: } & \quad \text{xt} \quad = -91/2*e^(4*t) + 629/2*e^(-4*t) + 1 \\
\text{sage: } & \quad \text{yt} \quad = 91/8*e^(4*t) + 629/8*e^(-4*t) \\
\text{sage: } & \quad \text{p1} = \text{plot(xt,0,1/2,rgbcolor=(1,0,0))} \\
\text{sage: } & \quad \text{p2} = \text{plot(yt,0,1/2,rgbcolor=(0,1,0))} \\
\text{sage: } & \quad \text{(p1+p2).save(os.path.join(SAGE_TMP, ”de_plot.png”))}
\end{align*}
\]

Another example:

\[
\begin{align*}
\text{sage: } & \quad \text{var(’a,s,t’) } \\
& \quad \text{(a, s, t)} \\
\text{sage: } & \quad f = \text{exp} (2*t + a) * \sin(t) * t; \quad f \\
& \quad t*e^(a + 2*t)*\sin(t) \\
\text{sage: } & \quad L = \text{laplace}(f, t, s); \quad L \\
& \quad 2*(s - 2)*e^a/(s^2 - 4*s + 5)^2 \\
\text{sage: } & \quad \text{inverse_laplace}(L, s, t) \\
& \quad t*e^(a + 2*t)*\sin(t)
\end{align*}
\]

Unable to compute solution with Maxima:

\[
\begin{align*}
\text{sage: } & \quad \text{laplace(heaviside(t-1), t, s)} \\
& \quad \text{laplace(heaviside(t - 1), t, s)}
\end{align*}
\]

Heaviside step function can be handled with different interfaces. Try with giac:

\[
\begin{align*}
\text{sage: } & \quad \text{laplace(heaviside(t-1), t, s, algorithm=’giac’)} \\
& \quad e^(-s)/s
\end{align*}
\]

Try with SymPy:
sage: laplace(heaviside(t-1), t, s, algorithm='sympy')
(e^(-s)/s, 0, True)

sage.calculus.calculus.lim(expr, dir=None, taylor=False, algorithm='maxima', **argv)

Return the limit as the variable \( v \) approaches \( a \) from the given direction.

expr.limit(x = a)
expr.limit(x = a, dir='+')

INPUT:

- \textbf{dir} - (default: None); dir may have the value ‘plus’ (or ‘+’ or ‘right’ or ‘above’) for a limit from above, ‘minus’ (or ‘-’ or ‘left’ or ‘below’) for a limit from below, or may be omitted (implying a two-sided limit is to be computed).

- \textbf{taylor} - (default: False); if True, use Taylor series, which allows more limits to be computed (but may also crash in some obscure cases due to bugs in Maxima).

- \textbf{**argv} - 1 named parameter

\textbf{Note: } The output may also use ‘und’ (undefined), ‘ind’ (indefinite but bounded), and ‘infinity’ (complex infinity).

EXAMPLES:

sage: x = var('x')
sage: f = (1 + 1/x)^x
sage: f.limit(x=oo)
e
sage: f.limit(x=5)
7776/3125
sage: f.limit(x=1.2)
2.06961575467...

sage: f.limit(x=I, taylor=True)
(-I + 1)^I

sage: f(x=1.2)
2.0696157546720...

sage: f(x=I)
(-I + 1)^I

sage: CDF(f(x=I))
2.0628722350809046 + 0.7450070621797239*I
sage: CDF(f.limit(x=I))
2.0628722350809046 + 0.7450070621797239*I

Notice that Maxima may ask for more information:

sage: var('a')
a
sage: limit(x^a, x=0)
Traceback (most recent call last):
... ValueError: Computation failed since Maxima requested additional constraints; using the 'assume' command before evaluation *may* help (example of legal syntax is 'assume(a>0)', see 'assume?' for more details)
Is a positive, negative or zero?
With this example, Maxima is looking for a LOT of information:

```plaintext
sage: assume(a>0)
sage: limit(x^a, x=0)
Traceback (most recent call last):
  ...
ValueError: Computation failed since Maxima requested additional constraints; using the 'assume' command before evaluation *may* help (example of legal syntax is 'assume(a>0)', see `assume?` for more details)
Is a an integer?
sage: assume(a,'integer')
sage: limit(x^a, x=0)
Traceback (most recent call last):
  ...
ValueError: Computation failed since Maxima requested additional constraints; using the 'assume' command before evaluation *may* help (example of legal syntax is 'assume(a>0)', see `assume?` for more details)
Is a an even number?
sage: assume(a, 'even')
sage: limit(x^a, x=0)
0
sage: forget()
```

More examples:

```plaintext
sage: limit(x*log(x), x=0, dir='+')
0
sage: lim((x+1)^(1/x), x=0)
e
sage: lim(e^x/x, x=oo)
+Infinity
sage: lim(e^x/x, x=-oo)
0
sage: lim(-e^x/x, x=oo)
-Infinity
sage: lim((cos(x))/(x^2), x=0)
+Infinity
sage: lim(sqrt(x^2+1) - x, x=oo)
0
sage: lim(x^2/(sec(x)-1), x=0)
2
sage: lim(cos(x)/(cos(x)-1), x=0)
-Infinity
sage: lim(x*sin(1/x), x=0)
0
sage: limit(e^(-1/x), x=0, dir='right')
0
sage: limit(e^(-1/x), x=0, dir='left')
+Infinity
```

```plaintext
sage: f = log(log(x)) / log(x)
sage: forget(); assume(x < -2); lim(f, x=0, taylor=True)
0
sage: forget()
```

Here ind means “indefinite but bounded”:  

2.5. Symbolic Computation
sage: lim(sin(1/x), x = 0)
ind

We can use other packages than maxima:

\[
\begin{align*}
\text{sage}: & \quad \lim_{x \to -\infty} \frac{x}{x^2 + x + \cos(x)} \quad \text{algorithm='fricas'} & 1 \\
\text{sage}: & \quad \lim_{x \to 0} (e^{-1/x}, \text{dir='right'}), \text{algorithm='fricas'} & 0 \\
\text{sage}: & \quad \lim_{x \to 0} (e^{-1/x}, \text{dir='left'}), \text{algorithm='fricas'} & +\infty
\end{align*}
\]

\text{sage.calculus.calculus.limit (ex, dir=None, taylor=False, algorithm='maxima', **argv)}

Return the limit as the variable \( v \) approaches \( a \) from the given direction.

\[
\begin{align*}
\text{sage}: & \quad \lim_{x \to \infty} (1 + 1/x)^x \\
\text{sage}: & \quad \lim_{x \to 0} (e^{-1/x}, x=5) \\
\text{sage}: & \quad \lim_{x \to 0} (e^{-1/x}, x=5) + \infty
\end{align*}
\]

Note: The output may also use ‘und’ (undefined), ‘ind’ (indefinite but bounded), and ‘infinity’ (complex infinity).

EXAMPLES:

\[
\begin{align*}
\text{sage}: & \quad x = \text{var('x')} \\
\text{sage}: & \quad f = (1 + 1/x)^x \\
\text{sage}: & \quad f.limit(x=\infty) \\
\text{sage}: & \quad f.limit(x=5) \\
\text{sage}: & \quad f.limit(x=1.2) \\
\text{sage}: & \quad f.limit(x=\text{I}, taylor=True) \\
\text{sage}: & \quad f(x=1.2, taylor=True) \\
\text{sage}: & \quad f(x=\text{I}) \\
\text{sage}: & \quad \text{CDF}(f(x=\text{I}))
\end{align*}
\]

Notice that Maxima may ask for more information:
sage: var('a')
a
sage: limit(x^a, x=0)
Traceback (most recent call last):
...
ValueError: Computation failed since Maxima requested additional constraints; using the 'assume' command before evaluation *may* help (example of legal syntax is 'assume(a>0)', see `assume?` for more details)
Is a positive, negative or zero?

With this example, Maxima is looking for a LOT of information:

sage: assume(a>0)
sage: limit(x^a, x=0)
Traceback (most recent call last):
...
ValueError: Computation failed since Maxima requested additional constraints; using the 'assume' command before evaluation *may* help (example of legal syntax is 'assume(a>0)', see `assume?` for more details)
Is a an integer?
sage: assume(a,'integer')
sage: limit(x^a, x=0)
Traceback (most recent call last):
...
ValueError: Computation failed since Maxima requested additional constraints; using the 'assume' command before evaluation *may* help (example of legal syntax is 'assume(a>0)', see `assume?` for more details)
Is a an even number?
sage: assume(a, 'even')
sage: limit(x^a, x=0)
0
sage: forget()

More examples:

sage: limit(x*log(x), x=0, dir='+')
0
sage: lim((x+1)^(1/x), x=0)
e
sage: limit(e^x/x, x=oo)
+Infinity
sage: limit(e^x/x, x=-oo)
0
sage: limit(-e^x/x, x=oo)
-Infinity
sage: limit((cos(x))/(x^2), x=0)
+Infinity
sage: limit(sqrt(x^2+1) - x, x=oo)
0
sage: limit(x^2/(sec(x)-1), x=0)
2
sage: limit(cos(x)/(cos(x)-1), x=0)
-Infinity
sage: limit(x*sin(1/x), x=0)

(continues on next page)
sage: limit(e^(-1/x), x=0, dir='right')
0

sage: limit(e^(-1/x), x=0, dir='left')
+Infinity

sage: f = log(log(x)) / log(x)

sage: forget(); assume(x < -2); lim(f, x=0, taylor=True)
0

sage: forget()

Here ind means “indefinite but bounded”:

sage: lim(sin(1/x), x = 0)
ind

We can use other packages than maxima:

sage: (x / (x+2^x+cos(x))).limit(x=-infinity, algorithm='fricas')
1

sage: limit(e^(-1/x), x=0, dir='right', algorithm='fricas')
0

sage: limit(e^(-1/x), x=0, dir='left', algorithm='fricas')
+Infinity

sage.calculus.calculus.mapped_opts(v)
Used internally when creating a string of options to pass to Maxima.

INPUT:
• v - an object

OUTPUT: a string.

The main use of this is to turn Python bools into lower case strings.

EXAMPLES:

sage: sage.calculus.calculus.mapped_opts(True)
'true'
sage: sage.calculus.calculus.mapped_opts(False)
'false'
sage: sage.calculus.calculus.mapped_opts('bar')
'bar'

sage.calculus.calculus.maxima_options(**kwds)
Used internally to create a string of options to pass to Maxima.

EXAMPLES:

sage: sage.calculus.calculus.maxima_options(an_option=True, another=False, foo=
'bar')
'an_option=true,another=false,foo=bar'
sage.calculus.calculus.minpoly(ex, var='x', algorithm=None, bits=None, degree=None, epsilon=0)

Return the minimal polynomial of self, if possible.

INPUT:
- var - polynomial variable name (default 'x')
- algorithm - 'algebraic' or 'numerical' (default both, but with numerical first)
- bits - the number of bits to use in numerical approx
- degree - the expected algebraic degree
- epsilon - return without error as long as f(self) epsilon, in the case that the result cannot be proven.

All of the above parameters are optional, with epsilon=0, bits and degree tested up to 1000 and 24 by default respectively. The numerical algorithm will be faster if bits and/or degree are given explicitly. The algebraic algorithm ignores the last three parameters.

OUTPUT: The minimal polynomial of self. If the numerical algorithm is used then it is proved symbolically when epsilon=0 (default).

If the minimal polynomial could not be found, two distinct kinds of errors are raised. If no reasonable candidate was found with the given bit/degree parameters, a ValueError will be raised. If a reasonable candidate was found but (perhaps due to limits in the underlying symbolic package) was unable to be proved correct, a NotImplementedError will be raised.

ALGORITHM: Two distinct algorithms are used, depending on the algorithm parameter. By default, the numerical algorithm is attempted first, then the algebraic one.

Algebraic: Attempt to evaluate this expression in QQbar, using cyclotomic fields to resolve exponential and trig functions at rational multiples of pi, field extensions to handle roots and rational exponents, and computing composites to represent the full expression as an element of a number field where the minimal polynomial can be computed exactly. The bits, degree, and epsilon parameters are ignored.

Numerical: Computes a numerical approximation of self and use PARI’s algdep to get a candidate minpoly \( f \). If \( f(self) \), evaluated to a higher precision, is close enough to 0 then evaluate \( f(self) \) symbolically, attempting to prove vanishing. If this fails, and epsilon is non-zero, return \( f \) if and only if \( f(self) < \epsilon \). Otherwise raise a ValueError (if no suitable candidate was found) or a NotImplementedError (if a likely candidate was found but could not be proved correct).

EXAMPLES: First some simple examples:

```
sage: sqrt(2).minpoly()
x^2 - 2
sage: minpoly(2^(1/3))
x^3 - 2
sage: minpoly(sqrt(2) + sqrt(-1))
x^4 - 2*x^2 + 9
sage: minpoly(sqrt(2)-3^(1/3))
x^6 - 6*x^4 + 6*x^3 + 12*x^2 + 36*x + 1
```

Works with trig and exponential functions too.

```
sage: sin(pi/3).minpoly()
x^2 - 3/4
sage: sin(pi/7).minpoly()
x^6 - 7/4*x^4 + 7/8*x^2 - 7/64
sage: minpoly(exp(1*pi/17))
x^16 - x^15 + x^14 - x^13 + x^12 - x^11 + x^10 - x^9 + x^8 - x^7 + x^6 - x^5 + x^4 - x^3 + x^2 - x + 1
```

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Here we verify it gives the same result as the abstract number field.

```python
sage: (sqrt(2) + sqrt(3) + sqrt(6)).minpoly()
x^4 - 22*x^2 - 48*x - 23
sage: K.<a,b> = NumberField([x^2-2, x^2-3])
sage: (a+b+a*b).absolute_minpoly()
x^4 - 22*x^2 - 48*x - 23
```

The minpoly function is used implicitly when creating number fields:

```python
sage: x = var('x')
sage: eqn = x^3 + sqrt(2)*x + 5 == 0
sage: a = solve(eqn, x)[0].rhs()
sage: QQ[a]
Number Field in a with defining polynomial x^6 + 10*x^3 - 2*x^2 + 25 with a = 0. →71852724658288467 - 1.721353471724806?*I
```

Here we solve a cubic and then recover it from its complicated radical expansion.

```python
sage: f = x^3 - x + 1
sage: a = f.solve(x)[0].rhs(); a
-1/2*(1/18*sqrt(23)*sqrt(3) - 1/2)^(1/3)*(I*sqrt(3) + 1) - 1/6*(-I*sqrt(3) + 1)/
→(1/18*sqrt(23)*sqrt(3) - 1/2)^(1/3)
sage: a.minpoly()
x^3 - x + 1
```

Note that simplification may be necessary to see that the minimal polynomial is correct.

```python
sage: a = sqrt(2)+sqrt(3)+sqrt(5)
sage: f = a.minpoly(); f
x^8 - 40*x^6 + 352*x^4 - 960*x^2 + 576
sage: f(a)
(sqrt(5) + sqrt(3) + sqrt(2))^8 - 40*(sqrt(5) + sqrt(3) + sqrt(2))^6 +
→352*(sqrt(5) + sqrt(3) + sqrt(2))^4 - 960*(sqrt(5) + sqrt(3) + sqrt(2))^2 + 576
sage: f(a).expand()
0
```

The degree must be high enough (default tops out at 24).

```python
sage: a = sqrt(3) + sqrt(2)
sage: a.minpoly(algorithm='numerical', bits=100, degree=3)
Traceback (most recent call last):
... ValueError: Could not find minimal polynomial (100 bits, degree 3).
sage: a.minpoly(algorithm='numerical', bits=100, degree=10)
x^4 - 10*x^2 + 1
```

```python
sage: cos(pi/33).minpoly(algorithm='algebraic')
x^10 + 1/2*x^9 - 5/2*x^8 - 5/4*x^7 + 17/8*x^6 + 17/16*x^5 - 43/64*x^4 - 43/128*x^3 + 3/64*x^2 + 3/128*x + 1/1024
sage: cos(pi/33).minpoly(algorithm='numerical')
```

(continues on next page)
Sometimes it fails, as it must given that some numbers aren’t algebraic:

```
sage: sin(1).minpoly(algorithm='numerical')
Traceback (most recent call last):
  ...  
ValueError: Could not find minimal polynomial (1000 bits, degree 24).
```

### Note

Of course, failure to produce a minimal polynomial does not necessarily indicate that this number is transcendental.

```
sage.calculus.calculus.nintegral(ex, x, a, b, desired_relative_error='1e-8', maximum_num_subintervals=200)
```

Return a floating point machine precision numerical approximation to the integral of self from \(a\) to \(b\), computed using floating point arithmetic via maxima.

**INPUT:**
- \(x\) - variable to integrate with respect to
- \(a\) - lower endpoint of integration
- \(b\) - upper endpoint of integration
- \(\text{desired_relative_error}\) - (default: ‘1e-8’) the desired relative error
- \(\text{maximum_num_subintervals}\) - (default: 200) maxima number of subintervals

**OUTPUT:**
- float: approximation to the integral
- float: estimated absolute error of the approximation
- the number of integrand evaluations
- an error code:
  - 0 - no problems were encountered
  - 1 - too many subintervals were done
  - 2 - excessive roundoff error
  - 3 - extremely bad integrand behavior
  - 4 - failed to converge
  - 5 - integral is probably divergent or slowly convergent
  - **6** - the input is invalid; this includes the case of \(\text{desired_relative_error}\) being too small to be achieved

**ALIAS:** nintegrate is the same as nintegral

**REMARK:** There is also a function `numerical_integral` that implements numerical integration using the GSL C library. It is potentially much faster and applies to arbitrary user defined functions.

Also, there are limits to the precision to which Maxima can compute the integral due to limitations in quadpack. In the following example, remark that the last value of the returned tuple is 6, indicating that the input was invalid, in this case because of a too high desired precision.
```sage
sage: f = x
sage: f.nintegral(x,0,1,1e-14)
(0.0, 0.0, 0, 6)
```

**EXAMPLES:**

```sage
sage: f(x) = exp(-sqrt(x))

```

```sage
sage: f.nintegral(x, 0, 1)
(0.5284822353142306, 4.163...e-11, 231, 0)
```

We can also use the `numerical_integral` function, which calls the GSL C library.

```sage
sage: numerical_integral(f, 0, 1)
(0.528482232253147, 6.83928460...e-07)
```

Note that in exotic cases where floating point evaluation of the expression leads to the wrong value, then the output can be completely wrong:

```sage
sage: f = exp(pi*sqrt(163)) - 262537412640768744

```

Despite appearance, \( f \) is really very close to 0, but one gets a nonzero value since the definition of `float(f)` is that it makes all constants inside the expression floats, then evaluates each function and each arithmetic operation using float arithmetic:

```sage
sage: float(f)
-480.0
```

Computing to higher precision we see the truth:

```sage
sage: f.n(200)
-7.49927402801814311206461436622348652078895136533593355718e-13
sage: f.n(300)
-7.
```

Now numerically integrating, we see why the answer is wrong:

```sage
sage: f.nintegrate(x,0,1)
(-480.0000000000001, 5.32907051820075...e-12, 21, 0)
```

It is just because every floating point evaluation of return -480.0 in floating point.

Important note: using PARI/GP one can compute numerical integrals to high precision:

```sage
sage: gp.eval('intnum(x=17,42,exp(-x^2)*log(x))')
'2.565728500561051474934096410 E-127' # 32-bit
'2.5657285005610514829176211363206621657 E-127' # 64-bit
sage: old_prec = gp.set_real_precision(50)

```

```sage
sage: gp.eval('intnum(x=17,42,exp(-x^2)*log(x))')
'2.5657285005610514829176211363206621657 E-127'

```

```sage
sage: gp.set_real_precision(old_prec)
```

Note that the input function above is a string in PARI syntax.

```sage
sage.calculus.calculus.nintegrate(x, a, b, desired_relative_error='1e-8', maximum_num_subintervals=200)
```
Return a floating point machine precision numerical approximation to the integral of \( \text{self} \) from \( a \) to \( b \), computed using floating point arithmetic via maxima.

INPUT:

- \( x \) - variable to integrate with respect to
- \( a \) - lower endpoint of integration
- \( b \) - upper endpoint of integration
- desired\_relative\_error - (default: ‘1e-8’) the desired relative error
- maximum\_num\_subintervals - (default: 200) maxima number of subintervals

OUTPUT:

- float: approximation to the integral
- float: estimated absolute error of the approximation
- the number of integrand evaluations
- an error code:
  - 0 - no problems were encountered
  - 1 - too many subintervals were done
  - 2 - excessive roundoff error
  - 3 - extremely bad integrand behavior
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ALIAS: nintegrate is the same as nintegral

REMARK: There is also a function numerical\_integral that implements numerical integration using the GSL C library. It is potentially much faster and applies to arbitrary user defined functions.

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```
sage: f = x
sage: f.nintegral(x,0,1,1e-14)
(0.0, 0.0, 0, 6)
```

EXAMPLES:

```
sage: f(x) = exp(-sqrt(x))
sage: f.nintegral(x, 0, 1)
(0.528482232253147, 6.83928460399332e-07)
```

We can also use the numerical\_integral function, which calls the GSL C library.

```
sage: numerical\_integral(f, 0, 1)
(0.528482232253147, 6.83928460399332e-07)
```

Note that in exotic cases where floating point evaluation of the expression leads to the wrong value, then the output can be completely wrong.
Despite appearance, \( f \) is really very close to 0, but one gets a nonzero value since the definition of \( \text{float}(f) \) is that it makes all constants inside the expression floats, then evaluates each function and each arithmetic operation using float arithmetic:

\[
\text{sage: float(f)} \quad -480.0
\]

Computing to higher precision we see the truth:

\[
\text{sage: f.n(200)}
\]
\[
-7.49927402801814311120614366626300913729262589621789352095066181709095575681963967103004e-13
\]

Now numerically integrating, we see why the answer is wrong:

\[
\text{sage: f.nintegrate(x,0,1)}
\]
\[
(-480.0000000000001, 5.32907051820075...e-12, 21, 0)
\]

It is just because every floating point evaluation of return -480.0 in floating point.

Important note: using PARI/GP one can compute numerical integrals to high precision:

\[
\text{sage: gp.eval('intnum(x=17,42,exp(-x^2)*log(x))')}
\]
\[
'2.565728500561051474934096410 E-127' \quad \# \quad 32-bit
\]
\[
'2.5657285005610514829176211363206621657 E-127' \quad \# \quad 64-bit
\]

\[
\text{sage: old_prec = gp.set_real_precision(50)}
\]
\[
\text{sage: gp.eval('intnum(x=17,42,exp(-x^2)*log(x))')}
\]
\[
'2.5657285005610514829173563961304957417746108003917 E-127'
\]

\[
\text{sage: gp.set_real_precision(old_prec)}
\]

\[
57
\]

Note that the input function above is a string in PARI syntax.

\[
\text{sage.calculus.calculus.symbolic_expression_from_maxima_string(x, equals_sub=False, maxima=Maxima_lib)}
\]

Given a string representation of a Maxima expression, parse it and return the corresponding Sage symbolic expression.

INPUT:

- x - a string
- equals_sub - (default: False) if True, replace ‘=’ by ‘==’ in self
- maxima - (default: the calculus package’s Maxima) the Maxima interpreter to use.

EXAMPLES:
sage: \( f = \text{function('f')(x)} \)
\[ f(2) != 1 \]
\[ a = \text{sage.calculus.calculus.maxima('x#0')}; a \]
\[ x != 0 \]

sage.calculus.calculus.symbolic_expression_from_string(s, syms=None, accept_sequence=False)

Given a string, (attempt to) parse it and return the corresponding Sage symbolic expression. Normally used to return Maxima output to the user.

INPUT:

• `s` - a string
• `syms` - (default: None) dictionary of strings to be regarded as symbols or functions
• `accept_sequence` - (default: False) controls whether to allow a (possibly nested) set of lists and tuples as input

EXAMPLES:

sage: y = var('y')
sage: sage.calculus.calculus.symbolic_expression_from_string('[sin(y), x^2, →3*spam+e^pi]', syms={'spam':y}, accept_sequence=True)
[0, 3*y + e^pi]

sage.calculus.calculus.symbolic_product(expression, v, a, b, algorithm='maxima', hold=False)

Return the symbolic product \( \prod_{v=a}^{b} expression \) with respect to the variable \( v \) with endpoints \( a \) and \( b \).

INPUT:

• `expression` - a symbolic expression
• `v` - a variable or variable name
• `a` - lower endpoint of the product
• `b` - upper endpoint of the product
• `algorithm` - (default: 'maxima') one of
  - 'maxima' - use Maxima (the default)
  - 'giac' - use Giac
  - 'sympy' - use SymPy
  - 'mathematica' - (optional) use Mathematica
• `hold` - (default: False) if True don’t evaluate

EXAMPLES:

sage: i, k, n = var('i,k,n')
sage: from sage.calculus.calculus import symbolic_product
sage: symbolic_product(k, k, 1, n)
factorial(n)
sage: symbolic_product(x + i*(i+1)/2, i, 1, 4)
x^4 + 20*x^3 + 127*x^2 + 288*x + 180
sage: symbolic_product(i^2, i, 1, 7)
25401600
sage: f = function('f')
sage: symbolic_product(f(i), i, 1, 7)
f(7)*f(6)*f(5)*f(4)*f(3)*f(2)*f(1)
sage: symbolic_product(f(i), i, 1, n)
product(f(i), i, 1, n)
sage: assume(k>0)
sage: symbolic_product(integrate (x^k, x, 0, 1), k, 1, n)
1/factorial(n + 1)
sage: symbolic_product(f(i), i, 1, n).log().log_expand()
sum(log(f(i)), i, 1, n)

sage.calculus.calculus.symbolic_sum(expression, v, a, b, algorithm='maxima', hold=False)
Return the symbolic sum $\sum_{v=a}^{b} expression$ with respect to the variable $v$ with endpoints $a$ and $b$.

INPUT:

- **expression** - a symbolic expression
- **v** - a variable or variable name
- **a** - lower endpoint of the sum
- **b** - upper endpoint of the sum
- **algorithm** - (default: 'maxima') one of
  - 'maxima' - use Maxima (the default)
  - 'maple' - (optional) use Maple
  - 'mathematica' - (optional) use Mathematica
  - 'giac' - (optional) use Giac
  - 'sympy' - use SymPy
- **hold** - (default: False) if True don't evaluate

EXAMPLES:

sage: k, n = var('k,n')
sage: from sage.calculus.calculus import symbolic_sum
sage: symbolic_sum(k, k, 1, n).factor()
1/2*(n + 1)*n
sage: symbolic_sum(1/k^4, k, 1, oo)
1/90*pi^4
sage: symbolic_sum(1/k^5, k, 1, oo)
zeta(5)

A well known binomial identity:

sage: symbolic_sum(binomial(n,k), k, 0, n)
2^n

And some truncations thereof:
sage: assume(n>1)
sage: symbolic_sum(binomial(n,k),k,1,n)
2^n - 1
sage: symbolic_sum(binomial(n,k),k,2,n)
2^n - n - 1
sage: symbolic_sum(binomial(n,k),k,0,n-1)
2^n - 1
sage: symbolic_sum(binomial(n,k),k,1,n-1)
2^n - 2

The binomial theorem:

sage: x, y = var('x, y')
sage: symbolic_sum(binomial(n,k) * x^k * y^(n-k), k, 0, n)
(x + y)^n
sage: symbolic_sum(k * binomial(n, k), k, 1, n)
2^(n - 1)*n
sage: symbolic_sum((-1)^k*binomial(n,k), k, 0, n)
0
sage: symbolic_sum(2^(-k)/(k*(k+1)), k, 1, oo)
-log(2) + 1

Summing a hypergeometric term:

sage: symbolic_sum(binomial(n, k) * factorial(k) / factorial(n+1+k), k, 0, n)
1/2*sqrt(pi)/factorial(n + 1/2)

We check a well known identity:

sage: bool(symbolic_sum(k^3, k, 1, n) == symbolic_sum(k, k, 1, n)^2)
True

A geometric sum:

sage: a, q = var('a, q')
sage: symbolic_sum(a*q^k, k, 0, n)
(a*q^n + 1 - a)/(q - 1)

For the geometric series, we will have to assume the right values for the sum to converge:

sage: assume(abs(q) < 1)
sage: symbolic_sum(a*q^k, k, 0, oo)
-a/(q - 1)

A divergent geometric series. Don’t forget to forget your assumptions:

sage: forget()
sage: assume(q > 1)
sage: symbolic_sum(a*q^k, k, 0, oo)
Traceback (most recent call last):
... ValueError: Sum is divergent.
sage: forget()

(continued from previous page)

sage: assumptions()  # check the assumptions were really forgotten
[]

This summation only Mathematica can perform:

sage: symbolic_sum(1/(1+k^2), k, -oo, oo, algorithm = 'mathematica')  #<
pi*coth(pi)

An example of this summation with Giac:

sage: symbolic_sum(1/(1+k^2), k, -oo, oo, algorithm = 'giac')
(pi*e^(2*pi) - pi*e^(-2*pi))/(e^(2*pi) + e^(-2*pi) - 2)

SymPy can’t solve that summation:

sage: symbolic_sum(1/(1+k^2), k, -oo, oo, algorithm = 'sympy')
Traceback (most recent call last):
... AttributeError: Unable to convert SymPy result (=Sum(1/(k^2 + 1), (k, -oo, oo))) into Sage

SymPy and Maxima 5.39.0 can do the following (see trac ticket #22005):

sage: sum(1/((2*n+1)^2-4)^2, n, 0, Infinity, algorithm='sympy')
1/64*pi^2

sage: sum(1/((2*n+1)^2-4)^2, n, 0, Infinity)
1/64*pi^2

Use Maple as a backend for summation:

sage: symbolic_sum(binomial(n,k)*x^k, k, 0, n, algorithm = 'maple')  #<
(x + 1)^n

If you don’t want to evaluate immediately give the hold keyword:

sage: s = sum(n, n, 1, k, hold=True); s
sum(n, n, 1, k)
sage: s.unhold()
1/2*k^2 + 1/2*k
sage: s.subs(k == 10)
55
sage: s.subs(k == 10).unhold()
55
sage: s.subs(k == 10).n()
55.0000000000000

Note: Sage can currently only understand a subset of the output of Maxima, Maple and Mathematica, so even if the chosen backend can perform the summation the result might not be convertible into a Sage expression.
2.6 Units of measurement

This is the units package. It contains information about many units and conversions between them.

TUTORIAL:

To return a unit:

```
sage: units.length.meter
meter
```

This unit acts exactly like a symbolic variable:

```
sage: s = units.length.meter
sage: s^2
meter^2
sage: s + var('x')
meter + x
```

Units have additional information in their docstring:

```
sage: # You would type: units.force.dyne?
sage: print(units.force.dyne.__doc__)
CGS unit for force defined to be gram*centimeter/second^2.
Equal to 10^-5 newtons.
```

You may call the convert function with units:

```
sage: t = units.mass.gram*units.length.centimeter/units.time.second^2
sage: t.convert(units.mass.pound*units.length.foot/units.time.hour^2)
5400000000000/5760623099*(foot*pound/hour^2)
sage: t.convert(units.force.newton)
1/100000*newton
```

Calling the convert function with no target returns base SI units:

```
sage: t.convert()
1/100000*kilogram*meter/second^2
```

Giving improper units to convert to raises a ValueError:

```
sage: t.convert(units.charge.coulomb)
Traceback (most recent call last):
...  
ValueError: Incompatible units
```

Converting temperatures works as well:

```
sage: s = 68*units.temperature.fahrenheit
sage: s.convert(units.temperature.celsius)
20*celsius
sage: s.convert()
293.150000000000*kelvin
```

Trying to multiply temperatures by another unit then converting raises a ValueError:
AUTHORS:

- David Ackerman
- William Stein

```python
sage: wrong = 50*units.temperature.celsius*units.length.foot
sage: wrong.convert()
Traceback (most recent call last):
...
ValueError: Cannot convert
```

```python
class sage.symbolic.units.UnitExpression
    Bases: sage.symbolic.expression.Expression
    A symbolic unit.

    EXAMPLES:

sage: acre = units.area.acre
sage: type(acre)
<class 'sage.symbolic.units.UnitExpression'>
```

```python
class sage.symbolic.units.Units(data, name='')
    Bases: sage.interfaces.tab_completion.ExtraTabCompletion
    A collection of units of some type.

    EXAMPLES:

sage: units.power
Collection of units of power: cheval_vapeur horsepower watt
```

```python
sage.symbolic.units.base_units(unit)
    Converts unit to base SI units.

    INPUT:
    - unit -- a unit

    OUTPUT:
    - a symbolic expression

    EXAMPLES:

sage: sage.symbolic.units.base_units(units.length.foot)
381/1250*meter

If unit is already a base unit, it just returns that unit:

sage: sage.symbolic.units.base_units(units.length.meter)
meter

Derived units get broken down into their base parts:

sage: sage.symbolic.units.base_units(units.force.newton)
kilogram*meter/second^2
sage: sage.symbolic.units.base_units(units.volume.liter)
1/1000*meter^3

Returns variable if ‘unit’ is not a unit:
sage: sage.symbolic.units.base_units(var('x'))
x

sage.symbolic.units.convert(expr, target)

Converts units between expr and target. If target is None then converts to SI base units.

INPUT:

- expr – the symbolic expression converting from
- target – (default None) the symbolic expression converting to

OUTPUT:

- a symbolic expression

EXAMPLES:

sage: sage.symbolic.units.convert(units.length.foot, None)
381/1250*meter

sage: sage.symbolic.units.convert(units.mass.kilogram, units.mass.pound)
100000000/45359237*pound

Raises ValueError if expr and target are not convertible:

sage: sage.symbolic.units.convert(units.mass.kilogram, units.length.foot)
Traceback (most recent call last):
  ...
ValueError: Incompatible units

sage: sage.symbolic.units.convert(units.length.meter^2, units.length.foot)
Traceback (most recent call last):
  ...
ValueError: Incompatible units

Recognizes derived unit relationships to base units and other derived units:

sage: sage.symbolic.units.convert(units.length.foot/units.time.second^2, units.acceleration.galileo)
762/25*galileo

sage: sage.symbolic.units.convert(units.mass.kilogram*units.length.meter/units.time.second^2, units.force.newton)
newton

sage: sage.symbolic.units.convert(units.length.foot^3, units.area.acre*units.length.inch)
1/3630*(acre*inch)

sage: sage.symbolic.units.convert(units.charge.coulomb, units.current.ampere*units.time.second)
(ampere*second)

sage: sage.symbolic.units.convert(units.pressure.pascal*units.si_prefixes.kilo, units.pressure.pounds_per_square_inch)
1290320000000/8896443230521*pounds_per_square_inch

For decimal answers multiply 1.0:

sage: sage.symbolic.units.convert(units.pressure.pascal*units.si_prefixes.kilo, units.pressure.pounds_per_square_inch)*1.0
0.145037737730209*pounds_per_square_inch

You can also convert quantities of units:

2.6. Units of measurement
Quantities may contain variables (not for temperature conversion, though):

```
sage: sage.symbolic.units.convert(50 * x * units.area.square_meter, units.area.˓→acre)
acre*(1953125/158080329*x)
```

`sage.symbolic.units.convert_temperature(expr, target)`
Function for converting between temperatures.

**INPUT:**
- `expr` – a unit of temperature
- `target` – a units of temperature

**OUTPUT:**
- a symbolic expression

**EXAMPLES:**

```
sage: t = 32*units.temperature.fahrenheit
sage: t.convert(units.temperature.celsius)
0
sage: t.convert(units.temperature.kelvin)
273.150000000000*kelvin
```

If target is None then it defaults to kelvin:

```
sage: t.convert()
273.150000000000*kelvin
```

Raises `ValueError` when either input is not a unit of temperature:

```
sage: t.convert(units.length.foot)
Traceback (most recent call last):
  ...
ValueError: Cannot convert
sage: wrong = units.length.meter*units.temperature.fahrenheit
sage: wrong.convert()
Traceback (most recent call last):
  ...
ValueError: Cannot convert
```

We directly call the `convert_temperature` function:

```
sage: sage.symbolic.units.convert_temperature(37*units.temperature.celsius, units.˓→temperature.fahrenheit)
493/5*fahrenheit
```
(continues on next page)
sage: sage.symbolic.units.evalunitdict()

Replace all the string values of the unitdict variable by their evaluated forms, and builds some other tables for ease of use. This function is mainly used internally, for efficiency (and flexibility) purposes, making it easier to describe the units.

EXAMPLES:

sage: sage.symbolic.units.evalunitdict()

sage.symbolic.units.is_unit(s)

Returns a boolean when asked whether the input is in the list of units.

INPUT:

• s – an object

OUTPUT:

• a boolean

EXAMPLES:

sage: sage.symbolic.units.is_unit(1)
False
sage: sage.symbolic.units.is_unit(units.length.meter)
True

The square of a unit is not a unit:

sage: sage.symbolic.units.is_unit(units.length.meter^2)
False

You can also directly create units using var, though they won’t have a nice docstring describing the unit:

sage: sage.symbolic.units.is_unit(var('meter'))
True

sage.symbolic.units.str_to_unit(name)

Create the symbolic unit with given name. A symbolic unit is a class that derives from symbolic expression, and has a specialized docstring.

INPUT:

• name – a string

OUTPUT:

• a UnitExpression

EXAMPLES:

sage: sage.symbolic.units.str_to_unit('acre')
acre
sage: type(sage.symbolic.units.str_to_unit('acre'))
<class 'sage.symbolic.units.UnitExpression'>
sage.symbolic.units.unit_derivations_expr(v)
Given derived units name, returns the corresponding units expression. For example, given ‘acceleration’ output the symbolic expression length/time^2.

INPUT:
- v – a string, name of a unit type such as ‘area’, ‘volume’, etc.

OUTPUT:
- a symbolic expression

EXAMPLES:
```
sage: sage.symbolic.units.unit_derivations_expr('volume')
length^3
sage: sage.symbolic.units.unit_derivations_expr('electric_potential')
length^2*mass/(current*time^3)
```
If the unit name is unknown, a KeyError is raised:
```
sage: sage.symbolic.units.unit_derivations_expr('invalid')
Traceback (most recent call last):
  ... KeyError: 'invalid'
```

sage.symbolic.units.unitdocs(unit)
Returns docstring for the given unit.

INPUT:
- unit – a unit

OUTPUT:
- a string

EXAMPLES:
```
sage: sage.symbolic.units.unitdocs('meter')
'SI base unit of length.\nDefined to be the distance light travels in vacuum in 1/299792458 of a second.'
sage: sage.symbolic.units.unitdocs('amu')
'Abbreviation for atomic mass unit.\nApproximately equal to 1.660538782*10^-27 kilograms.'
```
Units not in the list unit_docs will raise a ValueError:
```
sage: sage.symbolic.units.unitdocs('earth')
Traceback (most recent call last):
  ... ValueError: No documentation exists for the unit earth.
```

sage.symbolic.units.vars_in_str(s)
Given a string like ‘mass/(length*time)’, return the list ['mass', 'length', 'time'].

INPUT:
- s – a string

OUTPUT:
- a list of strings (unit names)
EXAMPLES:

```
sage: sage.symbolic.units.vars_in_str('mass/(length*time)')
['mass', 'length', 'time']
```

2.7 The symbolic ring

class sage.symbolic.ring.NumpyToSRMorphism
   Bases: sage.categories.morphism.Morphism

   A morphism from numpy types to the symbolic ring.

class sage.symbolic.ring.SymbolicRing
   Bases: sage.rings.ring.CommutativeRing

   Symbolic Ring, parent object for all symbolic expressions.

characteristic()
   Return the characteristic of the symbolic ring, which is 0.

   OUTPUT:
      • a Sage integer

   EXAMPLES:

   ```
sage: c = SR.characteristic(); c
0
sage: type(c)
<type 'sage.rings.integer.Integer'>
```

is_exact()
   Return False, because there are approximate elements in the symbolic ring.

   EXAMPLES:

   ```
sage: SR.is_exact()
False
```

Here is an inexact element.

```
sage: SR(1.9393)
1.93930000000000
```

is_field(proof=True)
   Returns True, since the symbolic expression ring is (for the most part) a field.

   EXAMPLES:

   ```
sage: SR.is_field()
True
```

is_finite()
   Return False, since the Symbolic Ring is infinite.

   EXAMPLES:

   ```
sage: SR.is_finite()
False
```
pi()

EXAMPLES:

```python
sage: SR.pi() is pi
True
```

subring(*args, **kwds)

Create a subring of this symbolic ring.

INPUT:

Choose one of the following keywords to create a subring.

- `accepting_variables` (default: None) — a tuple or other iterable of variables. If specified, then a symbolic subring of expressions in only these variables is created.
- `rejecting_variables` (default: None) — a tuple or other iterable of variables. If specified, then a symbolic subring of expressions in variables distinct to these variables is created.
- `no_variables` (default: False) — a boolean. If set, then a symbolic subring of constant expressions (i.e., expressions without a variable) is created.

OUTPUT:

A ring.

EXAMPLES:

Let us create a couple of symbolic variables first:

```python
sage: V = var('a, b, r, s, x, y')
```

Now we create a symbolic subring only accepting expressions in the variables \(a\) and \(b\):

```python
sage: A = SR.subring(accepting_variables=(a, b)); A
Symbolic Subring accepting the variables a, b
```

An element is

```python
sage: A.an_element()
a
```

From our variables in \(V\) the following are valid in \(A\):

```python
sage: tuple(v for v in V if v in A)
(a, b)
```

Next, we create a symbolic subring rejecting expressions with given variables:

```python
sage: R = SR.subring(rejecting_variables=(r, s)); R
Symbolic Subring rejecting the variables r, s
```

An element is

```python
sage: R.an_element()
some_variable
```

From our variables in \(V\) the following are valid in \(R\):

```python
sage: tuple(v for v in V if v in R)
(a, b, x, y)
```
We have a third kind of subring, namely the subring of symbolic constants:

```python
sage: C = SR.subring(no_variables=True); C
Symbolic Constants Subring
```

Note that this subring can be considered as a special accepting subring; one without any variables.

An element is

```python
sage: C.an_element()
I*pi*e
```

None of our variables in $V$ is valid in $C$:

```python
sage: tuple(v for v in V if v in C)
()
```

See also:

* Subrings of the Symbolic Ring

```
symbol(name=None, latex_name=None, domain=None)
```

**EXAMPLES:**

```python
sage: t0 = SR.symbol("t0")
sage: t0.conjugate()
conjugate(t0)
sage: t1 = SR.symbol("t1", domain='real')
sage: t1.conjugate()
t1
sage: t0.abs()
abs(t0)
sage: t0_2 = SR.symbol("t0", domain='positive')
sage: t0_2.abs()
t0
sage: bool(t0_2 == t0)
True
sage: t0.conjugate()
t0
sage: SR.symbol() # temporary variable
symbol...
```

We propagate the domain to the assumptions database:

```python
sage: n = var('n', domain='integer')
sage: solve([n^2 == 3],n)
[]
```

```
symbols
var(name, latex_name=None, n=None, domain=None)
```

Return a symbolic variable as an element of the symbolic ring.

**INPUT:**

- name – string or list of strings with the name(s) of the symbolic variable(s)
• **latex_name** – (optional) string used when printing in latex mode, if not specified use 'name'
• **n** – (optional) positive integer; number of symbolic variables, indexed from 0 to \( n - 1 \)
• **domain** – (optional) specify the domain of the variable(s); it is the complex plane by default, and possible options are (non-exhaustive list, see note below): 'real', 'complex', 'positive', 'integer' and 'noninteger'

**OUTPUT:**
Symbolic expression or tuple of symbolic expressions.

**See also:**
This function does not inject the variable(s) into the global namespace. For that purpose see `var()`.

**Note:** For a comprehensive list of acceptable features type `maxima('features')`, and see also the documentation of `Assumptions`.

**EXAMPLES:**
Create a variable \( zz \) (complex by default):

```sage
sage: zz = SR.var('zz'); zz
zz
```
The return type is a symbolic expression:

```sage
sage: type(zz)
<type 'sage.symbolic.expression.Expression'>
```

We can specify the domain as well:

```sage
sage: zz = SR.var('zz', domain='real')
sage: zz.is_real()
True
```
The real domain is also set with the integer domain:

```sage
sage: SR.var('x', domain='integer').is_real()
True
```
The `name` argument does not have to match the left-hand side variable:

```sage
sage: t = SR.var('theta2'); t
theta2
```

Automatic indexing is available as well:

```sage
sage: x = SR.var('x', 4)
sage: x[0], x[3]
(x0, x3)
sage: sum(x)
x0 + x1 + x2 + x3
```

**wild** \( (n=0) \)
Return the \( n \)-th wild-card for pattern matching and substitution.

**INPUT:**
• \( n \) - a nonnegative integer

OUTPUT:
• \( n^{th} \) wildcard expression

EXAMPLES:

```python
sage: x, y = var('x, y')
sage: w0 = SR.wild(0); w1 = SR.wild(1)
sage: pattern = sin(x)*w0*w1^2; pattern
\sin(x)w0w1^2
sage: f = atan(sin(x)*3*x^2); f
\arctan(3x^2\sin(x))
sage: f.has(pattern)
True
sage: f.subs(pattern == x^2)
\arctan(x^2)
```

```python
class sage.symbolic.ring.UnderscoreSageMorphism

Bases: sage.categories.morphism.Morphism

A Morphism which constructs Expressions from an arbitrary Python object by calling the \_sage\_() method on the object.

EXAMPLES:

```python
sage: import sympy
sage: from sage.symbolic.ring import UnderscoreSageMorphism
sage: b = sympy.var('b')
sage: f = UnderscoreSageMorphism(type(b), SR)
sage: f(b)
b
sage: _.parent()
Symbolic Ring
```

sage.symbolic.ring.is_SymbolicExpressionRing(R)

Returns True if \( R \) is the symbolic expression ring.

EXAMPLES:

```python
sage: from sage.symbolic.ring import is_SymbolicExpressionRing
sage: is_SymbolicExpressionRing(ZZ)
False
sage: is_SymbolicExpressionRing(SR)
True
```

sage.symbolic.ring.is_SymbolicVariable(x)

Return True if \( x \) is a variable.

EXAMPLES:

```python
sage: from sage.symbolic.ring import is_SymbolicVariable
sage: is_SymbolicVariable(x)
True
sage: is_SymbolicVariable(x+2)
False
```

sage.symbolic.ring.isidentifier(x)

Return whether \( x \) is a valid identifier.

2.7. The symbolic ring
INPUT:

• \( x \) – a string

OUTPUT:

Boolean. Whether the string \( x \) can be used as a variable name.

This function should return \( \text{False} \) for keywords, so we can not just use the \texttt{isidentifier} method of strings, because, for example, it returns \( \text{True} \) for “def” and for “None”.

EXAMPLES:

```python
sage: from sage.symbolic.ring import isidentifier
sage: isidentifier('x')
True
sage: isidentifier(' x')  # can't start with space
False
sage: isidentifier('ceci_n_est_pas_une_pipe')
True
sage: isidentifier('1 + x')
False
sage: isidentifier('2good')
False
sage: isidentifier('good2')
True
sage: isidentifier('lambda s:s+1')
False
sage: isidentifier('None')
False
sage: isidentifier('lambda')
False
sage: isidentifier('def')
False
```

\texttt{sage.symbolic.ring.the\_SymbolicRing()}

Return the unique symbolic ring object.

(This is mainly used for unpickling.)

EXAMPLES:

```python
sage: sage.symbolic.ring.the\_SymbolicRing()
Symbolic Ring
sage: sage.symbolic.ring.the\_SymbolicRing() is sage.symbolic.ring.the\_SymbolicRing()
True
sage: sage.symbolic.ring.the\_SymbolicRing() is SR
True
```

\texttt{sage.symbolic.ring.var(name, **kwds)}

EXAMPLES:

```python
sage: from sage.symbolic.ring import var
sage: var("x y z")
(x, y, z)
sage: var("x,y,z")
(x, y, z)
sage: var("x , y , z")
(x, y, z)
```

(continues on next page)
2.8 Subrings of the Symbolic Ring

Subrings of the symbolic ring can be created via the `subring()` method of SR. This will call `SymbolicSubring` of this module.

The following kinds of subrings are supported:

- A symbolic subring of expressions, whose variables are contained in a given set of symbolic variables (see `SymbolicSubringAcceptingVars`). E.g.

