

SYMPY: SYMBOLIC COMPUTING IN PYTHON

ONDŘEJ ČERTÍK*, ISURU FERNANDO†, AND ASHUTOSH SABOO‡

1. Introduction.

2. Architecture.

2.1. The Core. The core of a computer algebra system (CAS) refers to the module that is in charge of resending symbolic expressions and performing basic manipulations with them. In SymPy, every symbolic expression is an instance of a Python class. Expressions are represented by expression trees. The operators are represented by the type of an expression and the child nodes are stored in the `args` attribute. A leaf node in the expression tree has an empty `args`. The `args` attribute is provided by the class `Basic`, which is a superclass of all SymPy objects and provides common methods to all SymPy tree-elements. For example, consider the expression $xy + 2$:

```
>>> from sympy import *
>>> x, y = symbols('x y')
>>> expr = x*y + 2
```

The expression `expr` is an addition, so it is of type `Add`. The child nodes of `expr` are `x*y` and `2`.

```
>>> type(expr)
<class 'sympy.core.add.Add'>
>>> expr.args
(2, x*y)
```

We can dig further into the expression tree to see the full expression. For example, the first child node, given by `expr.args[0]` is `2`. Its class is `Integer`, and it has empty `args`, indicating that it is a leaf node.

```
>>> expr.args[0]
2
>>> type(expr.args[0])
<class 'sympy.core.numbers.Integer'>
>>> expr.args[0].args
()
```

The function `srepr` gives a string representing a valid Python code, containing all the nested class constructor calls to create the given expression.

```
>>> srepr(expr)
"Add(Mul(Symbol('x'), Symbol('y')), Integer(2))"
```

Every SymPy expression satisfies a key invariant, namely, `expr.func(*expr.args) == expr`. This means that expressions are rebuildable from their `args`¹. Here, we note that in SymPy, the `==` operator represents exact structural equality, not mathematical equality. This allows one to test if any two expressions are equal to one another as expression trees.

*Los Alamos National Laboratory (ondrej.certik@gmail.com).

†University of Moratuwa (isuru.11@cse.mrt.ac.lk).

‡Birla Institute of Technology and Science, Pilani, K.K. Birla Goa Campus (ashutosh.saboo@gmail.com).

¹`expr.func` is used instead of `type(expr)` to allow the function of an expression to be distinct from its actual Python class. In most cases the two are the same.

Python allows classes to overload operators. The Python interpreter translates the above `x*y + 2` to, roughly, `(x.__mul__(y)).__add__(2)`. `x` and `y`, returned from the `symbols` function, are `Symbol` instances. The `2` in the expression is processed by Python as a literal, and is stored as Python's builtin `int` type. When `2` is called by the `__add__` method, it is converted to the SymPy type `Integer(2)`. In this way, SymPy expressions can be built in the natural way using Python operators and numeric literals.

One must be careful in one particular instance. Python does not have a builtin rational literal type. Given a fraction of integers such as `1/2`, Python will perform floating point division and produce `0.5`². Python uses eager evaluation, so expressions like `x + 1/2` will produce `x + 0.5`, and by the time any SymPy function sees the `1/2` it has already been converted to `0.5` by Python. However, for a CAS like SymPy, one typically wants to work with exact rational numbers whenever possible. Working around this is simple, however: one can wrap one of the integers with `Integer`, like `x + Integer(1)/2`, or using `x + Rational(1, 2)`. SymPy provides a function `S` which can be used to convert objects to SymPy types with minimal typing, such as `x + S(1)/2`. This gotcha is a small downside to using Python directly instead of a custom domain specific language (DSL), and we consider it to be worth it for the advantages listed above.

2.2. Assumptions. An important feature of the SymPy core is the assumptions system. The assumptions system allows users to specify that symbols have certain common mathematical properties, such as being positive, imaginary, or integer. SymPy is careful to never perform simplifications on an expression unless the assumptions allow them. For instance, the identity $\sqrt{x^2} = x$ holds if x is nonnegative ($x \geq 0$). If x is real, the identity $\sqrt{x^2} = |x|$ holds. However, for general complex x , no such identity holds.

By default, SymPy performs all calculations assuming that variables are complex valued. This assumption makes it easier to treat mathematical problems in full generality.

```
>>> x = Symbol('x')
>>> sqrt(x**2)
sqrt(x**2)
```

By assuming symbols are complex by default, SymPy avoids performing mathematically invalid operations. However, in many cases users will wish to simplify expressions containing terms like $\sqrt{x^2}$.

Assumptions are set on `Symbol` objects when they are created. For instance `Symbol('x', positive=True)` will create a symbol named `x` that is assumed to be positive.

```
>>> x = Symbol('x', positive=True)
>>> sqrt(x**2)
x
```

Some common assumptions that SymPy allows are `positive`, `negative`, `real`, `nonpositive`, `nonnegative`, `real`, `integer`, and `commutative`³. Assumptions on any object can be checked with the `is_assumption` attributes, like `x.is_positive`.

Assumptions are only needed to restrict a domain so that certain simplifications

²This is the behavior in Python 3. In Python 2, `1/2` will perform integer division and produce `0`, unless one uses `from __future__ import division`.

³If A and B are Symbols created with `commutative=False` then SymPy will keep $A \cdot B$ and $B \cdot A$ distinct.

can be performed. It is not required to make the domain match the input of a function. For instance, one can create the object $\sum_{n=0}^m f(n)$ as `Sum(f(n), (n, 0, m))` without setting `integer=True` when creating the Symbol object `n`.

The assumptions system additionally has deductive capabilities. The assumptions use a three-valued logic using the Python builtin objects `True`, `False`, and `None`. `None` represents the “unknown” case. This could mean that the given assumption could be either true or false under the given information, for instance, `Symbol('x', real=True).is_positive` will give `None` because a real symbol might be positive or it might not. It could also mean not enough is implemented to compute the given fact, for instance, `(pi + E).is_irrational` gives `None`, because SymPy does not know how to determine if $\pi + e$ is rational or irrational, indeed, it is an open problem in mathematics.

Basic implications between the facts are used to deduce assumptions. For instance, the assumptions system knows that being an integer implies being rational, so `Symbol('x', integer=True).is_rational` returns `True`. Furthermore, expressions compute the assumptions on themselves based on the assumptions of their arguments. For instance, if `x` and `y` are both created with `positive=True`, then `(x + y).is_positive` will be `True`.

SymPy also has an experimental assumptions system where facts are stored separate from objects, and deductions are made with a SAT solver. We will not discuss this system here.

2.3. Extensibility. Extensibility is an important feature for SymPy. Because the same language, Python, is used both for the internal implementation and the external usage by users, all the extensibility capabilities available to users are also used by functions that are part of SymPy.

The typical way to create a custom SymPy object is to subclass an existing SymPy class, generally either `Basic`, `Expr`, or `Function`. All SymPy classes used for expression trees⁴ should be subclasses of the base class `Basic`, which defines some basic methods for symbolic expression trees. `Expr` is the subclass for mathematical expressions that can be added and multiplied together. Instances of `Expr` typically represent complex numbers, but may also include other “rings” like matrix expressions. Not all SymPy classes are subclasses of `Expr`. For instance, logic expressions, such as `And(x, y)` are subclasses of `Basic` but not of `Expr`.

The `Function` class is a subclass of `Expr` which makes it easier to define mathematical functions called with arguments. This includes named functions like $\sin(x)$ and $\log(x)$ as well as undefined functions like $f(x)$. Subclasses of `Function` should define a class method `eval`, which returns values for which the function should be automatically evaluated, and `None` for arguments that shouldn’t be automatically evaluated.

The behavior of classes in SymPy with various other SymPy functions is defined by defining a relevant `_eval_*` method on the class. For instance, an object can tell SymPy’s `diff` function how to take the derivative of itself by defining the `_eval_derivative(self, x)` method. The most common `_eval_*` methods relate to the assumptions. `_eval_is_assumption` defines the assumptions for *assumption*.

As an example of the notions presented in this section, we present below a stripped down version of the gamma function $\Gamma(x)$ from SymPy, which evaluates itself on positive integer arguments, has the positive and real assumptions defined, can be

⁴Some internal classes, such as those used in the polynomial module, do not follow this rule for efficiency reasons.

```

132 rewritten in terms of factorial with gamma(x).rewrite(factorial), and can be dif-
133 ferentiated. fdiff is a convenience method for subclasses of Function. fdiff returns
134 the derivative of the function without worrying about the chain rule. self.func is
135 used throughout instead of referencing gamma explicitly so that potential subclasses
136 of gamma can reuse the methods.
137 from sympy import Integer, Function, floor, factorial, polygamma
138
139 class gamma(Function)
140     @classmethod
141     def eval(cls, arg):
142         if isinstance(arg, Integer) and arg.is_positive:
143             return factorial(arg - 1)
144
145     def _eval_is_real(self):
146         x = self.args[0]
147         # noninteger means real and not integer
148         if x.is_positive or x.is_noninteger:
149             return True
150
151     def _eval_is_positive(self):
152         x = self.args[0]
153         if x.is_positive:
154             return True
155         elif x.is_noninteger:
156             return floor(x).is_even
157
158     def _eval_rewrite_as_factorial(self, z):
159         return factorial(z - 1)
160
161     def fdiff(self, argindex=1):
162         from sympy.core.function import ArgumentIndexError
163         if argindex == 1:
164             return self.func(self.args[0])*polygamma(0, self.args[0])
165         else:
166             raise ArgumentIndexError(self, argindex)
167
168     The actual gamma function defined in SymPy has many more capabilities, such
169     as evaluation at rational points and series expansion.

```

```

169 3. Numerics. The Float class holds an arbitrary-precision binary floating-point
170 value and a precision in bits. An operation between two Float inputs is rounded to
171 the larger of the two precisions. Since Python floating-point literals automatically
172 evaluate to double (53-bit) precision, strings should be used to input precise decimal
173 values:
174 >>> Float(1.1)
175 1.1000000000000000
176 >>> Float(1.1, 30) # precision equivalent to 30 digits
177 1.10000000000000000881784197001
178 >>> Float("1.1", 30)
179 1.100000000000000000000000000000000000000000

```


The mpmath library includes support for special functions, root-finding, linear algebra, polynomial approximation, and numerical computation of limits, derivatives, integrals, infinite series, and ODE solutions. All features work in arbitrary precision and use algorithms that support computing hundreds of digits rapidly, except in degenerate cases.

The double exponential (tanh-sinh) quadrature is used for numerical integration by default. For smooth integrands, this algorithm usually converges extremely rapidly, even when the integration interval is infinite or singularities are present at the endpoints [26, 4]. However, for good performance, singularities in the middle of the interval must be specified by the user. To evaluate slowly converging limits and infinite series, mpmath automatically attempts to apply Richardson extrapolation and the Shanks transformation (Euler-Maclaurin summation can also be used) [5]. A function to evaluate oscillatory integrals by means of convergence acceleration is also available.

A wide array of higher mathematical functions are implemented with full support for complex values of all parameters and arguments, including complete and incomplete gamma functions, Bessel functions, orthogonal polynomials, elliptic functions and integrals, zeta and polylogarithm functions, the generalized hypergeometric function, and the Meijer G-function.

Most special functions are implemented as linear combinations of the generalized hypergeometric function ${}_pF_q$, which is computed by a combination of direct summation, argument transformations (for ${}_2F_1$, ${}_3F_2$, ...) and asymptotic expansions (for ${}_0F_1$, ${}_1F_1$, ${}_1F_2$, ${}_2F_2$, ${}_2F_3$) to cover the whole complex domain. Numerical integration and generic convergence acceleration are also used in a few special cases.

In general, linear combinations and argument transformations give rise to singularities that have to be removed for certain combinations of parameters. A typical example is the modified Bessel function of the second kind

$$K_\nu(z) = \frac{1}{2} \left[\left(\frac{z}{2} \right)^{-\nu} \Gamma(\nu) {}_0F_1 \left(1 - \nu, \frac{z^2}{4} \right) - \left(\frac{z}{2} \right)^\nu \frac{\pi}{\nu \sin(\pi\nu) \Gamma(\nu)} {}_0F_1 \left(\nu + 1, \frac{z^2}{4} \right) \right]$$

where the limiting value $\lim_{\epsilon \rightarrow 0} K_{n+\epsilon}(z)$ has to be computed when $\nu = n$ is an integer. A generic algorithm is used to evaluate hypergeometric-type linear combinations of the above type. This algorithm automatically detects cancellation problems, and computes limits numerically by perturbing parameters whenever internal singularities occur (the perturbation size is automatically decreased until the result is detected to converge numerically).

Due to this generic approach, particular combinations of hypergeometric functions can be specified easily. The implementation of the Meijer G-function takes only a few dozen lines of code, yet covers the whole input domain in a robust way. The Meijer G-function instance $G_{1,3}^{3,0} \left(0; \frac{1}{2}, -1, -\frac{3}{2} | x \right)$ is a good test case [27]; past versions of both Maple and Mathematica produced incorrect numerical values for large $x > 0$. Here, mpmath automatically removes the internal singularity and compensates for cancellations (amounting to 656 bits of precision when $x = 10000$), giving correct values:

```
>>> mpmath.mp.dps = 15
>>> mpmath.meijerg([], [0], [[-0.5, -1, -1.5], []], 10000)
mpf('2.4392576907199564e-94')
```

Equivalently, with SymPy's interface this function can be evaluated as:

```
>>> meijerg([], [0], [[-S(1)/2, -1, -S(3)/2], []], 10000).evalf()
```

274 2.43925769071996e-94

275 We highlight the generalized hypergeometric functions and the Meijer G-function,
 276 due to those functions' frequent appearance in closed forms for integrals and sums
 277 [todo: crossref symbolic integration]. Via mpmath, SymPy has relatively good sup-
 278 port for evaluating sums and integrals numerically, using two complementary ap-
 279 proaches: direct numerical evaluation, or first computing a symbolic closed form
 280 involving special functions. [example?]