  ```python
  sage: SR.subring(accepting_variables=('a', 'b'))
  Symbolic Subring accepting the variables a, b
  ```

- A symbolic subring of expressions, whose variables are disjoint to a given set of symbolic variables (see `SymbolicSubringRejectingVars`). E.g.

  ```python
  sage: SR.subring(rejecting_variables=('r', 's'))
  Symbolic Subring rejecting the variables r, s
  ```

- The subring of symbolic constants (see `SymbolicConstantsSubring`). E.g.

  ```python
  sage: SR.subring(no_variables=True)
  Symbolic Constants Subring
  ```

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2.8.1 Classes and Methods

```python
class sage.symbolic.subring.GenericSymbolicSubring(vars)
   Bases: sage.symbolic.ring.SymbolicRing
   An abstract base class for a symbolic subring.
   INPUT:
   * vars – a tuple of symbolic variables.

   has_valid_variable(variable)
   Return whether the given variable is valid in this subring.
   INPUT:
   * variable – a symbolic variable.
   OUTPUT:
   A boolean.
```

EXAMPLES:
```python
sage: from sage.symbolic.subring import GenericSymbolicSubring
sage: GenericSymbolicSubring(vars=tuple()).has_valid_variable(x)
Traceback (most recent call last):
...   NotImplementedError: Not implemented in this abstract base class
```

```python
class sage.symbolic.subring.GenericSymbolicSubringFunctor(vars)
    Bases: sage.categories.pushout.ConstructionFunctor

A base class for the functors constructing symbolic subrings.

INPUT:

- `vars` – a tuple, set, or other iterable of symbolic variables.

EXAMPLES:
```
sage: from sage.symbolic.subring import SymbolicSubring
sage: SymbolicSubring(no_variables=True).construction()[0]  # indirect doctest
Subring<accepting no variable>
```

See also:
```
sage.categories.pushout.ConstructionFunctor.
```

```python
merge(other)
    Merge this functor with other if possible.

INPUT:

- `other` – a functor.

OUTPUT:

A functor or None.

EXAMPLES:
```
sage: from sage.symbolic.subring import SymbolicSubring
sage: F = SymbolicSubring(accepting_variables=('a',)).construction()[0]
sage: F.merge(F) is F
True
```
```
class sage.symbolic.subring.SymbolicConstantsSubring(vars)
    Bases: sage.symbolic.subring.SymbolicSubringAcceptingVars

The symbolic subring consisting of symbolic constants.

```python
has_valid_variable(variable)
    Return whether the given variable is valid in this subring.

INPUT:

- `variable` – a symbolic variable.

OUTPUT:

A boolean.

EXAMPLES:
```
```
**class** `sage.symbolic.subring.SymbolicSubringAcceptingVars(v)`  
**Bases:** `sage.symbolic.subring.GenericSymbolicSubring`  

The symbolic subring consisting of symbolic expressions in the given variables.

**construction()**  
Return the functorial construction of this symbolic subring.

**OUTPUT:**
A tuple whose first entry is a construction functor and its second is the symbolic ring.

**EXAMPLES:**

```python
sage: from sage.symbolic.subring import SymbolicSubring
sage: S = SymbolicSubring(accepting_variables=('a',)).construction()
(Subring<accepting a>, Symbolic Ring)
```

**has_valid_variable(variable)**  
Return whether the given variable is valid in this subring.

**INPUT:**
- variable – a symbolic variable.

**OUTPUT:**
A boolean.

**EXAMPLES:**

```python
sage: from sage.symbolic.subring import SymbolicSubring
sage: S = SymbolicSubring(accepting_variables=('a',))
sage: S.has_valid_variable('a')
True
sage: S.has_valid_variable('r')
False
sage: S.has_valid_variable('x')
False
```

**class** `sage.symbolic.subring.SymbolicSubringAcceptingVarsFunctor(v)`  
**Bases:** `sage.symbolic.subring.GenericSymbolicSubringFunctor`  

**merge(other)**  
Merge this functor with other if possible.

**INPUT:**
- other – a functor.

**OUTPUT:**
A functor or None.
EXAMPLES:

```python
sage: from sage.symbolic.subring import SymbolicSubring
sage: F = SymbolicSubring(accepting_variables=('a',)).construction()[0]
sage: G = SymbolicSubring(rejecting_variables=('r',)).construction()[0]
sage: F.merge(F) is F
True
sage: F.merge(G) is G
True
```

class sage.symbolic.subring.SymbolicSubringFactory

Bases: sage.structure.factory.UniqueFactory

A factory creating a symbolic subring.

INPUT:

Specify one of the following keywords to create a subring.

- **accepting_variables** (default: None) – a tuple or other iterable of variables. If specified, then a symbolic subring of expressions in only these variables is created.

- **rejecting_variables** (default: None) – a tuple or other iterable of variables. If specified, then a symbolic subring of expressions in variables distinct to these variables is created.

- **no_variables** (default: False) – a boolean. If set, then a symbolic subring of constant expressions (i.e., expressions without a variable) is created.

EXAMPLES:

```python
sage: from sage.symbolic.subring import SymbolicSubring
sage: V = var('a, b, c, r, s, t, x, y, z')
sage: A = SymbolicSubring(accepting_variables=(a, b, c)); A
Symbolic Subring accepting the variables a, b, c
sage: tuple((v, v in A) for v in V)
((a, True), (b, True), (c, True),
 (r, False), (s, False), (t, False),
 (x, False), (y, False), (z, False))
sage: R = SymbolicSubring(rejecting_variables=(r, s, t)); R
Symbolic Subring rejecting the variables r, s, t
sage: tuple((v, v in R) for v in V)
((a, True), (b, True), (c, True),
 (r, False), (s, False), (t, False),
 (x, True), (y, True), (z, True))
sage: C = SymbolicSubring(no_variables=True); C
Symbolic Constants Subring
sage: tuple((v, v in C) for v in V)
((a, False), (b, False), (c, False),
 (r, False), (s, False), (t, False),
 (x, False), (y, False), (z, False))
```

`create_key_and_extra_args` (accepting_variables=None, rejecting_variables=None, no_variables=False, **kwds)

Given the arguments and keyword, create a key that uniquely determines this object.

See `SymbolicSubringFactory` for details.
create_object (version, key, **kwds)
Create an object from the given arguments.
See SymbolicSubringFactory for details.

class sage.symbolic.subring.SymbolicSubringRejectingVars (vars)
Bases: sage.symbolic.subring.GenericSymbolicSubring
The symbolic subring consisting of symbolic expressions whose variables are none of the given variables.

construction ()
Return the functorial construction of this symbolic subring.

OUTPUT:
A tuple whose first entry is a construction functor and its second is the symbolic ring.

EXAMPLES:

    sage: from sage.symbolic.subring import SymbolicSubring
    sage: SymbolicSubring(rejecting_variables=('r',)).construction()
    (Subring<rejecting r>, Symbolic Ring)

has_valid_variable (variable)
Return whether the given variable is valid in this subring.

INPUT:

• variable – a symbolic variable.

OUTPUT:
A boolean.

EXAMPLES:

    sage: from sage.symbolic.subring import SymbolicSubring
    sage: S = SymbolicSubring(rejecting_variables=('r',))
    sage: S.has_valid_variable('a')
    True
    sage: S.has_valid_variable('r')
    False
    sage: S.has_valid_variable('x')
    True

class sage.symbolic.subring.SymbolicSubringRejectingVarsFunctor (vars)
Bases: sage.symbolic.subring.GenericSymbolicSubringFunctor

merge (other)
Merge this functor with other if possible.

INPUT:

• other – a functor.

OUTPUT:
A functor or None.

EXAMPLES:

    sage: from sage.symbolic.subring import SymbolicSubring
    sage: F = SymbolicSubring(accepting_variables=('a',)).construction()[0]
    sage: G = SymbolicSubring(rejecting_variables=('r',)).construction()[0]
2.9 Classes for symbolic functions

To enable their usage as part of symbolic expressions, symbolic function classes are derived from one of the subclasses of `Function`:

- **BuiltinFunction**: the code of these functions is written in Python; many special functions are of this type
- **GinacFunction**: the code of these functions is written in C++ and part of the Pynac support library; most elementary functions are of this type
- **SymbolicFunction**: symbolic functions defined on the Sage command line are of this type

Sage uses `BuiltinFunction` and `GinacFunction` for its symbolic builtin functions. Users can define any other additional `SymbolicFunction` through the `function()` factory, see `Factory for symbolic functions`

Several parameters are supported by the superclass’ `__init__()` method. Examples follow below.

- **nargs**: the number of arguments
- **name**: the string that is printed on the CLI; the name of the member functions that are attempted for evaluation of Sage element arguments; also the name of the Pynac function that is associated with a `GinacFunction`
- **alt_name**: the second name of the member functions that are attempted for evaluation of Sage element arguments
- **latex_name**: what is printed when `latex(f(...))` is called
- **conversions**: a dict containing the function’s name in other CAS
- **evalf_params_first**: if False, when floating-point evaluating the expression do not evaluate function arguments before calling the `_evalf_()` member of the function
- **preserved_arg**: if nonzero, the index (starting with 1) of the function argument that determines the return type. Note that, e.g, `atan2()` uses both arguments to determine return type, through a different mechanism

Function classes can define the following Python member functions:

- **_eval_(args)**: the only mandatory member function, evaluating the argument and returning the result; if None is returned the expression stays unevaluated
- **_eval_numpy_(args)**: evaluation of `f(args)` with arguments of nump type
- **_evalf_(args, **kwds)**: called when the expression is floating-point evaluated; may receive a parent keyword specifying the expected parent of the result. If not defined an attempt is made to convert the result of `_eval_()`.
- **_conjugate_(args)**, **_real_part_(args)**, **_imag_part_(args)**: return conjugate, real part, imaginary part of the expression `f(args)`
- **_derivative_(args, index)**: return derivative with respect to the parameter indexed by index (starting with 0) of `f(args)`
- **_tderivative_()**: same as `_derivative_()` but don’t apply chain rule; only one of the two functions may be defined
- **_power_(args, expo)**: return `f(args)^expo`
• \_series\_(*args, \*\*kwds): return the power series at at up to order with respect to var of \( f(args) \); these three values are received in kwds. If not defined the series is attempted to be computed by differentiation.

• print(*args): return what should be printed on the CLI with \( f(args) \)

• print_latex(*args): return what should be output with \texttt{latex}(f(args))

The following examples are intended for Sage developers. Users can define functions interactively through the function() factory, see \textit{Factory for symbolic functions}.

EXAMPLES:

The simplest example is a function returning nothing, it practically behaves like a symbol. Setting \texttt{nargs=0} allows any number of arguments:

```python
sage: from sage.symbolic.function import BuiltinFunction
sage: class Test1(BuiltinFunction):
    ....:     def __init__(self):
    ....:         BuiltinFunction.__init__(self, 'test', nargs=0)
    ....:     def _eval_(self, *args):
    ....:         pass
sage: f = Test1()
sage: f()
test()
sage: f(1,2,3)*f(1,2,3)
test(1, 2, 3)^2
```

In the following the \texttt{sin} function of \texttt{CBF(0)} is called because with floating point arguments the \texttt{CBF} element's \texttt{my_sin()} member function is attempted, and after that \texttt{sin()} which succeeds:

```python
sage: class Test2(BuiltinFunction):
    ....:     def __init__(self):
    ....:         BuiltinFunction.__init__(self, 'my_sin', alt_name='sin',
    ....:         latex_name=r'\SIN', nargs=1)
    ....:     def _eval_(self, x):
    ....:         return 5
    ....:     def _evalf_(self, x, \*\*kwds):
    ....:         return 3.5
sage: f = Test2()
sage: f(0)
5
sage: f(0, hold=True)
my_sin(0)
sage: f(0, hold=True).n()
3.50000000000000
sage: f(CBF(0))
0
sage: latex(f(0, hold=True))
\SIN\left(0\right)
sage: f(1,2)
Traceback (most recent call last):
  ...
TypeError: Symbolic function my_sin takes exactly 1 arguments (2 given)
```

\begin{verbatim}
class sage.symbolic.function.BuiltinFunction
    Bases: sage.symbolic.function.Function

    This is the base class for symbolic functions defined in Sage.
\end{verbatim}
If a function is provided by the Sage library, we don’t need to pickle the custom methods, since we can just initialize the same library function again. This allows us to use Cython for custom methods.

We assume that each subclass of this class will define one symbolic function. Make sure you use subclasses and not just call the initializer of this class.

class sage.symbolic.function.DeprecatedSFunction
Bases: sage.symbolic.function.SymbolicFunction

EXAMPLES:

```python
sage: from sage.symbolic.function import DeprecatedSFunction
sage: foo = DeprecatedSFunction("foo", 2)
sage: foo
foo
sage: foo(x, 2)
foo(x, 2)
sage: foo(2)
Traceback (most recent call last):
... TypeError: Symbolic function foo takes exactly 2 arguments (1 given)
```

class sage.symbolic.function.Function
Bases: sage.structure.sage_object.SageObject

Base class for symbolic functions defined through Pynac in Sage.

This is an abstract base class, with generic code for the interfaces and a __call__() method. Subclasses should implement the _is_registered() and _register_function() methods.

This class is not intended for direct use, instead use one of the subclasses BuiltinFunction or SymbolicFunction.

default_variable()
Returns a default variable.

EXAMPLES:

```python
sage: sin.default_variable()
x
```

name()
Returns the name of this function.

EXAMPLES:

```python
sage: foo = function("foo", nargs=2)
sage: foo.name()
'foo'
```

number_of_arguments()
Returns the number of arguments that this function takes.

EXAMPLES:

```python
sage: foo = function("foo", nargs=2)
sage: foo.number_of_arguments()
2
sage: foo(x, x)
foo(x, x)
```
variables()

Returns the variables (of which there are none) present in this SFunction.

EXAMPLES:

```python
sage: sin.variables()
()`
```

class sage.symbolic.function.GinacFunction

Bases: sage.symbolic.function.BuiltinFunction

This class provides a wrapper around symbolic functions already defined in Pynac/GiNaC.

GiNaC provides custom methods for these functions defined at the C++ level. It is still possible to define new custom functionality or override those already defined.

There is also no need to register these functions.

sage.symbolic.function.PrimitiveFunction

alias of sage.symbolic.function.DeprecatedSFunction

sage.symbolic.function.SFunction

alias of sage.symbolic.function.DeprecatedSFunction

class sage.symbolic.function.SymbolicFunction

Bases: sage.symbolic.function.Function

This is the basis for user defined symbolic functions. We try to pickle or hash the custom methods, so subclasses must be defined in Python not Cython.

sage.symbolic.function.get_sfunction_from_serial(serial)

Return an already created SFunction given the serial. These are stored in the dictionary sage.symbolic.function.sfunction_serial_dict.

EXAMPLES:

```python
sage: from sage.symbolic.function import get_sfunction_from_serial
g
```

sage.symbolic.function.pickle_wrapper(f)

Returns a pickled version of the function f if f is not None; otherwise, it returns None. This is a wrapper around pickle_function().

EXAMPLES:

```python
sage: from sage.symbolic.function import pickle_wrapper
def f(x):
    return x*x
g = pickle_wrapper(f)
```
sage.symbolic.function.unpickle_wrapper(p)
Returns a unpickled version of the function defined by p if p is not None; otherwise, it returns None. This is a wrapper around unpickle_function().

EXAMPLES:

```python
sage: from sage.symbolic.function import pickle_wrapper, unpickle_wrapper
tsage: def f(x): return x*x
tsage: s = pickle_wrapper(f)
tsage: g = unpickle_wrapper(s)
tsage: g(2)
4
tsage: unpickle_wrapper(None) is None
True
```

2.10 Factory for symbolic functions

sage.symbolic.function_factory.deprecated_custom_evalf_wrapper(func)
This is used while pickling old symbolic functions that define a custom evalf method.

The protocol for numeric evaluation functions was changed to include a parent argument instead of prec. This function creates a wrapper around the old custom method, which extracts the precision information from the given parent, and passes it on to the old function.

EXAMPLES:

```python
sage: from sage.symbolic.function_factory import deprecated_custom_evalf_wrapper
˓→as dcew
tsage: def old_func(x, prec=0): print("x: \$s, prec: \$s" % (x, prec))
tsage: new_func = dcew(old_func)
tsage: new_func(5, parent=RR)
x: 5, prec: 53
tsage: new_func(0r, parent=ComplexField(100))
x: 0, prec: 100
```

sage.symbolic.function_factory.function(s, *args, **kwds)
Create a formal symbolic function with the name s.

INPUT:

- args - arguments to the function, if specified returns the new function evaluated at the given arguments (deprecated as of trac ticket #17447)
- nargs=0 - number of arguments the function accepts, defaults to variable number of arguments, or 0
- latex_name - name used when printing in latex mode
- conversions - a dictionary specifying names of this function in other systems, this is used by the interfaces internally during conversion
- eval_func - method used for automatic evaluation
- evalf_func - method used for numeric evaluation
- evaf_params_first - bool to indicate if parameters should be evaluated numerically before calling the custom evaf function
- conjugate_func - method used for complex conjugation
- real_part_func - method used when taking real parts
• `imag_part_func` - method used when taking imaginary parts

• `derivative_func` - method to be used for (partial) derivation This method should take a keyword argument `deriv_param` specifying the index of the argument to differentiate w.r.t.

• `tderivative_func` - method to be used for derivatives

• `power_func` - method used when taking powers This method should take a keyword argument `power_param` specifying the exponent

• `series_func` - method used for series expansion This method should expect keyword arguments - `order` - order for the expansion to be computed - `var` - variable to expand w.r.t. - `at` - expand at this value

• `print_func` - method for custom printing

• `print_latex_func` - method for custom printing in latex mode

Note that custom methods must be instance methods, i.e., expect the instance of the symbolic function as the first argument.

**EXAMPLES:**

```python
sage: from sage.symbolic.function_factory import function
sage: var('a, b')
(a, b)
sage: cr = function('cr')
sage: f = cr(a)
sage: g = f.diff(a).integral(b)
sage: g
b*diff(cr(a), a)
sage: foo = function("foo", nargs=2)
sage: x,y,z = var("x y z")
sage: foo(x, y) + foo(y, z)^2
foo(y, z)^2 + foo(x, y)
```

In Sage 4.0, you need to use `substitute_function()` to replace all occurrences of a function with another:

```python
sage: g.substitute_function(cr, cos)
-b*sin(a)
sage: g.substitute_function(cr, (sin(x) + cos(x)).function(x))
b*(cos(a) - sin(a))
```

In Sage 4.0, basic arithmetic with unevaluated functions is no longer supported:

```python
sage: x = var('x')
sage: f = function('f')
sage: 2*f
Traceback (most recent call last):
...
TypeError: unsupported operand parent(s) for *: 'Integer Ring' and '<class 'sage.symbolic.function_factory...NewSymbolicFunction'>'
```

You now need to evaluate the function in order to do the arithmetic:

```python
sage: 2*f(x)
2*f(x)
```
We create a formal function of one variable, write down an expression that involves first and second derivatives, and extract off coefficients.

```
sage: r, kappa = var('r,kappa')
sage: psi = function('psi', nargs=1)(r); psi
psi(r)
sage: g = 1/r^2*(2*r*psi.derivative(r,1) + r^2*psi.derivative(r,2)); g
(r^2*diff(psi(r), r, r) + 2*r*diff(psi(r), r))/r^2
sage: g.expand()
2*diff(psi(r), r)/r + diff(psi(r), r, r)
sage: g.coefficient(psi.derivative(r,2))
1
sage: g.coefficient(psi.derivative(r,1))
2/r
```

Defining custom methods for automatic or numeric evaluation, derivation, conjugation, etc. is supported:

```
sage: def ev(self, x):
    return 2*x
sage: foo = function("foo", nargs=1, eval_func=ev)
sage: foo(x)
2*x
sage: foo = function("foo", nargs=1, eval_func=lambda self, x: 5)
sage: foo(x)
5
sage: def ef(self, x):
pass
sage: bar = function("bar", nargs=1, eval_func=ef)
sage: bar(x)
bar(x)
sage: def evalf_f(self, x, parent=None, algorithm=None):
    return 6
sage: foo = function("foo", nargs=1, evalf_func=evalf_f)
sage: foo(x)
foo(x)
```

(continues on next page)
..:    return sum(args[0]^i for i in range(kwds['order']))
sage: foo = function("foo", nargs=1, series_func=expand)
sage: foo(y).series(y, 5)
(y,0,0,5,0,1)
y^4 + y^3 + y^2 + y + 1

sage: def my_print(self, *args): return "my args are: " + ', '.join(map(repr, args))
sage: foo = function('t', nargs=2, print_func=my_print)
sage: foo(x,y^z)
my args are: x, y^z

sage: latex(foo(x,y^z))
t\left(x, y^{z}\right)
sage: foo = function('t', nargs=2, print_latex_func=my_print)
sage: foo(x,y^z)
t(x, y^z)
sage: latex(foo(x,y^z))
my args are: x, y^z

sage: foo = function('t', nargs=2, latex_name='foo')
sage: latex(foo(x,y^z))
foo\left(x, y^{z}\right)

Chain rule:

sage: def print_args(self, *args, **kwds): print("args: "); print("kwds: "); return args[0]
sage: foo = function('t', nargs=2, tderivative_func=print_args)
sage: foo(x,x).derivative(x)
args: (x, x)
kwds: {'diff_param': x}
x

my args are: x, y^z

sage: latex(foo(x,y^z))
t(x, y^z)

sage: latex(foo(x,y^z))
t(x, y^z)

sage: latex(foo(x,y^z))
t(x, y^z)

sage: latex(foo(x,y^z))
t(x, y^z)

sage: latex(foo(x,y^z))
t(x, y^z)

sage: latex(foo(x,y^z))
t(x, y^z)

Create a formal symbolic function. For an explanation of the arguments see the documentation for the method

*function*().

**EXAMPLES:**

2.10. Factory for symbolic functions
```python
sage: from sage.symbolic.function_factory import function_factory
sage: f = function_factory('f', 2, '\foo', {'mathematica':'Foo'})
sage: f(2, 4)
f(2, 4)
sage: latex(f(1,2))
\foo\left(1, 2\right)
sage: f._mathematica_init_()
'Foo'

sage: def evalf_f(self, x, parent=None, algorithm=None): return x*.5r
sage: g = function_factory('g',1,evalf_func=evalf_f)

sage: def conjugate_f(self, x): return x/2r

sage: def pickle_f(self, x, parent=None, algorithm=None): return 2r*x + 5r

sage: def pickle_wrap_f(self, x, parent=None, algorithm=None): return x

sage: def conjugate_wrap_f(self, x, parent=None, algorithm=None): return x

sage: def pickle_unpickle_f(self, x, parent=None, algorithm=None): return x

sage: def evalf_wrap_f(self, x, parent=None, algorithm=None): return x

sage: def pickle_unpickle_wrap_f(self, x, parent=None, algorithm=None): return x

sage: def pickle_conjugate_wrap_f(self, x, parent=None, algorithm=None): return x

sage: def pickle_conjugate_unpickle_wrap_f(self, x, parent=None, algorithm=None): return x

sage: def pickle_conjugate_unpickle_conjugate_wrap_f(self, x, parent=None, algorithm=None): return x

sage: def pickle_conjugate_unpickle_conjugate_unpickle_wrap_f(self, x, parent=None, algorithm=None): return x

sage: def pickle_conjugate_unpickle_conjugate_unpickle_conjugate_wrap_f(self, x, parent=None, algorithm=None): return x

sage: g = function_factory('g', 1, [pickle_f, pickle_wrap_f, pickle_conjugate_f])

sage: g(2)
g(2)
sage: g(2).n()
1.00000000000000

sage: g(3)
g(3)
```

The `sage.symbolic.function_factory.unpickle_function` function is called during unpickling to recreate the given function. It calls `function_factory()` with the supplied arguments.

**EXAMPLES:**

```python
sage: from sage.symbolic.function_factory import unpickle_function
sage: nf = unpickle_function('f', 2, '\foo', {'mathematica':'Foo'}, True, [])

sage: nf
f
sage: nf(1,2)
f(1, 2)
sage: latex(nf(x,x))
\foo\left(x, x\right)

sage: def evalf_f(self, x, parent=None, algorithm=None): return x*.5r
sage: g = function_factory('g',1,evalf_func=evalf_f)

sage: g(2)
g(2)
```
2.11 Functional notation support for common calculus methods

EXAMPLES: We illustrate each of the calculus functional functions.

```
sage: simplify(x - x)
0
sage: a = var('a')
sage: derivative(x^a + sin(x), x)
a*x^(a - 1) + cos(x)
sage: diff(x^a + sin(x), x)
a*x^(a - 1) + cos(x)
sage: derivative(x^a + sin(x), x)
a*x^(a - 1) + cos(x)
sage: integral(a*x*sin(x), x)
-(x*cos(x) - sin(x))*a
sage: integrate(a*x*sin(x), x)
-(x*cos(x) - sin(x))*a
sage: limit(a*sin(x)/x, x=0)
a
sage: taylor(a*sin(x)/x, x, 0, 4)
1/120*a*x^4 - 1/6*a*x^2 + a
sage: expand((x-a)^3)
-a^3 + 3*a^2*x - 3*a*x^2 + x^3
```

sage.calculus.functional.derivative(f, *args, **kwds)
The derivative of $f$.

Repeated differentiation is supported by the syntax given in the examples below.

ALIAS: diff

EXAMPLES: We differentiate a callable symbolic function:

```
sage: f(x,y) = x*y + sin(x^2) + exp(-x)
sage: f
(x, y) |--> x*y + exp(-x) + sin(x^2)
sage: derivative(f, x)
(x, y) |--> 2*x*cos(x^2) + y - exp(-x)
sage: derivative(f, y)
(x, y) |--> x
```

We differentiate a polynomial:

```
sage: t = polygen(QQ, 't')
sage: f = (1-t)^5; f
-t^5 + 5*t^4 - 10*t^3 + 10*t^2 - 5*t + 1
sage: derivative(f)
-5*t^4 + 20*t^3 - 30*t^2 + 20*t - 5
sage: derivative(f, t)
-5*t^4 + 20*t^3 - 30*t^2 + 20*t - 5
```

(continues on next page)
We differentiate a symbolic expression:

```
sage: var('a x')
(a, x)
sage: f = exp(sin(a - x^2))/x
sage: derivative(f, x)
-2*cos(-x^2 + a)*e^(sin(-x^2 + a)) - e^(sin(-x^2 + a))/x^2
sage: derivative(f, a)
cos(-x^2 + a)*e^(sin(-x^2 + a))/x
```

Syntax for repeated differentiation:

```
sage: R.<u, v> = PolynomialRing(QQ)
sage: f = u^4*v^5
sage: derivative(f, u)
4*u^3*v^5
sage: f.derivative(u)    # can always use method notation too
4*u^3*v^5
sage: derivative(f, u, u)
12*u^2*v^5
sage: derivative(f, u, u, u)
24*u*v^5
sage: derivative(f, u, 3)
24*u*v^5
sage: derivative(f, u, v)
20*u^3*v^4
sage: derivative(f, u, 2, v)
60*u^2*v^4
sage: derivative(f, u, v, 2)
80*u^3*v^3
sage: derivative(f, [u, v, v])
80*u^3*v^3
```

We differentiate a scalar field on a manifold:

```
sage: M = Manifold(2, 'M')
sage: X.<x,y> = M.chart()
sage: f = M.scalar_field(x^2*y, name='f')
sage: derivative(f)
1-form df on the 2-dimensional differentiable manifold M
sage: derivative(f).display()
df = 2*x*y dx + x^2 dy
```

We differentiate a differentiable form, getting its exterior derivative:

```
sage: a = M.one_form(-y, x, name='a'); a.display()
a = -y dx + x dy
sage: derivative(a)
2-form da on the 2-dimensional differentiable manifold M
sage: derivative(a).display()
da = 2 dx/
dy
```
The derivative of \( f \).

Repeated differentiation is supported by the syntax given in the examples below.

**ALIAS:** diff

**EXAMPLES:** We differentiate a callable symbolic function:

```python
sage: f(x, y) = x*y + sin(x^2) + e^(-x)
```

```python
sage: f
(x, y) |--> x*y + e^(-x) + sin(x^2)
```

```python
sage: derivative(f, x)
(x, y) |--> 2*x*cos(x^2) + y - e^(-x)
```

```python
sage: derivative(f, y)
(x, y) |--> x
```

We differentiate a polynomial:

```python
sage: t = polygen(QQ, 't')
sage: f = (1-t)^5; f
-t^5 + 5*t^4 - 10*t^3 + 10*t^2 - 5*t + 1
sage: derivative(f)
-5*t^4 + 20*t^3 - 30*t^2 + 20*t - 5
sage: derivative(f, t)
-5*t^4 + 20*t^3 - 30*t^2 + 20*t - 5
sage: derivative(f, t, t)
-20*t^3 + 60*t^2 - 60*t + 20
sage: derivative(f, t, 2)
-20*t^3 + 60*t^2 - 60*t + 20
sage: derivative(f, 2)
-20*t^3 + 60*t^2 - 60*t + 20
```

We differentiate a symbolic expression:

```python
sage: var('a x')
(a, x)
sage: f = exp(sin(a - x^2))/x
dsage: derivative(f, x)
-2*cos(-x^2 + a)*e^(sin(-x^2 + a)) - e^(sin(-x^2 + a))/x^2
dsage: derivative(f, a)
cos(-x^2 + a)*e^(sin(-x^2 + a))/x
```

Syntax for repeated differentiation:

```python
sage: R.<u, v> = PolynomialRing(QQ)
sage: f = u^4*v^5
sage: derivative(f, u)
4*u^3*v^5
sage: f.derivative(u)  # can always use method notation too
4*u^3*v^5
```

```python
sage: derivative(f, u, u)
12*u^2*v^5
sage: derivative(f, u, u, u)
24*u*v^5
sage: derivative(f, u, 3)
24*u*v^5
```

2.11. Functional notation support for common calculus methods
We differentiate a scalar field on a manifold:

```
sage: M = Manifold(2, 'M')
sage: X.<x,y> = M.chart()
sage: f = M.scalar_field(x^2*y, name='f')
sage: derivative(f)
1-form df on the 2-dimensional differentiable manifold M
dsage: derivative(f).display()
df = 2*x*y dx + x^2 dy
```

We differentiate a differentiable form, getting its exterior derivative:

```
sage: a = M.one_form(-y, x, name='a'); a.display()
a = -y dx + x dy
sage: derivative(a)
2-form da on the 2-dimensional differentiable manifold M
dsage: derivative(a).display()
da = 2 dx/
```

You can also use expand on polynomial, integer, and other factorizations:

```
sage: x = polygen(ZZ)
sage: F = factor(x^12 - 1); F
(x - 1) * (x + 1) * (x^2 - x + 1) * (x^2 + 1) * (x^2 + x + 1) * (x^4 - x^2 + 1)
sage: expand(F)
x^12 - 1
sage: F.expand()
x^12 - 1
sage: F = factor(2007); F
3^2 * 223
sage: expand(F)
2007
```

Note: If you want to compute the expanded form of a polynomial arithmetic operation quickly and the coefficients of the polynomial all lie in some ring, e.g., the integers, it is vastly faster to create a polynomial ring and do the arithmetic there.

```
sage: x = polygen(ZZ)  # polynomial over a given base ring.
sage: f = sum(x^n for n in range(5))
```

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The integral of \( f \).

**EXAMPLES:**

\[
\text{sage: } \int \sin(x) \, dx = -\cos(x) \\
\text{sage: } \int \sin(x)^2 \, dx, \pi, 123\pi/2 = 121/4\pi \\
\text{sage: } \int \sin(x) \, dx, 0, \pi = 2 \\
\]

We integrate a symbolic function:

\[
\text{sage: } f(x, y, z) = x*y/z + \sin(z) \\
\text{sage: } \int f, z \rightarrow x*y*\log(z) - \cos(z) \\
\]

\[
\text{sage: } \text{var('a,b')} \\
(a, b) \\
\text{sage: } \text{assume(b-a>0)} \\
\text{sage: } \int \sin(x) \, dx, a, b = \cos(a) - \cos(b) \\
\text{sage: } \text{forget()} \\
\]

\[
\text{sage: } \int (x/(x^3-1), x) = 1/3*\sqrt(3)*\arctan(1/3*\sqrt(3)*(2*x + 1)) - 1/6*\log(x^2 + x + 1) + 1/3*\log(x - 1) \\
\]

We define the Gaussian, plot and integrate it numerically and symbolically:

\[
\text{sage: } f(x) = 1/(\sqrt(2*\pi)) * e^{-x^2/2} \\
\text{sage: } \text{P = plot(f, -4, 4, hue=0.8, thickness=2)} \\
\text{sage: } \text{P.show(ymin=0, ymax=0.4)} \\
\text{sage: } \text{numerical_integral(f, -4, 4)} # random output \\
(0.999366575163376, 1.1101527003413533e-14) \\
\text{sage: } \int \exp(-x^2), x \rightarrow 1/2*\sqrt(\pi)*\text{erf}(x) \\
\]

You can have Sage calculate multiple integrals. For example, consider the function \( e^{x^2} \) on the region between the lines \( x = y \), \( x = 1 \), and \( y = 0 \). We find the value of the integral on this region using the command:

\[
\text{sage: } \text{area = integral(integral(exp(y^2),x,0,y),y,0,1); area} \\
1/2*\exp - 1/2 \\
\text{sage: } \text{float(area)} \\
0.85914091429522... \\
\]

We compute the line integral of \( \sin(x) \) along the arc of the curve \( x = y^4 \) from \( (1, -1) \) to \( (1, 1) \):
sage: t = var('t')
sage: (x,y) = (t^4,t)
sage: (dx,dy) = (diff(x,t), diff(y,t))
sage: integral(sin(x)*dx, t,-1, 1)
0
sage: restore('x,y')  # restore the symbolic variables x and y

Sage is now (trac ticket #27958) able to compute the following integral:

sage: integral(exp(-x^2)*log(x), x)
1/2*sqrt(pi)*erf(x)*log(x) - x*hypergeometric((1/2, 1/2), (3/2, 3/2), -x^2)

and its value:

sage: integral( exp(-x^2)*ln(x), x, 0, oo)
-1/4*sqrt(pi)*(euler_gamma + 2*log(2))

This definite integral is easy:

sage: integral( ln(x)/x, x, 1, 2)
1/2*log(2)^2

Sage cannot do this elliptic integral (yet):

sage: integral(1/sqrt(2*t^4 - 3*t^2 - 2), t, 2, 3)
integrate(1/(sqrt(2*t^2 + 1)*sqrt(t^2 - 2)), t, 2, 3)

A double integral:

sage: y = var('y')
sage: integral(integral(x*y^2, x, 0, y), y, -2, 2)
32/5

This illustrates using assumptions:

sage: integral(abs(x), x, 0, 5)
25/2
sage: a = var("a")
sage: integral(abs(x), x, 0, a)
1/2*a*abs(a)
sage: integral(abs(x)*x, x, 0, a)
Traceback (most recent call last):
  ... ValueError: Computation failed since Maxima requested additional constraints; using the 'assume' command before evaluation *may* help (example of legal syntax is 'assume(a>0)', see 'assume?' for more details)
Is a positive, negative or zero?
sage: assume(a>0)
sage: integral(abs(x)*x, x, 0, a)
1/3*a^3
sage: forget()  # forget the assumptions.

We integrate and differentiate a huge mess:

sage: f = (x^2-1+3*(1+x^2)^(1/3))/(1+x^2)^(2/3)*x/(x^2+2)^2
sage: g = integral(f, x)
sage: h = f - diff(g, x)
```sage
sage: [float(h(i)) for i in range(5)] # random
[0.0, -1.1102230246251565e-16, -5.5511151231257827e-17, -5.5511151231257827e-17, -6.9388939039072284e-17]
sage: h.factor()
0
sage: bool(h == 0)
True
```

```sage
sage.calculus.functional.integrate(f, *args, **kwds)
The integral of f.

EXAMPLES:
```
```sage
sage: integral(sin(x), x)
-cos(x)
sage: integral(sin(x)^2, x, pi, 123*pi/2)
121/4*pi
sage: integral( sin(x), x, 0, pi)
2
```

We integrate a symbolic function:
```
```sage
sage: f(x,y,z) = x*y/z + sin(z)
sage: integral(f, z)
(x, y, z) |--> x*y*log(z) - cos(z)
sage: var('a,b')
(a, b)
sage: assume(b-a>0)
sage: integral( sin(x), x, a, b)
cos(a) - cos(b)
sage: forget()
sage: integral(x/(x^3-1), x)
1/3*sqrt(3)*arctan(1/3*sqrt(3)*(2*x + 1)) - 1/6*log(x^2 + x + 1) + 1/3*log(x - 1)
```

We define the Gaussian, plot and integrate it numerically and symbolically:
```
```sage
sage: f(x) = 1/(sqrt(2*pi)) * e^(-x^2/2)
sage: P = plot(f, -4, 4, hue=0.8, thickness=2)
sage: P.show(ymin=0, ymax=0.4)
sage: numerical_integral(f, -4, 4) # random output
(0.99993665751633376, 1.1101527003413533e-14)
sage: integrate(f, x)
x |--> 1/2*erf(1/2*sqrt(2)*x)
```

You can have Sage calculate multiple integrals. For example, consider the function $e^x$ on the region between the lines $x = y$, $x = 1$, and $y = 0$. We find the value of the integral on this region using the command:
We compute the line integral of \( \sin(x) \) along the arc of the curve \( x = y^4 \) from \((1, -1)\) to \((1, 1)\):

\[
\begin{align*}
\text{sage: } & \ t = \text{var('t')} \\
\text{sage: } & \ (x, y) = (t^4, t) \\
\text{sage: } & \ (dx, dy) = (\text{diff}(x, t), \text{diff}(y, t)) \\
\text{sage: } & \ \integrand = \sin(x) \cdot \text{diff}(x, t), \ t, -1, 1) \\
& 0 \\
\text{sage: } & \ \text{restore('x,y')} \quad \# \ \text{restore the symbolic variables} \ x \ \text{and} \ y
\end{align*}
\]

Sage is now (trac ticket #27958) able to compute the following integral:

\[
\begin{align*}
\text{sage: } & \ \integrand = \text{exp}(-x^2) \cdot \text{log}(x), \ x \\
& 1/2 \cdot \text{sqrt}(\pi) \cdot \text{erf}(x) \cdot \text{log}(x) - x \cdot \text{hypergeometric}((1/2, 1/2), (3/2, 3/2), -x^2)
\end{align*}
\]

and its value:

\[
\begin{align*}
\text{sage: } & \ \integrand = \text{exp}(-x^2) \cdot \text{log}(x), \ x, 0, \infty \\
& -1/4 \cdot \text{sqrt}(\pi) \cdot (\text{euler} \_\gamma + 2 \cdot \text{log}(2))
\end{align*}
\]

This definite integral is easy:

\[
\begin{align*}
\text{sage: } & \ \integrand = \text{log}(x) / x, \ x, 1, 2 \\
& 1/2 \cdot \text{log}(2)^2
\end{align*}
\]

Sage cannot do this elliptic integral (yet):

\[
\begin{align*}
\text{sage: } & \ \integrand = \text{log}(x) / x, \ x, 2, 3 \\
& 1/2 \cdot \text{log}(2)^2
\end{align*}
\]

A double integral:

\[
\begin{align*}
\text{sage: } & \ y = \text{var('y')} \\
\text{sage: } & \ \integrand = \text{exp}(y^2) \cdot x, \ y, 0, 2 \\
& 32/5
\end{align*}
\]

This illustrates using assumptions:

\[
\begin{align*}
\text{sage: } & \ \integrand = \text{exp}(y^2) \cdot x, \ y, 0, 5 \\
& 25/2
\end{align*}
\]

\[
\begin{align*}
\text{sage: } & \ a = \text{var}('a') \\
\text{sage: } & \ \integrand = \text{exp}(y^2) \cdot x, \ y, 0, a \\
& 1/2 \cdot a \cdot \text{abs}(a)
\end{align*}
\]

\[
\begin{align*}
\text{sage: } & \ \integrand = \text{exp}(y^2) \cdot x, \ y, 0, a \\
& \text{Traceback (most recent call last):} \\
& \text{...} \\
& \text{ValueError: Computation failed since Maxima requested additional} \\
& \text{constraints; using the 'assume' command before evaluation} \\
& \text{*may* help (example of legal syntax is 'assume(a>0)')} \\
& \text{see 'assume?' for more details) \\
& \text{Is a positive, negative or zero?} \\
\text{sage: } & \ \text{assume(a>0)} \\
\text{sage: } & \ \integrand = \text{exp}(y^2) \cdot x, \ y, 0, a
\end{align*}
\]
We integrate and differentiate a huge mess:

\[
\text{sage: } f = \frac{(x^2-1+3(1+x^2)^{1/3})}{(1+x^2)^{2/3}}x/(x^2+2)^2 \\
\text{sage: } g = \text{integral}(f, x) \\
\text{sage: } h = f - \text{diff}(g, x)
\]

\[
\text{[float}(h(i)) \text{ for } i \text{ in range}(5)] \text{ #random}
\]

\[
[0.0, \\
-1.1102230246251565e-16, \\
-5.5511151231257827e-17, \\
-5.5511151231257827e-17, \\
-6.9388939039072284e-17]
\]

\[
\text{sage: } h.\text{factor}() \\
0
\]

\[
\text{sage: } \text{bool}(h == 0) \\
\text{True}
\]

\[
\text{sage.calculus.functional.}\text{lim}(f, \text{dir=None, taylor=False, }**\text{argv})
\]

Return the limit as the variable \(v\) approaches \(a\) from the given direction.

\[
\text{INPUT:

• dir -(default: None); dir may have the value ‘plus’ (or ‘above’) for a limit from above, ‘minus’ (or ‘below’) for a limit from below, or may be omitted (implying a two-sided limit is to be computed).

• taylor -(default: False); if True, use Taylor series, which allows more limits to be computed (but may also crash in some obscure cases due to bugs in Maxima).

• \*\*\*argv - 1 named parameter
\]

ALIAS: You can also use \text{lim} instead of \text{limit}.

\[
\text{EXAMPLES:

\text{sage: } \text{limit}(\sin(x)/x, \text{ x=}0) \\
1 \\
\text{sage: } \text{limit}(\exp(x), \text{ x=}\infty) \\
+\text{Infinity} \\
\text{sage: } \text{lim}(\exp(x), \text{ x=}\infty) \\
0 \\
\text{sage: } \text{lim}(\text{1/x}, \text{ x=}0) \\
\text{Infinity} \\
\text{sage: } \text{limit}(\text{sqrt(x^2+x+1)}+x, \text{ taylor=}\text{True}, \text{ x=}\infty) \\
-1/2 \\
\text{sage: } \text{limit}((\tan(\sin(x)) - \sin(\tan(x)))/x^7, \text{ taylor=}\text{True, x=}0) \\
1/30
\]

Sage does not know how to do this limit (which is 0), so it returns it unevaluated:

\[
\text{sage: } \text{lim}(\exp(x^2)*(1-\text{erf}(x)), \text{ x=}\text{infinity}) \\
-\text{limit}((\text{erf}(x) - 1)*e^{x^2}, \text{ x, +Infinity})
\]
sage.calculus.functional.limit(f, dir=None, taylor=False, **argv)

Return the limit as the variable \( v \) approaches \( a \) from the given direction.

```python
limit(expr, x = a)
limit(expr, x = a, dir='above')
```

**INPUT:**

- **dir** - (default: None); dir may have the value ‘plus’ (or ‘above’) for a limit from above, ‘minus’ (or ‘below’) for a limit from below, or may be omitted (implying a two-sided limit is to be computed).
- **taylor** - (default: False); if True, use Taylor series, which allows more limits to be computed (but may also crash in some obscure cases due to bugs in Maxima).
- **\*\*argv** - 1 named parameter

**ALIAS:** You can also use \texttt{lim} instead of \texttt{limit}.

**EXAMPLES:**

```
sage: limit(sin(x)/x, x=0)
1
sage: limit(exp(x), x=oo)
+Infinity
sage: limit(exp(x), x=-oo)
0
sage: limit(1/x, x=0)
Infinity
sage: limit(sqrt(x^2+x+1)+x, taylor=True, x=-oo)
-1/2
sage: limit((tan(sin(x)) - sin(tan(x)))/x^7, taylor=True, x=0)
1/30
```

Sage does not know how to do this limit (which is 0), so it returns it unevaluated:

```
sage: limit(exp(x^2)*(1-erf(x)), x=infinity)
-\text{limit}\left((\text{erf}(x) - 1)*e^{(x^2)}, x, +\text{Infinity}\right)
```

sage.calculus.functional.simplify(f)

Simplify the expression \( f \).

**EXAMPLES:** We simplify the expression \( i + x - x \).

```
sage: f = I + x - x; simplify(f)
I
```

In fact, printing \( f \) yields the same thing - i.e., the simplified form.

sage.calculus.functional.taylor(f, *args)

Expands self in a truncated Taylor or Laurent series in the variable \( v \) around the point \( a \), containing terms through \((x-a)^n\). Functions in more variables are also supported.

**INPUT:**

- **\*args** - the following notation is supported
- \( x, a, n \) - variable, point, degree
- \((x, a), (y, b), \ldots, n\) - variables with points, degree of polynomial

**EXAMPLES:**

```
sage: var('x,k,n')
(x, k, n)
sage: taylor (sqrt (1 - k^2*sin(x)^2), x, 0, 6)
-1/720*(45*k^6 - 60*k^4 + 16*k^2)*x^6 - 1/24*(3*k^4 - 4*k^2)*x^4 - 1/2*k^2*x^2 + 1
sage: taylor ((x + 1)^n, x, 0, 4)
1/24*(n^4 - 6*n^3 + 11*n^2 - 6*n)*x^4 + 1/6*(n^3 - 3*n^2 + 2*n)*x^3 + 1/2*(n^2 - n)*x^2 + n*x + 1

Taylor polynomial in two variables:
sage: x,y=var('x y'); taylor(x*y^3,(x,1),(y,-1),4)
(x - 1)*(y + 1)^3 - 3*(x - 1)*(y + 1)^2 + (y + 1)^3 + 3*(x - 1)*(y + 1) - 3*(y + 1)^2 - x + 3*y + 3

2.12 Symbolic Series

Symbolic series are special kinds of symbolic expressions that are constructed via the `Expression.series` method. They usually have an `Order()` term unless the series representation is exact, see `is_terminating_series()`.

For series over general rings see power series and Laurent series.

EXAMPLES:

We expand a polynomial in \(x\) about 0, about 1, and also truncate it back to a polynomial:

```
sage: var('x,y')
(x, y)
sage: f = (x^3 - sin(y)*x^2 - 5*x + 3); f
x^3 - x^2*sin(y) - 5*x + 3
sage: g = f.series(x, 4); g
3 + (-5)*x + (-sin(y))*x^2 + 1*x^3 + Order(x^4)
sage: g.truncate()
3 - x^2*sin(y) - 5*x + 3
sage: h = g.series(x==1, oo); g
(-sin(y) - 1) + (cos(1) - 2*sin(1))*(x - 1) + (-2*cos(1) + 5/2*sin(1))*(x - 1)^2 + Order((x - 1)^3)
sage: h.truncate(); h
(-sin(y) - 1) + (-2*sin(y) - 2)*(x - 1) + (-sin(y) + 3)*(x - 1)^2 + 1*(x - 1)^3
sage: h.expand()
(x - 1)^3 - (x - 1)^2*(sin(y) - 3) - 2*(x - 1)*(sin(y) + 1) - sin(y) - 1
```

We compute another series expansion of an analytic function:

```
sage: f = sin(x)/x^2
sage: f.series(x,7)
1*x^(-1) + (-1/6)*x + 1/120*x^3 + (-1/5040)*x^5 + Order(x^7)
sage: f.series(x==1,3)
(-sin(1)) + (cos(1) - 2*sin(1))*(x - 1) + (-2*cos(1) + 5/2*sin(1))*(x - 1)^2 + Order((x - 1)^3)
```

(continues on next page)
Following the GiNaC tutorial, we use John Machin’s amazing formula \( \pi = 16\tan^{-1}(1/5) - 4\tan^{-1}(1/239) \) to compute digits of \( \pi \). We expand the arc tangent around 0 and insert the fractions 1/5 and 1/239.

```python
sage: x = var('x')
sage: f = atan(x).series(x, 10); f
1*x + (-1/3)*x^3 + 1/5*x^5 + (-1/7)*x^7 + 1/9*x^9 + Order(x^10)
sage: (16*f.subs(x==1/5) - 4*f.subs(x==1/239)).n()
3.14159268240440
```

Note: The result of an operation or function of series is not automatically expanded to a series. This must be explicitly done by the user:

```python
sage: ex1 = sin(x).series(x, 4); ex1
1*x + (-1/6)*x^3 + Order(x^4)
sage: ex2 = cos(x).series(x, 4); ex2
1 + (-1/2)*x^2 + Order(x^4)
sage: ex1 + ex2
(1 + (-1/2)*x^2 + Order(x^4)) + (1*x + (-1/6)*x^3 + Order(x^4))
sage: (ex1 + ex2).series(x, 4)
1 + 1*x + (-1/2)*x^2 + (-1/6)*x^3 + Order(x^4)
sage: x*ex1
x*(1*x + (-1/6)*x^3 + Order(x^4))
sage: (x*ex1).series(x,5)
1*x^2 + (-1/6)*x^4 + Order(x^5)
sage: sin(ex1)
sin(1*x + (-1/6)*x^3 + Order(x^4))
sage: sin(ex1).series(x,9)
1*x + (-1/3)*x^3 + 11/120*x^5 + (-53/2520)*x^7 + Order(x^9)
sage: (sin(x^2)^(-5)).series(x,3)
1*x^(-10) + 5/6*x^(-6) + 3/8*x^(-2) + 367/3024*x^2 + Order(x^3)
sage: (cot(x)^(-3)).series(x,4)
1*x^3 + Order(x^4)
sage: (cot(x)^(-3)).series(x,4)
1*x^3 + Order(x^4)
```

```python
class sage.symbolic.series.SymbolicSeries
    Bases: sage.symbolic.expression.Expression

    Trivial constructor.

    EXAMPLES:

    ```python
    sage: loads(dumps((x+x^3).series(x,2)))
    1*x + Order(x^2)
    ```

    coefficients(x=None, sparse=True)

    Return the coefficients of this symbolic series as a list of pairs.

    INPUT:

    - `x` – optional variable.

    - `sparse` – Boolean. If False return a list with as much entries as the order of the series.

    OUTPUT:
Depending on the value of `sparse`,

- A list of pairs `(expr, n)`, where `expr` is a symbolic expression and `n` is a power (sparse=True, default)
- A list of expressions where the `n`-th element is the coefficient of `x^n` when `self` is seen as polynomial in `x` (sparse=False).

**EXAMPLES:**

```python
sage: s=(1/(1-x)).series(x,6); s
1 + 1*x + 1*x^2 + 1*x^3 + 1*x^4 + 1*x^5 + Order(x^6)
sage: s.coefficients()
[[1, 0], [1, 1], [1, 2], [1, 3], [1, 4], [1, 5]]
sage: s.coefficients(x, sparse=False)
[1, 1, 1, 1, 1, 1]
sage: x,y = var("x,y")
sage: s=(1/(1-y*x-x)).series(x,3); s
1 + (y + 1)*x + ((y + 1)^2)*x^2 + Order(x^3)
sage: s.coefficients(x, sparse=False)
[1, y + 1, (y + 1)^2]
```

**default_variable()**

Return the expansion variable of this symbolic series.

**EXAMPLES:**

```python
sage: s=(1/(1-x)).series(x,3); s
1 + 1*x + 1*x^2 + Order(x^3)
sage: s.default_variable()
x
```

**is_terminating_series()**

Return True if the series is without order term. A series is terminating if it can be represented exactly, without requiring an order term. You can explicitly request terminating series by setting the order to positive infinity.

**OUTPUT:**

Boolean. True if the series has no order term.

**EXAMPLES:**

```python
sage: (x^5+x^2+1).series(x, +oo)
1 + 1*x^2 + 1*x^5
sage: (x^5+x^2+1).series(x, +oo).is_terminating_series()
True
sage: SR(5).is_terminating_series()
False
sage: exp(x).series(x,10).is_terminating_series()
False
```

**power_series(base_ring)**

Return algebraic power series associated to this symbolic series. The coefficients must be coercible to the base ring.

**EXAMPLES:**

```python
sage: ex=(gamma(1-x)).series(x,3); ex
1 + euler_gamma*x + (1/2*euler_gamma^2 + 1/12*pi^2)*x^2 + Order(x^3)
sage: g=ex.power_series(SR); g
1 + euler_gamma*x + (1/2*euler_gamma^2 + 1/12*pi^2)*x^2 + O(x^3)
sage: g.parent()
Power Series Ring in x over Symbolic Ring

**truncate()**

Given a power series or expression, return the corresponding expression without the big oh.

**OUTPUT:**

A symbolic expression.

**EXAMPLES:**

```sage
sage: f = sin(x)/x^2
sage: f.truncate()
sin(x)/x^2
sage: f.series(x,7)
1*x^(-1) + (-1/6)*x + 1/120*x^3 + (-1/5040)*x^5 + Order(x^7)
sage: f.series(x,7).truncate()
-1/5040*x^5 + 1/120*x^3 - 1/6*x + 1/x
sage: f.series(x==1,3).truncate().expand()
-2*x^2*cos(1) + 5/2*x^2*sin(1) + 5*x*cos(1) - 7*x*sin(1) - 3*cos(1) + 11/2*sin(1)
```

### 2.13 Symbolic Integration

**class** sage.symbolic.integration.integral.DefiniteIntegral

**Bases:** sage.symbolic.function.BuiltinFunction

The symbolic function representing a definite integral.

**EXAMPLES:**

```sage
sage: from sage.symbolic.integration.integral import definite_integral
sage: definite_integral(sin(x),x,0,pi)
2
```

**class** sage.symbolic.integration.integral.IndefiniteIntegral

**Bases:** sage.symbolic.function.BuiltinFunction

Class to represent an indefinite integral.

**EXAMPLES:**

```sage
sage: from sage.symbolic.integration.integral import indefinite_integral
sage: indefinite_integral(log(x), x)  # indirect doctest
x*log(x) - x
sage: indefinite_integral(x^2, x)
1/3*x^3
sage: indefinite_integral(4*x*log(x), x)
2*x^2*log(x) - x^2
sage: indefinite_integral(exp(x), 2*x)
2*e^x
```
Return the indefinite integral with respect to the variable \( v \), ignoring the constant of integration. Or, if endpoints \( a \) and \( b \) are specified, returns the definite integral over the interval \([a, b]\).

If \texttt{self} has only one variable, then it returns the integral with respect to that variable.

If definite integration fails, it could be still possible to evaluate the definite integral using indefinite integration with the Newton - Leibniz theorem (however, the user has to ensure that the indefinite integral is continuous on the compact interval \([a, b]\) and this theorem can be applied).

**INPUT:**

- \( v \) - a variable or variable name. This can also be a tuple of the variable (optional) and endpoints (i.e., \((x, 0, 1)\) or \((0, 1)\)).
- \( a \) - (optional) lower endpoint of definite integral
- \( b \) - (optional) upper endpoint of definite integral
- \texttt{algorithm} - (default: ‘maxima’) one of
  - ‘maxima’ - use maxima (the default)
  - ‘sympy’ - use sympy (also in Sage)
  - ‘mathematica_free’ - use http://integrals.wolfram.com/
  - ‘fricas’ - use FriCAS (the optional fricas spkg has to be installed)
  - ‘giac’ - use Giac

To prevent automatic evaluation use the \texttt{hold} argument.

**See also:**

To integrate a polynomial over a polytope, use the optional \texttt{latte_int} package \texttt{sage.geometry.polyhedron.base.Polyhedron_base.integrate()}.  

**EXAMPLES:**

```python
sage: x = var('x')
sage: h = sin(x)/(cos(x))^2
sage: h.integral(x)
1/cos(x)
sage: f = x^2/(x+1)^3
sage: f.integral(x)
1/2*(4*x + 3)/(x^2 + 2*x + 1) + log(x + 1)
sage: f = x*cos(x^2)
sage: f.integral(x, 0, sqrt(pi))
0
sage: f.integral(x, a=-pi, b=pi)
0
sage: f(x) = sin(x)
sage: f.integral(x, 0, pi/2)
1
```

The variable is required, but the endpoints are optional:
sage: y = var('y')
sage: integral(sin(x), x)
-cos(x)
sage: integral(sin(x), y)
y*sin(x)
sage: integral(sin(x), x, pi, 2*pi)
-2
sage: integral(sin(x), y, pi, 2*pi)
pi*sin(x)
sage: integral(sin(x), (x, pi, 2*pi))
-2
sage: integral(sin(x), (y, pi, 2*pi))
pi*sin(x)

Using the hold parameter it is possible to prevent automatic evaluation, which can then be evaluated via simplify():

sage: integral(x^2, x, 0, 3)
9
sage: a = integral(x^2, x, 0, 3, hold=True) ; a
integrate(x^2, x, 0, 3)
sage: a.simplify()
9

Constraints are sometimes needed:

sage: var('x, n')
(x, n)
sage: integral(x^n,x)
Traceback (most recent call last):
... ValueError: Computation failed since Maxima requested additional constraints; using the 'assume' command before evaluation may help (example of legal syntax is 'assume(n>0)', see 'assume?' for more details)
Is n equal to -1?
sage: assume(n > 0)
sage: integral(x^n,x)
x^(n + 1)/(n + 1)
sage: forget()

Usually the constraints are of sign, but others are possible:

sage: assume(n==-1)
sage: integral(x^n,x)
log(x)

Note that an exception is raised when a definite integral is divergent:

sage: forget() # always remember to forget assumptions you no longer need
sage: integrate(1/x^3,(x,0,1))
Traceback (most recent call last):
... ValueError: Integral is divergent.
sage: integrate(1/x^3,x,-1,3)
Traceback (most recent call last):
... ValueError: Integral is divergent.
But Sage can calculate the convergent improper integral of this function:

```
sage: integrate(1/x^3,x,1,infinity)
1/2
```

The examples in the Maxima documentation:

```
sage: var('x, y, z, b')
(x, y, z, b)
sage: integral(sin(x)^3, x)
1/3*cos(x)^3 - cos(x)
sage: integral(x/sqrt(b^2-x^2), b)
x*log(2*b + 2*sqrt(b^2 - x^2))
sage: integral(x/sqrt(b^2-x^2), x)
-sqrt(b^2 - x^2)
sage: integral(cos(x)^2 * exp(x), x, 0, pi)
3/5*e^pi - 3/5
sage: integral(x^2 * exp(-x^2), x, -oo, oo)
1/2*sqrt(pi)
```

We integrate the same function in both Mathematica and Sage (via Maxima):

```
sage: _ = var('x, y, z')
sage: f = sin(x^2) + y^z
sage: g = mathematica(f)  # optional - mathematica
sage: print(g)  # optional - mathematica
z 2
y + Sin[x ]

sage: print(g.Integrate(x))  # optional - mathematica
z Pi 2
x y + Sqrt[--] FresnelS[Sqrt[--] x]
2 Pi

sage: print(f.integrate(x))  # optional - internet
x*y^z + 1/16*sqrt(pi)*fresnel_sin(sqrt(2)*x/sqrt(pi))
```

Alternatively, just use algorithm='mathematica_free' to integrate via Mathematica over the internet (does NOT require a Mathematica license!):

```
sage: _ = var('x, y, z')  # optional - internet
sage: f = sin(x^2) + y^z  # optional - internet
sage: f.integrate(x, algorithm='mathematica_free')  # optional - internet
x*y^z + sqrt(1/2)*sqrt(pi)*fresnel_sin(sqrt(2)*x/sqrt(pi))
```

We can also use Sympy:

```
sage: integrate(x*sin(log(x)), x)
-1/5*x^2*(cos(log(x)) - 2*sin(log(x)))
sage: integrate(x*sin(log(x)), x, algorithm='sympy')
-1/5*x^2*cos(log(x)) + 2/5*x^2*sin(log(x))
sage: _ = var('y, z')
sage: (x*y - z).integrate(y)
-y*z + x*y/log(x)
sage: (x*y - z).integrate(y, algorithm="sympy")
-y*z + cases(((log(x) != 0, x*y/log(x)), (1, y)))
```

We integrate the above function in Maple now:
We next integrate a function with no closed form integral. Notice that the answer comes back as an expression that contains an integral itself.

\[
sage: A = \int_1^{(x-4) \times (x^3+2x+1)} x \, dx; A
\]
\[-\frac{1}{73} \int \frac{x^2 + 4x + 18}{x^3 + 2x + 1} \, dx + \frac{1}{73} \log(x - 4)
\]

We now show that floats are not converted to rationals automatically since we by default have keepfloat: true in maxima.

\[
sage: \int \exp(-x^2), (x, 0, 0.1)
\]
\[0.05623145800914245 \times \sqrt{\pi}
\]

An example of an integral that fricas can integrate:

\[
sage: f(x) = \sqrt{x + \sqrt{x^2 + 1}} / x
\]
\[
sage: \int f(x), x, \text{algorithm}="\text{fricas}" \quad \# \text{optional - fricas}
\]
\[2 \times \sqrt{x + \sqrt{x^2 + 1}} - 2 \times \arctan(\sqrt{x + \sqrt{x^2 + 1}}) - \log(\sqrt{x + \sqrt{x^2 + 1}} + 1) + \log(\sqrt{x + \sqrt{x^2 + 1}} - 1)
\]

where the default integrator obtains another answer:

\[
sage: \int f(x), x, \text{algorithm}='\text{maxima}'
\]
\[\frac{1}{8} \times \sqrt{x} \times \Gamma\left(\frac{1}{4}\right) \times \Gamma\left(-\frac{1}{4}\right)^2 \times \text{hypergeom}\left([-\frac{1}{4}, -\frac{1}{4}, \frac{1}{4}], \left[\frac{1}{2}, \frac{3}{4}\right], -\frac{1}{x^2}\right) / (\pi \times \Gamma\left(\frac{3}{4}\right))
\]

The following definite integral is not found by maxima:

\[
sage: f(x) = (x^4 - 3x^2 + 6) / (x^6 - 5x^4 + 5x^2 + 4)
\]
\[
sage: \int f(x), x, 1, 2, \text{algorithm}='\text{maxima}'
\]
\[\int \frac{x^4 - 3x^2 + 6}{x^6 - 5x^4 + 5x^2 + 4}, x, 1, 2
\]

but is nevertheless computed:

\[
sage: \int f(x), x, 1, 2
\]
\[-\frac{1}{2} \times \pi + \arctan(8) + \arctan(5) + \arctan(2) + \arctan(1/2)
\]

Both fricas and sympy give the correct result:

\[
sage: \int f(x), x, 1, 2, \text{algorithm}='\text{fricas}' \quad \# \text{optional - fricas}
\]
\[-\frac{1}{2} \times \pi + \arctan(8) + \arctan(5) + \arctan(2) + \arctan(1/2)
\]
\[
sage: \int f(x), x, 1, 2, \text{algorithm}='\text{sympy}'
\]
\[-\frac{1}{2} \times \pi + \arctan(8) + \arctan(5) + \arctan(2) + \arctan(1/2)
\]

Using Giac to integrate the absolute value of a trigonometric expression:

\[
sage: \int |\cos(x)|, x, 0, 2\pi, \text{algorithm}='\text{giac}'
\]
\[4
\]
\[
sage: \int |\cos(x)|, x, 0, 2\pi
\]
\[4
\]

ALIASES: integral() and integrate() are the same.

EXAMPLES:
Here is an example where we have to use `assume`:

```sage
sage: a,b = var('a,b')
sage: integrate(1/(x^3 *(a+b*x)^(1/3)), x)
Traceback (most recent call last):
  ... 
ValueError: Computation failed since Maxima requested additional 
constraints; using the 'assume' command before evaluation
*may* help (example of legal syntax is 'assume(a>0)', see `assume?`
for more details)
Is a positive or negative?
```

So we just assume that \(a > 0\) and the integral works:

```sage
sage: assume(a>0)
sage: integrate(1/(x^3 *(a+b*x)^(1/3)), x)
```

```
2/9*b^2*arctan(1/3*sqrt(3)*2*(b*x + a)^(1/3) + a^(1/3))/a^(7/3) -
- 1/9*b^2*log((b*x + a)^(1/3) + a^(1/3))/a^(7/3) + 2/
+ 9*b^2*log((b*x + a)^(1/3) - a^(1/3))/a^(7/3) + 1/6*(4*(b*x + a)^(5/3)*b^2 -
- 7*(b*x + a)^(2/3)*a*b^2)/(b*x + a)^2 + 2*(b*x + a)*a^3 + a^4)
```

Sage's symbolic integration function `integrate(expression, v=None, a=None, b=None, algorithm=None, hold=False)`

Return the indefinite integral with respect to the variable \(v\), ignoring the constant of integration. Or, if endpoints \(a\) and \(b\) are specified, returns the definite integral over the interval \([a, b]\).

If `self` has only one variable, then it returns the integral with respect to that variable.

If definite integration fails, it could be still possible to evaluate the definite integral using indefinite integration with the Newton - Leibniz theorem (however, the user has to ensure that the indefinite integral is continuous on the compact interval \([a, b]\) and this theorem can be applied).

**INPUT:**

- **v** - a variable or variable name. This can also be a tuple of the variable (optional) and endpoints (i.e., \((x, 0, 1)\) or \((0, 1)\)).
- **a** - (optional) lower endpoint of definite integral
- **b** - (optional) upper endpoint of definite integral
- **algorithm** - (default: `maxima`) one of
  - `'maxima'` - use maxima (the default)
  - `'sympy'` - use sympy (also in Sage)
  - `'mathematica_free'` - use http://integrals.wolfram.com/
  - `'fricas'` - use FriCAS (the optional fricas spkg has to be installed)
  - `'giac'` - use Giac

To prevent automatic evaluation use the `hold` argument.

**See also:**

To integrate a polynomial over a polytope, use the optional `latte_int` package `sage.geometry.polyhedron_base.Polyhedron_base.integrate()`.

**EXAMPLES:**

2.13. Symbolic Integration 219
sage: x = var('x')
sage: h = sin(x)/(cos(x))^2
sage: h.integral(x)
1/cos(x)

sage: f = x^2/(x+1)^3
sage: f.integral(x)
1/2*(4*x + 3)/(x^2 + 2*x + 1) + log(x + 1)

sage: f = x*cos(x^2)
sage: f.integral(x, 0, sqrt(pi))
0
sage: f.integral(x, a=-pi, b=pi)
0

sage: f(x) = sin(x)
sage: f.integral(x, 0, pi/2)
1

The variable is required, but the endpoints are optional:

sage: y = var('y')
sage: integral(sin(x), x)
-int*cos(x)
sage: integral(sin(x), y)
y*sin(x)
sage: integral(sin(x), x, pi, 2*pi)
-2
sage: integral(sin(x), y, pi, 2*pi)
pi*sin(x)
sage: integral(sin(x), (x, pi, 2*pi))
-2
sage: integral(sin(x), (y, pi, 2*pi))
pi*sin(x)

Using the `hold` parameter it is possible to prevent automatic evaluation, which can then be evaluated via `simplify()`:

sage: integral(x^2, x, 0, 3)
9
sage: a = integral(x^2, x, 0, 3, hold=True) ; a
integrate(x^2, x, 0, 3)
sage: a.simplify()
9

Constraints are sometimes needed:

sage: var('x, n')
(x, n)
sage: integral(x^n,x)
Traceback (most recent call last):
...     ValueError: Computation failed since Maxima requested additional constraints; using the 'assume' command before evaluation may* help (example of legal syntax is 'assume(n>0)', see 'assume?' for more details)
Is \( n \) equal to \(-1\)?

```
sage: assume(n > 0)
sage: integral(x^n,x)
x^(n + 1)/(n + 1)
sage: forget()
```

Usually the constraints are of sign, but others are possible:

```
sage: assume(n==-1)
sage: integral(x^n,x)
log(x)
```

Note that an exception is raised when a definite integral is divergent:

```
sage: forget() # always remember to forget assumptions you no longer need
sage: integrate(1/x^3,(x,0,1))
Traceback (most recent call last):
  ... ValueError: Integral is divergent.
sage: integrate(1/x^3,(x,-1,3))
Traceback (most recent call last):
  ... ValueError: Integral is divergent.
```

But Sage can calculate the convergent improper integral of this function:

```
sage: integrate(1/x^3,x,1,infinity)
1/2
```

The examples in the Maxima documentation:

```
sage: var('x, y, z, b')
(x, y, z, b)
sage: integral(sin(x)^3, x)
1/3*cos(x)^3 - cos(x)
sage: integral(x/sqrt(b^2-x^2), b)
x*log(2*b + 2*sqrt(b^2 - x^2))
sage: integral(x/sqrt(b^2-x^2), x)
-sqrt(b^2 - x^2)
sage: integral(cos(x)^2 * exp(x), x, 0, pi)
3/5*e^pi - 3/5
sage: integral(x^2 * exp(-x^2), x, -oo, oo)
1/2*sqrt(pi)
```

We integrate the same function in both Mathematica and Sage (via Maxima):

```
sage: _ = var('x, y, z')
sage: f = sin(x^2) + y^z
sage: g = mathematica(f)                   # optional - mathematica
sage: print(g)                            # optional - mathematica
z 2
y + Sin[x]
sage: print(g.Integrate(x))              # optional - mathematica
z 2 Pi
x y + Sqrt[--] FresnelS[Sqrt[--] x]     2 Pi
```

(continues on next page)
Alternatively, just use algorithm='mathematica_free' to integrate via Mathematica over the internet (does NOT require a Mathematica license!):

```python
sage: _ = var('x, y, z') # optional - internet
sage: f = sin(x^2) + y^z # optional - internet
sage: f.integrate(x, algorithm="mathematica_free") # optional - internet
x*y^z + sqrt(1/2)*sqrt(pi)*fresnel_sin(sqrt(2)*x/sqrt(pi))
```

We can also use Sympy:

```python
sage: integrate(x*sin(log(x)), x) # optional - internet
-1/5*x^2*(cos(log(x)) - 2*sin(log(x)))
```

We integrate the above function in Maple now:

```python
sage: g = maple(f); g.sort() # optional - maple
y^z+sin(x^2)
```

We next integrate a function with no closed form integral. Notice that the answer comes back as an expression that contains an integral itself.

```python
sage: A = integral(1/ ((x-4) * (x^3+2*x+1)), x); A
-1/73*integrate((x^2 + 4*x + 18)/(x^3 + 2*x + 1), x) + 1/73*log(x - 4)
```

An example of an integral that fricas can integrate:

```python
sage: f(x) = sqrt(x+sqrt(1+x^2))/x
sage: integrate(f(x), x, algorithm="fricas") # optional - fricas
2*sqrt(x + sqrt(x^2 + 1)) - 2*arctan(sqrt(x + sqrt(x^2 + 1))) - log(sqrt(x + sqrt(x^2 + 1)) + 1) + log(sqrt(x + sqrt(x^2 + 1)) - 1)
```

where the default integrator obtains another answer:

```python
sage: integrate(f(x), x)
1/8*sqrt(x)*gamma(1/4)*gamma(-1/4)^2*hypergeometric((-1/4, -1/4, 1/4), (1/2, 3/4), -1/x^2)/(pi*gamma(3/4))
```
The following definite integral is not found by maxima:

\begin{verbatim}
sage: f(x) = (x^4 - 3*x^2 + 6) / (x^6 - 5*x^4 + 5*x^2 + 4)
sage: integrate(f(x), x, 1, 2, algorithm='maxima')
integrate((x^4 - 3*x^2 + 6)/(x^6 - 5*x^4 + 5*x^2 + 4), x, 1, 2)
\end{verbatim}

but is nevertheless computed:

\begin{verbatim}
sage: integrate(f(x), x, 1, 2)
-1/2*pi + arctan(8) + arctan(5) + arctan(2) + arctan(1/2)
\end{verbatim}

Both fricas and sympy give the correct result:

\begin{verbatim}
sage: integrate(f(x), x, 1, 2, algorithm="fricas") # optional - fricas
-1/2*pi + arctan(8) + arctan(5) + arctan(2) + arctan(1/2)
sage: integrate(f(x), x, 1, 2, algorithm="sympy")
-1/2*pi + arctan(8) + arctan(5) + arctan(2) + arctan(1/2)
\end{verbatim}

Using Giac to integrate the absolute value of a trigonometric expression:

\begin{verbatim}
sage: integrate(abs(cos(x)), x, 0, 2*pi, algorithm='giac')
4
sage: integrate(abs(cos(x)), x, 0, 2*pi)
4
\end{verbatim}

ALIASES: integral() and integrate() are the same.

EXAMPLES:

Here is an example where we have to use assume:

\begin{verbatim}
sage: a,b = var('a,b')
sage: integrate(1/(x^3 *(a+b*x)^(1/3)), x)
Traceback (most recent call last):
...
ValueError: Computation failed since Maxima requested additional constraints; using the 'assume' command before evaluation *may* help (example of legal syntax is 'assume(a>0)', see `assume?' for more details)
Is a positive or negative?

So we just assume that \( a > 0 \) and the integral works:
\end{verbatim}

\begin{verbatim}
sage: assume(a>0)
sage: integrate(1/(x^3 *(a+b*x)^(1/3)), x)
2/9*b^2*arctan(1/3*sqrt(3)*sqrt((a+b*x)^(1/3) + 1/3))/a^(7/3)
\end{verbatim}
2.14 TESTS::

\begin{verbatim}
from sage.symbolic.integration.external import fricas_integrator
sage: fricas_integrator(sin(x), x) # optional - fricas
-cos(x)

from sage.symbolic.integration.external import giac_integrator
sage: giac_integrator(sin(x), x) # optional - giac
-cos(x)

from sage.symbolic.integration.external import maxima_integrator
sage: maxima_integrator(sin(x), x) # optional - maxima
-cos(x)

from sage.symbolic.integration.external import mma_free_integrator
sage: mma_free_integrator(sin(x), x) # optional - internet
-cos(x)
\end{verbatim}

Integration using FriCAS

EXAMPLES:

\begin{verbatim}
sage: fricas_integrator(sin(x), x) # optional - fricas
-cos(x)
sage: fricas_integrator(cos(x), x) # optional - fricas
sin(x)
sage: fricas_integrator(1/(x^2-2), x, 0, 1) # optional - fricas
1/4*sqrt(2)*(log(3*sqrt(2) - 4) - log(sqrt(2)))
sage: fricas_integrator(1/(x^2+6), x, -oo, oo) # optional - fricas
1/6*sqrt(6)*pi
\end{verbatim}

Integration using Giac

EXAMPLES:

\begin{verbatim}
sage: giac_integrator(sin(x), x)
-cos(x)
sage: giac_integrator(1/(x^2+6), x, -oo, oo)
1/6*sqrt(6)*pi
\end{verbatim}

Integration using Maxima

EXAMPLES:

\begin{verbatim}
sage: maxima_integrator(sin(x), x)
-cos(x)
sage: f(x) = function('f')(x)
sage: maxima_integrator(f(x), x)
\end{verbatim}

Integration using Mathematica’s online integrator

EXAMPLES:

\begin{verbatim}
sage: mma_free_integrator(sin(x), x) # optional - internet
-cos(x)
\end{verbatim}
A definite integral:

```
sage: mma_free_integrator(e^(-x), x, a=0, b=oo)  # optional - internet
1
```

```
sage.symbolic.integration.external.parse_moutput_from_json(page_data, verbose=False)
```

Return the list of outputs found in the json (with key 'moutput')

**INPUT:**
- `page_data` – json obtained from Wolfram Alpha
- `verbose` – bool (default: False)

**OUTPUT:**
list of unicode strings

**EXAMPLES:**

```
sage: page_data = request_wolfram_alpha('integrate Sin[x]')  # optional internet
sage: parse_moutput_from_json(page_data)  # optional internet
[u'-Cos[x]']
sage: page_data = request_wolfram_alpha('Sin[x]')  # optional internet
sage: L = parse_moutput_from_json(page_data)  # optional internet
sage: sorted(L)  # optional internet
['-Cos[x]', '{{x == 0}}', '{{x == Pi C[1], Element[C[1], Integers]}}']
```

```
sage.symbolic.integration.external.request_wolfram_alpha(input, verbose=False)
```

Request Wolfram Alpha website.

**INPUT:**
- `input` – string
- `verbose` – bool (default: False)

**OUTPUT:**
json

**EXAMPLES:**

```
sage: page_data = request_wolfram_alpha('integrate Sin[x]')  # optional internet
sage: page_data['queryresult'].keys()  # optional internet
['datatypes', 'encryptedEvaluatedExpression', 'encryptedParsedExpression', 'error', 'host', 'id', 'numpods', ...
```

(continues on next page)
sage.symbolic.integration.external.symbolic_expression_from_mathematica_string(mexpr)
Translate a mathematica string into a symbolic expression

INPUT:
• mexpr – string

OUTPUT:
symbolic expression

EXAMPLES:

```python
sage: from sage.symbolic.integration.external import symbolic_expression_from_mathematica_string
sage: symbolic_expression_from_mathematica_string(u'-Cos[x]')
-cos(x)
```

sage.symbolic.integration.external.sympy_integrator(expression, v, a=None, b=None)
Integration using SymPy

EXAMPLES:

```python
sage: from sage.symbolic.integration.external import sympy_integrator
sage: sympy_integrator(sin(x), x)
-cos(x)
sage: sympy_integrator(cos(x), x)
sin(x)
```

## 2.15 A Sample Session using SymPy

In this first part, we do all of the examples in the SymPy tutorial (https://github.com/sympy/sympy/wiki/Tutorial), but using Sage instead of SymPy.

```python
sage: a = Rational((1,2))
sage: a
1/2
sage: a*2
1
sage: Rational(2)**50 / Rational(10)**50
1/88817841970012523233890533447265625
sage: 1.0/2
0.500000000000000
```
sage: 1/2
1/2
sage: pi^2
pi^2
sage: float(pi)
3.141592653589793
sage: RealField(200)(pi)
3.1415926535897932384626433832795028841971693993751058209749
sage: float(pi + exp(1))
5.8597448204883...

sage: oo != 2
True

sage: var('x y')
(x, y)

sage: x + y + x - y
2*x

sage: (x+y)^2
(x + y)^2
sage: (x+y)^2.expand()
x^2 + 2*x*y + y^2
sage: (x+y)^2.subs(x=1)
(y + 1)^2
sage: (x+y)^2.subs(x=y)
4*y^2

sage: limit(sin(x)/x, x=0)
1
sage: limit(x, x=oo)
+Infinity
sage: limit((5^x + 3^x)^(1/x), x=oo)
3

sage: diff(sin(x), x)
cos(x)

sage: diff(sin(2*x), x)
2*cos(2*x)

sage: diff(tan(x), x)
tan(x)^2 + 1

sage: limit((tan(x+y) - tan(x))/y, y=0)
cos(x)^(-2)

sage: diff(sin(2*x), x, 1)
2*cos(2*x)

sage: diff(sin(2*x), x, 2)
-4*sin(2*x)

sage: diff(sin(2*x), x, 3)
-8*cos(2*x)

sage: cos(x).taylor(x,0,10)
-1/3628800*x^10 + 1/40320*x^8 - 1/720*x^6 + 1/24*x^4 - 1/2*x^2 + 1

sage: (1/cos(x)).taylor(x,0,10)
50521/3628800*x^10 + 277/8064*x^8 + 61/720*x^6 + 5/24*x^4 + 1/2*x^2 + 1

sage: matrix([[1,0], [0,1]])
[1 0]

(continues on next page)

2.15. A Sample Session using SymPy
\[ \begin{bmatrix} 0 & 1 \\ \end{bmatrix} \]

```python
sage: var('x y')
(x, y)
sage: A = matrix([[1, x], [y, 1]])
sage: A
\begin{bmatrix} 1 & x \\ y & 1 \end{bmatrix}
sage: A^2
\begin{bmatrix} x*y + 1 & 2*x \\ 2*y & x*y + 1 \end{bmatrix}
sage: R.<x,y> = QQ[]
sage: A = matrix([[1, x], [y, 1]])
sage: A^10
\begin{bmatrix} x^5*y^5 + 45*x^4*y^4 + 210*x^3*y^3 + 210*x^2*y^2 + 45*x*y + 1 & 10*x^5*y^4 + 120*x^4*y^3 + 252*x^3*y^2 + 120*x^2*y + 10*x \\ 10*x^4*y^5 + 120*x^3*y^4 + 252*x^2*y^3 + 120*x*y^2 + 10*y & x^5*y^5 + 45*x^4*y^4 + 210*x^3*y^3 + 210*x^2*y^2 + 45*x*y + 1 \end{bmatrix}
sage: var('x y')
(x, y)
```

And here are some actual tests of sympy:

```python
sage: from sympy import Symbol, cos, sympify, pprint
sage: from sympy.abc import x
sage: e = (1/cos(x)^3)._sympy_(); e
cos(x)^(-3)
sage: f = e.series(x, 0, int(10)); f
1 + 3*x**2/2 + 11*x**4/8 + 241*x**6/240 + 8651*x**8/13440 + O(x**10)
```

And the pretty-printer. Since unicode characters are not working on some architectures, we disable it:

```python
sage: from sympy.printing import pprint_use_unicode
sage: prev_use = pprint_use_unicode(False)
sage: pprint(e)
\frac{1}{\cos (x)}
sage: pprint(f)
2 4 6 8
\frac{3*x^{11}}{240} + \frac{8651*x^{13}}{13440} + \frac{1}{x^{10}}
```

And the functionality to convert from sympy format to Sage format:

```python
sage: e._sage_()
cos(x)^(-3)
sage: e._sage_().taylor(x._sage_(), 0, 8)
8651/13440*x^8 + 241/240*x^6 + 11/8*x^4 + 3/2*x^2 + 1
sage: f._sage_()
8651/13440*x^8 + 241/240*x^6 + 11/8*x^4 + 3/2*x^2 + Order(x^10) + 1
```
Mixing SymPy with Sage:

```python
sage: import sympy
sage: var("x")._sympy_() + var("y")._sympy_()
x + y
sage: o = var("omega")
sage: t1 = s + o
sage: type(t1)
<class 'sympy.core.add.Add'>
sage: t2 = o + s
sage: type(t2)
<type 'sage.symbolic.expression.Expression'>
sage: t1, t2
(omega + x, omega + x)
sage: e=sympy.sin(var("y"))+sage.all.cos(sympy.Symbol("x"))
sage: type(e)
<class 'sympy.core.add.Add'>
sage: e
sin(y) + cos(x)
sage: e=e._sage_()
sage: type(e)
<type 'sage.symbolic.expression.Expression'>
sage: e
cos(x) + sin(y)
sage: e = sage.all.cos(var("y")**(3)**4)+var("x")**(2
sage: e = e._sympy_()
sage: e
x**2 + cos(y**3)**4
```

```python
sage: a = sympy.Matrix([1, 2, 3])
sage: a[1]
2
sage: sympify(1.5)
1.50000000000000
sage: sympify(2)
2
sage: sympify(-2)
-2
```

### 2.16 Calculus Tests and Examples

**Compute the Christoffel symbol.**

```python
sage: var('r t theta phi')
(r, t, theta, phi)
sage: m = matrix(SR, [[(1-1/r),0,0,0],[0,-(1-1/r)^(-1),0,0],[0,0,-r^2,0],[0,0,0,-r^2*(sin(theta))^2]])
sage: m
```

```
[   -1/r + 1 0 0 0]
[        0 1/(1/r - 1) 0 0]
[        0 0 -r^2 0]
[        0 0 0 -r^2*sin(theta)^2]
```
```python
sage: def christoffel(i,j,k,vars,g):
    s = 0
    ginv = g^(-1)
    for l in range(g.nrows()):
        s = s + (1/2)*ginv[k,l]*(g[j,l].diff(vars[i])+g[i,l].diff(vars[j])-g[i,j].diff(vars[l]))
    return s
```

```python
sage: christoffel(3,3,2, [t,r,theta,phi], m)
-cos(theta)*sin(theta)
sage: X = christoffel(1,1,1,[t,r,theta,phi],m)
sage: X
1/2/(r^2*(1/r - 1))
sage: X.rational_simplify()
-1/2/(r^2 - r)
```

Some basic things:

```python
sage: f(x,y) = x^3 + sinh(1/y)
sage: f
(x, y) |--> x^3 + sinh(1/y)
sage: f^3
(x, y) |--> (x^3 + sinh(1/y))^3
sage: (f^3).expand()
(x, y) |--> x^9 + 3*x^6*sinh(1/y) + 3*x^3*sinh(1/y)^2 + sinh(1/y)^3
```

A polynomial over a symbolic base ring:

```python
sage: R = SR['x']
sage: f = R([1/sqrt(2), 1/(4*sqrt(2))])
sage: f
1/8*sqrt(2)*x + 1/2*sqrt(2)
sage: -f
-1/8*sqrt(2)*x - 1/2*sqrt(2)
sage: (-f).degree()
1
```

A big product. Notice that simplifying simplifies the product further:

```python
sage: A = exp(I*pi/7)
sage: b = A^14
sage: b
1
```

We check a statement made at the beginning of Friedlander and Joshi’s book on Distributions:

```python
sage: f(x) = sin(x^2)
sage: g(x) = cos(x) + x^3
sage: u = f(x+t) + g(x-t)
sage: u
-(t - x)^3 + cos(-t + x) + sin((t + x)^2)
sage: u.diff(t,2) - u.diff(x,2)
0
```

Restoring variables after they have been turned into functions:
MATHEMATICA: Some examples of integration and differentiation taken from some Mathematica docs:

```
sage: var('x n a')
(x, n, a)
sage: diff(x^n, x)  # the output looks funny, but is correct
n*x^(n - 1)
sage: diff(x^2 * log(x+a), x)
2*x*log(a + x) + x^2/(a + x)
sage: derivative(arctan(x), x)
1/(x^2 + 1)
sage: derivative(x^n, x, 3)
(n - 1)*(n - 2)*n*x^(n - 3)
sage: derivative( function('f')(x), x)
diff(f(x), x)
sage: diff( 2*x*f(x^2), x)
4*x^2*D[0](f)(x^2) + 2*f(x^2)
sage: integrate( 1/(x^4 - a^4), x)
-1/2*arctan(x/a)/a^3 - 1/4*log(a + x)/a^3 + 1/4*log(-a + x)/a^3
sage: expand(integrate(log(1-x^2), x))
x*log(-x^2 + 1) - 2*x + log(x + 1) - log(x - 1)
```

This is an apparent regression in Maxima 5.39.0, although the antiderivative is correct, assuming we work with (poly)logs of complex argument. More convenient form is 1/2*log(x^2)*log(-x^2 + 1) + 1/2*dilog(-x^2 + 1). See also https://sourceforge.net/p/maxima/bugs/3275/:

```
sage: integrate(log(1-x^2)/x, x)
log(-x)*log(x + 1) + log(x)*log(-x + 1) + dilog(x + 1) + dilog(-x + 1)
```

No problems here:

```
sage: integrate(exp(1-x^2),x)
1/2*sqrt(pi)*erf(x)*e
sage: integrate(sin(x^2),x)
1/16*sqrt(pi)*((I + 1)*sqrt(2)*erf((1/2*I + 1/2)*sqrt(2)*x) + (I - 1)*sqrt(2)*erf((1/2*I - 1/2)*sqrt(2)*x) - (I - 1)*sqrt(2)*erf(sqrt(-I)*x) + (I + 1)*sqrt(2)*erf((-1)^^(1/4)*x))
sage: integrate((1-x^2)^n,x)
x*hypergeometric((1/2, -n), (3/2,), x^2*exp_polar(2*I*pi))
sage: integrate(x*x,x)
integrate(x^2, x)
sage: integrate(1/(x^3+1),x)
1/3*sqrt(3)*arctan(1/3*sqrt(3)*(2*x - 1)) - 1/6*log(x^2 - x + 1) + 1/3*log(x + 1)
sage: integrate(1/(x^3+1), x, 0, 1)
1/9*sqrt(3)*pi + 1/3*log(2)
```

(continues on next page)
```
sage: assume(c > 0)
sage: integrate(exp(-c*x^2), x, -oo, oo)
sqrt(pi)/sqrt(c)
sage: forget()
```

Other examples that now (trac ticket #27958) work:

```
sage: integrate(log(x)*exp(-x^2), x)
1/2*sqrt(pi)*erf(x)*log(x) - x*hypergeometric((1/2, 1/2), (3/2, 3/2), -x^2)
sage: integrate(log(1+sqrt(1+4*x)/2)/x, x, 0, 1)
Traceback (most recent call last):
  ... ValueError: Integral is divergent.
```

The following is an example of integral that Mathematica can do, but Sage currently cannot do:

```
sage: integrate(ceil(x^2 + floor(x)), x, 0, 5, algorithm='maxima')
integrate(ceil(x^2) + floor(x), x, 0, 5)
```

MAPLE: The basic differentiation and integration examples in the Maple documentation:

```
sage: diff(sin(x), x)
cos(x)
sage: diff(sin(x), y)
0
sage: diff(sin(x), x, 3)
-cos(x)
sage: diff(x*sin(cos(x)), x)
-x*cos(cos(x))*sin(x) + sin(cos(x))
sage: diff(tan(x), x)
tan(x)^2 + 1
sage: f = function('f'); f
def(f, x)
sage: diff(f(x), x)
diff(f(x), x)
sage: diff(f(x,y), x, y)
diff(f(x, y), x, y)
sage: diff(f(x,y), x, y) - diff(f(x,y), y, x)
0
sage: g = function('g')
sage: var('x y z')
(x, y, z)
sage: diff(g(x,y,z), x,z,z)
diff(g(x, y, z), x, z, z)
sage: integrate(sin(x), x)
-cos(x)
sage: integrate(sin(x), x, 0, pi)
2
```

```
sage: var('a b')
(a, b)
sage: integrate(sin(x), x, a, b)
cos(a) - cos(b)
```
We verify several standard differentiation rules:

```python
sage: f = function('f, g')
(f, g)
sage: diff(f(t)*g(t),t)
g(t)*diff(f(t), t) + f(t)*diff(g(t), t)
sage: diff(f(t)/g(t), t)
diff(f(t), t)/g(t) - f(t)*diff(g(t), t)/g(t)^2
sage: diff(f(t) + g(t), t)
diff(f(t), t) + diff(g(t), t)
sage: diff(c*f(t), t)
c*diff(f(t), t)
```

## 2.17 Conversion of symbolic expressions to other types

This module provides routines for converting new symbolic expressions to other types. Primarily, it provides a class `Converter` which will walk the expression tree and make calls to methods overridden by subclasses.

```python
class sage.symbolic.expression_conversions.AlgebraicConverter(field):
    Bases: sage.symbolic.expression_conversions.Converter

    EXAMPLES:
    sage: from sage.symbolic.expression_conversions import AlgebraicConverter
    sage: a = AlgebraicConverter(QQbar)
    sage: a.arithmetic(f, f.operator())
    1.414213562373095?
```

### arithmetric(ex, operator)
Convert a symbolic expression to an algebraic number.

**EXAMPLES:**

```python
sage: from sage.symbolic.expression_conversions import AlgebraicConverter
sage: a = AlgebraicConverter(QQbar)
sage: a.arithmetic(f, f.operator())
1.414213562373095?
```
composition \((ex, \text{operator})\)

Coerce to an algebraic number.

EXAMPLES:

```python
sage: from sage.symbolic.expression_conversions import AlgebraicConverter
sage: a = AlgebraicConverter(QQbar)
sage: a.composition(exp(I*pi/3, hold=True), exp)
0.500000000000000? + 0.866025403784439?*I
sage: a.composition(sin(pi/7), sin)
0.4338837391175581? + 0.?e-18*I
```

pyobject \((ex, \text{obj})\)

EXAMPLES:

```python
sage: from sage.symbolic.expression_conversions import AlgebraicConverter
sage: a = AlgebraicConverter(QQbar)
sage: f = SR(2)
sage: a.pyobject(f, f.pyobject())
2
sage: _.parent()
Algebraic Field
```

class `sage.symbolic.expression_conversions.Converter` \(\text{Convertible}(use\_fake\_div=False)\)

Bases: object

If `use\_fake\_div` is set to `True`, then the converter will try to replace expressions whose operator is `operator.mul` with the corresponding expression whose operator is `operator.truediv`.