281 **3.2. Numerical simplification.** The `nsimplify` function in SymPy (a wrapper
 282 of `identify` in mpmath) attempts to find a simple symbolic expression that evaluates
 283 to the same numerical value as the given input. It works by applying a few simple
 284 transformations (including square roots, reciprocals, logarithms and exponentials) to
 285 the input and, for each transformed value, using the PSLQ algorithm [12] to search
 286 for a matching algebraic number or optionally a linear combination of user-provided
 287 base constants (such as π).

```
288 >>> x = 1 / (sin(pi/5)+sin(2*pi/5)+sin(3*pi/5)+sin(4*pi/5))*2
289 >>> nsimplify(x)
290 -2*sqrt(5)/5 + 1
291 >>> nsimplify(pi, tolerance=0.01)
292 22/7
293 >>> nsimplify(1.783919626661888, [pi], tolerance=1e-12)
294 pi/(-1/3 + 2*pi/3)
```

295 **4. Features.** SymPy has an extensive feature set that encompasses too much to
 296 cover in-depth here. Bedrock areas, such a Calculus, receive their own sub-sections
 297 below. Additionally, Table 1 describes other capabilities present in the SymPy code
 298 base. This gives a sampling from the breadth of topics and application domains that
 299 SymPy services.

Table 1: SymPy Features and Descriptions

Feature	Description
Discrete Math	Summations, products, binomial coefficients, prime number tools, integer factorization, Diophantine equation solving, and boolean logic representation, equivalence testing, and inference.
Concrete Math	Tools for determining whether summation and product expressions are convergent, absolutely convergent, hypergeometric, and other properties. May also compute Gosper's normal form [24] for two univariate polynomials.
Plotting	Hooks for visualizing expressions via matplotlib [?] or as text drawings when lacking a graphical back-end.
Geometry	Allows the creation of 2D geometrical entities, such as lines and circles. Enables queries on these entities, including asking the area of an ellipse, checking for collinearity of a set of points, or finding the intersection between two lines.
Statistics	Support for a random variable type as well as the ability to declare this variable from prebuilt distribution functions such as Normal, Exponential, Coin, Die, and other custom distributions.

Polynomials	Computes polynomial algebras over various coefficient domains ranging from the simple (e.g., polynomial division) to the advanced (e.g., Gröbner bases [3] and multivariate factorization over algebraic number domains).
Sets	Representations of empty, finite, and infinite sets. This includes special sets such as for all natural, integer, and complex numbers.
Series	Implements series expansion, sequences, and limit of sequences. This includes special series, such as Fourier and power series.
Vectors	Provides basic vector math and differential calculus with respect to 3D Cartesian coordinate systems.
Matrices	Tools for creating matrices of symbols and expressions. This is capable of both sparse and dense representations and performing symbolic linear algebraic operations (e.g., inversion and factorization).
Combinatorics & Group Theory	Implements permutations, combinations, partitions, subsets, various permutation groups (such as polyhedral, Rubik, symmetric, and others), Gray codes [21], and Prufer sequences [6].
Code Generation	Enables generation of compilable and executable code in a variety of different programming languages directly from expressions. Target languages include C, Fortran, Julia, JavaScript, Mathematica, Matlab and Octave, Python, and Theano.
Tensors	Symbolic manipulation of indexed objects.
Lie Algebras	Represents Lie algebras and root systems.
Cryptography	Represents block and stream ciphers, including shift, Affine, substitution, Vigenere's, Hill's, bifid, RSA, Kid RSA, linear-feedback shift registers, and Elgamal encryption
Special Functions	Implements a number of well known special functions, including Dirac delta, Gamma, Beta, Gauss error functions, Fresnel integrals, Exponential integrals, Logarithmic integrals, Trigonometric integrals, Bessel, Hankel, Airy, B-spline, Riemann Zeta, Dirichlet eta, polylogarithm, Lerch transcendent, hypergeometric, elliptic integrals, Mathieu, Jacobi polynomials, Gegenbauer polynomial, Chebyshev polynomial, Legendre polynomial, Hermite polynomial, Laguerre polynomial, and spherical harmonic functions.

4.1. Basic Expression Manipulation. All symbols in SymPy must be instantiated and assigned to a variable before they can be used. This is typically done through the `symbols` function, which creates multiple symbols at once. For instance,

```
>>> x, y, z = symbols('x y z')
```

creates three symbols named `x`, `y`, and `z`, assigned to Python variables of the same name. The Python variable names that symbols are assigned to are immaterial—we could have just as well have written `a, b, c = symbol('x y z')`.

Expressions are created from symbols using Python syntax, which mirrors usual mathematical notation. Note that in Python, exponentiation is `**`.

```
>>> (x**2 - 2*x + 3)/y
```


310 `(x**2 - 2*x + 3)/y`

311 The generic way to simplify an expression is by calling the `simplify` function. It
 312 must be emphasized that simplification is not an unambiguously defined mathematical
 313 operation [10]. The `simplify` function applies several simplification routines along
 314 with some heuristics to make the output expression as “simple” as possible.

315 It is often preferable to apply more directed simplification functions. These apply
 316 very specific rules to the input expression, and are often able to make guarantees
 317 about the output (for instance, the `factor` function, given a polynomial with ra-
 318 tional coefficients in several variables, is guaranteed to produce a factorization into
 319 irreducible factors). Table 4.1 lists some common simplification functions.

expand	expand the expression
factor	factor a polynomial into irreducibles
collect	collect polynomial coefficients
cancel	rewrite a rational function as p/q with common factors can- celed
apart	compute the partial fraction decomposition of a rational function
trigsimp	simplify trigonometric expressions [13]

321 Substitutions are performed through the `.subs` method, which is sensible to some
 322 mathematical properties while matching, such as associativity, commutativity, addi-
 323 tive and multiplicative inverses, and matching of powers.

324 **4.2. Calculus.** Derivatives can be computed with the `diff` function.

325 `>>> diff(sin(x), x)`
 326 `cos(x)`

327 Unevaluated `Derivative` objects are also supported.

328 `>>> expr = Derivative(sin(x), x)`
 329 `>>> expr`
 330 `Derivative(sin(x), x)`

331 Unevaluated expressions can be evaluated with the `doit` method.

332 In [5]: `expr.doit()`
 333 Out[5]: `cos(x)`

334 Integrals can be analogously calculated either with the `integrate` function, or
 335 the unevaluated `Integral` objects.

336 `>>> integrate(sin(x), x)`
 337 `-cos(x)`
 338 `>>> expr = Integral(sin(x), x)`
 339 `>>> expr`
 340 `Integral(sin(x), x)`
 341 `>>> expr.doit()`
 342 `-cos(x)`

343 Definite integration can be calculated with the same method, by specifying a range
 344 of the integration variable. The following computes $\int_0^1 \sin(x) dx$.

345 `>>> integrate(sin(x), (x, 0, 1))`
 346 `-cos(1) + 1`

347 SymPy implements a combination of the Risch algorithm [9], table lookups, a
 348 reimplement of Manuel Bronstein’s “Poor Man’s Integrator” [8], and an algo-
 349 rithm for computing integrals based on Meijer G-functions. These allow SymPy to
 350 compute a wide variety of indefinite and definite integrals.

Summations and products are also supported, via the evaluated `summation` and `product` and unevaluated `Sum` and `Product`, and use the same syntax as `integrate`.

Summations are computed using a combination of Gosper's algorithm and an algorithm that uses Meijer G-functions. Products are computed via some heuristics.

4.3. Limits. The limit module implements the Gruntz algorithm [15].

Examples:

```
In [1]: limit(sin(x)/x, x, 0)
```

```
Out[1]: 1
```

```
In [2]: limit((2*E**((1-cos(x))/sin(x))-1)*(sinh(x)/atan(x)**2), x, 0)
```

```
Out[2]: E
```

We first define comparability classes by calculating L :

$$(1) \quad L \equiv \lim_{x \rightarrow \infty} \frac{\log |f(x)|}{\log |g(x)|}$$

And then we define the $<$, $>$ and \sim operations as follows: $f > g$ when $L = \pm\infty$ (f is more rapidly varying than g , i.e., f goes to ∞ or 0 faster than g , f is greater than any power of g), $f < g$ when $L = 0$ (f is less rapidly varying than g) and $f \sim g$ when $L \neq 0, \pm\infty$ (both f and g are bounded from above and below by suitable integral powers of the other).

Examples:

$$2 < x < e^x < e^{x^2} < e^{e^x}$$

$$2 \sim 3 \sim -5$$

$$x \sim x^2 \sim x^3 \sim \frac{1}{x} \sim x^m \sim -x$$

$$e^x \sim e^{-x} \sim e^{2x} \sim e^{x+e^{-x}}$$

$$f(x) \sim \frac{1}{f(x)}$$

The Gruntz algorithm, on an example:

$$f(x) = e^{x+2e^{-x}} - e^x + \frac{1}{x}$$

$$\lim_{x \rightarrow \infty} f(x) = ?$$

Strategy: mrv set: the set of most rapidly varying subexpressions $\{e^x, e^{-x}, e^{x+2e^{-x}}\}$, the same comparability class. Take an item ω from mrv, converging to 0 at infinity. Here $\omega = e^{-x}$. If not present in the mrv set, use the relation $f(x) \sim \frac{1}{f(x)}$.

Rewrite the mrv set using ω : $\{\frac{1}{\omega}, \omega, \frac{1}{\omega}e^{2\omega}\}$, substitute back into $f(x)$ and expand in ω :

$$f(x) = \frac{1}{x} - \frac{1}{\omega} + \frac{1}{\omega}e^{2\omega} = 2 + \frac{1}{x} + 2\omega + O(\omega^2)$$

The core idea of the algorithm: ω is from the mrv set, so in the limit $\omega \rightarrow 0$:

$$f(x) = \frac{1}{x} - \frac{1}{\omega} + \frac{1}{\omega}e^{2\omega} = 2 + \frac{1}{x} + 2\omega + O(\omega^2) \rightarrow 2 + \frac{1}{x}$$

We iterate until we get just a number, the final limit. Gruntz proved this algorithm always works and converges in his Ph.D. thesis [15].

Generally:

$$f(x) = \underbrace{O\left(\frac{1}{\omega^3}\right)}_{\infty} + \underbrace{\frac{C_{-2}(x)}{\omega^2}}_{\infty} + \underbrace{\frac{C_{-1}(x)}{\omega}}_{\infty} + C_0(x) + \underbrace{C_1(x)\omega}_0 + \underbrace{O(\omega^2)}_0$$

we look at the lowest power of ω . The limit is one of: 0, $\lim_{x \rightarrow \infty} C_0(x)$, ∞ .

4.4. Printers. SymPy has a rich collection of expression printers for displaying expressions to the user. By default, an interactive Python session will render the `str` form of an expression, which has been used in all the examples in this paper so far.

```
>>> phi0 = Symbol('phi0')
>>> str(Integral(sqrt(phi0), phi0))
Integral(sqrt(phi0 + 1), x)
```

Expressions can be printed with 2D monospace text with `pprint`. This uses Unicode characters to render mathematical symbols such as integral signs, square roots, and parentheses. Greek letters and subscripts in symbol names are rendered automatically.

Alternately, the `use_unicode=False` flag can be set, which causes the expression to be printed using only ASCII characters.

```
>>> pprint(Integral(sqrt(phi0 + 1), phi0), use_unicode=False)
/
|
| -----
| \ / phi0 + 1  d(phi0)
|
/
```

The function `latex` returns a \LaTeX representation of an expression.

```
>>> print(latex(Integral(sqrt(phi0 + 1), phi0)))
\int \sqrt{\phi_0 + 1}\, d\phi_0
```

Users are encouraged to run the `init_printing` function at the beginning of interactive sessions, which automatically enables the best pretty printing supported by their environment. In the Jupyter notebook or `qtconsole` [22] the \LaTeX printer is used to render expressions using MathJax or \LaTeX if it is installed on the system. The 2D text representation is used otherwise.

Other printers such as MathML are also available. SymPy uses an extensible printer subsystem which allows users to customize the printing for any given printer, and for custom objects to define their printing behavior for any printer. SymPy's code generation capabilities, which we will not discuss in-depth here, use the same printer model.

4.5. Sets. SymPy supports representation of a wide variety of mathematical sets. This is achieved by first defining abstract representations of atomic set classes and then combining and transforming them using various set operations.

Each of the set classes inherits from the base class `Set` and defines methods to check membership and calculate unions, intersections, and set differences. When these methods are not able to evaluate to atomic set classes, they are represented as abstract unevaluated objects.

SymPy has the following atomic set classes:

- `EmptySet` represents the empty set \emptyset .
- `UniversalSet` is an abstract “universal set” for which everything is a member. The union of the universal set with any set gives the universal set and

the intersection gives to the other set itself.

- **FiniteSet** is functionally equivalent to Python's built `inset` object. Its members can be any SymPy object including other sets themselves.
- **Integers** represents the set of Integers \mathbb{Z} .
- **Naturals** represents the set of Natural numbers \mathbb{N} , i.e., the set of positive integers.
- **Naturals0** represents the whole numbers, which are all the non-negative integers.
- **Range** represents a range of integers. A range is defined by specifying a start value, an end value, and a step size. Range is functionally equivalent to Python's `range` except it supports infinite endpoints, allowing the representation of infinite ranges.
- **Interval** represents an interval of real numbers. It is specified by giving the start and end point and specifying if it is open or closed in the respective ends.

Other than unevaluated classes of Union, Intersection and Set Difference operations, we have following set classes.