EXAMPLES:

```python
sage: from sage.symbolic.expression_conversions import Converter
sage: c = Converter(use_fake_div=True)
sage: c.get_fake_div(sin(x)/x)
FakeExpression([sin(x), x], <built-in function truediv>)
sage: c.get_fake_div(-1*sin(x))
FakeExpression([sin(x)], <built-in function neg>)
sage: c.get_fake_div(-x)
FakeExpression([x], <built-in function neg>)
```

arithmetic \((ex, \text{operator})\)

The input to this method is a symbolic expression and the infix operator corresponding to that expression. Typically, one will convert all of the arguments and then perform the operation afterward.

derivative \((ex, \text{operator})\)

The input to this method is a symbolic expression and its operator. This method will get called when you have a symbolic function application.

derivative \((ex, \text{operator})\)

The input to this method is a symbolic expression which corresponds to a relation.

generate_fake_div \((ex)\)

EXAMPLES:

```python
sage: from sage.symbolic.expression_conversions import Converter
sage: c = Converter(use_fake_div=True)
sage: c.get_fake_div(sin(x)/x)
FakeExpression([sin(x), x], <built-in function truediv>)
sage: c.get_fake_div(-1*sin(x))
FakeExpression([sin(x)], <built-in function neg>)
sage: c.get_fake_div(-x)
FakeExpression([x], <built-in function neg>)
```
sage: c.get_fake_div((2*x^3+2*x-1)/((x-2)*(x+1)))
FakeExpression([2*x^3 + 2*x - 1, FakeExpression([x + 1, x - 2], <built-in function mul>), <built-in function truediv>])

Check if trac ticket #8056 is fixed, i.e., if numerator is 1.:

sage: c.get_fake_div(1/pi/x)
FakeExpression([1, FakeExpression([pi, x], <built-in function mul>), <built-in function truediv>])

pyobject (ex, obj)
The input to this method is the result of calling pyobject() on a symbolic expression.

Note: Note that if a constant such as pi is encountered in the expression tree, its corresponding pyobject which is an instance of sage.symbolic.constants.Pi will be passed into this method. One cannot do arithmetic using such an object.

relation (ex, operator)
The input to this method is a symbolic expression which corresponds to a relation.

symbol (ex)
The input to this method is a symbolic expression which corresponds to a single variable. For example, this method could be used to return a generator for a polynomial ring.

class sage.symbolic.expression_conversions.ExpressionTreeWalker (ex)
Bases: sage.symbolic.expression_conversions.Converter

A class that walks the tree. Mainly for subclassing.

EXAMPLES:

sage: from sage.symbolic.expression_conversions import ExpressionTreeWalker
sage: from sage.symbolic.random_tests import random_expr
sage: ex = sin(atan(0,hold=True)+hypergeometric((1,),((1,),(1,)),x))

sage: s = ExpressionTreeWalker(ex)

sage: bool(s() == ex)
True

sage: foo = random_expr(20, nvars=2)

sage: s = ExpressionTreeWalker(foo)

sage: bool(s() == foo)
True

arithmetic (ex, operator)

EXAMPLES:

sage: from sage.symbolic.expression_conversions import ExpressionTreeWalker
sage: foo = function('foo')

sage: f = x*foo(x) + pi/foo(x)

sage: s = ExpressionTreeWalker(f)

sage: bool(s.arithmetic(f, f.operator()) == f)
True

composition (ex, operator)

EXAMPLES:
sage: from sage.symbolic.expression_conversions import ExpressionTreeWalker
sage: foo = function('foo')
sage: f = foo(atan2(0, 0, hold=True))
sage: s = ExpressionTreeWalker(f)
sage: bool(s.composition(f, f.operator()) == f)
True

**derivative** (*ex, operator*)

**EXAMPLES:**

sage: from sage.symbolic.expression_conversions import ExpressionTreeWalker
sage: foo = function('foo')
sage: f = foo(x).diff(x)
sage: s = ExpressionTreeWalker(f)
sage: bool(s.derivative(f, f.operator()) == f)
True

**pyobject** (*ex, obj*)

**EXAMPLES:**

sage: from sage.symbolic.expression_conversions import ExpressionTreeWalker
sage: f = SR(2)
.sage: s = ExpressionTreeWalker(f)
.sage: bool(s.pyobject(f, f.pyobject()) == f.pyobject())
True

**relation** (*ex, operator*)

**EXAMPLES:**

sage: from sage.symbolic.expression_conversions import ExpressionTreeWalker
sage: foo = function('foo')
.sage: eq = foo(x) == x
.sage: s = ExpressionTreeWalker(eq)
.sage: s.relation(eq, eq.operator()) == eq
True

**symbol** (*ex*)

**EXAMPLES:**

sage: from sage.symbolic.expression_conversions import ExpressionTreeWalker
.sage: s = ExpressionTreeWalker(x)
.sage: bool(s.symbol(x) == x)
True

**tuple** (*ex*)

**EXAMPLES:**

sage: from sage.symbolic.expression_conversions import ExpressionTreeWalker
.sage: foo = function('foo')
.sage: f = hypergeometric((1,2,3,), (x,), x)
.sage: s = ExpressionTreeWalker(f)
.sage: bool(s() == f)
True

class sage.symbolic.expression_conversions.FakeExpression (operands, operator)  
Bases: object
Pynac represents $x/y$ as $xy^{-1}$. Often, tree-walkers would prefer to see divisions instead of multiplications and negative exponents. To allow for this (since Pynac internally doesn’t have division at all), there is a possibility to pass use\_fake\_div=True; this will rewrite an Expression into a mixture of Expression and FakeExpression nodes, where the FakeExpression nodes are used to represent divisions. These nodes are intended to act sufficiently like Expression nodes that tree-walkers won’t care about the difference.

**operands()**

EXAMPLES:

```python
sage: from sage.symbolic.expression_conversions import FakeExpression
sage: import operator
sage: x, y = var('x,y')
sage: f = FakeExpression([x, y], operator.truediv)
sage: f.operands()
[x, y]
```

**operator()**

EXAMPLES:

```python
sage: from sage.symbolic.expression_conversions import FakeExpression
sage: import operator
sage: x, y = var('x,y')
sage: f = FakeExpression([x, y], operator.truediv)
sage: f.operator()
<built-in function truediv>
```

**pyobject()**

EXAMPLES:

```python
sage: from sage.symbolic.expression_conversions import FakeExpression
sage: import operator
sage: x, y = var('x,y')
sage: f = FakeExpression([x, y], operator.truediv)
sage: f.pyobject()
Traceback (most recent call last):
  ... 
TypeError: self must be a numeric expression
```

**class sage.symbolic.expression_conversions.FastCallableConverter(ex, etb)**

Bases: sage.symbolic.expression_conversions.Converter

EXAMPLES:

```python
sage: from sage.symbolic.expression_conversions import FastCallableConverter
sage: from sage.ext.fast_callable import ExpressionTreeBuilder
sage: etb = ExpressionTreeBuilder(vars=['x'])
sage: f = FastCallableConverter(x+2, etb)
sage: f.ex
x + 2
sage: f.etb
<sage.ext.fast_callable.ExpressionTreeBuilder object at 0x...>
sage: f.use_fake_div
True
```

**arithmetic(ex, operator)**

EXAMPLES:

```python
sage: from sage.ext.fast_callable import ExpressionTreeBuilder
sage: etb = ExpressionTreeBuilder(vars=['x','y'])
sage: var('x,y')
(x, y)
```

(continues on next page)
composition \((ex, function)\)

Given an ExpressionTreeBuilder, return an Expression representing this value.

EXAMPLES:

```python
sage: from sage.ext.fast_callable import ExpressionTreeBuilder
sage: etb = ExpressionTreeBuilder(vars=['x','y'])
sage: x, y = var('x,y')
```

```python
sage: sin(sqrt(x+y))._fast_callable_(etb)
sin(sqrt(add(v_0, v_1)))
```

```python
sage: arctan2(x,y)._fast_callable_(etb)
{arctan2}(v_0, v_1)
```

pyobject \((ex, obj)\)

EXAMPLES:

```python
sage: from sage.ext.fast_callable import ExpressionTreeBuilder
sage: etb = ExpressionTreeBuilder(vars=['x'])
```

```python
sage: pi._fast_callable_(etb)
pi
```

```python
sage: etb = ExpressionTreeBuilder(vars=['x'], domain=RDF)
```

```python
sage: pi._fast_callable_(etb)
3.141592653589793
```

relation \((ex, operator)\)

EXAMPLES:

```python
sage: ff = fast_callable(x == 2, vars=['x'])
```

```python
sage: ff(2)
0
```

```python
sage: ff(4)
2
```

```python
sage: ff = fast_callable(x < 2, vars=['x'])
Traceback (most recent call last):
  ... Not Implemented Error
```

symbol \((ex)\)

Given an ExpressionTreeBuilder, return an Expression representing this value.

EXAMPLES:

```python
sage: from sage.ext.fast_callable import ExpressionTreeBuilder
sage: etb = ExpressionTreeBuilder(vars=['x','y'])
```

```python
sage: x, y, z = var('x,y,z')
```

```python
sage: x._fast_callable_(etb)
v_0
```

```python
sage: y._fast_callable_(etb)
v_1
```

```python
sage: z._fast_callable_(etb)
```
Traceback (most recent call last):
...
ValueError: Variable 'z' not found

tuple\( (ex) \)
Given a symbolic tuple, return its elements as a Python list.

EXAMPLES:

```
sage: from sage.ext.fast_callable import ExpressionTreeBuilder
dsage: etb = ExpressionTreeBuilder(vars=['x'])
sage: SR._force_pyobject((2, 3, x^2))._fast_callable_(etb)
[2, 3, x^2]
```

class\ sage.symbolic.expression_conversions.\FastFloatConverter\( \(ex, *vars\)
Bases: sage.symbolic.expression_conversions.Converter

Returns an object which provides fast floating point evaluation of the symbolic expression \( ex \). This is a class used internally and is not meant to be used directly.

See \sage.ext.fast_eval\ for more information.

EXAMPLES:

```
sage: x,y,z = var('x,y,z')
sage: f = 1 + sin(x)/x + sqrt(z^2+y^2)/cosh(x)
sage: ff = f._fast_float_('x', 'y', 'z')
sage: f(x=1.0,y=2.0,z=3.0).n()
4.1780638977...
sage: ff(1.0,2.0,3.0)
4.1780638977...
```

Using \_fast_float\ without specifying the variable names is no longer possible:

```
sage: f = x._fast_float_()
Traceback (most recent call last):
...
ValueError: please specify the variable names
```

Using \_fast_float\ on a function which is the identity is now supported (see \trac ticket #10246):

```
sage: f = symbolic_expression(x).function(x)
sage: f._fast_float_(x)
<\sage.ext.fast_eval.FastDoubleFunc object at ...>
sage: f(22)
22
```

arithmetic\( (ex, operator) \)

EXAMPLES:

```
sage: x,y = var('x,y')
sage: f = x*x-y
sage: ff = f._fast_float_('x','y')
sage: ff(2,3)
1.0
```

(continues on next page)
sage: f = a._fast_float_('x', 'y')
sage: f(1,0)
1.0
sage: f(0,1)
2.0

sage: f = sqrt(x)._fast_float_('x'); f.op_list()
['load 0', 'call sqrt(1)']

sage: f = (1/2*x)._fast_float_('x'); f.op_list()
['load 0', 'push 0.5', 'mul']

composition (ex, operator)
EXAMPLES:

sage: f = sqrt(x)._fast_float_('x')
sage: f(2)
1.41421356237309...

sage: y = var('y')

sage: f = sqrt(x+y)._fast_float_('x', 'y')
sage: f(1,1)
1.41421356237309...

sage: f = sqrt(x+2*y)._fast_float_('x', 'y')
sage: f(2,0)
1.41421356237309...

pyobject (ex, obj)
EXAMPLES:

sage: f = SR(2)._fast_float_()

relation (ex, operator)
EXAMPLES:

sage: ff = fast_float(x == 2, 'x')

sage: f = x._fast_float_('x', 'y')

symbol (ex)
EXAMPLES:
class sage.symbolic.expression_conversions.FriCASConverter
Bases: sage.symbolic.expression_conversions.InterfaceInit

Converts any expression to FriCAS.

EXAMPLES:

```python
sage: var('x,y')
(x, y)
sage: f = exp(x^2) - arcsin(pi+x)/y
sage: f._fricas_()  # optional - fricas
2
x
y \exp - \arcsin(x + %pi)
----------------------
y
derivative(ex, operator)
Convert the derivative of self in FriCAS.

INPUT:

* ex -- a symbolic expression
* operator -- operator

EXAMPLES:

```python
sage: var('x,y,z')
(x, y, z)
sage: f = function("F")
sage: f(x)._fricas_()  # optional - fricas
F(x)
sage: diff(f(x,y,z), x, z, x)._fricas_()  # optional - fricas
F(x,y,z),1,1,3
```

Check that trac ticket #25838 is fixed:

```python
sage: var('x')
x
sage: F = function('F')
sage: integrate(F(x), x, algorithm="fricas")  # optional - fricas
integral(F(x), x)
sage: integrate(diff(F(x), x)*sin(F(x)), x, algorithm="fricas")  # optional - fricas
-cos(F(x))
```

class sage.symbolic.expression_conversions.HoldRemover(ex, exclude=None)
Bases: sage.symbolic.expression_conversions.ExpressionTreeWalker

A class that walks the tree and evaluates every operator that is not in a given list of exceptions.
EXAMPLES:

```python
sage: from sage.symbolic.expression_conversions import HoldRemover
sage: ex = sin(pi*cos(0, hold=True), hold=True); ex
sin(pi*cos(0))
sage: h = HoldRemover(ex)
sage: h()
0
sage: h = HoldRemover(ex, [sin])
sage: h()
sin(pi)
sage: h = HoldRemover(ex, [cos])
sage: h()
sin(pi*cos(0))
sage: ex = atan2(0, 0, hold=True) + hypergeometric([1,2], [3,4], 0, hold=True)
sage: h = HoldRemover(ex, [atan2])
sage: h()
arctan2(0, 0) + 1
sage: h = HoldRemover(ex, [hypergeometric])
sage: h()
NaN + hypergeometric((1, 2), (3, 4), 0)
```

`composition(ex, operator)`

EXAMPLES:

```python
sage: from sage.symbolic.expression_conversions import HoldRemover
sage: ex = sin(pi*cos(0, hold=True), hold=True); ex
sin(pi*cos(0))
sage: h = HoldRemover(ex)
sage: h()
0
```

```python
composition(ex, operator)

EXAMPLES:

```python
from sage.symbolic.expression_conversions import InterfaceInit
sage: m = InterfaceInit(maxima)
sage: a = pi + 2
sage: m(a)
'(%pi)+(2)'
sage: m(sin(a))
'sin((%pi)+(2))'
sage: m(exp(x^2) + pi + 2)
'(%pi)+(exp((_SAGE_VAR_x)^(2)))+(2)'
```

`arithmetic(ex, operator)`

EXAMPLES:

```python
```

```python
from sage.symbolic.expression_conversions import InterfaceInit
sage: m = InterfaceInit(maxima)
sage: m.arithmetic(x+2, sage.symbolic.operators.add_vararg)
'(_SAGE_VAR_x)+(2)'
```

`composition(ex, operator)`

EXAMPLES:
sage: from sage.symbolic.expression_conversions import InterfaceInit
sage: m = InterfaceInit(maxima)
sage: m.composition(sin(x), sin)
"sin(_SAGE_VAR_x)"
sage: m.composition(ceil(x), ceil)
'ceiling(_SAGE_VAR_x)'

sage: m = InterfaceInit(mathematica)
sage: m.composition(sin(x), sin)
'Sin\[x\]'

derivative(ex, operator)
EXAMPLES:

sage: from sage.symbolic.expression_conversions import InterfaceInit
sage: m = InterfaceInit(maxima)
sage: f = function('f')
sage: a = f(x).diff(x); a
diff(f(x), x)
sage: print(m.derivative(a, a.operator()))
diff('f(_SAGE_VAR_x), _SAGE_VAR_x, 1)
sage: b = f(x).diff(x, x)
sage: print(m.derivative(b, b.operator()))
diff('f(_SAGE_VAR_x), _SAGE_VAR_x, 2)

We can also convert expressions where the argument is not just a variable, but the result is an “at” expression using temporary variables:

sage: y = var('y')
sage: t = (f(x*y).diff(x))/y
sage: t
D[0](f)(x*y)
sage: m.derivative(t, t.operator())
"at(diff('f(_SAGE_VAR_t0), _SAGE_VAR_t0, 1), [_SAGE_VAR_t0 = (_SAGE_VAR_x)*(_SAGE_VAR_y)])"

pyobject(ex, obj)
EXAMPLES:

sage: from sage.symbolic.expression_conversions import InterfaceInit
sage: ii = InterfaceInit(gp)
sage: f = 2+I
sage: ii.pyobject(f, f.pyobject())
'I + 2'
sage: ii.pyobject(SR(2), 2)
'2'
sage: ii.pyobject(pi, pi.pyobject())
'Pi'

relation(ex, operator)
EXAMPLES:

sage: import operator
sage: from sage.symbolic.expression_conversions import InterfaceInit
sage: m = InterfaceInit(maxima)
(continues on next page)
symbol (ex)

EXAMPLES:

```python
sage: from sage.symbolic.expression_conversions import InterfaceInit
sage: m = InterfaceInit(maxima)
sage: m.symbol(x)
'_SAGE_VAR_x'
sage: f(x) = x
sage: m.symbol(f)
'_SAGE_VAR_x'
sage: ii = InterfaceInit(gp)
sage: ii.symbol(x)
'x'
```

tuple (ex)

EXAMPLES:

```python
sage: from sage.symbolic.expression_conversions import InterfaceInit
sage: m = InterfaceInit(maxima)
sage: t = SR._force_pyobject((3, 4, e^x))
sage: m.tuple(t)
'[3,4,exp(_SAGE_VAR_x)]'
```

class sage.symbolic.expression_conversions.LaurentPolynomialConverter(ex, 

Bases: sage.symbolic.expression_conversions.PolynomialConverter

A converter from symbolic expressions to Laurent polynomials.

See laurent_polynomial() for details.

class sage.symbolic.expression_conversions.PolynomialConverter(ex,  

Bases: sage.symbolic.expression_conversions.Converter

A converter from symbolic expressions to polynomials.

See polynomial() for details.

EXAMPLES:

```python
sage: from sage.symbolic.expression_conversions import PolynomialConverter
sage: x, y = var('x,y')
sage: p = PolynomialConverter(x+y, base_ring=QQ)
sage: p.base_ring
Rational Field
sage: p.ring
Multivariate Polynomial Ring in x, y over Rational Field
sage: p = PolynomialConverter(x, base_ring=QQ)
sage: p.base_ring
```
Rational Field
\texttt{sage}: \texttt{p.ring}
Univariate Polynomial Ring in \(x\) over Rational Field

\texttt{sage}: \texttt{p = PolynomialConverter(x, ring=QQ['x,y'])}
\texttt{sage}: \texttt{p.base_ring}
Rational Field
\texttt{sage}: \texttt{p.ring}
Multivariate Polynomial Ring in \(x, y\) over Rational Field

\texttt{sage}: \texttt{p = PolynomialConverter(x+y, ring=QQ['x'])}
Traceback (most recent call last):
...:
TypeError: \(y\) is not a variable of Univariate Polynomial Ring in \(x\) over Rational Field

\texttt{arithmetic(\textit{ex}, \textit{operator})}

\textbf{EXAMPLES:}

\texttt{sage}: \texttt{import operator}
\texttt{sage}: \texttt{from sage.symbolic.expression_conversions import PolynomialConverter}

\texttt{sage}: \texttt{x, y = var('x, y')}
\texttt{sage}: \texttt{p = PolynomialConverter(x, base_ring=RR)}
\texttt{sage}: \texttt{p.arithmetic(pi+e, operator.add)}
\texttt{5.8597448204884}
\texttt{sage}: \texttt{p.arithmetic(x^2, operator.pow)}
\texttt{x^2}

\texttt{sage}: \texttt{p = PolynomialConverter(x+y, base_ring=RR)}
\texttt{sage}: \texttt{p.arithmetic(x+y+y^2, operator.add)}
\texttt{x*y + y^2}

\texttt{sage}: \texttt{p = PolynomialConverter(y^(3/2), ring=SR['x'])}
\texttt{sage}: \texttt{p.arithmetic(y^(3/2), operator.pow)}
\texttt{y^(3/2)}
\texttt{sage}: \texttt{_.parent()}
Symbolic Ring

\texttt{composition(\textit{ex}, \textit{operator})}

\textbf{EXAMPLES:}

\texttt{sage}: \texttt{from sage.symbolic.expression_conversions import PolynomialConverter}
\texttt{sage}: \texttt{a = sin(2)}
\texttt{sage}: \texttt{p = PolynomialConverter(a*x, base_ring=RR)}
\texttt{sage}: \texttt{p.composition(a, a.operator())}
\texttt{0.909297426825682}

\texttt{pyobject(\textit{ex}, \textit{obj})}

\textbf{EXAMPLES:}

\texttt{sage}: \texttt{from sage.symbolic.expression_conversions import PolynomialConverter}
\texttt{sage}: \texttt{p = PolynomialConverter(x, base_ring=QQ)}
\texttt{sage}: \texttt{f = SR(2)}
\texttt{sage}: \texttt{p.pyobject(f, f.pyobject())}
\texttt{2}
relation \( (ex, op) \)

EXAMPLES:

```python
sage: import operator
sage: from sage.symbolic.expression_conversions import PolynomialConverter

sage: x, y = var('x, y')

sage: p = PolynomialConverter(x, base_ring=RR)

sage: p.relation(x==3, operator.eq)
x - 3.00000000000000

sage: p.relation(x==3, operator.lt)
Traceback (most recent call last):
... ValueError: Unable to represent as a polynomial

sage: p = PolynomialConverter(x - y, base_ring=QQ)

sage: p.relation(x^2 - y^3 + 1 == x^3, operator.eq)
-x^3 - y^3 + x^2 + 1
```

symbol \( (ex) \)

Returns a variable in the polynomial ring.

EXAMPLES:

```python
sage: from sage.symbolic.expression_conversions import PolynomialConverter

sage: p = PolynomialConverter(x, base_ring=QQ)

sage: p.symbol(x)
x

sage: _.parent()
Univariate Polynomial Ring in x over Rational Field

sage: y = var('y')

sage: p = PolynomialConverter(x*y, ring=SR['x'])

sage: p.symbol(y)
y
```

class `sage.symbolic.expression_conversions.RingConverter` \( (R, subs_dict=None) \)

Bases: `sage.symbolic.expression_conversions.Converter`

A class to convert expressions to other rings.

EXAMPLES:

```python
sage: from sage.symbolic.expression_conversions import RingConverter

sage: R = RingConverter(RIF, subs_dict={x:2})

sage: R.ring
Real Interval Field with 53 bits of precision

sage: R.subs_dict
{x: 2}

sage: R(pi+e)
5.85974482048847

sage: R(pi+e).simplify()<sage.symbolic.expression_conversions.RingConverter object at 0x...>
```
arithmetic *(ex, operator)*

EXAMPLES:

```
sage: from sage.symbolic.expression_conversions import RingConverter
sage: P.<z> = ZZ[]
sage: R = RingConverter(P, subs_dict={x:z})
sage: a = 2*x^2 + x + 3
sage: R(a)
2*z^2 + z + 3
```

composition *(ex, operator)*

EXAMPLES:

```
sage: from sage.symbolic.expression_conversions import RingConverter
sage: R = RingConverter(RIF)
sage: R(cos(2))
-0.4161468365471424?
```

pyobject *(ex, obj)*

EXAMPLES:

```
sage: from sage.symbolic.expression_conversions import RingConverter
sage: R = RingConverter(RIF)
sage: R(SR(5/2))
2.5000000000000000?
```

symbol *(ex)*

All symbols appearing in the expression must either appear in *subs_dict* or be convertible by the ring’s element constructor in order for the conversion to be successful.

EXAMPLES:

```
sage: from sage.symbolic.expression_conversions import RingConverter
sage: R = RingConverter(RIF, subs_dict={x:2})
sage: R(x+pi)
5.141592653589794?
```

```
sage: R = RingConverter(RIF)
sage: R(x+pi)
Traceback (most recent call last):
  ...
TypeError: unable to simplify to a real interval approximation
```

```
sage: R = RingConverter(QQ['x'])
sage: R(x^2+x)
x^2 + x
```

```
sage: R(x^2+x).parent()
Univariate Polynomial Ring in x over Rational Field
```

class sage.symbolic.expression_conversions.SubstituteFunction *(ex, original, new)*

Bases: sage.symbolic.expression_conversions.ExpressionTreeWalker

A class that walks the tree and replaces occurrences of a function with another.

EXAMPLES:

```
sage: from sage.symbolic.expression_conversions import SubstituteFunction
sage: foo = function('foo'); bar = function('bar')
```
sage: s = SubstituteFunction(foo(x), foo, bar)
sage: s(1/foo(foo(x)) + foo(2))
1/bar(bar(x)) + bar(2)

composition (ex, operator)

EXAMPLES:

sage: from sage.symbolic.expression_conversions import SubstituteFunction
sage: foo = function('foo'); bar = function('bar')
sage: s = SubstituteFunction(foo(x), foo, bar)
sage: f = foo(x)
sage: s.composition(f, f.operator())
bar(x)
sage: f = foo(foo(x))
sage: s.composition(f, f.operator())
bar(bar(x))
sage: f = sin(foo(x))
sage: s.composition(f, f.operator())
sin(bar(x))
sage: f = foo(sin(x))
sage: s.composition(f, f.operator())
bar(sin(x))

derivative (ex, operator)

EXAMPLES:

sage: from sage.symbolic.expression_conversions import SubstituteFunction
sage: foo = function('foo'); bar = function('bar')
sage: s = SubstituteFunction(foo(x), foo, bar)
sage: f = foo(x).diff(x)
sage: s.derivative(f, f.operator())
diff(bar(x), x)

class sage.symbolic.expression_conversions.SympyConverter
Bases: sage.symbolic.expression_conversions.Converter

Converts any expression to SymPy.

EXAMPLES:

sage: import sympy
sage: var('x,y')
(x, y)
sage: f = exp(x^2) - arcsin(pi+x)/y
sage: f._sympy_()
exp(x**2) - asin(x + pi)/y
sage: _.sage_()
-arcsin(pi + x)/y + e^(x^2)

sage: sympy.sympify(x)  # indirect doctest
x

arithmetic (ex, operator)

EXAMPLES:

sage: from sage.symbolic.expression_conversions import SympyConverter
sage: s = SympyConverter()
composition \((ex, operator)\)

**EXAMPLES:**

```python
sage: from sage.symbolic.expression_conversions import SympyConverter
sage: s = SympyConverter()
sage: f = sin(2)
sage: s.composition(f, f.operator())
sin(2)
sage: type(_)
sin
sage: f = arcsin(2)
sage: s.composition(f, f.operator())
asin(2)
```

derivative \((ex, operator)\)

Convert the derivative of `self` in sympy.

**INPUT:**

- `ex` – a symbolic expression
- `operator` – operator

**symbol\((ex)\)**

**EXAMPLES:**

```python
sage: import operator
sage: from sage.symbolic.expression_conversions import SympyConverter
sage: s = SympyConverter()
sage: s.symbol(x)
```

2.17. Conversion of symbolic expressions to other types
```python
sage: from sage.symbolic.expression_conversions import SympyConverter
sage: s = SympyConverter()
x
sage: type(_)
<class 'sympy.core.symbol.Symbol'>
```

**tuple** *(ex)*
Conversion of tuples.

**EXAMPLES:**
```python
sage: t = SR._force_pyobject((3, 4, e^x))
sage: t._sympy_()
(3, 4, e^x)
sage: t = SR._force_pyobject((cos(x),))
sage: t._sympy_()
(cos(x),)
```

`sage.symbolic.expression_conversions.algebraic`(ex, field)
Returns the symbolic expression *ex* as a element of the algebraic field *field*.

**EXAMPLES:**
```python
sage: a = SR(5/6)
sage: QQbar(a)
5/6
sage: type(QQbar(a))
<class 'sage.rings.qqbar.AlgebraicNumber'>
sage: QQbar(i)
I
sage: QQbar(sin(pi/3))
0.866025403784439?
```

`sage.symbolic.expression_conversions.fast_callable`(ex, etb)

---

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Given an ExpressionTreeBuilder \( etb \), return an Expression representing the symbolic expression \( ex \).

**EXAMPLES:**

```python
sage: from sage.ext.fast_callable import ExpressionTreeBuilder
eqb = ExpressionTreeBuilder
sage: x, y = var('x, y')
eqb = y + 2*x^2
sage: f._fast_callable_(etb)
add(mul(ipow(v_0, 2), 2), v_1)

sage: f = (2*x^3 + 2*x - 1)/((x-2)*(x+1))

sage: f._fast_callable_(etb)
div(add(add(mul(ipow(v_0, 3), 2), mul(v_0, 2)), -1), mul(add(v_0, 1), add(v_0, -2)))
```

`sage.symbolic.expression_conversions.fast_float(ex, *vars)`

Returns an object which provides fast floating point evaluation of the symbolic expression \( ex \).

See `sage.ext.fast_eval` for more information.

**EXAMPLES:**

```python
sage: from sage.symbolic.expression_conversions import fast_float
sage: f = sqrt(x+1)

sage: ff = fast_float(f, 'x')

sage: ff(1.0)
1.4142135623730951
```

`sage.symbolic.expression_conversions.laurent_polynomial(ex, base_ring=None, ring=None)`

Return a Laurent polynomial from the symbolic expression \( ex \).

**INPUT:**

- \( ex \) – a symbolic expression
- \( base\_ring, \text{ring} \) – Either a \( base\_ring \) or a Laurent polynomial ring can be specified for the parent of result. If just a \( base\_ring \) is given, then the variables of the \( base\_ring \) will be the variables of the expression \( ex \).

**OUTPUT:**

A Laurent polynomial.

**EXAMPLES:**

```python
sage: from sage.symbolic.expression_conversions import laurent_polynomial
sage: f = x^2 + 2/x

sage: laurent_polynomial(f, base_ring=QQ)
2*x^-1 + x^2

sage: _.parent()
Univariate Laurent Polynomial Ring in x over Rational Field

sage: laurent_polynomial(f, ring=LaurentPolynomialRing(QQ, 'x, y'))
x^2 + 2*x^-1

sage: _.parent()
Multivariate Laurent Polynomial Ring in x, y over Rational Field

sage: x, y = var('x, y')

sage: laurent_polynomial(x + 1/y^2, ring=LaurentPolynomialRing(QQ, 'x, y'))
```

(continues on next page)
\[ x + y^{-2} \]

```
sage: _.parent()
Multivariate Laurent Polynomial Ring in x, y over Rational Field
```

```
sage.symbolic.expression_conversions.polynomial(ex, base_ring=None, ring=None)

Return a polynomial from the symbolic expression \( ex \).

INPUT:

- \( ex \) – a symbolic expression
- \( base\_ring, ring \) – Either a \( base\_ring \) or a polynomial \( ring \) can be specified for the parent of result. If just a \( base\_ring \) is given, then the variables of the \( base\_ring \) will be the variables of the expression \( ex \).

OUTPUT:

A polynomial.

EXAMPLES:

```
sage: from sage.symbolic.expression_conversions import polynomial
sage: f = x^2 + 2
sage: polynomial(f, base_ring=QQ)
x^2 + 2
sage: _.parent()
Univariate Polynomial Ring in x over Rational Field
sage: polynomial(f, ring=QQ['x,y'])
x^2 + 2
sage: _.parent()
Multivariate Polynomial Ring in x, y over Rational Field
sage: x, y = var('x, y')
sage: polynomial(x + y^2, ring=QQ['x,y'])
y^2 + x
sage: _.parent()
Multivariate Polynomial Ring in x, y over Rational Field
sage: s,t=var('s,t')
sage: expr=t^2-2*s*t+1
sage: expr.polynomial(None,ring=SR['t'])
t^2 - 2*s*t + 1
sage: _.parent()
Univariate Polynomial Ring in t over Symbolic Ring
sage: polynomial(x*y, ring=SR['x'])
y*x
sage: polynomial(y - sqrt(x), ring=SR['y'])
y - sqrt(x)
sage: _.list()
[-sqrt(x), 1]
```

The polynomials can have arbitrary (constant) coefficients so long as they coerce into the base ring:

```
sage: polynomial(2*sin(2)*x^2 + exp(3), base_ring=RR)
1.87813065119873*x^2 + 20.0855369231877
```
2.18 Complexity Measures

Some measures of symbolic expression complexity. Each complexity measure is expected to take a symbolic expression as an argument, and return a number.

\texttt{sage.symbolic.complexity_measures.string_length(expr)}

Returns the length of \texttt{expr} after converting it to a string.

**INPUT:**
- \texttt{expr} – the expression whose complexity we want to measure.

**OUTPUT:**
A real number representing the complexity of \texttt{expr}.

**RATIONALE:**
If the expression is longer on-screen, then a human would probably consider it more complex.

**EXAMPLES:**
This expression has three characters, \(x\), ^, and 2:

```plaintext
sage: from sage.symbolic.complexity_measures import string_length
sage: f = x^2
sage: string_length(f)
3
```

2.19 Further examples from Wester’s paper

These are all the problems at \url{http://yacas.sourceforge.net/essaysmanual.html}

They come from the 1994 paper “Review of CAS mathematical capabilities”, by Michael Wester, who put forward 123 problems that a reasonable computer algebra system should be able to solve and tested the then current versions of various commercial CAS on this list. Sage can do most of the problems natively now, i.e., with no explicit calls to Maxima or other systems.

```plaintext
sage: # (YES) factorial of 50, and factor it
sage: factorial(50)
3041409320171337804361260816606476884437764156896051200000000000
sage: factor(factorial(50))
2^47 * 3^22 * 5^12 * 7^8 * 11^4 * 13^3 * 17^2 * 19^2 * 23^2 * 29 * 31 * 37 * 41 * 43...

sage: # (YES) 1/2+...+1/10 = 4861/2520
sage: sum(1/n for n in range(2,10+1)) == 4861/2520
True

sage: # (YES) Evaluate \(e^{\pi \sqrt{163}}\) to 50 decimal digits
sage: a = e^(pi*sqrt(163)); a
\(2.6253741264076874399999999999925007259719820e17\)
```

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sage: # (YES) Evaluate the Bessel function J[2] numerically at z=1+i.
sage: bessel_J(2, 1+I).n()
0.0415798869439621 + 0.247397641513306*I

sage: # (YES) Obtain period of decimal fraction 1/7=0.(142857).
sage: a = 1/7
sage: a
1/7
sage: a.period()
6

sage: # (YES) Continued fraction of 3.1415926535
sage: a = 3.1415926535
sage: continued_fraction(a)
[3; 7, 15, 1, 292, 1, 1, 6, 2, 13, 4]

sage: # (YES) Sqrt(2*sqrt(3)+4)=1+Sqrt(3).
sage: # The Maxima backend equality checker does this;
sage: # note the equality only holds for one choice of sign,
sage: # but Maxima always chooses the "positive" one
sage: a = sqrt(2*sqrt(3) + 4); b = 1 + sqrt(3)
sage: float(a-b)
0.0
sage: bool(a == b)
True

sage: # We can, of course, do this in a quadratic field
sage: k.<sqrt3> = QuadraticField(3)
sage: asqr = 2*sqrt3 + 4
sage: b = 1+sqrt3
sage: asqr == b^2
True

sage: # (YES) Sqrt(14+3*sqrt(3+2*sqrt(5-12*sqrt(3-2*sqrt(2)))))=3+Sqrt(2).
sage: a = sqrt(14+3*sqrt(3+2*sqrt(5-12*sqrt(3-2*sqrt(2)))))
sage: b = 3+sqrt(2)
sage: a, b
(sqrt(3*sqrt(2*sqrt(-12*sqrt(-2*sqrt(2) + 3) + 5) + 3) + 14), sqrt(2) + 3)
sage: bool(a==b)
True
sage: abs(float(a-b)) < 1e-10
True

sage: # 2*Infinity-3=Infinity.
sage: 2*infinity-3 == infinity
True

sage: # (YES) Standard deviation of the sample (1, 2, 3, 4, 5).
sage: v = vector(RDF, 5, [1,2,3,4,5])
sage: v.standard_deviation()  
1.581138830841898

sage: # (NO) Hypothesis testing with t-distribution.
sage: # (NO) Hypothesis testing with chi^2 distribution
sage: # (But both are included in Scipy and R)
\begin{verbatim}
sage: # (YES) (x^2-4)/(x^2+4*x+4)=(x-2)/(x+2).
sage: R.<x> = QQ[]
sage: (x^2-4)/(x^2+4*x+4) == (x-2)/(x+2)
True
sage: restore('x')
sage: # (YES -- Maxima doesn't immediately consider them
sage: # equal, but simplification shows that they are)
sage: f = (exp(x)-1)/(exp(x/2)+1)
sage: g = exp(x/2)-1
sage: f
(e^x - 1)/(e^(1/2*x) + 1)
sage: g
e^(1/2*x) - 1
sage: f.canonicalize_radical()
e^(1/2*x) - 1
sage: f(x=10.0).n(53), g(x=10.0).n(53)
(147.413159102577, 147.413159102577)
sage: bool(f == g)
True
sage: # (YES) Expand (1+x)^20, take derivative and factorize.
sage: # first do it using algebraic polys
sage: R.<x> = QQ[]
sage: f = (1+x)^20; f
x^20 + 20*x^19 + 190*x^18 + 1140*x^17 + 4845*x^16 + 15504*x^15 + 38760*x^14 + 77520*x^13 + 125970*x^12 + 167960*x^11 + 184756*x^10 + 167960*x^9 + 125970*x^8 + 77520*x^7 + 38760*x^6 + 15504*x^5 + 4845*x^4 + 1140*x^3 + 20*x^2 + 1
sage: deriv = f.derivative()
sage: deriv
20*x^19 + 380*x^18 + 3420*x^17 + 19380*x^16 + 77520*x^15 + 232560*x^14 + 542640*x^13 + 1007760*x^12 + 1511640*x^11 + 1847560*x^10 + 1847560*x^9 + 1511640*x^8 + 1007760*x^7 + 542640*x^6 + 232560*x^5 + 77520*x^4 + 19380*x^3 + 3420*x^2 + 380*x + 20
sage: deriv.factor()
20*(x + 1)^19
sage: restore('x')
sage: # next do it symbolically
sage: y
sage: f = (1+y)^20; f
(y + 1)^20
sage: g = f.expand(); g
y^20 + 20*y^19 + 190*y^18 + 1140*y^17 + 4845*y^16 + 15504*y^15 + 38760*y^14 + 77520*y^13 + 125970*y^12 + 167960*y^11 + 184756*y^10 + 167960*y^9 + 125970*y^8 + 77520*y^7 + 38760*y^6 + 15504*y^5 + 4845*y^4 + 1140*y^3 + 20*y^2 + 1
sage: deriv = g.derivative(); deriv
20*y^19 + 380*y^18 + 3420*y^17 + 19380*y^16 + 77520*y^15 + 232560*y^14 + 542640*y^13 + 1007760*y^12 + 1511640*y^11 + 1847560*y^10 + 1847560*y^9 + 1511640*y^8 + 1007760*y^7 + 542640*y^6 + 232560*y^5 + 77520*y^4 + 19380*y^3 + 3420*y^2 + 380*y + 20
sage: deriv.factor()
20*(y + 1)^19
\end{verbatim}

2.19. Further examples from Wester’s paper
sage: # (YES) Factorize $x^{100}-1$.
sage: factor(x^100-1)
(x^40 - x^30 + x^20 - x^10 + 1)*(x^40 - x^30 + x^20 - x^10 + 1)*
    (x^8 - x^6 + x^4 - x^2 + 1)*(x^4 - x^3 + x^2 + x + 1)*(x^4 - x^3 + x^2 - x^10 + 1)*
    (x^2 + 1)*(x + 1)*(x - 1)
sage: # Also, algebraically
sage: x = polygen(QQ)
sage: factor(x^100 - 1)
(x - 1) * (x + 1) * (x^2 + 1) * (x^4 - x^3 + x^2 - x + 1) * (x^4 + x^3 + x^2 + x + 1) *
    (x^8 - x^6 + x^4 - x^2 + 1) * (x^20 - x^15 + x^10 - x^5 + 1) * (x^20 + x^15 + x^10 + x^5 + 1) *
    (x^40 - x^30 + x^20 - x^10 + 1)
sage: restore('x')
sage: # (YES) Factorize $x^4-3*x^2+1$ in the field of rational numbers extended by roots of $x^2-x-1$.
sage: k.< a> = NumberField(x^2 - x -1)
sage: R.< y> = k[]
sage: f = y^4 - 3*y^2 + 1
sage: f
y^4 - 3*y^2 + 1
sage: factor(f)
(y - a) * (y - a + 1) * (y + a - 1) * (y + a)
sage: # (YES) Factorize $x^4-3*x^2+1$ mod 5.
sage: k.< x > = GF(5) [ ]
sage: f = x^4 - 3*x^2 + 1
sage: f.factor()
(x + 2)^2 * (x + 3)^2
sage: # Alternatively, from symbol x as follows:
sage: reset('x')
sage: f = x^4 - 3*x^2 + 1
sage: f.polynomial(GF(5)).factor()
(x + 2)^2 * (x + 3)^2
sage: # (YES) Partial fraction decomposition of $(x^2+2*x+3)/(x^3+4*x^2+5*x+2)$
sage: f = (x^2+2*x+3)/(x^3+4*x^2+5*x+2); f
(x^2 + 2*x + 3)/(x^3 + 4*x^2 + 5*x + 2)
sage: f.partial_fraction()
3/(x + 2) - 2/(x + 1) + 2/(x + 1)^2
sage: # (YES) Assuming $x>y$, $y>z$, $z>x$, deduce $x=z$.
sage: forget()
sage: var('x,y,z')
(x, y, z)
sage: assume(x>y, y>z, z>x)
sage: bool(x==z)
True
sage: # (YES) Assuming $x>y$, $y>0$, deduce $2*x^2>2*y^2$.
sage: forget()
sage: assume(x>y, y>0)
sage: sorted(assumptions())
[x > y, y > 0]
sage: bool(2*x^2 > 2*y^2)
True
(continues on next page)
sage: forget()
sage: assumptions()
[]

sage: # (NO) Solve the inequality \( \text{Abs}(x-1)>2 \).
sage: # Maxima doesn't solve inequalities
sage: # (but some Maxima packages do):
sage: eqn = \text{abs}(x-1) > 2
sage: eqn
\text{abs}(x - 1) > 2

sage: # (NO) Solve the inequality \((x-1)\cdots(x-5)<0\).
sage: eqn = \prod(x-i \text{ for } i \text{ in range}(1,5 +1)) < 0
sage: # but don't know how to solve
sage: eqn
(x - 1)*(x - 2)*(x - 3)*(x - 4)*(x - 5) < 0

sage: # (YES) \( \frac{\cos(3\cdot x)}{\cos(x)}=\cos(x)^2-3\cdot\sin(x)^2 \) or similar equivalent combination.
sage: f = \cos(3\cdot x)/\cos(x)
sage: g = \cos(x)^2 - 3*\sin(x)^2
sage: h = f-g
sage: h.trig_simplify()
0

sage: # (YES) \( \frac{\cos(3\cdot x)}{\cos(x)}=2\cdot\cos(2\cdot x)-1 \).
sage: f = \cos(3\cdot x)/\cos(x)
sage: g = 2*cos(2*x) - 1
sage: h = f-g
sage: h.trig_simplify()
0

sage: # (GOOD ENOUGH) Define rewrite rules to match \( \frac{\cos(3\cdot x)}{\cos(x)}=\cos(x)^2-3\cdot\sin(x)^2 \).
sage: # Sage has no notion of "rewrite rules", but
sage: # it can simplify both to the same thing.

sage: (\cos(3\cdot x)/\cos(x)).simplify_full()
4*\cos(x)^2 - 3
sage: (\cos(x)^2-3*\sin(x)^2).simplify_full()
4*\cos(x)^2 - 3

sage: # (YES) \( \sqrt{997}-(997^3)^{(1/6)}=0 \)

sage: a = \sqrt{997} - (997^3)^{(1/6)}
sage: a.simplify()
0
sage: bool(a == 0)
True

sage: # (YES) \( \sqrt{99983}-(99983^3)^{(1/6)}=0 \)

sage: a = \sqrt{99983} - (99983^3)^{(1/6)}
sage: bool(a==0)
True
sage: float(a)
1.1368683772...e-13
sage: 13*7691

(continues on next page)
sage: # (YES) \((2^{1/3} + 4^{1/3})^3 - 6*(2^{1/3} + 4^{1/3}) - 6 = 0\)
sage: a = (2^{1/3} + 4^{1/3})^3 - 6*(2^{1/3} + 4^{1/3}) - 6; a
(4^{1/3} + 2^{1/3})^3 - 6*4^{1/3} - 6*2^{1/3} - 6

sage: bool(a==0)
True
sage: abs(float(a)) < 1e-10
True

## or we can do it using number fields.
sage: reset('x')
sage: k.<b> = NumberField(x^3-2)
sage: a = (b + b^2)^3 - 6*(b + b^2) - 6
sage: a
0

sage: # (NO, except numerically) \(\ln(\tan(x/2 + \pi/4)) - \text{arcsinh}(\tan(x)) = 0\)
# Sage uses the Maxima convention when comparing symbolic expressions and
# returns True only when it can prove equality. Thus, in this case, we get
# False even though the equality holds.
sage: f = log(tan(x/2 + pi/4)) - arcsinh(tan(x))
sage: bool(f == 0)
False

sage: [abs(float(f(x=i/10))) < 1e-15 for i in range(1,5)]
[True, True, True, True]

sage: # Numerically, the expression \(\ln(\tan(x/2 + \pi/4)) - \text{arcsinh}(\tan(x)) = 0\) and its
# derivative at \(x=0\) are zero.
sage: g = f.derivative()
sage: abs(float(f(x=0))) < 1e-10
True
sage: abs(float(g(x=0))) < 1e-10
True
sage: g
-sqrt(tan(x)^2 + 1) + 1/2*(tan(1/4*pi + 1/2*x)^2 + 1)/tan(1/4*pi + 1/2*x)

sage: # (NO) \(\ln((2*\sqrt{r} + 1)/\sqrt{4*r + 4*\sqrt{r} + 1})) = 0\).
sage: var('r')
f
sage: f = log((2*sqrt(r) + 1)/sqrt(4*r + 4*sqrt(r) + 1))
sage: f
log((2*sqrt(r) + 1)/sqrt(4*r + 4*sqrt(r) + 1))
sage: bool(f == 0)
False

sage: [abs(float(f(r=i))) < 1e-10 for i in [0.1,0.3,0.5]]
[True, True, True]

sage: # (NO) \((4*r+4*\sqrt{r}+1)^{(\sqrt{r}/(2*\sqrt{r}+1))}*(2*\sqrt{r}+1)^{(-1)}-2*\sqrt{r}+1=0\), assuming \(r>0\).
# sage: assume(r>0)
# sage: f = (4*r+4*sqrt(r)+1)^{\sqrt{r}/(2*sqrt(r)+1)}*(2*sqrt(r)+1)^{-1}-2*sqrt(r)+1
sage: f
(4*r + 4*sqrt(r) + 1)^{\sqrt{r}/(2*sqrt(r)+1)}*(2*sqrt(r)+1)^{-1}-2*sqrt(r) - 1
\begin{verbatim}
sage: bool(f == 0)
False
sage: [abs(float(f(r=i))) < 1e-10 for i in [0.1, 0.3, 0.5]]
[True, True, True]

sage: # (YES) Obtain real and imaginary parts of Ln(3+4*I).
sage: a = log(3+4*I); a
log(4*I + 3)
sage: a.real()
log(5)
sage: a.imag()
arctan(4/3)

sage: # (YES) Obtain real and imaginary parts of Tan(x+I*y)

sage: z = var('z')
sage: a = tan(z); a
tan(z)
sage: a.real()
sin(2*real_part(z))/(cos(2*real_part(z)) + cosh(2*imag_part(z)))
sage: a.imag()
sinh(2*imag_part(z))/(cos(2*real_part(z)) + cosh(2*imag_part(z)))

sage: # (YES) Simplify Ln(Exp(z)) to z for -Pi<Im(z)<=Pi.

sage: f = log(exp(z)); f
log(e^z)
sage: f.simplify()
z
sage: forget()

sage: # (YES) Assuming Re(x)>0, Re(y)>0, deduce x^(1/n)*y^(1/n)-(x*y)^(1/n)=0.

sage: n = var('n')
sage: f = x^(1/n)*y^(1/n)-(x*y)^(1/n)
sage: assume(real(x) > 0, real(y) > 0)
sage: f.simplify()
x^(1/n)*y^(1/n) - (x*y)^(1/n)
sage: maxima = sage.calculus.calculus.maxima
sage: maxima.set('domain', 'real') # set domain to real
sage: f.simplify()
0
sage: maxima.set('domain', 'complex') # set domain back to its default value
sage: forget()

sage: # (YES) Transform equations, (x==2)/2+(1==1)=>x/2+1==2.

sage: eq1 = x == 2
sage: eq2 = SR(1) == SR(1)
sage: eq1/2 + eq2
\end{verbatim}
\[ \frac{1}{2} \times x + 1 = 2 \]