- **ProductSet** defines the Cartesian product of two or more sets. The product set is useful when representing higher dimensional spaces. For example to represent a three-dimensional space we simply take the Cartesian product of three real sets.
- **ImageSet** represents the image of a function when applied to a particular set. In notation, the image set of a function F with respect to a set S is $\{F(x)|x \in S\}$. SymPy uses image sets to represent sets of infinite solutions equations such as $\sin(x) = 0$.
- **ConditionSet** represents subset of a set whose members satisfies a particular condition. In notation, the condition set of the set S with respect to the condition H is $\{x|H(x), x \in S\}$. SymPy uses condition sets to represent the set of solutions of equations and inequalities, where the equation or the inequality is the condition and the set is the domain being solved over.

A few other classes are implemented as special cases of the classes described above. The set of real numbers, **Reals** is implemented as a special case of **Interval**, $(-\infty, \infty)$. **ComplexRegion** is implemented as a special case of **ImageSet**. **ComplexRegion** supports both polar and rectangular representation of regions on the complex plane.

4.6. Solvers. SymPy has module of equation solvers for symbolic equations. There are two submodules to solve algebraic equations in SymPy, referred to as old solve function, `solve`, and new solve function, `solveset`. `Solveset` is introduced with several design changes with respect to old `solve` function to resolve the issues with old `solve` function, for example old `solve` function's input API has many flags which are not needed and they make it hard for the user and the developers to work on solvers. In contrast to old solve function, the `solveset` has a clean input API, It only asks for the much needed information from the user, following are the function signatures of old and new solve function:

```
solve(f, *symbols, **flags) # old solve function
solveset(f, symbol, domain) # new solve function
```

The old `solve` function has an inconsistent output API for various types of inputs, whereas the `solveset` has a canonical output API which is achieved using sets. It can consistently return various types of solutions.

- Single solution

```

467 >>> solveset(x - 1)
468 >>> {1}
469     • Finite set of solution, quadratic equation
470 >>> solveset(x**2 - pi**2, x)
471 {-pi, pi}
472     • No Solution
473 >>> solveset(1, x)
474 EmptySet()
475     • Interval of solution
476 >>> solveset(x**2 - 3 > 0, x, domain=S.Reals)
477 (-oo, -sqrt(3)) U (sqrt(3), oo)
478     • Infinitely many solutions
479 >>> solveset(sin(x) - 1, x, domain=S.Reals)
480 ImageSet(Lambda(_n, 2*_n*pi + pi/2), Integers())
481 >>> solveset(x - x, x, domain=S.Reals)
482 (-oo, oo)
483 >>> solveset(x - x, x, domain=S.Complexes)
484 S.Complexes
485     • Linear system: finite and infinite solution for determined, under determined
486       and over determined problems.
487 >>> A = Matrix([[1, 2, 3], [4, 5, 6], [7, 8, 10]])
488 >>> b = Matrix([3, 6, 9])
489 >>> linsolve((A, b), x, y, z)
490 {(-1,2,0)}
491 >>> linsolve(Matrix([[1, 1, 1, 1], [1, 1, 2, 3]]), (x, y, z))
492 {(-y - 1, y, 2)}
493 The new solve i.e. solveset is under active development and is a planned replace-
494 ment for solve, Hence there are some features which are implemented in solve and is
495 not yet implemented in solveset. The table below show the current state of old and
496 new solve functions.

```

Solveset vs Solve		
Feature	solve	solveset
Consistent Output API	No	Yes
Consistent Input API	No	Yes
Univariate	Yes	Yes
Linear System	Yes	Yes (linsolve)
Non Linear System	Yes	Not yet
Transcendental	Yes	Not yet

```

498
499
500
501 Below are some of the examples of old solve function:
502     • Non Linear (multivariate) System of Equation: Intersection of a circle and a
503       parabola.
504 >>> solve([x**2 + y**2 - 16, 4*x - y**2 + 6], x, y)
505 [(-2 + sqrt(14), -sqrt(-2 + 4*sqrt(14))),
506  (-2 + sqrt(14), sqrt(-2 + 4*sqrt(14))),
507  (-sqrt(14) - 2, -I*sqrt(2 + 4*sqrt(14))),
508  (-sqrt(14) - 2, I*sqrt(2 + 4*sqrt(14)))]
509     • Transcendental Equation

```

```

510 >>> solve(x + log(x))**2 - 5*(x + log(x)) + 6, x)
511 [LambertW(exp(2)), LambertW(exp(3))]
512 >>> solve(x**3 + exp(x))
513 [-3*LambertW((-1)**(2/3)/3)]

```

Diophantine equations play a central and an important role in number theory. A Diophantine equation has the form, $f(x_1, x_2, \dots, x_n) = 0$ where $n \geq 2$ and x_1, x_2, \dots, x_n are integer variables. If we can find n integers a_1, a_2, \dots, a_n such that $x_1 = a_1, x_2 = a_2, \dots, x_n = a_n$ satisfies the above equation, we say that the equation is solvable.

Currently, following five types of Diophantine equations can be solved using SymPy's Diophantine module.

- Linear Diophantine equations: $a_1x_1 + a_2x_2 + \dots + a_nx_n = b$
- General binary quadratic equation: $ax^2 + bxy + cy^2 + dx + ey + f = 0$
- Homogeneous ternary quadratic equation: $ax^2 + by^2 + cz^2 + dxy + eyz + fzx = 0$
- Extended Pythagorean equation: $a_1x_1^2 + a_2x_2^2 + \dots + a_nx_n^2 = a_{n+1}x_{n+1}^2$
- General sum of squares: $x_1^2 + x_2^2 + \dots + x_n^2 = k$

When an equation is fed into Diophantine module, it factors the equation (if possible) and solves each factor separately. Then all the results are combined to create the final solution set. Following examples illustrate some of the basic functionalities of the Diophantine module.

```

529 >>> from sympy import symbols
530 >>> x, y, z = symbols("x, y, z", integer=True)
531
532 >>> diophantine(2*x + 3*y - 5)
533 set([(3*t_0 - 5, -2*t_0 + 5)])
534
535 >>> diophantine(2*x + 4*y - 3)
536 set()
537
538 >>> diophantine(x**2 - 4*x*y + 8*y**2 - 3*x + 7*y - 5)
539 set([(2, 1), (5, 1)])
540
541 >>> diophantine(x**2 - 4*x*y + 4*y**2 - 3*x + 7*y - 5)
542 set([(-2*t**2 - 7*t + 10, -t**2 - 3*t + 5)])
543
544 >>> diophantine(3*x**2 + 4*y**2 - 5*z**2 + 4*x*y - 7*y*z + 7*z*x)
545 set([(-16*p**2 + 28*p*q + 20*q**2, 3*p**2 + 38*p*q - 25*q**2, 4*p**2 - 24*p*q + 68*q**2)])
546
547 >>> from sympy.abc import a, b, c, d, e, f
548 >>> diophantine(9*a**2 + 16*b**2 + c**2 + 49*d**2 + 4*e**2 - 25*f**2)
549 set([(70*t1**2 + 70*t2**2 + 70*t3**2 + 70*t4**2 - 70*t5**2, 105*t1*t5, 420*t2*t5, 60*t3*t5, 210*t4*t5, 40*t5**2)])
550
551 >>> diophantine(a**2 + b**2 + c**2 + d**2 + e**2 + f**2 - 112)
552 set([(8, 4, 4, 4, 0, 0)])