```python
sage: # (SOMewhat) Solve Exp(x)=1 and get all solutions.
sage: solve(exp(x) == 1, x)
[x == 0]
```

```python
sage: # (SOMewhat) Solve Tan(x)=1 and get all solutions.
sage: solve(tan(x) == 1, x)
[x == 1/4*pi]
```

```python
sage: # (YES) Solve a degenerate 3x3 linear system.
sage: solve([x+y+z==6, 2*x+y+2*z==10, x+3*y+z==10], x,y,z)
[[x == -r1 + 4, y == 2, z == r1]]
```

```python
sage: # (YES) Invert a 2x2 symbolic matrix.
sage: R.<a,b> = QQ[]
sage: m = matrix(2,2,[a,b, 1, a*b])
sage: zz = m^(-1)
sage: zz
\[
\begin{bmatrix}
\frac{a}{a^2 - 1} & -\frac{1}{a^2 - 1} \\
-\frac{1}{a^2*b - b} & \frac{a}{a^2*b - b}
\end{bmatrix}
\]
```

```python
sage: # (YES) Compute and factor the determinant of the 4x4 Vandermonde matrix in a, \rightarrow b, c, d.
sage: var('a,b,c,d')

(a, b, c, d)

sage: m = matrix(SR, 4, 4, [[z^i for i in range(4)] for z in [a,b,c,d]])

sage: m
\[
\begin{bmatrix}
1 & a & a^2 & a^3 \\
1 & b & b^2 & b^3 \\
1 & c & c^2 & c^3 \\
1 & d & d^2 & d^3
\end{bmatrix}
\]

sage: d = m.determinant()
sage: d
(a - b)*(a - c)*(a - d)*(b - c)*(b - d)*(c - d)
```

```python
sage: # (YES) Compute and factor the determinant of the 4x4 Vandermonde matrix in a, \rightarrow b, c, d.
sage: # Do it instead in a multivariate ring
sage: R.<a,b,c,d> = QQ[]
sage: m = matrix(R, 4, 4, [[z^i for i in range(4)] for z in [a,b,c,d]])

sage: m
\[
\begin{bmatrix}
1 & a & a^2 & a^3 \\
1 & b & b^2 & b^3 \\
1 & c & c^2 & c^3 \\
1 & d & d^2 & d^3
\end{bmatrix}
\]

sage: d = m.determinant()
sage: d
```

(continues on next page)
\[ a^3 b^2 c - a^2 b^3 c - a^3 b c^2 + a b^3 c^2 - a^2 b^2 c^3 - a^3 b^2 d + a b^3 c^2 d - a^2 b^3 c^2 d - a^2 b^2 c^3 d + a^3 b^2 d^2 - a^2 b^3 d^2 - a^3 b^2 c^2 d^2 + a^2 b^3 c^2 d^2 + a c^3 d^2 - b c^3 d^2 - a^2 b c^3 d^2 + a b^2 c^3 d^2 + a^2 c c^2 d^3 + b^2 c^2 d^3 \]

```
sage: d.factor()
(-1) * (c - d) * (-b + c) * (b - d) * (-a + c) * (-a + b) * (a - d)
```

```
sage: m = matrix(QQ, 3, [5,-3,-7, -2,1,2, 2,-3,-4])
sage: m.eigenspaces_left()
[(3, Vector space of degree 3 and dimension 1 over Rational Field
 User basis matrix:
[ 1 0 -1]),
(1, Vector space of degree 3 and dimension 1 over Rational Field
 User basis matrix:
[ 1 1 -1]),
(-2, Vector space of degree 3 and dimension 1 over Rational Field
 User basis matrix:
[0 1 1])]
```

```
sage: # (YES) Find the eigenvalues of a 3x3 integer matrix.
sage: # (YES) Verify some standard limits found by L'Hopital’s rule:
sage: # (OK-ish) D(x) Abs(x)
sage: # (YES) (Integrate(x) Abs(x))=Abs(x)*x/2
```

```
sage: # (YES) Find the eigenvalues of a 3x3 integer matrix.
sage: m = matrix(QQ, 3, [5,-3,-7, -2,1,2, 2,-3,-4])
sage: m.eigenspaces_left()
[(3, Vector space of degree 3 and dimension 1 over Rational Field
 User basis matrix:
[ 1 0 -1]),
(1, Vector space of degree 3 and dimension 1 over Rational Field
 User basis matrix:
[ 1 1 -1]),
(-2, Vector space of degree 3 and dimension 1 over Rational Field
 User basis matrix:
[0 1 1])]
```

```
sage: # (YES) Verify some standard limits found by L'Hopital’s rule:
sage: # (YES) Verify(Limit(x,Infinity) (1+1/x)^x, Exp(1));
sage: # (YES) Verify(Limit(x,0) (1-Cos(x))/x^2, 1/2);
sage: limit( (1+1/x)^x, x = oo)
esage: limit( (1-cos(x))/(x^2), x = 1/2)
```

```
sage: # (OK-ish) D(x) Abs(x)
sage: # (YES) (Integrate(x) Abs(x))=Abs(x)*x/2
```

```
sage: # (YES) Compute derivative of Abs(x), piecewise defined.
sage: # (YES) (Integrate(x) Abs(x))=Abs(x)*x/2
```

```
sage: # (YES) Compute derivative of Abs(x), piecewise defined.
sage: # (YES) (Integrate(x) Abs(x))=Abs(x)*x/2
```

### 2.19. Further examples from Wester’s paper
sage: # (YES) Taylor series of 1/Sqrt(1-v^2/c^2) at v=0.
sage: var('v, c')
(v, c)
sage: taylor(1/sqrt(1-v^2/c^2), v, 0, 7)
1/2*v^2/c^2 + 3/8*v^4/c^4 + 5/16*v^6/c^6 + 1
sage: # (OK-ish) (Taylor expansion of Sin(x))/(Taylor expansion of Cos(x)) = (Taylor expansion of Tan(x)).
sage: # TestYacas(Taylor(x,0,5)(Taylor(x,0,5)Sin(x))//
sage: # (Taylor(x,0,5)Cos(x)), Taylor(x,0,5)Tan(x));
sage: f = taylor(sin(x), x, 0, 8)
sage: g = taylor(cos(x), x, 0, 8)
sage: h = taylor(tan(x), x, 0, 8)
sage: f = f.power_series(QQ)
sage: g = g.power_series(QQ)
sage: h = h.power_series(QQ)
sage: f - g/h
O(x^8)
sage: # (YES) Taylor expansion of Ln(x)^a*Exp(-b*x) at x=1.
sage: a,b = var('a,b')
sage: taylor(log(x)^a*exp(-b*x), x, 1, 3)
-1/48*(a^3*(x - 1)^a + a^2*(6*b + 5)*(x - 1)^a + 8*b^3*(x - 1)^a + 2*(6*b^2 + 5*b + 3)*a*(x - 1)^a + 12*b^2*(x - 1)^a + (x - 1)^2*e^(-b) - 1/2*(a*(x - 1)^a + 2*b*(x - 1)^a)*(x - 1)*e^(-b) + (x - 1)^a*e^(-b)
sage: # (YES) Taylor expansion of Ln(Sin(x)/x) at x=0.
sage: taylor(log(sin(x)/x), x, 0, 10)
-1/467775*x^10 - 1/37800*x^8 - 1/2835*x^6 - 1/180*x^4 - 1/6*x^2
sage: # (NO) Compute n-th term of the Taylor series of Ln(Sin(x)/x) at x=0.
sage: # need formal functions
sage: # (NO) Compute n-th term of the Taylor series of Exp(-x)*Sin(x) at x=0.
sage: # (Sort of, with some work)
sage: # Solve x=Sin(y)+Cos(y) for y as Taylor series in x at x=1.
sage: # TestYacas(InverseTaylor(y,0,4) Sin(y)+Cos(y),
sage: # (y-1)+(y-1)^2/2+(y-1)^3/3+(y-1)^4);
sage: f = sin(y) + cos(y)
sage: g = f.taylor(y, 0, 10)
sage: h = g.power_series(QQ)
sage: k = (h - 1).reverse()
sage: k
y + 1/2*y^2 + 2/3*y^3 + y^4 + 17/10*y^5 + 37/12*y^6 + 41/7*y^7 + 23/2*y^8 + 1667/72*y^9 + 3803/80*y^10 + O(y^11)
sage: # (OK) Compute Legendre polynomials directly from Rodrigues's formula, P[n]=1/(2^n*n!)*(Deriv(x,n)(x^2-1)^n).

(continues on next page)
sage: # \( P(n,x) := \text{Simplify}(1/(2\times n!!) \times \text{Deriv}(x,n) (x^2-1)^n) \);

sage: # TestYacas(P(4,x), (35\times x^4)/8+(-15\times x^2)/4+3/8);

sage: P = lambda n, x: simplify(diff((x^2-1)^n,x,n) / (2^n * factorial(n)))

sage: P(4,x).expand()
35/8*x^4 - 15/4*x^2 + 3/8

sage: # (YES) Define the polynomial \( p=\text{Sum}(i,1,5,a[i]\times x^i) \).

sage: # symbolically

sage: ps = sum(var('a\%s'%i)*x^i for i in range(1,6)); ps
a5\times^5 + a4\times^4 + a3\times^3 + a2\times^2 + a1\times

sage: ps.parent()
Symbolic Ring

sage: # algebraically

sage: R = PolynomialRing(QQ,5,names='a')

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

sage: p = S(list(R.gens()))*x; p
a4\times^5 + a3\times^4 + a2\times^3 + a1\times^2 + a0\times

sage: p.parent()
Univariate Polynomial Ring in x over Multivariate Polynomial Ring in a0, a1, a2, a3,\ldots
\rightarrow a4 over Rational Field

sage: # (YES) Convert the above to Horner's form.

sage: # Verify(Horner(p, x), ((((a5\times^5 + a4\times^4 + a3\times^3 + a2\times^2 + a1\times)*x)^x)));

sage: restore('x')

sage: SR(p).horner(x)
((((a4\times + a3)*x + a2)*x + a1)*x + a0)*x

sage: # (NO) Convert the result of problem 127 to Fortran syntax.

sage: # CForm(Horner(p, x));

sage: # (YES) Verify that True And False=False.

sage: (True and False) is False
True

sage: # (YES) Prove x Or Not x.

sage: for x in [True, False]:
    ....:     print(x or (not x))

True
True

sage: # (YES) Prove x Or y Or x And y=>x Or y.

sage: for x in [True, False]:
    ....:     for y in [True, False]:
    ....:         if x or y or x and y:
    ....:             if not (x or y):
    ....:                 print("failed!")

2.19. Further examples from Wester's paper
2.20 Solving ordinary differential equations

This file contains functions useful for solving differential equations which occur commonly in a 1st semester differential equations course. For another numerical solver see the `ode_solver()` function and the optional package Octave.

Solutions from the Maxima package can contain the three constants \( _C, _K1, \) and \( _K2 \) where the underscore is used to distinguish them from symbolic variables that the user might have used. You can substitute values for them, and make them into accessible usable symbolic variables, for example with `var("_C")`.

Commands:

- `desolve()` - Compute the “general solution” to a 1st or 2nd order ODE via Maxima.
- `desolve_laplace()` - Solve an ODE using Laplace transforms via Maxima. Initial conditions are optional.
- `desolve_rk4()` - Solve numerically an IVP for one first order equation, return list of points or plot.
- `desolve_system_rk4()` - Solve numerically an IVP for a system of first order equations, return list of points.
- `desolve_odeint()` - Solve numerically a system of first-order ordinary differential equations using `odeint` from scipy.integrate module.
- `desolve_system()` - Solve a system of 1st order ODEs of any size using Maxima. Initial conditions are optional.
- `eulers_method()` - Approximate solution to a 1st order DE, presented as a table.
- `eulers_method_2x2()` - Approximate solution to a 1st order system of DEs, presented as a table.
- `eulers_method_2x2_plot()` - Plot the sequence of points obtained from Euler’s method.

The following functions require the optional package `tides`:

- `desolve_mintides()` - Numerical solution of a system of 1st order ODEs via the Taylor series integrator method implemented in TIDES.
- `desolve_tides_mpfr()` - Arbitrary precision Taylor series integrator implemented in TIDES.

AUTHORS:

- David Joyner (3-2006) - Initial version of functions
- Marshall Hampton (7-2007) - Creation of Python module and testing
- Robert Marik (10-2009) - Some bugfixes and enhancements
- Miguel Marco (06-2014) - Tides desolvers

```python
sage.calculus.desolvers.desolve(de, dvar, ics=None, ivar=None, show_method=False, contrib_ode=False, algorithm='maxima')
```

Solve a 1st or 2nd order linear ODE, including IVP and BVP.

INPUT:

- `de` – an expression or equation representing the ODE
- `dvar` – the dependent variable (hereafter called `y`)
- `ics` – (optional) the initial or boundary conditions
  - for a first-order equation, specify the initial `x` and `y`
  - for a second-order equation, specify the initial `x`, `y`, and `dy/dx`, i.e. write \([x_0, y(x_0), y'(x_0)]\)
– for a second-order boundary solution, specify initial and final \( x \) and \( y \) boundary conditions, i.e. write \([x_0, y(x_0), x_1, y(x_1)]\).

– gives an error if the solution is not SymbolicEquation (as happens for example for a Clairaut equation)

• \( \text{ivar} \) – (optional) the independent variable (hereafter called \( x \)), which must be specified if there is more than one independent variable in the equation

• \( \text{show\_method} \) – (optional) if True, then Sage returns pair \([\text{solution}, \text{method}]\), where method is the string describing the method which has been used to get a solution (Maxima uses the following order for first order equations: linear, separable, exact (including exact with integrating factor), homogeneous, bernoulli, generalized homogeneous) - use carefully in class, see below the example of an equation which is separable but this property is not recognized by Maxima and the equation is solved as exact.

• \( \text{contrib\_ode} \) – (optional) if True, desolve allows to solve Clairaut, Lagrange, Riccati and some other equations. This may take a long time and is thus turned off by default. Initial conditions can be used only if the result is one SymbolicEquation (does not contain a singular solution, for example).

• \( \text{algorithm} \) – (default: 'maxima') one of
  - 'maxima' - use maxima
  - 'fricas' - use FriCAS (the optional fricas spkg has to be installed)

OUTPUT:

In most cases return a SymbolicEquation which defines the solution implicitly. If the result is in the form \( y(x) = \ldots \) (happens for linear eqs.), return the right-hand side only. The possible constant solutions of separable ODEs are omitted.

Note: Use desolve? <tab> if the output in the Sage notebook is truncated.

EXAMPLES:

```sage
sage: x = var('x')
sage: y = function('y')(x)
sage: desolve(diff(y,x) + y - 1, y)
(_C + e^x)*e^(-x)
```

```sage
sage: f = desolve(diff(y,x) + y - 1, y, ics=[10,2]); f
(e^10 + e^x)*e^(-x)
```

```sage
sage: plot(f)
Graphics object consisting of 1 graphics primitive
```

We can also solve second-order differential equations:

```sage
sage: x = var('x')
sage: y = function('y')(x)
sage: de = diff(y,x,2) - y == x
sage: desolve(de, y)
_K2*e^(-x) + _K1*e^x - x
```

```sage
sage: f = desolve(de, y, [10,2,1]); f
-x + 7*e^(x - 10) + 5*e^(-x + 10)
```

```sage
sage: f(x=10)
2
```
\texttt{sage}: \texttt{diff(f,x)(x=10)}
\begin{verbatim}
1
\end{verbatim}

\texttt{sage}: \texttt{de = diff(y,x,2) + y == 0}
\texttt{sage}: \texttt{desolve(de, y)}
\begin{verbatim}
_K2*cos(x) + _K1*sin(x)
\end{verbatim}

\texttt{sage}: \texttt{desolve(de, y, [0,1,pi/2,4])}
\begin{verbatim}
cos(x) + 4*sin(x)
\end{verbatim}

\texttt{sage}: \texttt{desolve(y*diff(y,x)+sin(x)==0,y)}
\begin{verbatim}
-1/2*y(x)^2 == _C - cos(x)
\end{verbatim}

Clairaut equation: general and singular solutions:
\texttt{sage}: \texttt{desolve(diff(y,x)^2+x*diff(y,x)-y==0,y,contrib_ode=True,show_method=True)}
\begin{verbatim}
[[y(x) == _C^2 + _C*x, y(x) == -1/4*x^2], 'clairault']
\end{verbatim}

For equations involving more variables we specify an independent variable:
\texttt{sage}: \texttt{a,b,c,n=var('a b c n')}  
\texttt{sage}: \texttt{desolve(x^2*diff(y,x)==a+b*x^n+c*x^2*y^2,y,ivar=x,contrib_ode=True)}
\begin{verbatim}
[[y(x) == 0, (b*x^(n - 2) + a/x^2)*c^2*u == 0], 'riccati']
\end{verbatim}

Higher order equations, not involving independent variable:
\texttt{sage}: \texttt{desolve(diff(y,x,2)+y*(diff(y,x,1))^3==0,y).expand()}
\begin{verbatim}
1/6*y(x)^3 + _K1*y(x) == _K2 + x
\end{verbatim}

Separable equations - Sage returns solution in implicit form:
\texttt{sage}: \texttt{desolve(diff(y,x)*sin(y) == cos(x),y)}
\begin{verbatim}
-cos(y(x)) == _C + sin(x)
\end{verbatim}

Linear equation - Sage returns the expression on the right hand side only:
\texttt{sage}: \texttt{desolve(diff(y,x)+(y) == cos(x),y)}
\begin{verbatim}
1/2*(((cos(x) + sin(x))*e^x + 2*_C)*e^(-x)
\end{verbatim}
This ODE with separated variables is solved as exact. Explanation - factor does not split $e^x-y$ in Maxima into $e^x e^y$:

```
sage: desolve(diff(y,x)==exp(x-y),y,show_method=True) [-e^x + e^y(x) == _C, 'exact']
```

You can solve Bessel equations, also using initial conditions, but you cannot put (sometimes desired) the initial condition at $x = 0$, since this point is a singular point of the equation. Anyway, if the solution should be bounded at $x = 0$, then $\_K2=0$.

```
sage: desolve(x^2*diff(y,x,x)+x*diff(y,x)+(x^2-4)*y==0,y) \_K1*bessel_J(2, x) + \_K2*bessel_Y(2, x)
```

Example of difficult ODE producing an error:

```
sage: desolve(sqrt(y)*diff(y,x)+e^(y)+cos(x)-sin(x+y)==0,y) # not tested
Traceback (click to the left for traceback)
...
NotImplementedError, "Maxima was unable to solve this ODE. Consider to set option contrib_ode to True."
```

Another difficult ODE with error - moreover, it takes a long time:

```
sage: desolve(sqrt(y)*diff(y,x)+e^(y)+cos(x)-sin(x+y)==0,y,contrib_ode=True) # not tested
```

Some more types of ODEs:

```
sage: desolve(x*diff(y,x)^2-(1+x*y)*diff(y,x)+y==0,y,contrib_ode=True,show_method=True)
[[y(x) == \_C + log(x), y(x) == \_C*e^x], 'factor']
```

These two examples produce an error (as expected, Maxima 5.18 cannot solve equations from initial conditions). Maxima 5.18 returns false answer in this case!

```
sage: desolve(diff(y,x,2)+y*(diff(y,x,1))^3==0,y,[0,1,2]).expand() # not tested
Traceback (click to the left for traceback)
...
NotImplementedError, "Maxima was unable to solve this ODE. Consider to set option contrib_ode to True."
```

(continues on next page)
Second order linear ODE:

\[
\begin{align*}
\text{sage: } & \text{desolve(diff(y,x,2)+2*diff(y,x)+y == cos(x),y)} \\
& (_K2*x + _K1) e^{-x} + 1/2*\sin(x)
\end{align*}
\]

\[
\begin{align*}
\text{sage: } & \text{desolve(diff(y,x,2)+2*diff(y,x)+y == cos(x),y,show_method=True)} \\
& [(_K2*x + _K1)*e^{-x} + 1/2*\sin(x), 'variationofparameters']
\end{align*}
\]

\[
\begin{align*}
\text{sage: } & \text{desolve(diff(y,x,2)+2*diff(y,x)+y == cos(x),y,[0,3,1])} \\
& 1/2*(7*x + 6)*e^{-x} + 1/2*\sin(x)
\end{align*}
\]

\[
\begin{align*}
\text{sage: } & \text{desolve(diff(y,x,2)+2*diff(y,x)+y == cos(x),y,[0,3,pi/2,2],show_method=True)} \\
& [3*(x*(e^{(1/2*pi) - 2})/pi + 1)*e^{-x} + 1/2*\sin(x), 'variationofparameters']
\end{align*}
\]

\[
\begin{align*}
\text{sage: } & \text{desolve(diff(y,x,2)+2*diff(y,x)+y == 0,y)} \\
& (_K2*x + _K1)*e^{-x}
\end{align*}
\]

\[
\begin{align*}
\text{sage: } & \text{desolve(diff(y,x,2)+2*diff(y,x)+y == 0,y,show_method=True)} \\
& [(_K2*x + _K1)*e^{-x}, 'constcoeff']
\end{align*}
\]

\[
\begin{align*}
\text{sage: } & \text{desolve(diff(y,x,2)+2*diff(y,x)+y == 0,y,[0,3,1])} \\
& (4*x + 3)*e^{-x}
\end{align*}
\]

\[
\begin{align*}
\text{sage: } & \text{desolve(diff(y,x,2)+2*diff(y,x)+y == 0,y,[0,3,pi/2,2],show_method=True)} \\
& [(2*x*(2*e^{(1/2*pi) - 3})/pi + 3)*e^{-x}, 'constcoeff']
\end{align*}
\]

Using \texttt{algorithm='fricas'} we can invoke the differential equation solver from FriCAS. For example, it can solve higher order linear equations:

\[
\begin{align*}
\text{sage: } & \text{de} = x^3*\text{diff}(y, x, 3) + x^2*\text{diff}(y, x, 2) - 2*x*\text{diff}(y, x, 2) + 2*y - 2*x^4 \\
\text{sage: } & \text{Y = desolve(de, y, algorithm='fricas'); Y} \quad \# \text{optional - fricas} \\
& (2*x^3 - 3*x^2 + 2)*_C0/x + (x^3 - 1)*_C1/x \\
& + (x^3 - 3*x^2 - 1)*_C2/x + 1/15*(x^5 - 10*x^3 + 20*x^2 + 4)/x
\end{align*}
\]

The initial conditions are then interpreted as \([x_0,y(x_0),y'(x_0),\ldots,y^{(n)}(x_0)]\):

\[
\begin{align*}
\text{sage: } & \text{Y = desolve(de, y, ics=[1,3,7], algorithm='fricas'); Y} \quad \# \text{optional - fricas} \\
& 1/15*(x^5 + 15*x^3 + 50*x^2 + 21)/x
\end{align*}
\]
FriCAS can also solve some non-linear equations:

```
sage: de = diff(y, x) == y / (x+y*log(y))
sage: Y = desolve(de, y, algorithm="fricas"); Y
1/2*(log(y(x))^2*y(x) - 2*x)/y(x)
```

AUTHORS:

- David Joyner (1-2006)
- Robert Bradshaw (10-2008)
- Robert Marik (10-2009)

`sage.calculus.desolvers.desolve_laplace(de, dvar, ics=None, ivar=None)`

Solve an ODE using Laplace transforms. Initial conditions are optional.

**INPUT:**

- `de` - a lambda expression representing the ODE (e.g. `de = diff(y, x, 2) == diff(y, x)+sin(x)`)  
- `dvar` - the dependent variable (e.g. `y`)  
- `ivar` - (optional) the independent variable (hereafter called `x`), which must be specified if there is more than one independent variable in the equation.  
- `ics` - a list of numbers representing initial conditions, (e.g. `f(0)=1, f'(0)=2` corresponds to `ics = [0,1,2]`)  

**OUTPUT:**

Solution of the ODE as symbolic expression

**EXAMPLES:**

```
sage: u=function('u')(x)
sage: eq = diff(u,x) - exp(-x) - u == 0
sage: desolve_laplace(eq,u)
1/2*(2*u(0) + 1)*e^x - 1/2*e^(-x)
```

We can use initial conditions:

```
sage: desolve_laplace(eq,u,ics=[0,3])
-1/2*e^(-x) + 7/2*e^x
```

The initial conditions do not persist in the system (as they persisted in previous versions):

```
sage: desolve_laplace(eq,u)
1/2*(2*u(0) + 1)*e^x - 1/2*e^(-x)
```

```
sage: f=function('f')(x)
sage: eq = diff(f,x) + f == 0
sage: desolve_laplace(eq,f,[0,1])
e^(-x)
```

```
sage: x = var('x')
sage: f = function('f')(x)
sage: de = diff(f,x,x) - 2*diff(f,x) + f
sage: desolve_laplace(de,f)
-x*e^x*f(0) + x*e^x*D[0](f)(0) + e^x*f(0)
```

2.20. Solving ordinary differential equations 269
sage: desolve_laplace(de, f, ics=[0, 1, 2])
x*e^x + e^x

AUTHORS:
• David Joyner (1-2006,8-2007)
• Robert Marik (10-2009)

sage.calculus.desolvers.desolve_mintides(f, ics, initial, final, delta, tolrel=1e-16, tolabs=1e-16)
Solve numerically a system of first order differential equations using the taylor series integrator implemented in mintides.

INPUT:
• f – symbolic function. Its first argument will be the independent variable. Its output should be de derivatives of the dependent variables.
• ics – a list or tuple with the initial conditions.
• initial – the starting value for the independent variable.
• final – the final value for the independent value.
• delta – the size of the steps in the output.
• tolrel – the relative tolerance for the method.
• tolabs – the absolute tolerance for the method.

OUTPUT:
• A list with the positions of the IVP.

EXAMPLES:
We integrate a periodic orbit of the Kepler problem along 50 periods:

sage: var('t,x,y,X,Y')
t, x, y, X, Y
sage: f(t,x,y,X,Y)=[X, Y, -x/(x^2+y^2)^(3/2), -y/(x^2+y^2)^(3/2)]
sage: ics = [0.8, 0, 0, 1.22474487139159]
sage: t = 100*pi
sage: sol = desolve_mintides(f, ics, 0, t, t, 1e-12, 1e-12)
   # optional -tides
sage: sol
   # optional -tides # abs tol 1e-5
[[0.000000000000000, 0.800000000000000, 0.000000000000000, 0.000000000000000, 1.22474487139159],
 [314.159265358979, 0.800000000000000, -5.91973525754241e-9, 7.56887091890590e-9, 1.22474487136329]]

ALGORITHM:
Uses TIDES.

REFERENCES:


```
sage.calculus.desolvers.desolve_odeint(des, ics, times, dvars, ivar=None, compute_jac=False, args=(), atol=None, rtol=None, tcrit=None, h0=0.0, hmax=0.0, hmin=0.0, ixpr=0, mxstep=0, mxhnil=0, mxordn=12, mxords=5, printmessg=0)
```

Solve numerically a system of first-order ordinary differential equations using `odeint` from `scipy.integrate` module.

**INPUT:**
- `des` – right hand sides of the system
- `ics` – initial conditions
- `times` – a sequence of time points in which the solution must be found
- `dvars` – dependent variables. ATTENTION: the order must be the same as in `des`, that means: 
  \[ \frac{d(dvars[i])}{dt} = des[i] \]
- `ivar` – independent variable, optional.
- `compute_jac` – boolean. If True, the Jacobian of `des` is computed and used during the integration of Stiff Systems. Default value is False.

**Other Parameters** (taken from the documentation of `odeint` function from `scipy.integrate` module.)
- `rtol, atol` : float The input parameters `rtol` and `atol` determine the error control performed by the solver. The solver will control the vector, `e`, of estimated local errors in `y`, according to an inequality of the form:
  \[ \text{max-norm of } (e / ewt) \leq 1 \]
  where `ewt` is a vector of positive error weights computed as:
  \[ \text{ewt} = rtol \times \text{abs}(y) + atol \]
  `rtol` and `atol` can be either vectors the same length as `y` or scalars.
- `tcrit` : array Vector of critical points (e.g. singularities) where integration care should be taken.
- `h0` : float, (0: solver-determined) The step size to be attempted on the first step.
- `hmax` : float, (0: solver-determined) The maximum absolute step size allowed.
- `hmin` : float, (0: solver-determined) The minimum absolute step size allowed.
- `ixpr` : boolean. Whether to generate extra printing at method switches.
- `mxstep` : integer, (0: solver-determined) Maximum number of (internally defined) steps allowed for each integration point in `t`.
- `mxhnil` : integer, (0: solver-determined) Maximum number of messages printed.
- `mxordn` : integer, (0: solver-determined) Maximum order to be allowed for the nonstiff (Adams) method.
- `mxords` : integer, (0: solver-determined) Maximum order to be allowed for the stiff (BDF) method.

**OUTPUT:**
Return a list with the solution of the system at each time in `times`.

**EXAMPLES:**

2.20. Solving ordinary differential equations
Lotka Volterra Equations:

```python
sage: from sage.calculus.desolvers import desolve_odeint
sage: x,y=var('x,y')
sage: f=[x*(1-y),-y*(1-x)]
sage: sol=desolve_odeint(f,[0.5,2],srange(0,10,0.1),[x,y])
sage: p=line(zip(sol[:,0],sol[:,1]))
sage: p.show()
```

Lorenz Equations:

```python
sage: x,y,z=var('x,y,z')
sage: # Next we define the parameters
sage: sigma=10
sage: rho=28
sage: beta=8/3
sage: # The Lorenz equations
sage: lorenz=[sigma*(y-x),x*(rho-z)-y,x*y-beta*z]  
```

```python
sage: # Time and initial conditions
sage: times=srange(0,50.05,0.05)
```

```python
sage: ics=[0,1,1]
sage: sol=desolve_odeint(lorenz,ics,times,[x,y,z],rtol=1e-13,atol=1e-14)
```

One-dimensional Stiff system:

```python
sage: y= var('y')
sage: epsilon=0.01
sage: f=y^2*(1-y)
sage: ic=epsilon
sage: t=srange(0,2/epsilon,1)
```

```python
sage: sol=desolve_odeint(f,ic,t,y,rtol=1e-9,atol=1e-10,compute_jac=True)
sage: p=points(zip(t,sol))
sage: p.show()
```

Another Stiff system with some optional parameters with no default value:

```python
sage: y1,y2,y3=var('y1,y2,y3')
sage: f1=77.27*(y2+y1*(1-8.375*1e-6*y1-y2))
sage: f2=1/77.27*(y3-(1+y1)*y2)
sage: f3=0.16*(y1-y3)
sage: f=[f1,f2,f3]
sage: ci=[0.2,0.4,0.7]
sage: t=srange(0,10,0.01)
sage: v=[y1,y2,y3]
```

```python
sage: sol=desolve_odeint(f,ci,t,v,rtol=1e-3,atol=1e-4,h0=0.1,hmax=1,hmin=1e-4,  
\hspace{1cm} mxstep=1000,mxords=17)
```

AUTHOR:

- Oriol Castejon (05-2010)

sage.calculus.desolvers.desolve_rk4(de, dvar, ics=None, ivar=None, end_points=None, step=0.1, output='list', **kwds)

Solve numerically one first-order ordinary differential equation.

**INPUT:**

Input is similar to desolve command. The differential equation can be written in a form close to the `plot_slope_field` or `desolve` command.
**Variant 1 (function in two variables)**
- `de` - right hand side, i.e. the function $f(x, y)$ from ODE $y' = f(x, y)$
- `dvar` - dependent variable (symbolic variable declared by `var`)

**Variant 2 (symbolic equation)**
- `de` - equation, including term with `diff(y,x)`
- `dvar` - dependent variable (declared as function of independent variable)

**Other parameters**
- `ivar` - should be specified, if there are more variables or if the equation is autonomous
- `ics` - initial conditions in the form $[x_0, y_0]$
- `end_points` - the end points of the interval
  * if `end_points` is a or $[a]$, we integrate between $\min(ics[0], a)$ and $\max(ics[0], a)$
  * if `end_points` is None, we use `end_points=ics[0]+10`
  * if `end_points` is $[a, b]$ we integrate between $\min(ics[0], a)$ and $\max(ics[0], b)$
- `step` - (optional, default: 0.1) the length of the step (positive number)
- `output` - (optional, default: 'list') one of 'list', 'plot', 'slope_field' (graph of the solution with slope field)

**OUTPUT:**
Return a list of points, or plot produced by `list_plot`, optionally with slope field.

**See also:**
`ode_solver()`.

**EXAMPLES:**

```sage
sage: from sage.calculus.desolvers import desolve_rk4
```

**Variant 2 for input - more common in numerics:**

```sage
sage: x, y = var('x, y')
sage: desolve_rk4(x*y*(2-y), y, ics=[0,1], end_points=1, step=0.5)
[[0, 1], [0.5, 1.12419127424558], [1.0, 1.461590162288825]]
```

**Variant 1 for input - we can pass ODE in the form used by desolve function. In this example we integrate backwards, since end_points < ics[0]:**

```sage
sage: y = function('y')(x)
sage: desolve_rk4(diff(y,x)+y*(y-1) == x-2, y, ics=[1,1], step=0.5, end_points=0)
[[0.0, 8.904257108962112], [0.5, 1.909327945361535], [1, 1]]
```

Here we show how to plot simple pictures. For more advanced applications use `list_plot` instead. To see the resulting picture use `show(P)` in Sage notebook.

```sage
sage: x, y = var('x, y')
sage: P = desolve_rk4(y*(2-y), y, ics=[0,.1], ivar=x, output='slope_field', end_points=[-→4,6], thickness=3)
```
ALGORITHM:

4th order Runge-Kutta method. Wrapper for command \texttt{rk} in Maxima’s dynamics package. Perhaps could be faster by using \texttt{fast_float} instead.

AUTHORS:

• Robert Marik (10-2009)

\texttt{sage.calculus.desolvers.desolve_rk4_determine_bounds}(ics, end_points=\texttt{None})

Used to determine bounds for numerical integration.

• If end_points is None, the interval for integration is from \texttt{ics[0]} to \texttt{ics[0]+10}
• If end_points is \texttt{a} or \texttt{[a]}, the interval for integration is from \texttt{min(ics[0],a)} to \texttt{max(ics[0],a)}
• If end_points is \texttt{[a,b]}, the interval for integration is from \texttt{min(ics[0],a)} to \texttt{max(ics[0],b)}

EXAMPLES:

\begin{verbatim}
sage: from sage.calculus.desolvers import desolve_rk4_determine_bounds
desolve_rk4_determine_bounds([0,2],1)
(0, 1)
sage: desolve_rk4_determine_bounds([0,2])
(0, 10)
sage: desolve_rk4_determine_bounds([0,2],[-2])
(-2, 0)
sage: desolve_rk4_determine_bounds([0,2],[-2,4])
(-2, 4)
\end{verbatim}

\texttt{sage.calculus.desolvers.desolve_system}(des, vars, ics=\texttt{None}, ivar=\texttt{None}, algorithm=\texttt{'maxima'})

Solve a system of any size of 1st order ODEs. Initial conditions are optional.

One dimensional systems are passed to \texttt{desolve_laplace()}.

INPUT:

• \texttt{des} – list of ODEs
• \texttt{vars} – list of dependent variables
• \texttt{ics} – (optional) list of initial values for ivar and vars; if ics is defined, it should provide initial conditions for each variable, otherwise an exception would be raised
• \texttt{ivar} – (optional) the independent variable, which must be specified if there is more than one independent variable in the equation
• \texttt{algorithm} – (default: 'maxima') one of
  • 'maxima' - use maxima
  • 'fricas' - use FriCAS (the optional fricas spkg has to be installed)

EXAMPLES:

\begin{verbatim}
sage: t = var('t')
sage: x = function('x')(t)
sage: y = function('y')(t)
\end{verbatim}
The same system solved using FriCAS:

```plaintext
sage: desolve_system([de1, de2], [x,y], algorithm='fricas')  # optional - fricas
[x(t) == -C0*cos(t) + cos(t)^2 + C1*sin(t) + sin(t)^2,
 y(t) == -C1*cos(t) + C0*sin(t) + 1]
```

Now we give some initial conditions:

```plaintext
sage: sol = desolve_system([de1, de2], [x,y], ics=[0,1,2]); sol
[x(t) == -sin(t) + 1, y(t) == cos(t) + 1]
```

```plaintext
sage: solnx, solny = sol[0].rhs(), sol[1].rhs()
sage: plot([solnx,solny],(0,1))  # not tested
sage: parametric_plot((solnx,solny),(0,1))  # not tested
```

**AUTHORS:**
- Robert Bradshaw (10-2008)
- Sergey Bykov (10-2014)

`sage.calculus.desolvers.desolve_system_rk4(des, vars, ics=None, ivar=None, end_points=None, step=0.1)`

Solve numerically a system of first-order ordinary differential equations using the 4th order Runge-Kutta method. Wrapper for Maxima command `rk`.

**INPUT:**

input is similar to `desolve_system` and `desolve_rk4` commands

- `des` - right hand sides of the system
- `vars` - dependent variables
- `ivar` - (optional) should be specified, if there are more variables or if the equation is autonomous and the independent variable is missing
- `ics` - initial conditions in the form `[x0,y01,y02,y03,...]`
- `end_points` - the end points of the interval
  - if `end_points` is a or `[a]`, we integrate on between `min(ics[0], a)` and `max(ics[0], a)`
  - if `end_points` is `None`, we use `end_points=ics[0]+10`
  - if `end_points` is `[a,b]` we integrate on between `min(ics[0], a)` and `max(ics[0], b)`
- `step` - (optional, default: 0.1) the length of the step

**OUTPUT:**

Return a list of points.

**See also:**

`ode_solver()`.

**EXAMPLES:**
sage: from sage.calculus.desolvers import desolve_system_rk4

Lotka Volterra system:

sage: from sage.calculus.desolvers import desolve_system_rk4
sage: x,y,t=var('x y t')

sage: P=desolve_system_rk4([x*(1-y),-y*(1-x)],[x,y],ics=[0,0.5,2],ivar=t,end_points=20)

sage: Q=[[i,j] for i,j,k in P]

sage: LP=list_plot(Q)

sage: Q=[[j,k] for i,j,k in P]

sage: LP=list_plot(Q)

ALGORITHM:

4th order Runge-Kutta method. Wrapper for command rk in Maxima’s dynamics package. Perhaps could be faster by using fast_float instead.

AUTHOR:

• Robert Marik (10-2009)

sage.calculus.desolvers.desolve_tides_mpfr(f, ics, initial, final, delta, tolrel=1e-16, tolabs=1e-16, digits=50)

Solve numerically a system of first order differential equations using the taylor series integrator in arbitrary precision implemented in tides.

INPUT:

• $f$ – symbolic function. Its first argument will be the independent variable. Its output should be the derivatives of the dependent variables.

• ics – a list or tuple with the initial conditions.

• initial – the starting value for the independent variable.

• final – the final value for the independent value.

• delta – the size of the steps in the output.

• tolrel – the relative tolerance for the method.

• tolabs – the absolute tolerance for the method.

• digits – the digits of precision used in the computation.

OUTPUT:

• A list with the positions of the IVP.

EXAMPLES:

We integrate the Lorenz equations with Salztman values for the parameters along 10 periodic orbits with 100 digits of precision:

sage: var('t,x,y,z')
(t, x, y, z)
sage: s = 10
sage: r = 28
sage: b = 8/3
sage: f(t,x,y,z)=[s*(y-x),x*(r-z)-y,x*y-b*z]
sage: x0 = -13.

(continues on next page)
sage: y0 = -19.
sage: z0 = 27
sage: T = 15.

\[
\begin{align*}
\text{sage: } \text{sol} &= \text{desolve_tides_mpfr}(f, [x0, y0, z0], 0 , T, T, 1e-100, 1e-100, 100) \\
\text{sage: } \text{sol} &= \left[0.000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000, -13.76361068213420052501401054361538641008648540923684535378642921202827747268115852940239346395139.5787519425179553883804144600955886611424005342764386497913342954263547461475264197316550670426.999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999999\right]
\end{align*}
\]

ALGORITHM:
Uses TIDES.

**Warning:** This requires the package tides.

REFERENCES:

- [ABBR2011]
- [ABBR2012]

\[\text{sage.calculus.desolvers.eulers_method}(f, x0, y0, h, +x1, algorithm='table')\]

This implements Euler’s method for finding numerically the solution of the 1st order ODE \( y' = f(x, y), y(a) = c \). The \( x \) column of the table increments from \( x_0 \) to \( x_1 \) by \( h \) (so \( (x_1 - x_0)/h \) must be an integer). In the \( y \) column, the new \( y \)-value equals the old \( y \)-value plus the corresponding entry in the last column.

**Note:** This function is for pedagogical purposes only.

EXAMPLES:
```python
sage: from sage.calculus.desolvers import eulers_method
sage: x, y = PolynomialRing(QQ, 2, "xy").gens()
sage: eulers_method(5*x+y-5, 0, 1, 1/2, 1)
\[
\begin{array}{ccc}
x & y & \text{h} \cdot f(x, y) \\
0 & 1 & -2 \\
1/2 & -1 & -7/4 \\
1 & -11/4 & -11/8 \\
\end{array}
\]

sage: x, y = PolynomialRing(QQ, 2, "xy").gens()
sage: eulers_method(5*x+y-5, 0, 1, 1/2, 1, algorithm="none")
\[
[[0, 1], [1/2, -1], [1, -11/4], [3/2, -33/8]]
\]

sage: RR = RealField(sci_not=0, prec=4, rnd='RNDU')
sage: x, y = PolynomialRing(RR, 2, "xy").gens()
sage: eulers_method(5*x+y-5, 0, 1, 1/2, 1, algorithm="None")
\[
[[0, 1], [1/2, -1.0], [1, -2.7], [3/2, -4.0]]
\]

sage: RR = RealField(sci_not=0, prec=4, rnd='RNDU')
sage: x, y = PolynomialRing(RR, 2, "xy").gens()
sage: eulers_method(5*x+y-5, 0, 1, 1/2, 1)
\[
\begin{array}{ccc}
x & y & \text{h} \cdot f(x, y) \\
0 & 1 & -2.0 \\
1/2 & -1.0 & -1.7 \\
1 & -2.7 & -1.3 \\
\end{array}
\]

sage: x, y = PolynomialRing(QQ, 2, "xy").gens()
sage: eulers_method(5*x+y-5, 1, 1, 1/3, 2)
\[
\begin{array}{ccc}
x & y & \text{h} \cdot f(x, y) \\
1 & 1 & 1/3 \\
4/3 & 4/3 & 1 \\
5/3 & 7/3 & 17/9 \\
2 & 38/9 & 83/27 \\
\end{array}
\]

sage: eulers_method(5*x+y-5, 0, 1, 1/2, 1, algorithm="none")
\[
[[0, 1], [1/2, -1], [1, -11/4], [3/2, -33/8]]
\]

sage: pts = eulers_method(5*x+y-5, 0, 1, 1/2, 1, algorithm="none")
sage: P1 = list_plot(pts)
sage: P2 = line(pts)
sage: (P1+P2).show()
```

AUTHORS:

- David Joyner

`sage.calculus.desolvers.eulers_method_2x2 (f, g, t0, x0, y0, h, t1, algorithm='table')`

This implements Euler’s method for finding numerically the solution of the 1st order system of two ODEs

\[
x' = f(t, x, y), x(t_0) = x_0 \\
y' = g(t, x, y), y(t_0) = y_0.
\]

The t column of the table increments from \(t_0\) to \(t_1\) by \(h\) (so \(\frac{t_1-t_0}{h}\) must be an integer). In the x column, the new x-value equals the old x-value plus the corresponding entry in the next (third) column. In the y column, the new y-value equals the old y-value plus the corresponding entry in the next (last) column.
Note: This function is for pedagogical purposes only.

EXAMPLES:

```python
sage: from sage.calculus.desolvers import eulers_method_2x2
sage: t, x, y = PolynomialRing(QQ, 3, "txy").gens()

sage: f = x*y+t; g = x-y
eulers_method_2x2(f, g, 0, 0, 0, 1/3, 1, algorithm="none")
[[0, 0, 0], [1/3, 0, 0], [2/3, 1/9, 0], [1, 10/27, 1/27], [4/3, 68/81, 4/27]]

sage: eulers_method_2x2(f, g, 0, 0, 0, 1/3, 1)

t   x   h   f(t, x, y)   y
 0   0   0   0
1/3 0   0   1/9   0
2/3 1/9 7/27 0
1 10/27 38/81 1/27

sage: RR = RealField(sci_not=0, prec=4, rnd='RNDU')
sage: t, x, y = PolynomialRing(RR, 3, "txy").gens()

sage: f = x+y+t; g = x-y
eulers_method_2x2(f, g, 0, 0, 0, 1/3, 1)

t   x   h   f(t, x, y)   y
 0   0   0.00 0.00 0
1/3 0.00 0.13 0.00
2/3 0.13 0.29 0.00
1 0.41 0.57 0.043

To numerically approximate \( y(1) \), where \((1 + t^2)y'' + y' - y = 0, y(0) = 1, y'(0) = -1,\) using 4 steps of Euler’s method, first convert to a system: \( y'_1 = y_2, y_1(0) = 1; \ y'_2 = \frac{y_1-1}{1+t^2}, \ y_2(0) = -1.\):

```
sage: RR = RealField(sci_not=0, prec=4, rnd='RNDU')
sage: t, x, y = PolynomialRing(RR, 3, "txy").gens()
sage: f = x; g = (x-y)/(1+t^2)
eulers_method_2x2(f, g, 0, 0, 1/4, 1)
 0 0.50 1 -0.25 -1
1/4 0.75 -0.12 -0.50
1/2 0.63 -0.054 -0.21
3/4 0.63 -0.0078 -0.031
1 0.63 0.020 0.079
```

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To numerically approximate \( y(1) \), where \( y'' + ty' + y = 0 \), \( y(0) = 1 \), \( y'(0) = 0 \):

```python
t, x, y = PolynomialRing(RR, 3, "txy").gens()
f = y; g = -x - y * t
eulers_method_2x2(f, g, 0, 1, 0, 1/4, 1)
```

<table>
<thead>
<tr>
<th>( t )</th>
<th>( x )</th>
<th>( h )</th>
<th>( f(t, x, y) )</th>
<th>( y )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>0.00</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>1/4</td>
<td>-0.25</td>
<td>-0.062</td>
<td>-0.25</td>
<td></td>
</tr>
<tr>
<td>1/2</td>
<td>-0.23</td>
<td>-0.11</td>
<td>-0.46</td>
<td></td>
</tr>
<tr>
<td>3/4</td>
<td>-0.17</td>
<td>-0.15</td>
<td>-0.62</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>-0.10</td>
<td>-0.17</td>
<td>-0.68</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-0.015</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**AUTHORS:**

- David Joyner

**Note:** This function is for pedagogical purposes only.

**EXAMPLES:**

The following example plots the solution to \( \theta'' + \sin(\theta) = 0 \), \( \theta(0) = \frac{\pi}{4} \), \( \theta'(0) = 0 \). Type \( P[0].show() \) to plot the solution, \( (P[0]+P[1]).show() \) to plot \((t, \theta(t))\) and \((t, \theta'(t))\):

```python
from sage.calculus.desolvers import eulers_method_2x2_plot
f = lambda z : z[2]; g = lambda z : -sin(z[1])
P = eulers_method_2x2_plot(f, g, 0.0, 0.75, 0.0, 0.1, 1.0)
```

**Note:** This function is for pedagogical purposes only.

```python
sage: t = var('t')
sage: x = function('x')(t)
sage: y = function('y')(t)
sage: de1 = diff(x,t) + y - 1 == 0
sage: de2 = diff(y,t) - x + 1 == 0
sage: desolve_system([de1, de2], [x, y], algorithm="fricas")  # optional - → fricas
[x(t) == _C0*cos(t) + cos(t)^2 + _C1*sin(t) + sin(t)^2,
y(t) == -_C1*cos(t) + _C0*sin(t) + 1]
sage: desolve_system([de1, de2], [x,y], [0,1,2], algorithm="fricas")  # optional - → fricas
[x(t) == cos(t)^2 + sin(t)^2 - sin(t), y(t) == cos(t) + 1]
```

### 2.21 Discrete Wavelet Transform

Wraps GSL’s `gsl_wavelet_transform_forward()`, and `gsl_wavelet_transform_inverse()` and creates plot methods.