```

4.7. Matrices. SymPy supports matrices with symbolic expressions as elements.■

```

554 >>> x, y = symbols('x y')
555 >>> A = Matrix(2, 2, [x, x + y, y, x])
556 >>> A
557 Matrix([
558 [    x, x + y],

```

```

559 [ y, x]])
560 All SymPy matrix types can do linear algebra including matrix addition, multipli-
561 cation, exponentiation, computing determinant, solving linear systems and comput-
562 ing inverses using LU decomposition, LDL decomposition, Gauss-Jordan elimination,
563 Cholesky decomposition, Moore-Penrose pseudoinverse, and adjugate matrix.
564 All operations are computed are computed symbolically. Eigenvalues are com-
565 puted by generating the characteristic polynomial using the Berkowitz algorithm and
566 then solving it using polynomial routines. Diagonalizable matrices can be diagonalized
567 first to compute the eigenvalues.
568 >>> A.eigenvals()
569 {x - sqrt(y*(x + y)): 1, x + sqrt(y*(x + y)): 1}
570 Internally these matrices store the elements as a list making it a dense repre-
571 sentation. For storing sparse matrices, the SparseMatrix class can be used. Sparse
572 matrices store the elements in a dictionary of keys (DoK) format.
573 SymPy also supports matrices with symbolic dimension values. MatrixSymbol
574 represents a matrix with dimensions  $m \times n$ , where  $m$  and  $n$  can be symbolic. Matrix
575 addition and multiplication, scalar operations, matrix inverse and transpose are stored
576 symbolically as matrix expressions.
577 >>> m, n, p = symbols("m, n, p", integer=True)
578 >>> R = MatrixSymbol("R", m, n)
579 >>> S = MatrixSymbol("S", n, p)
580 >>> T = MatrixSymbol("t", m, p)
581 >>> U = R*S + 2*T
582 >>> u.shape
583 (m, p)
584 >>> U[0, 1]
585 2*T[0, 1] + Sum(R[0, _k]*S[_k, 1], (_k, 0, n - 1))
586 Block matrices are also supported in SymPy. BlockMatrix elements can be any
587 matrix expression which includes explicit matrices, matrix symbols, and block matri-
588 ces. All functionalities of matrix expressions are also present in BlockMatrix.
589 >>> n, m, l = symbols('n m l')
590 >>> X = MatrixSymbol('X', n, n)
591 >>> Y = MatrixSymbol('Y', m, m)
592 >>> Z = MatrixSymbol('Z', n, m)
593 >>> B = BlockMatrix([[X, Z], [ZeroMatrix(m, n), Y]])
594 >>> B
595 Matrix([
596 [X, Z],
597 [0, Y]])
598 >>> B[0, 0]
599 X[0, 0]
600 >>> B.shape
601 (m + n, m + n)

```

602 **5. Domain Specific Features.** SymPy includes several packages that allow
603 users to solve domain specific problems. For example, a comprehensive physics pack-
604 age is included that is useful for solving problems in classical mechanics, optics,
605 and quantum mechanics along with support for manipulating physical quantities with
606 units.

5.1. Vector Algebra. The `sympy.physics.vector` package provides reference frame, time, and space aware vector and dyadic objects that allow for three dimensional operations such as addition, subtraction, scalar multiplication, inner and outer products, cross products, etc. Both of these objects can be written in very compact notation that make it easy to express the vectors and dyadics in terms of multiple reference frames with arbitrarily defined relative orientations. The vectors are used to specify the positions, velocities, and accelerations of points, orientations, angular velocities, and angular accelerations of reference frames, and force and torques. The dyadics are essentially reference frame aware 3×3 tensors. The vector and dyadic objects can be used for any one-, two-, or three-dimensional vector algebra and they provide a strong framework for building physics and engineering tools.

Listing 1 Python interpreter session showing how a vector is created using the orthogonal unit vectors of three reference frames that are oriented with respect to each other and the result of expressing the vector in the A frame. The B frame is oriented with respect to the A frame using Z-X-Z Euler Angles of magnitude π , $\frac{\pi}{2}$, and $\frac{\pi}{3}$ rad, respectively whereas the C frame is oriented with respect to the B frame through a simple rotation about the B frame's X unit vector through $\frac{\pi}{2}$ rad.

```
>>> from sympy import pi
>>> from sympy.physics.vector import ReferenceFrame
>>> A = ReferenceFrame('A')
>>> B = ReferenceFrame('B')
>>> C = ReferenceFrame('C')
>>> B.orient(A, 'body', (pi, pi / 3, pi / 4), 'zxz')
>>> C.orient(B, 'axis', (pi / 2, B.x))
>>> v = 1 * A.x + 2 * B.z + 3 * C.y
>>> v
A.x + 2*B.z + 3*C.y
>>> v.express(A)
A.x + 5*sqrt(3)/2*A.y + 5/2*A.z
```

5.2. Classical Mechanics. The `physics.mechanics` package utilizes the `physics.vector` package to populate time aware particle and rigid body objects to fully describe the kinematics and kinetics of a rigid multi-body system. These objects store all of the information needed to derive the ordinary differential or differential algebraic equations that govern the motion of the system, i.e., the equations of motion. These equations of motion abide by Newton's laws of motion and can handle any arbitrary kinematical constraints or complex loads. The package offers two automated methods for formulating the equations of motion based on Lagrangian Dynamics [19] and Kane's Method [18]. Lastly, there are automated linearization routines for constrained dynamical systems based on [23].

5.3. Quantum Mechanics. The `sympy.physics.quantum` package provides quantum functions, states, operators, and computation of standard quantum models.

5.4. Optics. The `physics.optics` package provides Gaussian optics functions.

5.5. Units. The `physics.units` module provides around two hundred predefined prefixes and SI units that are commonly used in the sciences. Additionally, it

provides the `Unit` class which allows the user to define their own units. These prefixes and units are multiplied by standard SymPy objects to make expressions unit aware, allowing for algebraic and calculus manipulations to be applied to the expressions while the units are tracked in the manipulations. The units of the expressions can be easily converted to other desired units. There is also a new units system in `sympy.physics.unitsystems` that allows the user to work in specified unit systems.