**AUTHOR:**

- Josh Kantor (2006-10-07) - initial version
- David Joyner (2006-10-09) - minor changes to docstrings and examples.

```python
sage.calculus.transforms.dwt.DWT(n, wavelet_type, wavelet_k)
```

This function initializes an GSLDoubleArray of length n which can perform a discrete wavelet transform.

**INPUT:**

- `n` – a power of 2
- `T` – the data in the GSLDoubleArray must be real
- `wavelet_type` – the name of the type of wavelet, valid choices are:
  - 'daubechies'
  - 'daubechies_centered'
  - 'haar'
  - 'haar_centered'
  - 'bspline'
  - 'bspline_centered'

For daubechies wavelets, `wavelet_k` specifies a daubechie wavelet with \( k/2 \) vanishing moments. \( k = 4, 6, \ldots, 20 \) for \( k \) even are the only ones implemented.

For Haar wavelets, `wavelet_k` must be 2.

For bspline wavelets, `wavelet_k` of 103, 105, 202, 204, 206, 208, 301, 305, 307, 309 will give biorthogonal B-spline wavelets of order \( (i, j) \) where `wavelet_k` is \( 100 * i + j \). The wavelet transform uses \( J = \log_2(n) \) levels.

**OUTPUT:**

An array of the form \( (s_{-1,0}, d_{0,0}, d_{1,0}, d_{1,1}, d_{2,0}, \ldots, d_{J-1,2^{J-1}-1}) \) for \( d_{j,k} \) the detail coefficients of level \( j \). The centered forms align the coefficients of the sub-bands on edges.
EXAMPLES:

```python
sage: a = WaveletTransform(128,'daubechies',4)
sage: for i in range(1, 11):
    ....:     a[i] = 1
    ....:     a[128-i] = 1
sage: a.plot().show(ymin=0)
sage: a.forward_transform()
sage: a.plot().show()
sage: a = WaveletTransform(128,'haar',2)
sage: for i in range(1, 11): a[i] = 1; a[128-i] = 1
sage: a.forward_transform()
sage: a.plot().show(ymin=0)
sage: a = WaveletTransform(128,'bspline_centered',103)
sage: for i in range(1, 11): a[i] = 1; a[100+i] = 1
sage: a.forward_transform()
sage: a.plot().show(ymin=0)
```

This example gives a simple example of wavelet compression:

```python
sage: a = DWT(2048,'daubechies',6)
sage: for i in range(2048): a[i]=float(sin((i*5/2048)**2))
sage: a.plot().show()  # long time (7s on sage.math, 2011)
sage: a.forward_transform()
sage: for i in range(1800): a[2048-i-1] = 0
sage: a.backward_transform()
sage: a.plot().show()  # long time (7s on sage.math, 2011)
```

class sage.calculus.transforms.dwt.DiscreteWaveletTransform

Discrete wavelet transform class.

```python
backward_transform()
forward_transform()
plot (xmin=None, xmax=None, **args)
```

```
sage.calculus.transforms.dwt.WaveletTransform(n, wavelet_type, wavelet_k)
```

This function initializes an GSLDoubleArray of length n which can perform a discrete wavelet transform.

**INPUT:**

- n – a power of 2
- T – the data in the GSLDoubleArray must be real
- wavelet_type – the name of the type of wavelet, valid choices are:
  - 'daubechies'
  - 'daubechies_centered'
  - 'haar'
  - 'haar_centered'
  - 'bspline'
  - 'bspline_centered'

For daubechies wavelets, wavelet_k specifies a daubechies wavelet with \( k/2 \) vanishing moments. \( k = 4, 6, \ldots, 20 \) for \( k \) even are the only ones implemented.
For Haar wavelets, \texttt{wavelet\_k} must be 2.

For bspline wavelets, \texttt{wavelet\_k} of 103, 105, 202, 204, 206, 208, 301, 305, 307, 309 will give biorthogonal B-spline wavelets of order \((i, j)\) where \texttt{wavelet\_k} is 100 \(* i + j\). The wavelet transform uses \(J = \log_2(n)\) levels.

**OUTPUT:**

An array of the form \((s_{-1,0}, d_{0,0}, d_{1,0}, d_{1,1}, d_{2,0}, \ldots, d_{J-1,2^J-1})\) for \(d_{j,k}\) the detail coefficients of level \(j\). The centered forms align the coefficients of the sub-bands on edges.

**EXAMPLES:**

```python
sage: a = WaveletTransform(128,'daubechies',4)
sage: for i in range(1, 11):
    a[i] = 1
    a[128-i] = 1
sage: a.plot().show(ymin=0)
sage: a.forward_transform()
sage: a.plot().show()

sage: a = WaveletTransform(128,'haar',2)
sage: for i in range(1, 11): a[i] = 1; a[128-i] = 1
sage: a.forward_transform()
sage: a.plot().show(ymin=0)
sage: a = WaveletTransform(128,'bspline\_centered',103)
sage: for i in range(1, 11): a[i] = 1; a[100+i] = 1
sage: a.forward_transform()
sage: a.plot().show(ymin=0)
```

This example gives a simple example of wavelet compression:

```python
sage: a = DWT(2048,'daubechies',6)
sage: for i in range(2048): a[i]=float(sin((i*5/2048)**2))
sage: a.plot().show() # long time (7s on sage.math, 2011)
sage: a.forward_transform()
sage: for i in range(1800): a[2048-i-1] = 0
sage: a.backward_transform()
sage: a.plot().show() # long time (7s on sage.math, 2011)
```

**2.22 Discrete Fourier Transforms**

This file contains functions useful for computing discrete Fourier transforms and probability distribution functions for discrete random variables for sequences of elements of \(\mathbb{Q}\) or \(\mathbb{C}\), indexed by a \texttt{range(N)}, \(\mathbb{Z}/N\mathbb{Z}\), an abelian group, the conjugacy classes of a permutation group, or the conjugacy classes of a matrix group.

This file implements:

- \texttt{__eq__()}  
- \texttt{__mul__()}  (for right multiplication by a scalar)  
- \texttt{plotting, printing – IndexedSequence.plot(), IndexedSequence.plot_histogram(), _repr_, __str__()}  
- \texttt{dft} – computes the discrete Fourier transform for the following cases:
  - a sequence (over \(\mathbb{Q}\) or \texttt{CyclotomicField}) indexed by \texttt{range(N)} or \(\mathbb{Z}/N\mathbb{Z}\)
– a sequence (as above) indexed by a finite abelian group
– a sequence (as above) indexed by a complete set of representatives of the conjugacy classes of a finite
  permutation group
– a sequence (as above) indexed by a complete set of representatives of the conjugacy classes of a finite
  matrix group

• idft – computes the discrete Fourier transform for the following cases:
  – a sequence (over $\mathbb{Q}$ or CyclotomicField) indexed by $\text{range}(N)$ or $\mathbb{Z}/N\mathbb{Z}$

• dct, dst (for discrete Fourier/Cosine/Sine transform)

• convolution (in $\text{IndexedSequence.convolution()}$ and $\text{IndexedSequence.convolution_periodic()}$)

• fft, ifft – (fast Fourier transforms) wrapping GSL’s $\text{gsl_fft_complex_forward()}$, $\text{gsl_fft_complex_inverse()}$, using William Stein’s $\text{FastFourierTransform()}$

• dwt, idwt – (fast wavelet transforms) wrapping GSL’s $\text{gsl_dwt_forward()}$, $\text{gsl_dwt_backward()}$ using Joshua Kantor’s $\text{WaveletTransform()}$ class. Allows for wavelets of type:
  – “haar”
  – “daubechies”
  – “daubechies_centered”
  – “haar_centered”
  – “bspline”
  – “bspline_centered”

Todo:

• “filtered” DFTs
• more idfts
• more examples for probability, stats, theory of FTs

AUTHORS:

• David Joyner (2006-10)
• William Stein (2006-11) – fix many bugs

class sage.calculus.transforms.dft.IndexedSequence($L$, $\text{index\_object}$)

Bases: sage.structure.sage_object.SageObject

An indexed sequence.

INPUT:

• $L$ – A list
• $\text{index\_object}$ must be a Sage object with an $\text{\_\_iter\_\_}$ method containing the same number of elements as $\text{self}$, which is a list of elements taken from a field.

$\text{base\_ring()}$

This just returns the common parent $R$ of the $N$ list elements. In some applications (say, when computing the discrete Fourier transform, dft), it is more accurate to think of the base_ring as the group ring $\mathbb{Q}(\zeta_N)[R]$. 
EXAMPLES:

```
sage: J = list(range(10))
sage: A = [1/10 for j in J]
sage: s = IndexedSequence(A, J)
sage: s.base_ring()
Rational Field
```

**convolution**(other)
Convolves two sequences of the same length (automatically expands the shortest one by extending it by 0 if they have different lengths).

If \( \{a_n\} \) and \( \{b_n\} \) are sequences indexed by \( (n = 0, 1, ..., N - 1) \), extended by zero for all \( n \) in \( \mathbb{Z} \), then the convolution is

\[
c_j = \sum_{i=0}^{N-1} a_i b_{j-i}.
\]

**INPUT:**

- **other** – a collection of elements of a ring with index set a finite abelian group (under +)

**OUTPUT:**
The Dirichlet convolution of **self** and **other**.

**EXAMPLES:**

```
sage: J = list(range(5))
sage: A = [ZZ(1) for i in J]
sage: B = [ZZ(1) for i in J]
sage: s = IndexedSequence(A, J)
sage: t = IndexedSequence(B, J)
sage: s.convolution(t)
[1, 2, 3, 4, 5, 4, 3, 2, 1]
```

**AUTHOR:** David Joyner (2006-09)

**convolution_periodic**(other)
Convolves two collections indexed by a range(...) of the same length (automatically expands the shortest one by extending it by 0 if they have different lengths).

If \( \{a_n\} \) and \( \{b_n\} \) are sequences indexed by \( (n = 0, 1, ..., N - 1) \), extended periodically for all \( n \) in \( \mathbb{Z} \), then the convolution is

\[
c_j = \sum_{i=0}^{N-1} a_i b_{j-i}.
\]

**INPUT:**

- **other** – a sequence of elements of \( \mathbb{C} \), \( \mathbb{R} \) or \( \mathbb{F}_q \)

**OUTPUT:**
The Dirichlet convolution of **self** and **other**.

**EXAMPLES:**

```
sage: I = list(range(5))
sage: A = [ZZ(1) for i in I]
sage: B = [ZZ(1) for i in I]
```

(continues on next page)
sage: s = IndexedSequence(A,I)
sage: t = IndexedSequence(B,I)
sage: s.convolution_periodic(t)

[5, 5, 5, 5, 5, 5, 5, 5, 5]

**AUTHOR:** David Joyner (2006-09)

**dct()**

A discrete Cosine transform.

**EXAMPLES:**

```python
sage: J = list(range(5))
sage: A = [exp(-2*pi*i*I/5) for i in J]
sage: s = IndexedSequence(A,J)
sage: s.dct()
Indexed sequence: [1/16*(sqrt(5) + I*sqrt(-2*sqrt(5) + 10) + ...]
indexed by [0, 1, 2, 3, 4]
```

**dft(chi=<function IndexedSequence.<lambda> at 0x7fe027be57b8>)**

A discrete Fourier transform “over Q” using exact \( N \)-th roots of unity.

**EXAMPLES:**

```python
sage: J = list(range(6))
sage: A = [ZZ(1) for i in J]
sage: s = IndexedSequence(A,J)
sage: s.dft(lambda x:x^2)
Indexed sequence: [6, 0, 0, 6, 0, 0]
indexed by [0, 1, 2, 3, 4, 5]
sage: s.dft()
Indexed sequence: [6, 0, 0, 0, 0, 0]
indexed by [0, 1, 2, 3, 4, 5]
sage: G = SymmetricGroup(3)
sage: J = G.conjugacy_classes_representatives()
sage: s = IndexedSequence([1,2,3],J) # 1,2,3 are the values of a class fcn on G
sage: s.dft()
# the "scalar-valued Fourier transform" of this class fcn
Indexed sequence: [8, 2, 2]
indexed by [(), (1,2), (1,2,3)]
sage: J = AbelianGroup(2,[2,3],names='ab')
sage: s = IndexedSequence([1,2,3,4,5,6],J)
sage: s.dft()
# the precision of output is somewhat random and architecture-dependent.
Indexed sequence: [21.0000000000000, -2.99999999999997 - 1.73205080756885*I, -0.0000000000000097699626170137 - 0.0000000000000106581410364015*I, -0.0000000000000106581410364015*I] indexed by Multiplicative Abelian group isomorphic to C2 x C3
sage: J = CyclicPermutationGroup(6)
sage: s = IndexedSequence([1,2,3,4,5,6],J)
sage: s.dft()
# the precision of output is somewhat random and architecture-dependent.
Indexed sequence: [21.0000000000000, -2.99999999999997 - 1.73205080756885*I, -0.0000000000000097699626170137 - 0.0000000000000106581410364015*I]
```

(continues on next page)
indexed by Cyclic group of order 6 as a permutation group

sage: p = 7; J = list(range(p)); A = [kronecker_symbol(j,p) for j in J]
sage: s = IndexedSequence(A,J)
sage: Fs = s.dft()
sage: c = Fs.list()[1]; [x/c for x in Fs.list()]; s.list()
[0, 1, 1, -1, 1, -1, -1]

The DFT of the values of the quadratic residue symbol is itself, up to a constant factor (denoted c on the last line above).

Todo: Read the parent of the elements of S; if Q or C leave as is; if AbelianGroup, use abelian_group_dual; if some other implemented Group (permutation, matrix), call .characters() and test if the index list is the set of conjugacy classes.

dict()

Return a python dict of self where the keys are elements in the indexing set.

EXAMPLES:

sage: J = list(range(10))
sage: A = [1/10 for j in J]
sage: s = IndexedSequence(A,J)
sage: s.dict()
{0: 1/10, 1: 1/10, 2: 1/10, 3: 1/10, 4: 1/10, 5: 1/10, 6: 1/10, 7: 1/10, 8: 1/10, 9: 1/10}

dst()

A discrete Sine transform.

EXAMPLES:

sage: J = list(range(5))
sage: I = CC.0; pi = CC(pi)
sage: A = [exp(-2*pi*I*i/5) for i in J]
sage: s = IndexedSequence(A,J)
sage: s.dst()
# discrete sine
indexed by [0, 1, 2, 3, 4]

dwt(other='haar', wavelet_k=2)

Wraps the gsl WaveletTransform.forward in dwt (written by Joshua Kantor). Assumes the length of the sample is a power of 2. Uses the GSL function gsl_wavelet_transform_forward().

INPUT:

- other – the name of the type of wavelet; valid choices are:
  - 'daubechies'
  - 'daubechies_centered'
  - 'haar' (default)
- 'haar_centered'
- 'bspline'
- 'bspline_centered'

- `wavelet_k` – For Daubechies wavelets, `wavelet_k` specifies a Daubechies wavelet with $k/2$ vanishing moments. $k = 4, 6, \ldots, 20$ for $k$ even are the only ones implemented.

For Haar wavelets, `wavelet_k` must be 2.

For bspline wavelets, `wavelet_k` equal to 103, 105, 202, 204, 206, 208, 301, 305, 307, 309 will give biorthogonal B-spline wavelets of order $(i, j)$ where `wavelet_k` equals $100 \cdot i + j$.

The wavelet transform uses $J = \log_2(n)$ levels.

**EXAMPLES:**

```python
sage: J = list(range(8))
sage: A = [RR(1) for i in J]
sage: s = IndexedSequence(A, J)
sage: t = s.dwt()
sage: t # slightly random output
Indexed sequence: [2.8284271247499999, 0.00000000000000000, 0.00000000000000000, 0.00000000000000000, 0.00000000000000000, 0.00000000000000000, 0.00000000000000000, 0.00000000000000000]
  indexed by [0, 1, 2, 3, 4, 5, 6, 7]
```

**fft()**

Wraps the `gsl` FastFourierTransform.forward() in `fft`.

If the length is a power of 2 then this automatically uses the radix2 method. If the number of sample points in the input is a power of 2 then the wrapper for the GSL function `gsl_fft_complex_radix2_forward()` is automatically called. Otherwise, `gsl_fft_complex_forward()` is used.

**EXAMPLES:**

```python
sage: J = list(range(5))
sage: A = [RR(1) for i in J]
sage: s = IndexedSequence(A, J)
sage: t = s.fft(); t
Indexed sequence: [5.0000000000000000, 0.00000000000000000, 0.00000000000000000, 0.00000000000000000, 0.00000000000000000]
  indexed by [0, 1, 2, 3, 4]
```

**idft()**

A discrete inverse Fourier transform. Only works over $\mathbb{Q}$.

**EXAMPLES:**

```python
sage: J = list(range(5))
sage: A = [ZZ(1) for i in J]
sage: s = IndexedSequence(A, J)
sage: fs = s.dft(); fs
Indexed sequence: [5, 0, 0, 0, 0]
  indexed by [0, 1, 2, 3, 4]
sage: it = fs.idft(); it
Indexed sequence: [1, 1, 1, 1]
  indexed by [0, 1, 2, 3, 4]
```
idwt (other='haar', wavelet_k=2)
Implements the gsl WaveletTransform.backward() in dwt.
Assumes the length of the sample is a power of 2. Uses the GSL function
gsl_wavelet_transform_backward().

INPUT:
- other – Must be one of the following:
  - "haar"
  - "daubechies"
  - "daubechies_centered"
  - "haar_centered"
  - "bspline"
  - "bspline_centered"
- wavelet_k – For daubechies wavelets, wavelet_k specifies a daubechies wavelet with \( k/2 \) vanishing moments. \( k = 4, 6, \ldots, 20 \) for \( k \) even are the only ones implemented.
  For Haar wavelets, wavelet_k must be 2.
  For bspline wavelets, wavelet_k equal to 103, 105, 202, 204, 206, 208, 301, 305, 307, 309 will give biorthogonal B-spline wavelets of order \((i, j)\) where wavelet_k equals \(100 \cdot i + j\).

EXAMPLES:

```python
sage: J = list(range(8))
sage: A = [RR(1) for i in J]
sage: s = IndexedSequence(A, J)
sage: t = s.dwt()
# random arch dependent output
Indexed sequence: [2.828427124749999, 0.000000000000000, 0.000000000000000, 0.000000000000000, 0.000000000000000, 0.000000000000000, 0.000000000000000, 0.000000000000000]
  indexed by [0, 1, 2, 3, 4, 5, 6, 7]
sage: t.idwt()  # random arch dependent output
Indexed sequence: [0.000000000000000, 0.000000000000000, 0.000000000000000, 0.000000000000000, 0.000000000000000, 0.000000000000000, 0.000000000000000, 0.000000000000000]
  indexed by [0, 1, 2, 3, 4, 5, 6, 7]
sage: t.idwt() == s
True
sage: J = list(range(16))
sage: A = [RR(1) for i in J]
sage: s = IndexedSequence(A, J)
sage: t = s.dwt("bspline", 103)
# random arch dependent output
Indexed sequence: [4.000000000000000, 0.000000000000000, 0.000000000000000, 0.000000000000000, 0.000000000000000, 0.000000000000000, 0.000000000000000, 0.000000000000000]
  indexed by [0, 1, 2, 3, 4, 5, 6, 7]
sage: t.idwt() == s
True
```

(continues on next page)
indexed by \([0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15]\)

```
sage: t.idwt("bspline", 103) == s
True
```

**ifft()**

Implements the gsl FastFourierTransform.inverse in **fft**.

If the number of sample points in the input is a power of 2 then the wrapper for the GSL function `gsl_fft_complex_radix2_inverse()` is automatically called. Otherwise, `gsl_fft_complex_inverse()` is used.

**EXAMPLES:**

```
sage: J = list(range(5))
sage: A = [RR(1) for i in J]
sage: s = IndexedSequence(A, J)
sage: t = s.fft(); t
Indexed sequence: [5.00000000000000, 0.000000000000000, 0.000000000000000, 0.000000000000000, 0.000000000000000]
  indexed by [0, 1, 2, 3, 4]
sage: t.ifft()  # ifft() returns an indexed sequence
Indexed sequence: [1.000000000000000, 1.000000000000000, 1.000000000000000, 1.000000000000000, 1.000000000000000]
  indexed by [0, 1, 2, 3, 4]
sage: t.ifft() == s
1
```

**index_object()**

Return the indexing object.

**EXAMPLES:**

```
sage: J = list(range(10))
sage: A = [1/10 for j in J]
sage: s = IndexedSequence(A, J)
sage: s.index_object()
[0, 1, 2, 3, 4, 5, 6, 7, 8, 9]
```

**list()**

Return the list of self.

**EXAMPLES:**

```
sage: J = list(range(10))
sage: A = [1/10 for j in J]
sage: s = IndexedSequence(A, J)
sage: s.list()
[1/10, 1/10, 1/10, 1/10, 1/10, 1/10, 1/10, 1/10, 1/10, 1/10]
```

**plot()**

Plot the points of the sequence.

Elements of the sequence are assumed to be real or from a finite field, with a real indexing set \( I = \text{range}(\text{len}(\text{self})) \).

**EXAMPLES:**
```python
sage: I = list(range(3))
sage: A = [ZZ(i^2)+1 for i in I]
sage: s = IndexedSequence(A, I)
sage: P = s.plot()
sage: show(P)  # Not tested
```

```python
plot_histogram(clr=0, 0, 1, eps=0.4)
```

Plot the histogram plot of the sequence.

The sequence is assumed to be real or from a finite field, with a real indexing set \( I \) coercible into \( \mathbb{R} \).

Options are `clr`, which is an RGB value, and `eps`, which is the spacing between the bars.

**EXAMPLES:**

```python
sage: J = list(range(3))
sage: A = [ZZ(i^2)+1 for i in J]
sage: s = IndexedSequence(A, J)
sage: P = s.plot_histogram()
sage: show(P)  # Not tested
```

### 2.23 Fast Fourier Transforms Using GSL

**AUTHORS:**

- William Stein (2006-9): initial file (radix2)
- D. Joyner (2006-10): Minor modifications (from radix2 to general case and some documentation).
- M. Hansen (2013-3): Fix radix2 backwards transformation

**sage.calculus.transforms.fft.FFT(size, base_ring=None)**

Create an array for fast Fourier transform conversion using gsl.

**INPUT:**

- `size` – The size of the array
- `base_ring` – Unused (2013-03)

**EXAMPLES:**

We create an array of the desired size:

```python
sage: a = FastFourierTransform(8)
sage: a
[(0.0, 0.0), (0.0, 0.0), (0.0, 0.0), (0.0, 0.0), (0.0, 0.0), (0.0, 0.0), (0.0, 0.0), (0.0, 0.0)]
```

Now, set the values of the array:

```python
sage: for i in range(8): a[i] = i + 1
sage: a
[(1.0, 0.0), (2.0, 0.0), (3.0, 0.0), (4.0, 0.0), (5.0, 0.0), (6.0, 0.0), (7.0, 0.0), (8.0, 0.0)]
```

We can perform the forward Fourier transform on the array:
sage: a.forward_transform()
sage: a  # abs tol 1e-2
[(36.0, 0.0), (-4.00, 9.65), (-4.0, 1.65), (-4.0, 0.0), (-4.0, -1.65),
(-4.0, -4.0), (-4.0, -9.65)]

And backwards:

sage: a.backward_transform()
sage: a  # abs tol 1e-2
[(8.0, 0.0), (16.0, 0.0), (24.0, 0.0), (32.0, 0.0), (40.0, 0.0), (48.0, 0.0),
(56.0, 0.0), (64.0, 0.0)]

Other example:

```python
sage: a = FastFourierTransform(128)
sage: for i in range(1, 11):
    ....:     a[i] = 1
    ....:     a[128-i] = 1
sage: a[:6:2]
[(0.0, 0.0), (1.0, 0.0), (1.0, 0.0)]
sage: a.plot().show(ymin=0)
sage: a.forward_transform()
sage: a.plot().show()
```

```
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sage.calculus.transforms.fft.FastFourierTransform(size, base_ring=None)
Create an array for fast Fourier transform conversion using gsl.

INPUT:
• size – The size of the array
• base_ring – Unused (2013-03)

EXAMPLES:
We create an array of the desired size:

```python
sage: a = FastFourierTransform(8)
sage: a
[(0.0, 0.0), (0.0, 0.0), (0.0, 0.0), (0.0, 0.0), (0.0, 0.0), (0.0, 0.0),
(0.0, 0.0), (0.0, 0.0)]
```

Now, set the values of the array:

```python
sage: for i in range(8): a[i] = i + 1
sage: a
[(1.0, 0.0), (2.0, 0.0), (3.0, 0.0), (4.0, 0.0), (5.0, 0.0), (6.0, 0.0),
(7.0, 0.0), (8.0, 0.0)]
```

We can perform the forward Fourier transform on the array:

```python
sage: a.forward_transform()
sage: a  # abs tol 1e-2
[(36.0, 0.0), (-4.00, 9.65), (-4.0, 1.65), (-4.0, 0.0), (-4.0, -1.65),
(-4.0, -4.0), (-4.0, -9.65)]
```

And backwards:
sage: a.backward_transform()
sage: a  # abs tol 1e-2
[(8.0, 0.0), (16.0, 0.0), (24.0, 0.0), (32.0, 0.0), (40.0, 0.0), (48.0, 0.0), (56.0, 0.0), (64.0, 0.0)]

Other example:

sage: a = FastFourierTransform(128)
sage: for i in range(1, 11):
    ....:  a[i] = 1
    ....:  a[128-i] = 1
sage: a[:6:2]
[(0.0, 0.0), (1.0, 0.0), (1.0, 0.0)]
sage: a.plot().show(ymin=0)
sage: a.forward_transform()
sage: a.plot().show()

class sage.calculus.transforms.fft.FastFourierTransform_base
Bases: object
class sage.calculus.transforms.fft.FastFourierTransform_complex
Bases: sage.calculus.transforms.fft.FastFourierTransform_base

Wrapper class for GSL’s fast Fourier transform.

backward_transform()
Compute the in-place backwards Fourier transform of this data using the Cooley-Tukey algorithm.

OUTPUT:
• None, the transformation is done in-place.

This is the same as inverse_transform() but lacks normalization so that \( f.\) forward_transform().backward_transform() == n*f. Where n is the size of the array.

EXAMPLES:

sage: a = FastFourierTransform(125)
sage: b = FastFourierTransform(125)
sage: for i in range(1, 60): a[i]=1
sage: for i in range(1, 60): b[i]=1
sage: a.forward_transform()
sage: a.backward_transform()

Here we check it with a power of two:

sage: a = FastFourierTransform(128)
sage: b = FastFourierTransform(128)
sage: for i in range(1, 60): a[i]=1
sage: for i in range(1, 60): b[i]=1
sage: a.forward_transform()
sage: a.backward_transform()
sage: (a.plot() + b.plot()).show(ymin=0)  # long time (2s on sage.math, 2011)
sage: abs(sum([CDF(a[i])/125-CDF(b[i]) for i in range(125)]) < 2**-16
True

forward_transform()
Compute the in-place forward Fourier transform of this data using the Cooley-Tukey algorithm.
None, the transformation is done in-place.

If the number of sample points in the input is a power of 2 then the gsl function `gsl_fft_complex_radix2_forward` is automatically called. Otherwise, `gsl_fft_complex_forward` is called.

EXAMPLES:

```python
sage: a = FastFourierTransform(4)
sage: for i in range(4): a[i] = i
sage: a.forward_transform()
sage: a
#abs tol 1e-2
[(6.0, 0.0), (-2.0, 2.0), (-2.0, 0.0), (-2.0, -2.0)]
```

inverse_transform()
Compute the in-place inverse Fourier transform of this data using the Cooley-Tukey algorithm.

OUTPUT:

• None, the transformation is done in-place.

If the number of sample points in the input is a power of 2 then the function `gsl_fft_complex_radix2_inverse` is automatically called. Otherwise, `gsl_fft_complex_inverse` is called.

This transform is normalized so `f.forward_transform().inverse_transform() == f` modulo round-off errors. See also `backward_transform()`.

EXAMPLES:

```python
sage: a = FastFourierTransform(125)
sage: b = FastFourierTransform(125)
sage: for i in range(1, 60): a[i]=1
sage: for i in range(1, 60): b[i]=1
sage: a.forward_transform()
sage: a.inverse_transform()
sage: (a.plot()+b.plot())
Graphics object consisting of 250 graphics primitives
sage: abs(sum([CDF(a[i])-CDF(b[i]) for i in range(125)])) < 2**-16
True
```

Here we check it with a power of two:

```python
sage: a = FastFourierTransform(128)
sage: b = FastFourierTransform(128)
sage: for i in range(1, 60): a[i]=1
sage: for i in range(1, 60): b[i]=1
sage: a.forward_transform()
sage: a.inverse_transform()
sage: (a.plot()+b.plot())
Graphics object consisting of 256 graphics primitives
```

plot (style='rect', xmin=None, xmax=None, **args)
Plot a slice of the array.

• style – Style of the plot, options are "rect" or "polar"
  – rect – height represents real part, color represents imaginary part.
  – polar – height represents absolute value, color represents argument.
- **xmin** – The lower bound of the slice to plot. 0 by default.
- **xmax** – The upper bound of the slice to plot. `len(self)` by default.
- ****args** – passed on to the line plotting function.

**OUTPUT:**
- A plot of the array.

**EXAMPLES:**

```python
sage: a = FastFourierTransform(16)
sage: for i in range(16): a[i] = (random(),random())
sage: A = plot(a)
sage: type(A)  #class 'sage.plot.graphics.Graphics'
sage: type(B)  #class 'sage.plot.graphics.Graphics'
sage: a = FastFourierTransform(125)
sage: b = FastFourierTransform(125)
sage: for i in range(1, 60): a[i]=1
sage: for i in range(1, 60): b[i]=1
sage: a.forward_transform()
sage: a.inverse_transform()
sage: (a.plot()+b.plot())
```

```python
Graphics object consisting of 250 graphics primitives
```

class `sage.calculus.transforms.fft.FourierTransform_complex`  
Bases: object

class `sage.calculus.transforms.fft.FourierTransform_real`  
Bases: object

## 2.24 Solving ODE numerically by GSL

**AUTHORS:**
- Joshua Kantor (2004-2006)
- Robert Marik (2010 - fixed docstrings)

class `sage.calculus.ode.PyFunctionWrapper`  
Bases: object

class `sage.calculus.ode.ode_solver`  
(function=None, jacobian=None, h=0.01, error_abs=1e-10, error_rel=1e-10, a=False, a_dydt=False, scale_abs=False, algorithm='rkf45', y_0=None, t_span=None, params=[])

Bases: object

`ode_solver()` is a class that wraps the GSL libraries ode solver routines To use it instantiate a class:

```python
sage: T=ode_solver()
```

To solve a system of the form \( \frac{dy_i}{dt} = f_i(t, y) \), you must supply a vector or tuple/list valued function \( f \) representing \( f_i \). The functions \( f \) and the jacobian should have the form \( f(t, y) \) or \( f(t, y, params) \). params which is optional allows for your function to depend on one or a tuple of parameters. Note if you use
it, params must be a tuple even if it only has one component. For example if you wanted to solve $y'' + y = 0$. You need to write it as a first order system:

\[
\begin{align*}
{y_0}' &= {y_1} \\
{y_1}' &= -{y_0}
\end{align*}
\]

In code:

```python
sage: f = lambda t,y:[y[1],-y[0]]
sage: T.function=f
```

For some algorithms the jacobian must be supplied as well, the form of this should be a function return a list of lists of the form `[ [df_1/dy_1,...,df_1/dy_n], ..., [df_n/dy_1,...,df_n/dy_n], [df_1/dt,...,df_n/dt] ]`. There are examples below, if your jacobian was the function `my_jacobian` you would do:

```python
sage: T.jacobian = my_jacobian  # not tested, since it doesn't make sense to...
```

There are a variety of algorithms available for different types of systems. Possible algorithms are:

- **rkf45** - runga-kutta-felhberg (4,5)
- **rk2** - embedded runga-kutta (2,3)
- **rk4** - 4th order classical runga-kutta
- **rk8pd** - runga-kutta prince-dormand (8,9)
- **rk2imp** - implicit 2nd order runga-kutta at gaussian points
- **rk4imp** - implicit 4th order runga-kutta at gaussian points
- **bsimp** - implicit burlisch-stoer (requires jacobian)
- **gear1** - M=1 implicit gear
- **gear2** - M=2 implicit gear

The default algorithm is **rkf45**. If you instead wanted to use **bsimp** you would do:

```python
sage: T.algorithm="bsimp"
```

The user should supply initial conditions in `y_0`. For example if your initial conditions are $y_0=1,y_1=1$, do:

```python
sage: T.y_0=[1,1]
```

The actual solver is invoked by the method `ode_solve()`. It has arguments `t_span`, `y_0`, `num_points`, `params`. `y_0` must be supplied either as an argument or above by assignment. Params which are optional and only necessary if your system uses params can be supplied to `ode_solve` or by assignment.

`t_span` is the time interval on which to solve the ode. There are two ways to specify `t_span`:

- If `num_points` is not specified then the sequence `t_span` is used as the time points for the solution. Note that the first element `t_span[0]` is the initial time, where the initial condition `y_0` is the specified solution, and subsequent elements are the ones where the solution is computed.
- If `num_points` is specified and `t_span` is a sequence with just 2 elements, then these are the starting and ending times, and the solution will be computed at `num_points` equally spaced points between `t_span[0]` and `t_span[1]`. The initial condition is also included in the output so that `num_points+1` total points are returned. E.g. if `t_span = [0.0, 1.0]` and `num_points =
10, then solution is returned at the 11 time points [0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0].

(Note that if num_points is specified and t_span is not length 2 then t_span are used as the time points and num_points is ignored.)

Error is estimated via the expression $D_i = \text{error_abs} \cdot s_i + \text{error_rel} \cdot (a |y_i| + a_{dydt} h |y_i'|)$.

The user can specify error_abs (1e-10 by default), error_rel (1e-10 by default) a (1 by default), a_(dydt) (0 by default) and $s_i$ (as scaling_abs which should be a tuple and is 1 in all components by default). If you specify one of $a$ or $a_{dydt}$ you must specify the other. You may specify $a$ and $a_{dydt}$ without scaling_abs (which will be taken =1 be default).

ode_solve solves the solution as a list of tuples of the form, [(t_0, [y_1,...,y_n]),(t_1, [y_1,...,y_n]),...,(t_n, [y_1,...,y_n])].

This data is stored in the variable solutions:

```
sage: T.solution  # not tested
```

**EXAMPLES:**

Consider solving the Van der Pol oscillator $x''(t) + u x'(t)(x(t)^2 - 1) + x(t) = 0$ between $t = 0$ and $t = 100$. As a first order system it is $x' = y$, $y' = -x + u y(1 - x^2)$. Let us take $u = 10$ and use initial conditions $(x, y) = (1, 0)$ and use the runga-kutta prince-dormand algorithm.

```
sage: def f_1(t,y,params):
....: return [y[1],-y[0]-params[0]*y[1]*(y[0]**2-1.0)]

sage: def j_1(t,y,params):
....: return
....: [[0.0, 1.0],[-2.0*params[0]*y[0]*y[1]-1.0,-params[0]*(y[0]*y[0]-
˓→1.0)],[0.0, 0.0]]

sage: T=ode_solver()

sage: T.algorithm="rk8pd"

sage: T.function=f_1

sage: T.jacobian=j_1

sage: T.ode_solve(y_0=[1,0],t_span=[0,100],params=[10.0],num_points=1000)

sage: outfile = os.path.join(SAGE_TMP, 'sage.png')

sage: T.plot_solution(filename=outfile)
```

The solver line is equivalent to:

```
sage: T.ode_solve(y_0=[1,0],t_span=[x/10.0 for x in range(1000)],params = [10.0])
```

Let's try a system:

```
y_0'=y_1*y_2
y_1'=-y_0*y_2
y_2'=-.51*y_0*y_1
```

We will not use the jacobian this time and will change the error tolerances.

```
sage: g_1= lambda t,y: [y[1]*y[2],-y[0]*y[2],-0.51*y[0]*y[1]]

sage: T.function=g_1

sage: T.y_0=[0,1,1]

sage: T.scale_abs=[1e-4,1e-4,1e-5]

sage: T.error_rel=1e-4

sage: T.ode_solve(t_span=[0,12],num_points=100)
```

By default T.plot_solution() plots the y_0, to plot general y_i use:

```
sage: T.plot_solution(y=2, filename=outfile)
```

2.24. Solving ODE numerically by GSL
The method interpolate_solution will return a spline interpolation through the points found by the solver. By default $y_0$ is interpolated. You can interpolate $y_i$ through the keyword argument $i$.

```python
sage: f = T.interpolate_solution()
sage: plot(f,0,12).show()
sage: f = T.interpolate_solution(i=1)
sage: plot(f,0,12).show()
sage: f = T.interpolate_solution(i=2)
sage: plot(f,0,12).show()
sage: f = T.interpolate_solution()
sage: f(pi)
0.5379...
```

The solver attributes may also be set up using arguments to ode_solver. The previous example can be rewritten as:

```python
sage: T = ode_solver(g_1,y_0=[0,1,1],scale_abs=[1e-4,1e-4,1e-5],error_rel=1e-4,
algorithm="rk8pd")
sage: T.ode_solve(t_span=[0,12],num_points=100)
sage: f = T.interpolate_solution()
sage: f(pi)
0.5379...
```

Unfortunately because Python functions are used, this solver is slow on systems that require many function evaluations. It is possible to pass a compiled function by deriving from the class `ode_system` and overloading `c_f` and `c_j` with C functions that specify the system. The following will work in the notebook:

```python
%cython
cimport sage.calculus.ode
import sage.calculus.ode
from sage.libs.gsl.all cimport *

cdef class van_der_pol(sage.calculus.ode.ode_system):
    cdef int c_f(self,double t, double *y,double *dydt):
        dydt[0]=y[1]
        dydt[1]=-y[0]-1000*y[1]*(y[0]*y[0]-1)
        return GSL_SUCCESS
    cdef int c_j(self, double t,double *y,double *dfdy,double *dfdt):
        dfdy[0]=0
        dfdy[1]=1.0
        dfdy[2]=-2.0*1000*y[0]*y[1]-1.0
        dfdy[3]=-1000*y[0]*y[0]-1.0
        dfdt[0]=0
        dfdt[1]=0
        return GSL_SUCCESS
```

After executing the above block of code you can do the following (WARNING: the following is not automatically doctested):

```python
sage: T = ode_solver()  # not tested
sage: T.algorithm = "bsimp"  # not tested
sage: vander = van_der_pol()  # not tested
sage: T.function=vander  # not tested
```
sage: T.ode_solve(y_0 = [1,0], t_span=[0,2000], num_points=1000)  # not tested
sage: T.plot_solution(i=0, filename=os.path.join(SAGE_TMP, 'test.png'))  # not tested

interpolate_solution (i=0)

ode_solve (t_span=False, y_0=False, num_points=False, params=[])  

plot_solution (i=0, filename=None, interpolate=False, **kwds)

Plot a one dimensional projection of the solution.

INPUT:

• i – (non-negative integer) composant of the projection
• filename – (string or None) whether to plot the picture or save it in a file
• interpolate – whether to interpolate between the points of the discretized solution
• additional keywords are passed to the graphics primitive

EXAMPLES:

sage: T = ode_solver()
sage: T.function = lambda t,y: [cos(y[0]) * sin(t)]
sage: T.jacobian = lambda t,y: [[-sin(y[0]) * sin(t)]]
sage: T.ode_solve(y_0=[1],t_span=[0,20],num_points=1000)
sage: T.plot_solution()

And with some options:

sage: T.plot_solution(color='red', axes_labels=['t', 'x(t)'])

2.25 Numerical Integration

AUTHORS:

• Josh Kantor (2007-02): first version
• William Stein (2007-02): rewrite of docs, conventions, etc.
• Robert Bradshaw (2008-08): fast float integration
• Jeroen Demeyer (2011-11-23): trac ticket #12047: return 0 when the integration interval is a point; reformat documentation and add to the reference manual.

class sage.calculus.integration.PyFunctionWrapper
Bases: object

class sage.calculus.integration.compiled_integrand
Bases: object

sage.calculus.integration.monte_carlo_integral (func, xl, xu, calls, algorithm='plain', params=None)

Integrate func by Monte-Carlo method.
Integrate func over the dim-dimensional hypercubic region defined by the lower and upper limits in the arrays xl and xu, each of size dim.

The integration uses a fixed number of function calls and obtains random sampling points using the default gsl’s random number generator.

**ALGORITHM:** Uses calls to the GSL (GNU Scientific Library) C library. Documentation can be found in [GSL] chapter “Monte Carlo Integration”.

**INPUT:**
- func – the function to integrate
- params – used to pass parameters to your function
- xl – list of lower limits
- xu – list of upper limits
- calls – number of functions calls used
- algorithm – valid choices are:
  - ‘plain’ – The plain Monte Carlo algorithm samples points randomly from the integration region to estimate the integral and its error.
  - ‘miser’ – The MISER algorithm of Press and Farrar is based on recursive stratified sampling
  - ‘vegas’ – The VEGAS algorithm of Lepage is based on importance sampling

**EXAMPLES:**

```python
sage: x, y = SR.var('x,y')
sage: monte_carlo_integral(x*y, [0,0], [2,2], 10000)  # abs tol 0.1
(4.0, 0.0)
sage: integral(integral(x*y, (x,0,2)), (y,0,2))
4
```

An example with a parameter:

```python
sage: x, y, z = SR.var('x,y,z')
sage: monte_carlo_integral(x*y*z, [0,0,-1], [2,2,1], 10000, params=[1.2])  # abs tol 0.1
(4.8, 0.0)
```

Integral of a constant:

```python
sage: monte_carlo_integral(3, [0,0], [2,2], 10000)  # abs tol 0.1
(12, 0.0)
```

Test different algorithms:

```python
sage: x, y, z = SR.var('x,y,z')
sage: f(x,y,z) = exp(z) * cos(x + sin(y))
sage: for algo in ['plain', 'miser', 'vegas']:  # abs tol 0.01
....:     monte_carlo_integral(f, [0,0,-1], [2,2,1], 10^6, algorithm=algo)
(-1.06, 0.01)
(-1.06, 0.01)
(-1.06, 0.01)
```

Tests with Python functions:
sage: def f(u, v): return u * v
sage: monte_carlo_integral(f, [0,0], [2,2], 10000)  # abs tol 0.1
(4.0, 0.0)
sage: monte_carlo_integral(lambda u,v: u*v, [0,0], [2,2], 10000)  # abs tol 0.1
(4.0, 0.0)
sage: def f(x1,x2,x3,x4): return x1*x2*x3*x4
sage: monte_carlo_integral(f, [0,0], [2,2], 1000, params=[0.6,2])  # abs tol 0.2
(4.8, 0.0)

AUTHORS:

- Vincent Delecroix
- Vincent Klein

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- Vincent Klein

sage.calculus.integration.numerical_integral(func, a, b=None, algorithm='qag',
max_points=87, params=[], eps_abs=1e-06, eps_rel=1e-06, rule=6)

Return the numerical integral of the function on the interval from a to b and an error bound.

INPUT:

- a, b – The interval of integration, specified as two numbers or as a tuple/list with the first element the lower bound and the second element the upper bound. Use +Infinity and -Infinity for plus or minus infinity.
- algorithm – valid choices are:
  - ‘qag’ – for an adaptive integration
  - ‘qags’ – for an adaptive integration with (integrable) singularities
  - ‘qng’ – for a non-adaptive Gauss-Kronrod (samples at a maximum of 87pts)
- max_points – sets the maximum number of sample points
- params – used to pass parameters to your function
- eps_abs, eps_rel – sets the absolute and relative error tolerances which satisfies the relation |
RESULT - I| <= max(eps_abs, eps_rel * |I|), where I = |int_a^b f(x) d x|.
- rule – This controls the Gauss-Kronrod rule used in the adaptive integration:
  - rule=1 – 15 point rule
  - rule=2 – 21 point rule
  - rule=3 – 31 point rule
  - rule=4 – 41 point rule
  - rule=5 – 51 point rule
  - rule=6 – 61 point rule

Higher key values are more accurate for smooth functions but lower key values deal better with discontinuities.

OUTPUT:

A tuple whose first component is the answer and whose second component is an error estimate.

REMARK:

There is also a method nintegral on symbolic expressions that implements numerical integration using Maxima. It is potentially very useful for symbolic expressions.
EXAMPLES:

To integrate the function $x^2$ from 0 to 1, we do

```python
sage: numerical_integral(x^2, 0, 1, max_points=100)
(0.3333333333333333, 3.700743415417188e-15)
```

To integrate the function $\sin(x)^3 + \sin(x)$ we do

```python
sage: numerical_integral(sin(x)^3 + sin(x), 0, pi)
(3.333333333333333, 3.700743415417188e-14)
```

The input can be any callable:

```python
sage: numerical_integral(lambda x: sin(x)^3 + sin(x), 0, pi)
(3.333333333333333, 3.700743415417188e-14)
```

We check this with a symbolic integration:

```python
sage: (sin(x)^3+sin(x)).integral(x,0,pi)
10/3
```

If we want to change the error tolerances and gauss rule used:

```python
sage: f = x^2
sage: numerical_integral(f, 0, 1, max_points=200, eps_abs=1e-7, eps_rel=1e-7, rule=4)
(0.3333333333333333, 3.700743415417188e-15)
```

For a Python function with parameters:

```python
sage: f(x,a) = 1/(a+x^2)
sage: [numerical_integral(f, 1, 2, max_points=100, params=[n]) for n in range(10)]  # random output (architecture and os dependent)
[(0.4999999999999982, 0.0),
 (0.3217505543966455, 0.0),
 (0.2403090314729292, 0.0),
 (0.1925308257671169, 0.0),
 (0.1608752771953237, 0.0),
 (0.1382754567634941, 0.0),
 (0.1212997593370274, 0.0),
 (0.1080667419168306, 0.0),
 (0.0974544662554884, 0.0),
 (0.0887506830502177, 0.0)]
```

```python
c: y = var('y')
sage: numerical_integral(x*y, 0, 1)
Traceback (most recent call last):
... ValueError: The function to be integrated depends on 2 variables (x, y),
and so cannot be integrated in one dimension. Please fix additional
variables with the 'params' argument
```

Note the parameters are always a tuple even if they have one component.

It is possible to integrate on infinite intervals as well by using +Infinity or -Infinity in the interval argument. For example:

```python
```python
sage: f = exp(-x)
sage: numerical_integral(f, 0, +Infinity)  # random output
(0.99999999999957279, 1.8429811298996553e-07)
```

Note the coercion to the real field RR, which prevents underflow:

```python
sage: f = exp(-x**2)
sage: numerical_integral(f, -Infinity, +Infinity)  # random output
(1.7724538509060035, 3.4295192165889879e-08)
```

One can integrate any real-valued callable function:

```python
sage: numerical_integral(lambda x: abs(zeta(x)), [1.1,1.5])  # random output
(1.8488570602160455, 2.052643677492633e-14)
```

We can also numerically integrate symbolic expressions using either this function (which uses GSL) or the native integration (which uses Maxima):

```python
sage: exp(-1/x).nintegral(x, 1, 2)  # via maxima
(0.50479221787318..., 5.60431942934407...e-15, 21, 0)
sage: numerical_integral(exp(-1/x), 1, 2)
(0.50479221787318..., 5.60431942934407...e-15)
```

We can also integrate constant expressions:

```python
sage: numerical_integral(2, 1, 7)
(12.0, 0.0)
```

If the interval of integration is a point, then the result is always zero (this makes sense within the Lebesgue theory of integration), see trac ticket #12047:

```python
sage: numerical_integral(log, 0, 0)
(0.0, 0.0)
sage: numerical_integral(lambda x: sqrt(x), (-2.0, -2.0))
(0.0, 0.0)
```

In the presence of integrable singularity, the default adaptive method might fail and it is advised to use 'qags':

```python
sage: b = 1.81759643554688
sage: F(x) = sqrt((-x + b)/((x - 1.0)*x))
sage: numerical_integral(F, 1, b)  # inf, nan
sage: numerical_integral(F, 1, b, algorithm='qags')  # abs tol 1e-10
(1.1817104238446596, 3.387268288079781e-07)
```

AUTHORS:

- Josh Kantor
- William Stein
- Robert Bradshaw
- Jeroen Demeyer

ALGORITHM: Uses calls to the GSL (GNU Scientific Library) C library. Documentation can be found in [GSL] chapter “Numerical Integration”.