6. Other Projects that use SymPy. There are several projects that use SymPy as a library for implementing a part of their project, or even as a part of back-end for their application as well. Some of them are listed below:

- **Cadabra:** Cadabra is a symbolic computer algebra system (CAS) designed specifically for the solution of problems encountered in field theory.
- **Octave Symbolic:** The Octave-Forge Symbolic package adds symbolic calculation features to GNU Octave. These include common Computer Algebra System tools such as algebraic operations, calculus, equation solving, Fourier and Laplace transforms, variable precision arithmetic and other features.
- **SymPy.jl:** Provides a Julia interface to SymPy using PyCall.
- **Mathics:** Mathics is a free, general-purpose online CAS featuring Mathematica compatible syntax and functions. It is backed by highly extensible Python code, relying on SymPy for most mathematical tasks.
- **Mathpix:** An iOS App, that uses Artificial Intelligence to detect handwritten math as input, and uses SymPy Gamma, to evaluate the math input and generate the relevant steps to solve the problem.
- **Sage:** A CAS, visioned to be a viable free open source alternative to Magma, Maple, Mathematica and Matlab.
- **SageMathCloud:** SageMathCloud is a web-based cloud computing and course management platform for computational mathematics.
- **PyDy:** Multibody Dynamics with Python.
- **galgebra:** Geometric algebra (previously `sympy.galgebra`).
- **yt:** Python package for analyzing and visualizing volumetric data (`yt.units` uses SymPy).
- **SfePy:** Simple finite elements in Python.
- **Quameon:** Quantum Monte Carlo in Python.
- **Lcapy:** Experimental Python package for teaching linear circuit analysis.
- **Quantum Programming in Python:** Quantum 1D Simple Harmonic Oscillator and Quantum Mapping Gate.
- **LaTeX Expression project:** Easy LaTeX typesetting of algebraic expressions in symbolic form with automatic substitution and result computation.
- **Symbolic statistical modeling:** Adding statistical operations to complex physical models.

7. Conclusion and future work.

8. References.

REFERENCES

- [1] <https://github.com/sympy/sympy/blob/master/doc/src/modules/polys/ringseries.rst>.
- [2] *The software engineering of the wolfram system*, 2016, <https://reference.wolfram.com/language/tutorial/TheSoftwareEngineeringOfTheWolframSystem.html>.
- [3] W. W. ADAMS AND P. LOUSTAUNAU, *An introduction to Gröbner bases*, no. 3, American Mathematical Soc., 1994.

- [4] D. H. BAILEY, K. JEYABALAN, AND X. S. LI, *A comparison of three high-precision quadrature schemes*, Experimental Mathematics, 14 (2005), pp. 317–329.
- [5] C. M. BENDER AND S. A. ORSZAG, *Advanced Mathematical Methods for Scientists and Engineers*, Springer, 1st ed., October 1999.
- [6] N. BIGGS, E. K. LLOYD, AND R. J. WILSON, *Graph Theory, 1736-1936*, Oxford University Press, 1976.
- [7] R. P. BRENT AND P. ZIMMERMANN, *Modern Computer Arithmetic*, Cambridge University Press, version 0.5.1 ed.
- [8] M. BRONSTEIN, *Poor Man's Integrator*, <http://www-sop.inria.fr/cafe/Manuel.Bronstein/pmint>.
- [9] M. BRONSTEIN, *Symbolic Integration I: Transcendental Functions*, Springer-Verlag, New York, NY, USA, 2005.
- [10] J. CARETTE, *Understanding Expression Simplification*, in ISSAC '04: Proceedings of the 2004 International Symposium on Symbolic and Algebraic Computation, New York, NY, USA, 2004, ACM Press, pp. 72–79, <http://dx.doi.org/http://doi.acm.org/10.1145/1005285.1005298>.
- [11] R. J. FATEMAN, *A review of Mathematica*, Journal of Symbolic Computation, 13 (1992), pp. 545–579, [http://dx.doi.org/DOI:10.1016/S0747-7171\(10\)80011-2](http://dx.doi.org/DOI:10.1016/S0747-7171(10)80011-2).
- [12] H. R. P. FERGUSON, D. H. BAILEY, AND S. ARNO, *Analysis of PSLQ, an integer relation finding algorithm*, Mathematics of Computation, 68 (1999), pp. 351–369.
- [13] H. FU, X. ZHONG, AND Z. ZENG, *Automated and Readable Simplification of Trigonometric Expressions*, Mathematical and Computer Modelling, 55 (2006), pp. 1169–1177.
- [14] D. GOLDBERG, *What every computer scientist should know about floating-point arithmetic*, ACM Computing Surveys (CSUR), 23 (1991), pp. 5–48.
- [15] D. GRUNTZ, *On Computing Limits in a Symbolic Manipulation System*, PhD thesis, Swiss Federal Institute of Technology, Zürich, Switzerland, 1996.
- [16] D. GRUNTZ AND W. KOEPF, *Formal power series*, (1993).
- [17] C. V. HORSEN, *GMPLY*, <https://pypi.python.org/pypi/gmpy2>, 2015.
- [18] T. R. KANE AND D. A. LEVINSON, *Dynamics, Theory and Applications*, McGraw Hill, 1985.
- [19] J. LAGRANGE, *Mécanique analytique*, no. v. 1 in Mécanique analytique, Ve Courcier, 1811.
- [20] M. MOSKEWICZ, C. MADIGAN, AND S. MALIK, *Method and system for efficient implementation of boolean satisfiability*, Aug. 26 2008, <http://www.google.co.in/patents/US7418369>. US Patent 7,418,369.
- [21] A. NIJENHUIS AND H. S. WILF, *Combinatorial Algorithms: For Computers and Calculators*, Academic Press, New York, NY, USA, second ed., 1978.
- [22] F. PÉREZ AND B. E. GRANGER, *Ipython: a system for interactive scientific computing*, Computing in Science & Engineering, 9 (2007), pp. 21–29.
- [23] D. L. PETERSON, G. GEDE, AND M. HUBBARD, *Symbolic linearization of equations of motion of constrained multibody systems*, Multibody System Dynamics, 33 (2014), pp. 143–161, <http://dx.doi.org/10.1007/s11044-014-9436-5>.
- [24] M. PETKOVŠEK, H. S. WILF, AND D. ZEILBERGER, *A = bak peters*, Wellesley, MA, (1996).
- [25] M. SOFRONIOU AND G. SPALETTA, *Precise numerical computation*, Journal of Logic and Algebraic Programming, 64 (2005), pp. 113–134.
- [26] H. TAKAHASI AND M. MORI, *Double exponential formulas for numerical integration*, Publications of the Research Institute for Mathematical Sciences, 9 (1974), pp. 721–741.
- [27] V. T. TOTH, *Maple and meijer's g-function: a numerical instability and a cure*, <http://www.vttoth.com/CMS/index.php/technical-notes/67>, 2007.

9. Supplement.

9.1. Series.

9.1.1. Series Expansion. SymPy is able to calculate the symbolic series expansion of an arbitrary series or expression involving elementary and special functions and multiple variables. For this it has two different implementations- the `series` method and `Ring Series`.