2.25. Numerical Integration 303
2.26 Riemann Mapping

AUTHORS:

• Ethan Van Andel (2009-2011): initial version and upgrades
• Robert Bradshaw (2009): his “complex_plot” was adapted for plot_colored

Development supported by NSF award No. 0702939.

class sage.calculus.riemann.Riemann_Map
    Bases: object

The Riemann_Map class computes an interior or exterior Riemann map, or an Ahlfors map of a region given by the supplied boundary curve(s) and center point. The class also provides various methods to evaluate, visualize, or extract data from the map.

A Riemann map conformally maps a simply connected region in the complex plane to the unit disc. The Ahlfors map does the same thing for multiply connected regions.

Note that all the methods are numerical. As a result all answers have some imprecision. Moreover, maps computed with small number of collocation points, or for unusually shaped regions, may be very inaccurate. Error computations for the ellipse can be found in the documentation for analytic_boundary() and analytic_interior().

[BSV2010] provides an overview of the Riemann map and discusses the research that lead to the creation of this module.

INPUT:

• fs – A list of the boundaries of the region, given as complex-valued functions with domain 0 to 2 * pi. Note that the outer boundary must be parameterized counter clockwise (i.e. e^(I*t)) while the inner boundaries must be clockwise (i.e. e^(-I*t)).
• fprimes – A list of the derivatives of the boundary functions. Must be in the same order as fs.
• a – Complex, the center of the Riemann map. Will be mapped to the origin of the unit disc. Note that a MUST be within the region in order for the results to be mathematically valid.

The following inputs may be passed in as named parameters:

• N – integer (default: 500), the number of collocation points used to compute the map. More points will give more accurate results, especially near the boundaries, but will take longer to compute.
• exterior – boolean (default: False), if set to True, the exterior map will be computed, mapping the exterior of the region to the exterior of the unit circle.

The following inputs may be passed as named parameters in unusual circumstances:

•ncorners – integer (default: 4), if mapping a figure with (equally t-spaced) corners – corners that make a significant change in the direction of the boundary – better results may be sometimes obtained by accurately giving this parameter. Used to add the proper constant to the theta correspondence function.
• opp – boolean (default: False), set to True in very rare cases where the theta correspondence function is off by pi, that is, if red is mapped left of the origin in the color plot.

EXAMPLES:

The unit circle identity map:

```
sage: f(t) = e^(I*t)
sage: fprime(t) = I*e^(I*t)
sage: m = Riemann_Map([f], [fprime], 0) # long time (4 sec)
```
The exterior map for the unit circle:

```python
sage: m = Riemann_Map([f], [fprime], 0, exterior=True) # long time (4 sec)
```

The unit circle with a small hole:

```python
sage: f(t) = e^(I*t)
sage: fprime(t) = I*e^(I*t)
sage: hf(t) = 0.5*e^(-I*t)
sage: hfprime(t) = 0.5*(-I)*e^(-I*t)
sage: m = Riemann_Map([f, hf], [fprime, hfprime], 0.5 + 0.5*I)
sage: #spiderweb and color plots cannot be added for multiply
sage: #connected regions. Instead we do this.
sage: m.plot_spiderweb(withcolor = True) # long time
```

A square:

```python
sage: ps = polygon_spline([(-1, -1), (1, -1), (1, 1), (-1, 1)])
sage: f = lambda t: ps.value(real(t))
sage: fprime = lambda t: ps.derivative(real(t))
sage: m = Riemann_Map([f], [fprime], 0.25, ncorners=4)
sage: m.plot_colored() + m.plot_spiderweb() # long time
```

Compute rough error for this map:

```python
sage: x = 0.75
sage: print("error = {}".format(m.inverse_riemann_map(m.riemann_map(x)) - x)) # long time
```

A fun, complex region for demonstration purposes:

```python
sage: f(t) = e^(I*t)
sage: fp(t) = I*e^(I*t)
sage: ef1(t) = .2*e^(-I*t) +.4+.4*I
sage: ef1p(t) = -I*.2*e^(-I*t)
sage: ef2(t) = .2*e^(-I*t) -.4+.4*I
sage: ef2p(t) = -I*.2*e^(-I*t)
sage: pts = [(-.5,-.15-20/1000),(-.6,-.27-10/1000),(-.45,-.45),(.45,-.45),(.6,-.27-10/1000),(.5,-.15-10/1000),(.45,-.45),(.6,-.27-10/1000),(.5,-.15-10/1000),(.45,-.45)]
sage: pts.reverse()
sage: cs = complex_cubic_spline(pts)
sage: mf = lambda x:cs.value(x)
sage: mprime = lambda x: cs.derivative(x)
sage: m = Riemann_Map([f,ef1,ef2,mf],[fp,ef1p,ef2p,mprime],0,N = 400) # long time
```

ALGORITHM:
This class computes the Riemann Map via the Szego kernel using an adaptation of the method described by [KT1986].

**compute_on_grid**(plot_range, x_points)

Computes the Riemann map on a grid of points. Note that these points are complex of the form $z = x + y*i$.

**INPUT:**

- plot_range – a tuple of the form $[xmin, xmax, ymin, ymax]$. If the value is $[]$, the default plotting window of the map will be used.
- x_points – int, the size of the grid in the x direction. The number of points in the y direction is scaled accordingly.

**OUTPUT:**

- a tuple containing $[z_values, xmin, xmax, ymin, ymax]$ where $z_values$ is the evaluation of the map on the specified grid.

**EXAMPLES:**

General usage:

```python
sage: f(t) = e^(I*t) - 0.5*e^(-I*t)
sage: fprime(t) = I*e^(I*t) + 0.5*I*e^(-I*t)
sage: m = Riemann_Map([f], [fprime], 0)
sage: data = m.compute_on_grid([], 5)
sage: data[0][8, 1]
(-0.0879...+0.9709...j)
```

**get_szego**(boundary=-1, absolute_value=False)

Return a discretized version of the Szego kernel for each boundary function.

**INPUT:**

The following inputs may be passed in as named parameters:

- boundary – integer (default: -1) if $< 0$, get_theta_points() will return the points for all boundaries. If $>= 0$, get_theta_points() will return only the points for the boundary specified.
- absolute_value – boolean (default: False) if True, will return the absolute value of the (complex valued) Szego kernel instead of the kernel itself. Useful for plotting.

**OUTPUT:**

A list of points of the form $[t \text{ value, value of the Szego kernel at that } t]$. 

**EXAMPLES:**

Generic use:

```python
sage: f(t) = e^(I*t) - 0.5*e^(-I*t)
sage: fprime(t) = I*e^(I*t) + 0.5*I*e^(-I*t)
sage: m = Riemann_Map([f], [fprime], 0)
sage: sz = m.get_szego(boundary=0)
sage: points = m.get_szego(absolute_value=True)
sage: list_plot(points)
Graphics object consisting of 1 graphics primitive
```

Extending the points by a spline:
sage: s = spline(points)
sage: s(3*pi / 4)
0.0012158...

sage: plot(s,0,2*pi) # plot the kernel
Graphics object consisting of 1 graphics primitive

The unit circle with a small hole:

sage: f(t) = e^(I*t)
sage: fprime(t) = I*e^(I*t)
sage: hf(t) = 0.5*e^(-I*t)
sage: hfprime(t) = 0.5*I*e^(-I*t)
sage: m = Riemann_Map([f, hf], [fprime, hfprime], 0.5 + 0.5*I)

Getting the szego for a specific boundary:

sage: sz0 = m.get_szego(boundary=0)
sage: sz1 = m.get_szego(boundary=1)

get_theta_points(boundary=-l)
Return an array of points of the form \([t \text{ value}, \theta \text{ in } e^{(I*\theta)}]\), that is, a discretized version of the theta/boundary correspondence function. In other words, a point in this array \([t_1, t_2]\) represents that the boundary point given by \(f(t_1)\) is mapped to a point on the boundary of the unit circle given by \(e^{(I*t_2)}\).

For multiply connected domains, get_theta_points will list the points for each boundary in the order that they were supplied.

INPUT:
The following input must all be passed in as named parameters:
- boundary – integer (default: -1) if < 0, get_theta_points will return the points for all boundaries. If >= 0, get_theta_points will return only the points for the boundary specified.

OUTPUT:
A list of points of the form \([t \text{ value}, \theta \text{ in } e^{(I*\theta)}]\).

EXAMPLES:
Getting the list of points, extending it via a spline, getting the points for only the outside of a multiply connected domain:

sage: f(t) = e^(I*t) - 0.5*e^(-I*t)
sage: fprime(t) = I*e^(I*t) + 0.5*I*e^(-I*t)
sage: m = Riemann_Map([f], [fprime], 0)
sage: points = m.get_theta_points()
sage: list_plot(points)
Graphics object consisting of 1 graphics primitive

Extending the points by a spline:

sage: s = spline(points)
sage: s(3*pi / 4)
1.627660...

The unit circle with a small hole:
sage: f(t) = e^(I*t)
sage: fprime(t) = I*e^(I*t)
sage: h(t) = 0.5*e^(-I*t)
sage: hprime(t) = 0.5*I*e^(-I*t)
sage: m = Riemann_Map([f, h], [h, hprime], 0.5 + 0.5*I)

Getting the boundary correspondence for a specific boundary:

```sage```

tp0 = m.get_theta_points(boundary=0)
tp1 = m.get_theta_points(boundary=1)
```

inverse_riemann_map (pt)

Return the inverse Riemann mapping of a point.

That is, given pt on the interior of the unit disc, inverse_riemann_map() will return the point on the original region that would be Riemann mapped to pt. Note that this method does not work for multiply connected domains.

INPUT:

- pt – A complex number (usually with absolute value <= 1) representing the point to be inverse mapped.

OUTPUT:

The point on the region that Riemann maps to the input point.

EXAMPLES:

Can work for different types of complex numbers:

```sage```

sage: f(t) = e^(I*t) - 0.5*e^(-I*t)
sage: fprime(t) = I*e^(I*t) + 0.5*I*e^(-I*t)
sage: m = Riemann_Map([f], [fprime], 0)
sage: m.inverse_riemann_map(0.5 + sqrt(-0.5))
(0.406880...+0.3614702...j)
sage: m.inverse_riemann_map(0.95)
(0.486319...-4.90019052...j)
sage: m.inverse_riemann_map(0.25 - 0.3*I)
(0.1653244...-0.180936...j)
sage: import numpy as np
sage: m.inverse_riemann_map(np.complex(-0.2, 0.5))
(-0.156280...+0.321819...j)
```

plot_boundaries (plotjoined=True, rgbcolor=[0, 0, 0], thickness=1)

Plots the boundaries of the region for the Riemann map. Note that this method DOES work for multiply connected domains.

INPUT:

The following inputs may be passed in as named parameters:

- plotjoined – boolean (default: True) If False, discrete points will be drawn; otherwise they will be connected by lines. In this case, if plotjoined=False, the points shown will be the original collocation points used to generate the Riemann map.

- rgbcolor – float array (default: [0, 0, 0]) the red-green-blue color of the boundary.

- thickness – positive float (default: 1) the thickness of the lines or points in the boundary.

EXAMPLES:
General usage:

```python
sage: f(t) = e^(I*t) - 0.5*e^(-I*t)
sage: fprime(t) = I*e^(I*t) + 0.5*I*e^(-I*t)
sage: m = Riemann_Map([f], [fprime], 0)
```

Default plot:

```python
sage: m.plot_boundaries()
Graphics object consisting of 1 graphics primitive
```

Big blue collocation points:

```python
sage: m.plot_boundaries(plotjoined=False, rgbcolor=[0,0,1], thickness=6)
Graphics object consisting of 1 graphics primitive
```

**plot_colored**(plot_range=[], plot_points=100, interpolation='catrom', **options)

Generates a colored plot of the Riemann map. A red point on the colored plot corresponds to a red point on the unit disc.

**INPUT:**

The following inputs may be passed in as named parameters:

- **plot_range** – (default: []) list of 4 values (xmin, xmax, ymin, ymax). Declare if you do not want the plot to use the default range for the figure.

- **plot_points** – integer (default: 100), number of points to plot in the x direction. Points in the y direction are scaled accordingly. Note that very large values can cause this function to run slowly.

**EXAMPLES:**

Given a Riemann map m, general usage:

```python
sage: f(t) = e^(I*t) - 0.5*e^(-I*t)
sage: fprime(t) = I*e^(I*t) + 0.5*I*e^(-I*t)
sage: m = Riemann_Map([f], [fprime], 0)
sage: m.plot_colored()
Graphics object consisting of 1 graphics primitive
```

Plot zoomed in on a specific spot:

```python
sage: m.plot_colored(plot_range=[0,1,.25,.75])
Graphics object consisting of 1 graphics primitive
```

High resolution plot:

```python
sage: m.plot_colored(plot_points=1000)  # long time (29s on sage.math, 2012)
Graphics object consisting of 1 graphics primitive
```

To generate the unit circle map, it’s helpful to see what the colors correspond to:

```python
sage: f(t) = e^(I*t)
sage: fprime(t) = I*e^(I*t)
sage: m = Riemann_Map([f], [fprime], 0, 1000)
sage: m.plot_colored()
Graphics object consisting of 1 graphics primitive
```
plot_spiderweb(spokes=16, circles=4, pts=32, linescale=0.99, rgbcolor=[0, 0, 0], thickness=1, plotjoined=True, withcolor=False, plot_points=200, min_mag=0.001, interpolation='catrom', **options)

Generates a traditional “spiderweb plot” of the Riemann map. Shows what concentric circles and radial lines map to. The radial lines may exhibit erratic behavior near the boundary; if this occurs, decreasing linescale may mitigate the problem.

For multiply connected domains the spiderweb is by necessity generated using the forward mapping. This method is more computationally intensive. In addition, these spiderwebs cannot be added to color plots. Instead the withcolor option must be used.

In addition, spiderweb plots are not currently supported for exterior maps.

INPUT:

The following inputs may be passed in as named parameters:

- **spokes** – integer (default: 16) the number of equally spaced radial lines to plot.
- **circles** – integer (default: 4) the number of equally spaced circles about the center to plot.
- **pts** – integer (default: 32) the number of points to plot. Each radial line is made by \(1 \times \text{pts}\) points, each circle has \(2 \times \text{pts}\) points. Note that high values may cause erratic behavior of the radial lines near the boundaries. - only for simply connected domains
- **linescale** – float between 0 and 1. Shrinks the radial lines away from the boundary to reduce erratic behavior. - only for simply connected domains
- **rgbcolor** – float array (default: \([0, 0, 0]\)) the red-green-blue color of the spiderweb.
- **thickness** – positive float (default: 1) the thickness of the lines or points in the spiderweb.
- **plotjoined** – boolean (default: True) If False, discrete points will be drawn; otherwise they will be connected by lines. - only for simply connected domains
- **withcolor** – boolean (default: False) If True, The spiderweb will be overlaid on the basic color plot.
- **plot_points** – integer (default: 200) the size of the grid in the \(x\) direction The number of points in the \(y\) direction is scaled accordingly. Note that very large values can cause this function to run slowly. - only for multiply connected domains
- **min_mag** – float (default: 0.001) The magnitude cutoff below which spiderweb points are not drawn. This only applies to multiply connected domains and is designed to prevent “fuzz” at the edge of the domain. Some complicated multiply connected domains (particularly those with corners) may require a larger value to look clean outside.

EXAMPLES:

General usage:

```python
sage: f(t) = e^(I*t) - 0.5*e^(-I*t)
sage: fprime(t) = I*e^(I*t) + 0.5*I*e^(-I*t)
sage: m = Riemann_Map([f], [fprime], 0)
sage: m.plot_spiderweb()
```

Default plot:

```python
sage: m.plot_spiderweb()
Graphics object consisting of 21 graphics primitives
```

Simplified plot with many discrete points:

```python
sage: m.plot_spiderweb(spokes=16, circles=4, pts=32, linescale=0.99, rgbcolor=[0, 0, 0], thickness=1, plotjoined=True, withcolor=False, plot_points=200, min_mag=0.001, interpolation='catrom', **options)
```

```sage
sage: m.plot_spiderweb(spokes=4, circles=1, pts=400, linescale=0.95, plotjoined=False)
Graphics object consisting of 6 graphics primitives
```

Plot with thick, red lines:

```sage
sage: m.plot_spiderweb(rgbcolor=[1,0,0], thickness=3)
Graphics object consisting of 21 graphics primitives
```

To generate the unit circle map, it’s helpful to see what the original spiderweb looks like:

```sage
sage: f(t) = e^(I*t)
sage: fprime(t) = I*e^(I*t)
sage: m = Riemann_Map([f], [fprime], 0, 1000)
sage: m.plot_spiderweb()
```

A multiply connected region with corners. We set \texttt{min_mag} higher to remove “fuzz” outside the domain:

```sage
sage: ps = polygon_spline([(-4,-2),(4,-2),(4,2),(-4,2)])
sage: z1 = lambda t: ps.value(t); z1p = lambda t: ps.derivative(t)
sage: z2(t) = -2+exp(-I*t); z2p(t) = -I*exp(-I*t)
sage: z3(t) = 2+exp(-I*t); z3p(t) = -I*exp(-I*t)
sage: m = Riemann_Map([z1,z2,z3],[z1p,z2p,z3p],0,ncorners=4) # long time
sage: p = m.plot_spiderweb(withcolor=True,plot_points=500, thickness = 2.0, min_mag=0.1) # long time
```

\textbf{riemann\_map (pt)}

Return the Riemann mapping of a point.

That is, given \texttt{pt} on the interior of the mapped region, \texttt{riemann\_map} will return the point on the unit disk that \texttt{pt} maps to. Note that this method only works for interior points; accuracy breaks down very close to the boundary. To get boundary correspondence, use \texttt{get\_theta\_points()}.

**INPUT:**

- \texttt{pt} – A complex number representing the point to be inverse mapped.

**OUTPUT:**

A complex number representing the point on the unit circle that the input point maps to.

**EXAMPLES:**

Can work for different types of complex numbers:

```sage
sage: f(t) = e^(I*t) - 0.5*e^(-I*t)
sage: fprime(t) = I*e^(I*t) + 0.5*I*e^(-I*t)
sage: m = Riemann_Map([f], [fprime], 0)
sage: m.riemann_map(0.25 + sqrt(-0.5))
(0.137514...+0.876696...j)
sage: I = CDF.gen()
sage: m.riemann_map(1.3*I)
(-1.56...e-05+0.989694...j)
sage: m.riemann_map(0.4)
(0.73324...+3.2...e-06j)
sage: import numpy as np
sage: m.riemann_map(np.complex(-3, 0.0001))
(1.405757...e-05+8.06...e-10j)
```
sage.calculus.riemann.analytic_boundary\((t, n, \epsilon)\)
Provides an exact (for \(n = \infty\)) Riemann boundary correspondence for the ellipse with axes \(1 + \epsilon\) and \(1 - \epsilon\). The boundary is therefore given by \(e^{(1+i)t} + \epsilon e^{(1-i)t}\). It is primarily useful for testing the accuracy of the numerical Riemann Map.

**INPUT:**
- \(t\) – The boundary parameter, from 0 to 2\(\pi\)
- \(n\) – integer - the number of terms to include. 10 is fairly accurate, 20 is very accurate.
- \(\epsilon\) – float - the skew of the ellipse (0 is circular)

**OUTPUT:**
A theta value from 0 to 2\(\pi\), corresponding to the point on the circle \(e^{i\theta}\)

sage.calculus.riemann.analytic_interior\((z, n, \epsilon)\)
Provides a nearly exact computation of the Riemann Map of an interior point of the ellipse with axes \(1 + \epsilon\) and \(1 - \epsilon\). It is primarily useful for testing the accuracy of the numerical Riemann Map.

**INPUT:**
- \(z\) – complex - the point to be mapped.
- \(n\) – integer - the number of terms to include. 10 is fairly accurate, 20 is very accurate.

sage.calculus.riemann.cauchy_kernel\((t, \text{args})\)
Intermediate function for the integration in analytic_interior().

**INPUT:**
- \(t\) – The boundary parameter, meant to be integrated over
- \(\text{args}\) – a tuple containing:
  - \(\epsilon\) – float - the skew of the ellipse (0 is circular)
  - \(z\) – complex - the point to be mapped.
  - \(n\) – integer - the number of terms to include. 10 is fairly accurate, 20 is very accurate.
  - \(\text{part}\) – will return the real (‘r’), imaginary (‘i’) or complex (‘c’) value of the kernel

sage.calculus.riemann.complex_to_rgb\((z_{\text{values}})\)
Convert from a (Numpy) array of complex numbers to its corresponding matrix of RGB values. For internal use of plot_colored() only.

**INPUT:**
- \(z_{\text{values}}\) – A Numpy array of complex numbers.

**OUTPUT:**
An \(N \times M \times 3\) floating point Numpy array \(X\), where \(X[i, j]\) is an (r,g,b) tuple.

**EXAMPLES:**

```
sage: from sage.calculus.riemann import complex_to_rgb
sage: import numpy
sage: complex_to_rgb(numpy.array([[0, 1, 1000]], dtype = numpy.complex128))
array([[[1., 1., 1.],
   [1., 0.05558355, 0.05558355],
   [0.17301243, 0., 0.]]])
```

```
sage: complex_to_rgb(numpy.array([[0, 1j, 1000j]], dtype = numpy.complex128))
```

(continues on next page)
sage.calculus.riemann.complex_to_spiderweb(z_values, dr, dtheta, spokes, circles, rgbcolor, thickness, withcolor, min_mag)

Converts a grid of complex numbers into a matrix containing rgb data for the Riemann spiderweb plot.

**INPUT:**

- `z_values` – A grid of complex numbers, as a list of lists.
- `dr` – grid of floats, the r derivative of `z_values`. Used to determine precision.
- `dtheta` – grid of floats, the theta derivative of `z_values`. Used to determine precision.
- `spokes` – integer - the number of equally spaced radial lines to plot.
- `circles` – integer - the number of equally spaced circles about the center to plot.
- `rgbcolor` – float array - the red-green-blue color of the lines of the spiderweb.
- `thickness` – positive float - the thickness of the lines or points in the spiderweb.
- `withcolor` – boolean - If True the spiderweb will be overlaid on the basic color plot.
- `min_mag` – float - The magnitude cutoff below which spiderweb points are not drawn. This only applies to multiply connected domains and is designed to prevent “fuzz” at the edge of the domain. Some complicated multiply connected domains (particularly those with corners) may require a larger value to look clean outside.

**OUTPUT:**

An $N \times M \times 3$ floating point Numpy array $X$, where $X[i,j]$ is an (r,g,b) tuple.

**EXAMPLES:**

```python
sage: from sage.calculus.riemann import complex_to_spiderweb
sage: import numpy
sage: zval = numpy.array([[0, 1, 1000],[.2+.3j,1,-.3j],[0,0,0]],dtype = numpy_complex128)
sage: deriv = numpy.array([[.1]],dtype = numpy.float64)
sage: complex_to_spiderweb(zval, deriv, deriv, 4,4,[0,0,0],1,0.001)
array([[1., 1., 1.],
       [1., 1., 1.],
       [1., 1., 1.]])
```

```python
sage: complex_to_spiderweb(zval, deriv, deriv, 4,4,[0,0,0],1,0.001)
array([[1., 1., 1.],
       [1., 1., 1.],
       [1., 1., 1.],
       [1., 1., 1.]])
```
sage.calculus.riemann.get_derivatives(z_values, xstep, ystep)

Computes the r*e^(I*theta) form of derivatives from the grid of points. The derivatives are computed using quick-and-dirty taylor expansion and assuming analyticity. As such get_derivatives is primarily intended to be used for comparisons in plot_spiderweb and not for applications that require great precision.

INPUT:

• z_values – The values for a complex function evaluated on a grid in the complex plane, usually from compute_on_grid.
• xstep – float, the spacing of the grid points in the real direction

OUTPUT:

• A tuple of arrays, [dr, dtheta], with each array 2 less in both dimensions than z_values
  – dr - the abs of the derivative of the function in the +r direction
  – dtheta - the rate of accumulation of angle in the +theta direction

EXAMPLES:

Standard usage with compute_on_grid:

```python
sage: from sage.calculus.riemann import get_derivatives
sage: f(t) = e^(I*t) - 0.5*e^(-I*t)
sage: fprime(t) = I*e^(I*t) + 0.5*I*e^(-I*t)

sage: m = Riemann_Map([f], [fprime], 0)

sage: data = m.compute_on_grid([],19)

sage: xstep = (data[2]-data[1])/19
sage: ystep = (data[4]-data[3])/19

sage: dr, dtheta = get_derivatives(data[0],xstep,ystep)

sage: dr[8,8]
0.241...

sage: dtheta[5,5]
5.907...
```

### 2.27 Real Interpolation using GSL

**class** `sage.calculus.interpolation.Spline`

```
Bases: object

Create a spline interpolation object.

Given a list v of pairs, s = spline(v) is an object s such that s(x) is the value of the spline interpolation through the points in v at the point x.

The values in v do not have to be sorted. Moreover, one can append values to v, delete values from v, or change values in v, and the spline is recomputed.

EXAMPLES:
```
Changing the points of the spline causes the spline to be recomputed:

```
sage: S[0] = (0, 2); S
[(0, 2), (1, 2), (4, 5), (5, 3)]
sage: S(1.5)
2.507575757575...
```

We may append to the list of interpolation points:

```
sage: S.append((4, 5)); S
[(0, 2), (1, 2), (5, 3), (4, 5)]
sage: S(1.5)
2.507575757575...
```

If we set the \( n \)-th interpolation point, where \( n \) is larger than \( \text{len}(S) \), then points \((0, 0)\) will be inserted between the interpolation points and the point to be added:

```
sage: S[6] = (6, 3); S
[(0, 2), (1, 2), (5, 3), (4, 5), (0, 0), (0, 0), (6, 3)]
```

This example is in the GSL documentation:

```
sage: v = [(i + sin(i)/2, i+cos(i^2)) for i in range(10)]
sage: s = spline(v)
sage: show(point(v) + plot(s,0,9, hue=.8))
```

We compute the area underneath the spline:

```
sage: s.definite_integral(0, 9)
41.196516041067...
```

The definite integral is additive:

```
sage: s.definite_integral(0, 4) + s.definite_integral(4, 9)
41.196516041067...
```

Switching the order of the bounds changes the sign of the integral:

```
sage: s.definite_integral(9, 0)
-41.196516041067...
```

We compute the first and second-order derivatives at a few points:

```
sage: s.derivative(5)
-0.16230085261803...
```

(continues on next page)
Only the first two derivatives are supported:

```python
sage: s.derivative(4, order=3)
Traceback (most recent call last):
...  
ValueError: Order of derivative must be 1 or 2.
```

**append**(xy)

**EXAMPLES:**

```python
sage: S = spline([(1,1), (2,3), (4,5)]); S.append((5,7)); S
[(1, 1), (2, 3), (4, 5), (5, 7)]
```

The spline is recomputed when points are appended (trac ticket #13519):

```python
sage: S = spline([(1,1), (2,3), (4,5)]); S
[(1, 1), (2, 3), (4, 5)]
sage: S(3)
4.25
sage: S.append((5, 5)); S
[(1, 1), (2, 3), (4, 5), (5, 5)]
sage: S(3)
4.375
```

**definite_integral**(a, b)

Value of the definite integral between a and b.

**INPUT:**

- a – Lower bound for the integral.
- b – Upper bound for the integral.

**EXAMPLES:**

We draw a cubic spline through three points and compute the area underneath the curve:

```python
sage: s = spline([(0, 0), (1, 3), (2, 0)])
sage: s.definite_integral(0, 2)
3.75
sage: s.definite_integral(0, 1)
1.875
sage: s.definite_integral(0, 1) + s.definite_integral(1, 2)
3.75
sage: s.definite_integral(2, 0)
-3.75
```

**derivative**(x, order=1)

Value of the first or second derivative of the spline at x.

**INPUT:**
• \(x\) – value at which to evaluate the derivative.
• \(\text{order}\) (default: 1) – order of the derivative. Must be 1 or 2.

EXAMPLES:

We draw a cubic spline through three points and compute the derivatives:

```
sage: s = spline([(0, 0), (2, 3), (4, 0)])
sage: s.derivative(0)
2.25
sage: s.derivative(2)
0.0
sage: s.derivative(4)
-2.25
sage: s.derivative(1, order=2)
-1.125
sage: s.derivative(3, order=2)
-1.125
```

\texttt{list()}

Underlying list of points that this spline goes through.

EXAMPLES:

```
sage: S = spline([(1,1), (2,3), (4,5)]); S.list()
[(1, 1), (2, 3), (4, 5)]
```

This is a copy of the list, not a reference (trac ticket #13530):

```
sage: S = spline([(1,1), (2,3), (4,5)])
sage: L = S.list(); L
[(1, 1), (2, 3), (4, 5)]
sage: L[2] = (3, 2)
sage: L
[(1, 1), (2, 3), (3, 2)]
sage: S.list()
[(1, 1), (2, 3), (4, 5)]
```

\texttt{sage.calculus.interpolation.spline}

alias of \texttt{sage.calculus.interpolation.Spline}

2.28 Complex Interpolation

AUTHORS:

• Ethan Van Andel (2009): initial version

Development supported by NSF award No. 0702939.

\texttt{class \ sage.calculus.interpolators.CCSpline}

Bases: object

A CCSpline object contains a cubic interpolation of a figure in the complex plane.

EXAMPLES:

A simple square:
sage: pts = [(-1, -1), (1, -1), (1, 1), (-1, 1)]
sage: cs = complex_cubic_spline(pts)
sage: cs.value(0)
(-1-1j)
sage: cs.derivative(0)
(0.9549296...-0.9549296...j)

**derivative(t)**
Return the derivative (speed and direction of the curve) of a given point from the parameter \( t \).

**INPUT:**

- \( t \) – double, the parameter value for the parameterized curve, between 0 and 2*pi.

**OUTPUT:**
A complex number representing the derivative at the point on the figure corresponding to the input \( t \).

**EXAMPLES:**

sage: pts = [(-1, -1), (1, -1), (1, 1), (-1, 1)]
sage: cs = complex_cubic_spline(pts)
sage: cs.derivative(3 / 5)
(1.40578892327...-0.225417136326...j)
sage: cs.derivative(0) - cs.derivative(2 * pi)
0j
sage: cs.derivative(-6)
(2.52047692949...-1.89392588310...j)

**value(t)**
Return the location of a given point from the parameter \( t \).

**INPUT:**

- \( t \) – double, the parameter value for the parameterized curve, between 0 and 2*pi.

**OUTPUT:**
A complex number representing the point on the figure corresponding to the input \( t \).

**EXAMPLES:**

sage: pts = [(-1, -1), (1, -1), (1, 1), (-1, 1)]
sage: cs = complex_cubic_spline(pts)
sage: cs.value(4 / 7)
(-0.303961332787...-1.34716728183...j)
sage: cs.value(0) - cs.value(2*pi)
0j
sage: cs.value(-2.73452)
(0.934561222231...+0.881366116402...j)

**class sage.calculus.interpolators.PSpline**

Bases: object

A CCSpline object contains a polygon interpolation of a figure in the complex plane.

**EXAMPLES:**

A simple square:
derivative \( (t) \)

Return the derivative (speed and direction of the curve) of a given point from the parameter \( t \).

**INPUT:**

- \( t \) – double, the parameter value for the parameterized curve, between 0 and 2\( \pi \).

**OUTPUT:**

A complex number representing the derivative at the point on the polygon corresponding to the input \( t \).

**EXAMPLES:**

```
sage: pts = [(-1, -1), (1, -1), (1, 1), (-1, 1)]
sage: ps = polygon_spline(pts)
sage: ps.derivative(1 / 3)
(1.27323954473...+0j)
sage: ps.derivative(0) - ps.derivative(2*pi)
0j
sage: ps.derivative(10)
(-1.27323954473...+0j)
```

value \( (t) \)

Return the derivative (speed and direction of the curve) of a given point from the parameter \( t \).

**INPUT:**

- \( t \) – double, the parameter value for the parameterized curve, between 0 and 2\( \pi \).

**OUTPUT:**

A complex number representing the point on the polygon corresponding to the input \( t \).

**EXAMPLES:**

```
sage: pts = [(-1, -1), (1, -1), (1, 1), (-1, 1)]
sage: ps = polygon_spline(pts)
sage: ps.value(.5)
(-0.363380227632...-1j)
sage: ps.value(0) - ps.value(2*pi)
0j
sage: ps.value(10)
(0.26760455264...+1j)
```

`sage.calculus.interpolators.complex_cubic_spline(pts)`

Creates a cubic spline interpolated figure from a set of complex or \( (x, y) \) points. The figure will be a parametric curve from 0 to 2\( \pi \). The returned values will be complex, not \( (x, y) \).

**INPUT:**

- \( pts \) A list or array of complex numbers, or tuples of the form \( (x, y) \).

**EXAMPLES:**

A simple square:
sage: pts = [(-1, -1), (1, -1), (1, 1), (-1, 1)]
sage: cs = complex_cubic_spline(pts)
sage: fx = lambda x: cs.value(x).real
sage: fy = lambda x: cs.value(x).imag
sage: show(parametric_plot((fx, fy), (0, 2*pi)))
sage: m = Riemann_Map([lambda x: cs.value(real(x))], [lambda x: cs
˓→derivative(real(x))], 0)
sage: show(m.plot_colored() + m.plot_spiderweb())

Polygon approximation of a circle:

sage: pts = [e^(I*t / 25) for t in range(25)]
sage: cs = complex_cubic_spline(pts)
sage: cs.derivative(2)
(-0.0470303661...+0.1520363883...j)

sage.calculus.interpolators.polygon_spline(pts)

creates a polygon from a set of complex or (x, y) points. The polygon will be a parametric curve from 0 to 2*pi. The returned values will be complex, not (x, y).

INPUT:

- pts -- A list or array of complex numbers of tuples of the form (x, y).

EXAMPLES:

A simple square:

sage: pts = [(-1, -1), (-1, 1), (1, 1), (1, -1)]
sage: ps = polygon_spline(pts)
sage: fx = lambda x: ps.value(x).real
sage: fy = lambda x: ps.value(x).imag
sage: show(parametric_plot((fx, fy), (0, 2*pi)))
sage: m = Riemann_Map([lambda x: ps.value(real(x))], [lambda x: ps
˓→derivative(real(x))], 0)
sage: show(m.plot_colored() + m.plot_spiderweb())

Polygon approximation of an circle:

sage: pts = [e^(I*t / 25) for t in range(25)]
sage: ps = polygon_spline(pts)
sage: ps.derivative(2)
(-0.0470303661...+0.1520363883...j)

2.29 Calculus functions

sage.calculus.functions.jacobian(functions, variables)

Return the Jacobian matrix, which is the matrix of partial derivatives in which the i,j entry of the Jacobian matrix is the partial derivative diff(functions[i], variables[j]).

EXAMPLES:

sage: x, y = var('x,y')
sage: g=x^2-2*x*y
sage: jacobian(g, (x,y))

\[
\begin{bmatrix}
2x - 2y & -2x
\end{bmatrix}
\]
The Jacobian of the Jacobian should give us the “second derivative”, which is the Hessian matrix:

```python
sage: jacobian(jacobian(g, (x,y)), (x,y))
[ 2 -2]
[-2  0]
```

```python
sage: g.hessian()
[ 2 -2]
[-2  0]
```

```python
sage: f=(x^3*sin(y), cos(x)*sin(y), exp(x))
```

```python
sage: jacobian(f, (x,y))
[ 3*x^2*sin(y) x^3*cos(y)]
[-sin(x)*sin(y) cos(x)*cos(y)]
[e^x 0]
```

```python
sage: jacobian(f, (y,x))
[x^3*cos(y) 3*x^2*sin(y)]
[cos(x)*cos(y) -sin(x)*sin(y)]
[0 e^x]
```

`sage.calculus.functions.wronskian(*args)`

Return the Wronskian of the provided functions, differentiating with respect to the given variable.

If no variable is provided, `diff(f)` is called for each function `f`.

`wronskian(f1, . . . , fn, x)` returns the Wronskian of `f1, . . . , fn`, with derivatives taken with respect to `x`.

`wronskian(f1, . . . , fn)` returns the Wronskian of `f1, . . . , fn` where `k`'th derivatives are computed by doing `.derivative(k)` on each function.

The Wronskian of a list of functions is a determinant of derivatives. The `n`th row (starting from 0) is a list of the `n`th derivatives of the given functions.

For two functions:

\[
\begin{vmatrix}
  f & g \\
  f' & g'
\end{vmatrix}
= f*g' - g*f'.
\]

EXAMPLES:

```python
sage: wronskian(e^x, x^2)
-x^2*e^x + 2*x*e^x
```

```python
sage: x,y = var('x, y')
sage: wronskian(x*y, log(x), x)
-y*log(x) + y
```

If your functions are in a list, you can use `*to turn them into arguments* : func ::

```python
sage: wronskian(*[x^k for k in range(1, 5)])
12*x^4
```

If you want to use ‘x’ as one of the functions in the Wronskian, you can’t put it last or it will be interpreted as the variable with respect to which we differentiate. There are several ways to get around this.

Two-by-two Wronskian of `sin(x)` and `e^x`:

```python
sage: wronskian(sin(x), e^x, x)
-cos(x)*e^x + e^x*sin(x)
```
Or don’t put x last:

```
sage: wronskian(x, sin(x), e^x)
(cos(x)*e^x + e^x*sin(x))*x - 2*e^x*sin(x)
```

Example where one of the functions is constant:

```
sage: wronskian(1, e^(-x), e^(2*x))
-6*e^x
```

REFERENCES:

- Wikipedia article Wronskian
- http://planetmath.org/encyclopedia/WronskianDeterminant.html

AUTHORS:

- Dan Drake (2008-03-12)

## 2.30 Symbolic variables

```
sage.calculus.var.clear_vars()
```

Delete all 1-letter symbolic variables that are predefined at startup of Sage.

Any one-letter global variables that are not symbolic variables are not cleared.

EXAMPLES:

```
sage: var('x y z')
(x, y, z)
sage: (x+y)^z
(x + y)^z
sage: k = 15
sage: clear_vars()
sage: (x+y)^z
Traceback (most recent call last):
  ... NameError: name 'x' is not defined
sage: expand((e + i)^2)
e^2 + 2*I*e - 1
sage: k
15
```

```
sage.calculus.var.function(s, **kwds)
```

Create a formal symbolic function with the name \( s \).

INPUT:

- `nargs=0` - number of arguments the function accepts, defaults to variable number of arguments, or 0
- `latex_name` - name used when printing in latex mode
- `conversions` - a dictionary specifying names of this function in other systems, this is used by the interfaces internally during conversion
- `eval_func` - method used for automatic evaluation
- `evalf_func` - method used for numeric evaluation
• `evalf_params_first` - bool to indicate if parameters should be evaluated numerically before calling the custom `evalf` function
• `conjugate_func` - method used for complex conjugation
• `real_part_func` - method used when taking real parts
• `imag_part_func` - method used when taking imaginary parts
• `derivative_func` - method to be used for (partial) derivation This method should take a keyword argument `deriv_param` specifying the index of the argument to differentiate w.r.t.
• `tderivative_func` - method to be used for derivatives
• `power_func` - method used when taking powers This method should take a keyword argument `power_param` specifying the exponent
• `series_func` - method used for series expansion This method should expect keyword arguments - `order` - order for the expansion to be computed - `var` - variable to expand w.r.t. - `at` - expand at this value
• `print_func` - method for custom printing
• `print_latex_func` - method for custom printing in latex mode

Note that custom methods must be instance methods, i.e., expect the instance of the symbolic function as the first argument.

**Note:** The new function is both returned and automatically injected into the global namespace. If you use this function in library code, it is better to use `sage.symbolic.function_factory.function`, since it will not touch the global namespace.

**EXAMPLES:**

We create a formal function called `supersin`:

```sage
function('supersin')
supersin
```

We can immediately use `supersin` in symbolic expressions:

```sage
y, z, A = var('y z A')
sage: supersin(y+z) + A^3
A^3 + supersin(y + z)
```

We can define other functions in terms of `supersin`:

```sage
g(x,y) = supersin(x)^2 + sin(y/2)
sage: g
(x, y) |--> supersin(x)^2 + sin(1/2*y)
sage: g.diff(y)
(x, y) |--> 1/2*cos(1/2*y)
sage: k = g.diff(x); k
(x, y) |--> 2*supersin(x)*diff(supersin(x), x)
```

We create a formal function of one variable, write down an expression that involves first and second derivatives, and extract off coefficients:
sage: r, kappa = var('r,kappa')
sage: psi = function('psi', nargs=1)(r); psi
psi(r)
sage: g = 1/r^2*(2*r*psi.derivative(r,1) + r^2*psi.derivative(r,2)); g
(r^2*diff(psi(r), r, r) + 2*r*diff(psi(r), r))/r^2
sage: g.expand()
2*diff(psi(r), r)/r + diff(psi(r), r, r)
sage: g.coefficient(psi.derivative(r,2))
1
sage: g.coefficient(psi.derivative(r,1))
2/r

Custom typesetting of symbolic functions in LaTeX, either using latex_name keyword:

sage: function('riemann', latex_name=r'\mathcal{R}')
riemann
sage: latex(riemann(x))
\mathcal{R}\left(x\right)
or passing a custom callable function that returns a latex expression:

sage: mu, nu = var('mu,nu')
sage: def my_latex_print(self, *args):
    return r'\psi_{' + ', '.join(map(latex, args)) + r'}'
sage: function('psi', print_latex_func=my_latex_print)
psi
sage: latex(psi(mu,nu))
\psi_{\mu, \nu}

Defining custom methods for automatic or numeric evaluation, derivation, conjugation, etc. is supported:

sage: def ev(self, x):
    return 2*x
sage: foo = function("foo", nargs=1, eval_func=ev)
sage: foo(x)
2*x
sage: foo = function("foo", nargs=1, eval_func=lambda self, x: 5)
sage: foo(x)
5
sage: def ef(self, x):
    pass
sage: bar = function("bar", nargs=1, eval_func=ef)
sage: bar(x)
bar(x)

sage: def evalf_f(self, x, parent=None, algorithm=None): return 6
sage: foo = function("foo", nargs=1, evalf_func=evalf_f)
sage: foo(x)
foo(x).
n() 6

sage: foo = function("foo", nargs=1, conjugate_func=ev)
sage: foo(x).conjugate()
2*x

sage: def deriv(self, *args, **kwds):
    print("{} {}".format(args, kwds)); return ...
sage: foo = function("foo", nargs=2, derivative_func=deriv)
```python
sage: foo(x,y).derivative(y)
(x, y) {'diff_param': 1}
y^2
sage: def pow(self, x, power_param=None): print("{} {}".format(x, power_param)); return x*power_param
sage: foo = function("foo", nargs=1, power_func=pow)
sage: foo(y)^(x+y)
y x + y
(x + y)*y
sage: from pprint import pformat
sage: def expand(self, *args, **kwds):
....: print("{} {}".format(args, pformat(kwds)))
....: return sum(args[0]^i for i in range(kwds['order']))
sage: foo = function("foo", nargs=1, series_func=expand)
sage: foo(y).series(y, 5)
y^4 + y^3 + y^2 + y + 1
sage: def my_print(self, *args):
....: return "my args are: " + ', '.join(map(repr, args))

sage: foo = function('t', nargs=2, print_func=my_print)
sage: foo(x,y^z)
my args are: x, y^z
sage: latex(foo(x,y^z))
t\left(x, y^{z}\right)
sage: foo = function('t', nargs=2, print_latex_func=my_print)
sage: foo(x,y^z)
t(x, y^z)
sage: latex(foo(x,y^z))
my args are: x, y^z
sage: foo = function('t', nargs=2, latex_name='foo')
sage: latex(foo(x,y^z))
foo\left(x, y^{z}\right)
```

Chain rule:
```
sage: def print_args(self, *args, **kwds):
....: print("args: {}".format(args)); print("kwds: {}".format(kwds)); return args[0]
sage: foo = function('t', nargs=2, tderivative_func=print_args)
sage: foo(x,x).derivative(x)
args: (x, x)
kwds: {'diff_param': x}
x
sage: foo = function('t', nargs=2, derivative_func=print_args)
sage: foo(x,x).derivative(x)
args: (x, x)
kwds: {'diff_param': 0}
args: (x, x)
kwds: {'diff_param': 1}
2*x
```

Since Sage 4.0, basic arithmetic with unevaluated functions is no longer supported:

2.30. Symbolic variables 325
sage: x = var('x')
sage: f = function('f')
sage: 2*f
Traceback (most recent call last):
  ...TypeError: unsupported operand parent(s) for *: 'Integer Ring' and '<class 'sage.symbolic.function_factory...NewSymbolicFunction'>'

You now need to evaluate the function in order to do the arithmetic:

sage: 2*f(x)
2*f(x)

Since Sage 4.0, you need to use substitute_function() to replace all occurrences of a function with another:

sage: var('a, b')
(a, b)
sage: cr = function('cr')
sage: f = cr(a)
sage: g = f.diff(a).integral(b)
sage: g
b*diff(cr(a), a)
sage: g.substitute_function(cr, cos)
-b*sin(a)
sage: g.substitute_function(cr, (sin(x) + cos(x)).function(x))
b*(cos(a) - sin(a))

sage.calculus.var.var(*args, **kwds)
Create a symbolic variable with the name s.

INPUT:

- args – A single string var('x y'), a list of strings var(['x', 'y']), or multiple strings var('x', 'y'). A single string can be either a single variable name, or a space or comma separated list of variable names. In a list or tuple of strings, each entry is one variable. If multiple arguments are specified, each argument is taken to be one variable. Spaces before or after variable names are ignored.
- kwds – keyword arguments can be given to specify domain and custom latex_name for variables. See EXAMPLES for usage.

Note: The new variable is both returned and automatically injected into the global namespace. If you need a symbolic variable in library code, you must use either SR.var() or SR.symbol().

OUTPUT:

If a single symbolic variable was created, the variable itself. Otherwise, a tuple of symbolic variables. The variable names are checked to be valid Python identifiers and a ValueError is raised otherwise.

EXAMPLES:

Here are the different ways to define three variables x, y, and z in a single line:

sage: var('x y z')
(x, y, z)
sage: var('x, y, z')
We define some symbolic variables:

```sage
sage: var('n xx yy zz')
(n, xx, yy, zz)
```

Then we make an algebraic expression out of them:

```sage
f = xx^n + yy^n + zz^n; f
xx^n + yy^n + zz^n
```

By default, var returns a complex variable. To define real or positive variables we can specify the domain as:

```sage
sage: x = var('x', domain=RR); x; x.conjugate()
x
x
sage: y = var('y', domain='real'); y.conjugate()
y
sage: y = var('y', domain='positive'); y.abs()
y
```

Custom latex expression can be assigned to variable:

```sage
sage: x = var('sui', latex_name="s_{u,i}"); x._latex_()
'\{s_{u,i}\}'
```

In notebook, we can also colorize latex expression:

```sage
sage: x = var('sui', latex_name='\color{red}\{s_{u,i}\}'); x._latex_()
'\{\color{red}\{s_{u,i}\}\}'
```

We can substitute a new variable name for \(n\):

```sage
f(n = var('sigma'))
xx^sigma + yy^sigma + zz^sigma
```

If you make an important built-in variable into a symbolic variable, you can get back the original value using `restore`:

```sage
sage: var('QQ RR')
(QQ, RR)
sage: QQ
QQ
sage: restore('QQ')
sage: QQ
Rational Field
```

We make two new variables separated by commas:
sage: var('theta, gamma')
(theta, gamma)
sage: theta^2 + gamma^3
gamma^3 + theta^2

The new variables are of type Expression, and belong to the symbolic expression ring:

sage: type(theta)
<type 'sage.symbolic.expression.Expression'>
sage: parent(theta)
Symbolic Ring

2.31 Operands

class sage.symbolic.getitem.OperandsWrapper
Bases: sage.structure.sage_object.SageObject

Operands wrapper for symbolic expressions.

EXAMPLES:

sage: x,y,z = var('x,y,z')
sage: e = x + x*y + z^y + 3*y*z; e
x*y + 3*y*z + x + z^y
sage: e.op[1]
3*y*z
sage: e.op[1,1]
z
sage: e.op[-1]
z^y
sage: e.op[1:]
[3*y*z, x, z^y]
sage: e.op[:2]
[x*y, 3*y*z]
sage: e.op[-2:]
[x, z^y]
sage: e.op[:−2]
[x*y, 3*y*z]
sage: e.op[-5]
Traceback (most recent call last):
  ... IndexError: operand index out of range, got -5, expect between -4 and 3
sage: e.op[5]
Traceback (most recent call last):
  ... IndexError: operand index out of range, got 5, expect between -4 and 3
sage: e.op[1,1,0]
Traceback (most recent call last):
  ... TypeError: expressions containing only a numeric coefficient, constant or symbol
  → have no operands
sage: e.op[:1.5]
Traceback (most recent call last):
  ... TypeError: slice indices must be integers or None or have an __index__ method
sage: e.op[:2:1.5]
Traceback (most recent call last):
...
ValueError: step value must be an integer

sage.symbolic.getitem.normalize_index_for_doctests(arg, nops)
Wrapper function to test normalize_index.
sage.symbolic.getitem.restore_op_wrapper(expr)

2.32 Access to Maxima methods

class sage.symbolic.maxima_wrapper.MaximaFunctionElementWrapper(obj, name)
Bases: sage.interfaces.interface.InterfaceFunctionElement

class sage.symbolic.maxima_wrapper.MaximaWrapper(exp)
Bases: sage.structure.sage_object.SageObject
Wrapper around Sage expressions to give access to Maxima methods.

We convert the given expression to Maxima and convert the return value back to a Sage expression. Tab completion and help strings of Maxima methods also work as expected.

EXAMPLES:

sage: t = log(sqrt(2) - 1) + log(sqrt(2) + 1); t
log(sqrt(2) + 1) + log(sqrt(2) - 1)
sage: u = t.maxima_methods(); u
MaximaWrapper(log(sqrt(2) + 1) + log(sqrt(2) - 1))
sage: type(u)
<class 'sage.symbolic.maxima_wrapper.MaximaWrapper'>
sage: u.logcontract()
log((sqrt(2) + 1)*(sqrt(2) - 1))
sage: u.logcontract().parent()
Symbolic Ring

sage()
Return the Sage expression this wrapper corresponds to.

EXAMPLES:

sage: t = log(sqrt(2) - 1) + log(sqrt(2) + 1); t
log(sqrt(2) + 1) + log(sqrt(2) - 1)
sage: u = t.maxima_methods().sage()
sage: u is t
True
2.33 Operators

```python
class sage.symbolic.operators.FDerivativeOperator(function, parameter_set)
    Bases: object

    EXAMPLES:
    sage: from sage.symbolic.operators import FDerivativeOperator
    sage: f = function('foo')
    sage: op = FDerivativeOperator(f, [0,1])
    sage: loads(dumps(op))
    D[0, 1](foo)

    change_function(new)
    Returns a new FDerivativeOperator with the same parameter set for a new function.
    sage: from sage.symbolic.operators import FDerivativeOperator
    sage: f = function('foo')
    sage: b = function('bar')
    sage: op = FDerivativeOperator(f, [0,1])
    sage: op.change_function(b)
    D[0, 1](bar)

    function()
    EXAMPLES:
    sage: from sage.symbolic.operators import FDerivativeOperator
    sage: f = function('foo')
    sage: op = FDerivativeOperator(f, [0,1])
    sage: op.function()
    foo

    parameter_set()
    EXAMPLES:
    sage: from sage.symbolic.operators import FDerivativeOperator
    sage: f = function('foo')
    sage: op = FDerivativeOperator(f, [0,1])
    sage: op.parameter_set()
    [0, 1]
```

`sage.symbolic.operators.add_vararg(first, *rest)`
Addition of a variable number of arguments.

**INPUT:**

- first, rest - arguments to add

**OUTPUT:** sum of arguments

**EXAMPLES:**

```python
sage: from sage.symbolic.operators import add_vararg
sage: add_vararg(1,2,3,4,5,6,7)
28
sage: F=(1+x+x^2)
sage: bool(F.operator()(*F.operands()) == F)
True
```

`sage.symbolic.operators.mul_vararg(first, *rest)`
Multiplication of a variable number of arguments.

**INPUT:**
• \texttt{args} - arguments to multiply

OUTPUT: product of arguments

EXAMPLES:

\begin{Verbatim}
sage: from sage.symbolic.operators import mul_vararg
sage: mul_vararg(9,8,7,6,5,4)
  60480
sage: G=x*cos(x)*sin(x)
sage: bool(G.operator()(*G.operands())==G)
  True
\end{Verbatim}

2.34 Substitution Maps

This object wraps Pynac \texttt{exmap} objects. These encode substitutions of symbolic expressions. The main use of this module is to hook into Pynac’s \texttt{subs()} methods and pass a wrapper for the substitution map back to Python.

\begin{classdef}
\texttt{sage.symbolic.substitution_map.SubstitutionMap}
\begin{_bases}
\texttt{sage.structure.sage_object.SageObject}
\end{bases}

\begin{methoddef}
\texttt{apply_to(expr, options)}
Apply the substitution to a symbolic expression

\end{methoddef}

\begin{example}
\begin{Verbatim}
sage: from sage.symbolic.substitution_map import make_map
sage: subs = make_map({x:x+1})
sage: subs.apply_to(x^2, 0)
(x + 1)^2
\end{Verbatim}
\end{example}

\begin{methoddef}
\texttt{make_map(subs_dict)}
Construct a new substitution map

\end{methoddef}

\begin{example}
\begin{Verbatim}
sage: from sage.symbolic.substitution_map import make_map
sage: make_map({x:x+1})
SubsMap
\end{Verbatim}
\end{example}

2.35 Benchmarks

Tests that will take a long time if something is wrong, but be very quick otherwise. See \url{https://wiki.sagemath.org/symbench}. The parameters chosen below are such that with pynac most of these take well less than a second, but would not even be feasible using Sage’s Maxima-based symbolics.

Problem R1

Important note. Below we do \texttt{s.expand().real()} because \texttt{s.real()} takes forever (TODO?).
Problem R2:

```python
sage: def hermite(n,y):
    ...:    if n == 1:
    ...:        return 2*y
    ...:    if n == 0:
    ...:        return 1
    ...:    return expand(2*y*hermite(n-1,y) - 2*(n-1)*hermite(n-2,y))
sage: hermite(15,var('y'))
```

```
32768*y^15 - 1720320*y^13 + 33546240*y^11 - 307507200*y^9 + 1383782400*y^7 - 2905943040*y^5 + 2421619200*y^3 - 518918400*y
```

Problem R3:

```python
sage: f = sum(var('x,y,z')); a = [bool(f==f) for _ in range(100000)]
```

Problem R4:

```python
sage: u=[e,pi,sqrt(2)]; Tuples(u,3).cardinality()
```

```
27
```

Problem R5:

```python
sage: def blowup(L,n):
    ...:    for i in [0..n]:
    ...:        L.append( (L[i] + L[i+1]) * L[i+2] )
sage: L = list(var('x,y,z'))
sage: blowup(L,15)
sage: len(set(L))
```

```
19
```

Problem R6:

```python
sage: sum(((x+sin(i))/x+(x-sin(i))/x) for i in range(100)).expand()
```

```
200
```

Problem R7:

```python
sage: f = x^24+34*x^12+45*x^3+9*x^18 +34*x^10+ 32*x^21
sage: a = [f(x=random()) for _ in range(10^4)]
```

Problem R10:

```python
sage: v = [float(z) for z in [-pi,-pi+1/100..,pi]]
```

Problem R11:

```python
sage: a = [random() + random()*I for w in [0..100]]
sage: a.sort()
```

Problem W3:
\textbf{PROBLEM S1:}

```python
sage: var('x,y,z')
sage: f = (x+y+z+1)^10
sage: g = expand(f*(f+1))
```

\textbf{PROBLEM S2:}

```python
sage: var('x,y')
sage: a = expand((x^sin(x) + y^cos(y) - z^(x+y))^100)
```

\textbf{PROBLEM S3:}

```python
sage: var('x,y,z')
sage: f = expand((x^y + y^z + z^x)^50)
sage: g = f.diff(x)
```

\textbf{PROBLEM S4:}

```python
w = (sin(x)*cos(x)).series(x,400)
```

### 2.36 Randomized tests of GiNaC / PyNaC

```python
sage.symbolic.random_tests.assert_strict_weak_order(a, b, c, cmp_func)
```

Check that \texttt{cmp\_func} is a strict weak order on the elements \texttt{a,b,c}.

A strict weak order is a binary relation \(<\text{ such that}\)

- For all \(x\), it is not the case that \(x < x\) (irreflexivity).
- For all \(x \neq y\), if \(x < y\) then it is not the case that \(y < x\) (asymmetry).
- For all \(x\), \(y\), and \(z\), if \(x < y\) and \(y < z\) then \(x < z\) (transitivity).
- For all \(x\), \(y\), and \(z\), if \(x\) is incomparable with \(y\), and \(y\) is incomparable with \(z\), then \(x\) is incomparable with \(z\) (transitivity of incomparability).

**INPUT:**

- \(a, b, c\) – anything that can be compared by \texttt{cmp\_func}.
- \texttt{cmp\_func} – function of two arguments that returns their comparison (i.e. either \texttt{True} or \texttt{False}).

**OUTPUT:**

Does not return anything. Raises a \texttt{ValueError} if \texttt{cmp\_func} is not a strict weak order on the three given elements.

**REFERENCES:**

Wikipedia article \texttt{Strict\_weak\_ordering}

**EXAMPLES:**

The usual ordering of integers is a strict weak order:
sage: from sage.symbolic.random_tests import assert_strict_weak_order
sage: a, b, c = [randint(-10, 10) for i in range(3)]

sage: assert_strict_weak_order(a, b, c, lambda x, y: x < y)

sage: x = [-SR(oo), SR(0), SR(oo)]

sage: cmp_M = matrix(3, 3, 0)

sage: for i in range(3):
    ....: for j in range(3):
    ....:     if x[i] < x[j]:
    ....:         cmp_M[i, j] = -1
    ....:     elif x[i] > x[j]:
    ....:         cmp_M[i, j] = 1

sage: cmp_M
\begin{bmatrix}
 0 & -1 & -1 \\
-1 & 0 & -1 \\
1 & 1 & 0
\end{bmatrix}

sage: from sage.symbolic.random_tests import assert_strict_weak_order
sage: a, b, c = [randint(-10, 10) for i in range(3)]

sage: assert_strict_weak_order(a, b, c, lambda x, y: x < y)

sage: x = [-SR(oo), SR(0), SR(oo)]

sage: cmp_M = matrix(3, 3, 0)

sage: for i in range(3):
    ....: for j in range(3):
    ....:     if x[i] < x[j]:
    ....:         cmp_M[i, j] = -1
    ....:     elif x[i] > x[j]:
    ....:         cmp_M[i, j] = 1

sage: cmp_M
\begin{bmatrix}
 0 & -1 & -1 \\
-1 & 0 & -1 \\
1 & 1 & 0
\end{bmatrix}

```
sage: from sage.symbolic.random_tests import assert_strict_weak_order
sage: a, b, c = [randint(-10, 10) for i in range(3)]

sage: assert_strict_weak_order(a, b, c, lambda x, y: x < y)

sage: x = [-SR(oo), SR(0), SR(oo)]

sage: cmp_M = matrix(3, 3, 0)

sage: for i in range(3):
    ....: for j in range(3):
    ....:     if x[i] < x[j]:
    ....:         cmp_M[i, j] = -1
    ....:     elif x[i] > x[j]:
    ....:         cmp_M[i, j] = 1

sage: cmp_M
\begin{bmatrix}
 0 & -1 & -1 \\
-1 & 0 & -1 \\
1 & 1 & 0
\end{bmatrix}
```

**sage.symbolic.random_tests.choose_from_prob_list** *(lst)*

**INPUT:**

- `lst` - A list of tuples, where the first element of each tuple is a nonnegative float (a probability), and the probabilities sum to one.

**OUTPUT:**

A tuple randomly selected from the list according to the given probabilities.

**EXAMPLES:**

```
sage: from sage.symbolic.random_tests import *

sage: v = [(0.1, False), (0.9, True)]

sage: choose_from_prob_list(v)
(0.900000000000000, True)

sage: true_count = 0

sage: for _ in range(10000):
    ....: if choose_from_prob_list(v)[1]:
    ....:     true_count += 1

sage: true_count
9033

sage: true_count - (10000 * 9/10)
33
```

```
sage: from sage.symbolic.random_tests import assert_strict_weak_order
sage: a, b, c = [randint(-10, 10) for i in range(3)]

sage: assert_strict_weak_order(a, b, c, lambda x, y: x < y)

sage: x = [-SR(oo), SR(0), SR(oo)]

sage: cmp_M = matrix(3, 3, 0)

sage: for i in range(3):
    ....: for j in range(3):
    ....:     if x[i] < x[j]:
    ....:         cmp_M[i, j] = -1
    ....:     elif x[i] > x[j]:
    ....:         cmp_M[i, j] = 1

sage: cmp_M
\begin{bmatrix}
 0 & -1 & -1 \\
-1 & 0 & -1 \\
1 & 1 & 0
\end{bmatrix}
```

**sage.symbolic.random_tests.normalize_prob_list** *(pl, extra=*())*

**INPUT:**

- `pl` - A list of tuples, where the first element of each tuple is a floating-point number (representing a relative probability). The second element of each tuple may be a list or any other kind of object.
- `extra` - A tuple which is to be appended to every tuple in `pl`.

This function takes such a list of tuples (a “probability list”) and normalizes the probabilities so that they sum to one. If any of the values are lists, then those lists are first normalized; then the probabilities in the list are multiplied by the main probability and the sublist is merged with the main list.

For example, suppose we want to select between group A and group B with 50% probability each. Then within group A, we select A1 or A2 with 50% probability each (so the overall probability of selecting A1 is 25%); and within group B, we select B1, B2, or B3 with probabilities in a 1:2:2 ratio.

**EXAMPLES:**
sage: from sage.symbolic.random_tests import *
sage: A = [(0.5, 'A1'), (0.5, 'A2')]
sage: B = [(1, 'B1'), (2, 'B2'), (2, 'B3')]
sage: top = [(50, A, 'Group A'), (50, B, 'Group B')]
sage: normalize_prob_list(top)
[(0.250000000000000, 'A1', 'Group A'), (0.250000000000000, 'A2', 'Group A'), (0.1, 'B1', 'Group B'), (0.2, 'B2', 'Group B'), (0.2, 'B3', 'Group B')]
sage.symbolic.random_tests.random_expr(size, nvars=1, ncoeffs=None, var_frac=0.5, internal=[(0.6, [(0.3, <built-in function add>), (0.1, <built-in function sub>), (0.3, <built-in function mul>), (0.2, <built-in function true_div>), (0.1, <built-in function pow>), (0.2, [(0.8, <built-in function neg>), (0.2, <built-in function inv>)]), 1], (0.2, [(1.0, Ei), (1.0, Order), (1.0, abs), (1.0, airy_ai), (1.0, airy_ai_prime), (1.0, airy_bi), (1.0, airy_bi_prime), (1.0, arccos), (1.0, arccot), (1.0, arccoth), (1.0, arcsec), (1.0, arcsech), (1.0, arcsin), (1.0, arctan), (1.0, arctan2), (1.0, arctanh), (1.0, arg), (1.0, bessel_J), (1.0, bessel_Y), (1.0, bessel_K), (1.0, beta), (1.0, binomial), (1.0, ceil), (1.0, chebyshev_T), (1.0, chebyshev_U), (1.0, complex_root_of), (1.0, conjugate), (1.0, cos), (1.0, cos_integral), (1.0, cosh), (1.0, cot), (1.0, coth), (1.0, csc), (1.0, csch), (1.0, dickman_rho), (1.0, dilog), (1.0, dirac_delta), (1.0, elliptic_e), (1.0, elliptic_ec), (1.0, elliptic_en), (1.0, elliptic_f), (1.0, elliptic_kc), (1.0, elliptic_pi), (1.0, erf), (1.0, erfc), (1.0, erfci), (1.0, erfiv), (1.0, exp), (1.0, exp_integral_e), (1.0, exp_integral_e1), (1.0, exp_integ}, (1.0, frac), (1.0, fresnel_cos), (1.0, fresnel_sin), (1.0, gamma_inc_lower), (1.0, gegenbauer), (1.0, gen_laguerre), (1.0, gen_legendre_P), (1.0, gen_legendre_Q), (1.0, hermite), (1.0, harmonic_number), (1.0, heaviside), (1.0, hermite), (1.0, hurwitz_zeta), (1.0, hypergeometric_M), (1.0, hypergeometric_U), (1.0, integrate), (1.0, inverse_jacobi_cd), (1.0, inverse_jacobi_cn), (1.0, inverse_jacobi_cs), (1.0, inverse_jacobi_dc), (1.0, inverse_jacobi_ds), (1.0, inverse_jacobi_nc), (1.0, inverse_jacobi_sn), (1.0, jacobi_P), (1.0, jacobi_am), (1.0, jacobi_cd), (1.0, jacobi_cn), (1.0, jacobi_cs), (1.0, jacobi_dc), (1.0, jacobi_sn), (1.0, kronecker_delta), (1.0, laguerre), (1.0, lambert_w), (1.0, legendre_P), (1.0, legendre_Q), (1.0, log), (1.0, log_chapman), (1.0, log_integ}, (1.0, log_integ_offset), (1.0, polylog), (1.0, prime_pi), (1.0, product), (1.0, real_nth_root), (1.0, real_part), (1.0, sec), (1.0, sech), (1.0, sgn), (1.0, sinh), (1.0, sinh_integral), (1.0, spherical_hankel1), (1.0, spherical_hankel2), (1.0, spherical_harmonic), (1.0, stieltjes), (1.0, struve_H), (1.0, struve_L), (1.0, sum,
Produce a random symbolic expression of the given size. By default, the expression involves (at most) one variable, an arbitrary number of coefficients, and all of the symbolic functions and constants (from the probability lists full_internal and full_nullary). It is possible to adjust the ratio of leaves between symbolic constants, variables, and coefficients (var_frac gives the fraction of variables, and nullary_frac the fraction of symbolic constants; the remaining leaves are coefficients).

The actual mix of symbolic constants and internal nodes can be modified by specifying different probability lists.

To use a different type for coefficients, you can specify coeff_generator, which should be a function that will return a random coefficient every time it is called.

This function will often raise an error because it tries to create an erroneous expression (such as a division by zero).

EXAMPLES:

```python
sage: from sage.symbolic.random_tests import *
sage: some_functions = [arcsinh, arctan, arctan2, arctanh, ...
                      arg, beta, binomial, ceil, conjugate, cos, cosh, cot, coth, ...
                      elliptic_pi, erf, exp, factorial, floor, heaviside, imag_part, ...
                      sech, sgn, sin, sinh, tan, tanh, unit_step, zeta, zetaderiv]
sage: my_internal = [(0.6, full_binary, 2), (0.2, full_unary, 1), ...
                   (0.2, [(1.0,f,f.number_of_arguments()) for f in some_functions])]
sage: set_random_seed(1)
sage: random_expr(50, nvars=3, internal=my_internal, ...
                   coeff_generator=CDF.random_element)
(v1^(0.9713408427702117 + 0.195868299334218*I)/cot(-pi + v1^2 + v3) +
 → tan(arctan(v2 + arctan2(-0.35859061674557324 + 0.9407509502498164*I, v3) - 0.
→ 8419115504372718 + 0.30375717982404615*I) + arctan2((0.2275357305882964 - 0.
→ 8258002386106038*I)/factorial(v2), -v3 - 0.7604559947718565 - 0.
→ 5543672548552057*I) + ceil(1/arctan2(v1, v1)))/v2
sage: random_expr(5, verbose=True)  # random
About to apply <built-in function inv> to [31]
About to apply sgn to [v1]
About to apply <built-in function add> to [1/31, sgn(v1)]
sgn(v1) + 1/31
```

sage.symbolic.random_tests.random_expr_helper (n_nodes, internal, leaves, verbose)

Produce a random symbolic expression of size n_nodes (or slightly larger). Internal nodes are selected from the internal probability list; leaves are selected from leaves. If verbose is True, then a message is printed before creating an internal node.

EXAMPLES:

```python
sage: from sage.symbolic.random_tests import *
sage: random_expr_helper(9, [(0.5, operator.add, 2), ...
                         (0.5, operator.neg, 1)], [(0.5, 1), (0.5, x)], True)
About to apply <built-in function add> to [1, x]
About to apply <built-in function add> to [x, x + 1]
About to apply <built-in function neg> to [1]
About to apply <built-in function neg> to [-1]
About to apply <built-in function neg> to [1]
About to apply <built-in function add> to [2*x + 1, -1]
2*x
```

sage.symbolic.random_tests.random_integer_vector (n, length)

Give a random list of length length, consisting of nonnegative integers that sum to n.

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This is an approximation to IntegerVectors(n, length).random_element(). That gives values uniformly at random, but might be slow; this routine is not uniform, but should always be fast.

(This routine is uniform if length is 1 or 2; for longer vectors, we prefer approximately balanced vectors, where all the values are around $n/\text{length}$.)

EXAMPLES:

```python
sage: from sage.symbolic.random_tests import *
sage: random_integer_vector(100, 2)
[11, 89]
sage: random_integer_vector(100, 2)
[51, 49]
sage: random_integer_vector(100, 2)
[4, 96]
sage: random_integer_vector(10000, 20)
[332, 529, 185, 738, 82, 964, 596, 892, 732, 134, 834, 765, 398, 608, 358, 300, 652, 249, 586, 66]
sage.symbolic.random_tests.test_symbolic_expression_order(repetitions=100)
```

Tests whether the comparison of random symbolic expressions satisfies the strict weak order axioms.

This is important because the C++ extension class uses `std::sort()` which requires a strict weak order. See also trac ticket #9880.

EXAMPLES:

```python
sage: from sage.symbolic.random_tests import test_symbolic_expression_order
tsage: test_symbolic_expression_order(200)
tsage: test_symbolic_expression_order(10000)
# long time
```

2.37 Pynac interface

sage.libs.pynac.pynac.doublefactorial(n)

The double factorial combinatorial function:

\[ n!! = n \times (n-2) \times (n-4) \times \ldots \times (2|1) \] with \( 0!! = 1 \)!! = 1.

INPUT:

- \( n \) – an integer \( \geq 1 \)

EXAMPLES:

```python
sage: from sage.libs.pynac.pynac import doublefactorial
dsage: doublefactorial(-1)
1
dsage: doublefactorial(0)
1
dsage: doublefactorial(1)
1
dsage: doublefactorial(5)
15
dsage: doublefactorial(20)
3715891200
sage: prod( [20,18,...,2] )
3715891200
```

Chapter 2. Internal functionality supporting calculus
sage.libs.pynac.pynac.get_fn_serial()
Return the overall size of the Pynac function registry which corresponds to the last serial value plus one.

EXAMPLES:

```
sage: from sage.libs.pynac.pynac import get_fn_serial
gsf = get_fn_serial()
sage: get_fn_serial() > 125
True
sage: print(get_sfunction_from_serial(get_fn_serial()))
None
sage: get_sfunction_from_serial(get_fn_serial() - 1) is not None
True
```

sage.libs.pynac.pynac.get_ginac_serial()
Number of C++ level functions defined by GiNaC. (Defined mainly for testing.)

EXAMPLES:

```
sage: get_ginac_serial() >= 35
True
```

sage.libs.pynac.pynac.init_function_table()
Initializes the function pointer table in Pynac. This must be called before Pynac is used; otherwise, there will be segfaults.

sage.libs.pynac.pynac.init_pynac_I()
Initialize the numeric I object in pynac. We use the generator of QQ(i).

EXAMPLES:

```
sage: I
I
sage: I^2
-1
```

Note that conversions to real fields will give TypeErrors:

```
sage: float(I)
Traceback (most recent call last):
... TypeError: unable to simplify to float approximation
sage: RR(I)
I
```

We can convert to complex fields:

```
sage: C = ComplexField(200); C
Complex Field with 200 bits of precision
sage: I
1.0000000000000000000000000000000000000000000000000000000000*I
sage: I._complex_mpfr_field_(ComplexField(53))
1.00000000000000*I
sage: I._complex_double_(CDF)
```
(continues on next page)
1.0*I
sage: CDF(I)
1.0*I

sage: z = I + I; z
2*I

sage: C(z)
2.0000000000000000000000000000000000000000000000000000000000*I

sage: 1e8*I
1.00000000000000e8*I

sage: complex(I)
lj

sage: QQbar(I)
I

sage: abs(I)
1

sage: I.minpoly()
x^2 + 1

sage: maxima(2*I)
2*%i

EXAMPLES:

sage: from sage.libs.pynac.pynac import paramset_from_Expression
sage: paramset_from_Expression(f(x).diff(x))
[0L] # 32-bit
[0] # 64-bit

sage: from sage.libs.pynac.pynac import py_atan2_for_doctests
sage: py_atan2_for_doctests(x,y)
Wrapper function to test py_atan2.

sage: from sage.libs.pynac.pynac import py_denom_for_doctests
sage: py_denom_for_doctests(n)
This function is used to test py_denom().

EXAMPLES:

sage: from sage.libs.pynac.pynac import py_eval_infinity_for_doctests
sage: py_eval_infinity_for_doctests()
This function tests py_eval_infinity.

sage: from sage.libs.pynac.pynac import py_eval_neg_infinity_for_doctests
sage: py_eval_neg_infinity_for_doctests()
This function tests py_eval_neg_infinity.

sage: from sage.libs.pynac.pynac import py_eval_unsigned_infinity_for_doctests
sage: py_eval_unsigned_infinity_for_doctests()
This function tests py_eval_unsigned_infinity.

sage: from sage.libs.pynac.pynac import py_exp_for_doctests
sage: py_exp_for_doctests(x)
This function tests py_exp.

EXAMPLES:
sage: from sage.libs.pynac.pynac import py_exp_for_doctests
sage: py_exp_for_doctests(CC(2))
7.38905609893065

sage.libs.pynac.pynac.py_factorial_py(x)
This function is a python wrapper around py_factorial(). This wrapper is needed when we override the eval() method for GiNaC’s factorial function in sage.functions.other.Function_factorial.

sage.libs.pynac.pynac.py_float_for_doctests(n, kwds)
This function is for testing py_float.

EXAMPLES:

sage: from sage.libs.pynac.pynac import py_float_for_doctests
sage: py_float_for_doctests(pi, {'parent':RealField(80)})
3.1415926535897932384626
sage: py_float_for_doctests(I, {'parent':RealField(80)})
1.0000000000000000000000*I
sage: py_float_for_doctests(I, {'parent':float})
1j
sage: py_float_for_doctests(pi, {'parent':complex})
(3.141592653589793+0j)

sage.libs.pynac.pynac.py_imag_for_doctests(x)
Used for doctesting py_imag.

sage.libs.pynac.pynac.py_is_cinteger_for_doctest(x)
Returns True if pynac should treat this object as an element of \( \mathbb{Z} \).

sage.libs.pynac.pynac.py_is_crational_for_doctest(x)
Returns True if pynac should treat this object as an element of \( \mathbb{Q} \).

sage.libs.pynac.pynac.py_is_integer_for_doctests(x)
Used internally for doctesting purposes.

sage.libs.pynac.pynac.py_latex_fderivative_for_doctests(id, params, args)
Used internally for writing doctests for certain cdef’d functions.

EXAMPLES:

sage: from sage.libs.pynac.pynac import py_latex_fderivative_for_doctests as py_˓→latex_fderivative, get_ginac_serial, get_fn_serial
sage: var('x,y,z')
(x, y, z)
sage: from sage.symbolic.function import get_sfunction_from_serial
sage: foo = function('foo', nargs=2)
sage: for i in range(get_ginac_serial(), get_fn_serial()):
  ....: if get_sfunction_from_serial(i) == foo: break
sage: get_sfunction_from_serial(i) == foo
True
sage: py_latex_fderivative(i, (0, 1, 0, 1), (x, y^z))
\text{D}_{0, 1, 0, 1}\left({\rm foo}\right)\left(x, y^{z}\right)

Test latex_name:

sage: foo = function('foo', nargs=2, latex_name=r'\text{bar}')
sage: for i in range(get_ginac_serial(), get_fn_serial()):
  (continues on next page)
....:    if get_sfunction_from_serial(i) == foo: break

sage: get_sfunction_from_serial(i) == foo
True
sage: py_latex_fderivative(i, (0, 1, 0, 1), (x, y^z))
\mathrm{D}_{0, 1, 0, 1}\left(\mathrm{bar}\right)\left(x, y^{z}\right)

Test custom func:

sage: def my_print(self, *args): return "func_with_args(\" + ', '.join(map(repr, args)) +\")"

sage: foo = function('foo', nargs=2, print_latex_func=my_print)

sage: for i in range(get_ginac_serial(), get_fn_serial()):
....:    if get_sfunction_from_serial(i) == foo: break

sage: get_sfunction_from_serial(i) == foo
True
sage: py_latex_fderivative(i, (0, 1, 0, 1), (x, y^z))
\mathrm{D}_{0, 1, 0, 1}\left(func_with_args(x, y^{z}\right)

sage.libs.pynac.pystring\(\) returns a string with the latex representation of the symbolic function specified by the given id applied to args.

See documentation of \texttt{py\_print\_function\_pystring} for more information.

\textbf{EXAMPLES:}

\begin{verbatim}
\texttt{sage: from sage.libs.pynac imported py\_latex\_function\_pystring, get\_ginac\_\rightarrow serial, get\_fn\_serial}
\texttt{sage: from sage.symbolic.function import get\_sfunction\_from\_serial}
\texttt{sage: var('x,y,z')}
\texttt{(x, y, z)}
\texttt{sage: foo = function('foo', nargs=2)}
\texttt{sage: for i in range(get\_ginac\_serial(), get\_fn\_serial()):}
....:    if get\_sfunction\_from\_serial(i) == foo: break

\texttt{sage: get\_sfunction\_from\_serial(i) == foo}
True
\texttt{sage: py\_latex\_function\_pystring(i, (x,y^z))}
'\{\rm foo\}\left(x, y^{z}\right)'
\end{verbatim}

Test latex_name:

\begin{verbatim}
\texttt{sage: foo = function('foo', nargs=2, latex_name=r'\mathrm{bar}')}
\texttt{sage: for i in range(get\_ginac\_serial(), get\_fn\_serial()):}
....:    if get\_sfunction\_from\_serial(i) == foo: break

\texttt{sage: get\_sfunction\_from\_serial(i) == foo}
True
\texttt{sage: py\_latex\_function\_pystring(i, (x,y^z))}
'\left(\{\mathrm{foo}\}\right)\left(x, y^{z}\right)'
\end{verbatim}

Test custom func:

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sage: def my_print(self, *args): return "my args are: " + ', '.join(map(repr, args))
sage: foo = function('foo', nargs=2, print_latex_func=my_print)
sage: for i in range(get_ginac_serial(), get_fn_serial()):
    ....: if get_sfunction_from_serial(i) == foo: break
sage: get_sfunction_from_serial(i) == foo
True
sage: py_latex_function_pystring(i, (x,y^z))
"my args are: x, y^z"

sage.libs.pynac.pynac.py_latex_variable_for_doctests(x)
Internal function used so we can doctest a certain cdef’d method.

EXAMPLES:

sage: sage.libs.pynac.pynac.py_latex_variable_for_doctests('x')
x
sage: sage.libs.pynac.pynac.py_latex_variable_for_doctests('sigma')
\sigma

sage.libs.pynac.pynac.py_lgamma_for_doctests(x)
This function tests py_lgamma.

EXAMPLES:

sage: from sage.libs.pynac.pynac import py_lgamma_for_doctests
sage: py_lgamma_for_doctests(CC(I))
-0.650923199301856 - 1.87243664726243*I

sage.libs.pynac.pynac.py_li2_for_doctests(x)
This function is a python wrapper so py_psi2 can be tested. The real tests are in the docstring for py_psi2.

EXAMPLES:

sage: from sage.libs.pynac.pynac import py_li2_for_doctests
sage: py_li2_for_doctests(-1.1)
-0.890838090262283

sage.libs.pynac.pynac.py_li_for_doctests(x, n, parent)
This function is a python wrapper so py_li can be tested. The real tests are in the docstring for py_li.

EXAMPLES:

sage: from sage.libs.pynac.pynac import py_li_for_doctests
sage: py_li_for_doctests(0,2,float)
0.000000000000000

sage.libs.pynac.pynac.py_log_for_doctests(x)
This function tests py_log.

EXAMPLES:

sage: from sage.libs.pynac.pynac import py_log_for_doctests
sage: py_log_for_doctests(CC(e))
1.00000000000000

sage.libs.pynac.pynac.py_mod_for_doctests(x, n)
This function is a python wrapper so py_mod can be tested. The real tests are in the docstring for py_mod.

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EXAMPLES:

```python
sage: from sage.libs.pynac.pynac import py_mod_for_doctests
sage: py_mod_for_doctests(5, 2)
1
```

`sage.libs.pynac.pynac.py_numer_for_doctests(n)`
This function is used to test `py_numer()`.

EXAMPLES:

```python
sage: from sage.libs.pynac.pynac import py_numer_for_doctests
sage: py_numer_for_doctests(2/3)
2
```

`sage.libs.pynac.pynac.py_print_fderivative_for_doctests(id, params, args)`
Used for testing a `cdef`d function.

EXAMPLES:

```python
sage: from sage.libs.pynac.pynac import py_print_fderivative_for_doctests as py___print_fderivative, get_ginac_serial, get_fn_serial
sage: var('x,y,z')
(x, y, z)
sage: from sage.symbolic.function import get_sfunction_from_serial
sage: foo = function('foo', nargs=2)
sage: for i in range(get_ginac_serial(), get_fn_serial()):
    ....:     if get_sfunction_from_serial(i) == foo:
        break
sage: get_sfunction_from_serial(i) == foo
True
sage: py_print_fderivative(i, (0, 1, 0, 1), (x, y^z))
D[0, 1, 0, 1](foo)(x, y^z)
```

Test custom print function:

```python
sage: def my_print(self, *args): return "func_with_args(" + ', '.join(map(repr, args)) + '")'
sage: foo = function('foo', nargs=2, print_func=my_print)
sage: for i in range(get_ginac_serial(), get_fn_serial()):
    ....:     if get_sfunction_from_serial(i) == foo:
        break
sage: get_sfunction_from_serial(i) == foo
True
sage: py_print_fderivative(i, (0, 1, 0, 1), (x, y^z))
D[0, 1, 0, 1]func_with_args(x, y^z)
```

`sage.libs.pynac.pynac.py_print_function_pystring(id, args, fname_paren=False)`
Return a string with the representation of the symbolic function specified by the given id applied to args.

INPUT:

- `id` – serial number of the corresponding symbolic function
- `params` – Set of parameter numbers with respect to which to take the derivative.
- `args` – arguments of the function.

EXAMPLES:
sage: from sage.libs.pynac.pynac import py_print_function_pystring, get_ginac__serial, get_fn_serial
sage: from sage.symbolic.function import get_sfunction_from_serial
sage: var('x,y,z')
(x, y, z)
sage: foo = function('foo', nargs=2)
sage: for i in range(get_ginac_serial(), get_fn_serial()):
    ....: if get_sfunction_from_serial(i) == foo: break
sage: get_sfunction_from_serial(i) == foo
True
sage: py_print_function_pystring(i, (x,y))
'foo(x, y)'
sage: py_print_function_pystring(i, (x,y), True)
'(foo)(x, y)'
sage: def my_print(self, *args):
    return "my args are: " + ', '.join(map(repr,
args))
sage: foo = function('foo', nargs=2, print_func=my_print)
sage: for i in range(get_ginac_serial(), get_fn_serial()):
    ....: if get_sfunction_from_serial(i) == foo: break
sage: get_sfunction_from_serial(i) == foo
True
sage: py_print_function_pystring(i, (x,y))
'my args are: x, y'

sage.libs.pynac.pynac.py_psi2_for_doctests(n, x)
This function is a python wrapper so py_psi2 can be tested. The real tests are in the docstring for py_psi2.

EXAMPLES:
sage: from sage.libs.pynac.pynac import py_psi2_for_doctests
sage: py_psi2_for_doctests(1, 2)
0.644934066848226

sage.libs.pynac.pynac.py_psi_for_doctests(x)
This function is a python wrapper so py_psi can be tested. The real tests are in the docstring for py_psi.

EXAMPLES:
sage: from sage.libs.pynac.pynac import py_psi_for_doctests
sage: py_psi_for_doctests(2)
0.422784335098467

sage.libs.pynac.pynac.py_real_for_doctests(x)
Used for doctesting py_real.

sage.libs.pynac.pynac.py_stieltjes_for_doctests(x)
This function is for testing py_stieltjes().

EXAMPLES:
sage: from sage.libs.pynac.pynac import py_stieltjes_for_doctests
sage: py_stieltjes_for_doctests(0.0)
0.577215664901533

sage.libs.pynac.pynac.py_tgamma_for_doctests(x)
This function is for testing py_tgamma().
This function is for testing py_zeta().

EXAMPLES:

```python
sage: from sage.libs.pynac.pynac import py_zeta_for_doctests
sage: py_zeta_for_doctests(CC.0)
0.00330022368532410 - 0.418155449141322*I
```

Add an object to the symbol table, along with how to convert it to other systems such as Maxima, Mathematica, etc. This table is used to convert from other systems back to Sage.

INPUT:

- `obj` – a symbolic object or function.
- `conversions` – a dictionary of conversions, where the keys are the names of interfaces (e.g., ‘maxima’), and the values are the string representation of `obj` in that system.

EXAMPLES:

```python
sage: sage.libs.pynac.pynac.register_symbol(SR(5),{'maxima':'five'})
sage: SR(maxima_calculus('five'))
5
```

The Binomial coefficients. It computes the binomial coefficients. For integer `n` and `k` and positive `n` this is the number of ways of choosing `k` objects from `n` distinct objects. If `n` is negative, the formula `binomial(n,k) == (-1)^k*binomial(k-n-1,k)` is used to compute the result.

INPUT:

- `n, k` – integers, with `k` >= 0.

OUTPUT:

integer

EXAMPLES:

```python
sage: import sage.libs.pynac.pynac
sage: sage.libs.pynac.pynac.test_binomial(5,2)
10
sage: sage.libs.pynac.pynac.test_binomial(-5,3)
-35
sage: -sage.libs.pynac.pynac.test_binomial(3-(-5)-1, 3)
-35
```

Utility function to test if something is a symbol.

Returns False for arguments that do not have an `is_symbol` attribute. Returns the result of calling the `is_symbol` method otherwise.

EXAMPLES:

```python
sage: from sage.libs.pynac.pynac import tolerant_is_symbol
sage: tolerant_is_symbol(var("x"))
True
sage: tolerant_is_symbol(None)
False
```
False

```
sage: None.is_symbol()
Traceback (most recent call last):
...
AttributeError: 'NoneType' object has no attribute 'is_symbol'
```

sage.libs.pynac.pynac.unpack_operands(ex)

**EXAMPLES:**

```
sage: from sage.libs.pynac.pynac import unpack_operands
sage: t = SR._force_pyobject((1, 2, x, x+1, x+2))
sage: unpack_operands(t)
(1, 2, x, x + 1, x + 2)
sage: type(unpack_operands(t))
<... 'tuple'>
sage: list(map(type, unpack_operands(t)))
[<type 'sage.rings.integer.Integer'>, <type 'sage.rings.integer.Integer'>, <type 'sage.symbolic.expression.Expression'>, <type 'sage.symbolic.expression.Expression'>, <type 'sage.symbolic.expression.Expression'>]
sage: u = SR._force_pyobject((t, x^2))
sage: unpack_operands(u)
((1, 2, x, x + 1, x + 2), x^2)
sage: type(unpack_operands(u)[0])
<... 'tuple'>
```
CHAPTER THREE

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