The first approach stores a series as an object of the `Basic` class. Each function has its specific implementation of its expansion which is able to evaluate the Puiseux series expansion about a specified point. For example, consider a Taylor expansion about 0:

```
>>> from sympy import symbols, series
>>> x, y = symbols('x, y')
```

```

740 >>> series(sin(x+y) + cos(x*y), x, 0, 2)
741 1 + sin(y) + x*cos(y) + O(x**2)

```

742 The newer and much faster[1] approach called Ring Series makes use of the ob-
743 servation that a truncated Taylor series, is in fact a polynomial. Ring Series uses the
744 efficient representation and operations of sparse polynomials. The choice of sparse
745 polynomials is deliberate as it performs well in a wider range of cases than a dense
746 representation. Ring Series gives the user the freedom to choose the type of coeffi-
747 cients he wants to have in his series, allowing the use of faster operations on certain
748 types.

749 For this, several low level methods for expansion of trigonometric, hyperbolic
750 and other elementary functions like inverse of a series, calculating n th root, etc, are
751 implemented using variants of the Newton[7] Method. All these support Puiseux series
752 expansion. The following example demonstrates the use of an elementary function
753 that calculates the Taylor expansion of the `sine` of a series.

```

754 >>> from sympy import ring
755 >>> from sympy.polys.ring_series import rs_sin
756 >>> R, x = ring('x', QQ)
757 >>> rs_sin(x**2 + x, x, 5)
758 -1/2*x**4 - 1/6*x**3 + x**2 + x

```

759 The function `sympy.polys.rs_series` makes use of these elementary functions
760 to expand an arbitrary SymPy expression. It does so by following a recursive strategy
761 of expanding the lower most functions first and then composing them recursively to
762 calculate the desired expansion. Currently it only supports expansion about 0 and
763 is under active development. Ring Series is several times faster than the default
764 implementation with the speed difference increasing with the size of the series. The
765 `sympy.polys.rs_series` takes as input any SymPy expression and hence there is no
766 need to explicitly create a polynomial ring. An example:

```

767 >>> from sympy.polys.ring_series import rs_series
768 >>> from sympy.abc import a, b
769 >>> from sympy import sin, cos
770 >>> rs_series(sin(a + b), a, 4)
771 -1/2*(sin(b))*a**2 + (sin(b)) - 1/6*(cos(b))*a**3 + (cos(b))*a

```

772 **9.1.2. Formal Power Series.** SymPy can be used for computing the Formal
773 Power Series of a function. The implementation is based on the algorithm described
774 in the paper on Formal Power Series[16]. The advantage of this approach is that an
775 explicit formula for the coefficients of the series expansion is generated rather than
776 just computing a few terms.

777 The following example shows how to use `fps`:

```

778 >>> f = fps(sin(x), x, x0=0)
779 >>> f.truncate(6)
780 x - x**3/6 + x**5/120 + O(x**6)
781 >>> f[15]
782 -x**15/1307674368000

```

783 **9.1.3. Fourier Series.** SymPy provides functionality to compute Fourier Series
784 of a function using the `fourier_series` function. Under the hood it just computes
785 a_0 , a_n , b_n using standard integration formulas.

786 Here's an example on how to compute Fourier Series in SymPy:

```

787 >>> L = symbols('L')
788 >>> f = fourier_series(2 * (Heaviside(x/L) - Heaviside(x/L - 1)) - 1, (x, 0, 2*L))■

```

```

789 >>> f.truncate(3)
790 4*sin(pi*x/L)/pi + 4*sin(3*pi*x/L)/(3*pi) + 4*sin(5*pi*x/L)/(5*pi)

```

791 **9.2. Logic.** SymPy supports construction and manipulation of boolean expres-
792 sions through the `logic` module. SymPy symbols can be used as propositional vari-
793 ables and also be substituted as `True` or `False`. A good number of manipulation
794 features for boolean expressions have been implemented in the `logic` module.

795 **9.2.1. Constructing boolean expressions.** A boolean variable can be de-
796 clared as a SymPy symbol. Python operators `&`, `|` and `~` are overloaded for logical
797 `And`, `Or` and `negate`. Several others like `Xor`, `Implies` can be constructed with `^`, `>>`
798 respectively. The above are just a shorthand, expressions can also be constructed by
799 directly calling `And()`, `Or()`, `Not()`, `Xor()`, `Nand()`, `Nor()`, etc.

```

800 >>> from sympy import *
801 >>> x, y, z = symbols('x y z')
802 >>> e = (x & y) | z
803 >>> e.subs({x: True, y: True, z: False})
804 True

```

805 **9.2.2. CNF and DNF.** Any boolean expression can be converted to conjunc-
806 tive normal form, disjunctive normal form and negation normal form. The API also
807 permits to check if a boolean expression is in any of the above mentioned forms.

```

808 >>> from sympy import *
809 >>> x, y, z = symbols('x y z')
810 >>> to_cnf((x & y) | z)
811 And(Or(x, z), Or(y, z))
812 >>> to_dnf(x & (y | z))
813 Or(And(x, y), And(x, z))
814 >>> is_cnf((x | y) & z)
815 True
816 >>> is_dnf((x & y) | z)
817 True

```

818 **9.2.3. Simplification and Equivalence.** The module supports simplification
819 of given boolean expression by making deductions on it. Equivalence of two expres-
820 sions can also be checked. If so, it is possible to return the mapping of variables of
821 two expressions so as to represent the same logical behaviour.

```

822 >>> from sympy import *
823 >>> a, b, c, x, y, z = symbols('a b c x y z')
824 >>> e = a & (~a | ~b) & (a | c)
825 >>> simplify(e)
826 And(Not(b), a)
827 >>> e1 = a & (b | c)
828 >>> e2 = (x & y) | (x & z)
829 >>> bool_map(e1, e2)
830 (And(Or(b, c), a), {b: y, a: x, c: z})

```

831 **9.2.4. SAT solving.** The module also supports satisfiability checking of a given
832 boolean expression. If satisfiable, it is possible to return a model for which the ex-
833 pression is satisfiable. The API also supports returning all possible models. The SAT
834 solver has a clause learning DPLL algorithm implemented with watch literal scheme
835 and VSIDS heuristic[20].

```

836 >>> from sympy import *
837 >>> a, b, c = symbols('a b c')
838 >>> satisfiable(a & (~a | b) & (~b | c) & ~c)
839 False
840 >>> satisfiable(a & (~a | b) & (~b | c) & c)
841 {b: True, a: True, c: True}

```

842 **9.3. SymPy Gamma.** SymPy Gamma is a simple web application that runs
843 on Google App Engine. It executes and displays the results of SymPy expressions as
844 well as additional related computations, in a fashion similar to that of Wolfram|Alpha.
845 For instance, entering an integer will display its prime factors, digits in the base-10
846 expansion, and a factorization diagram. Entering a function will display its docstring;
847 in general, entering an arbitrary expression will display its derivative, integral, series
848 expansion, plot, and roots.

849 SymPy Gamma also has several additional features than just computing the re-
850 sults using SymPy.

- 851 • It displays integration steps, differentiation steps in detail, which can be
852 viewed in Figure 1:

Integral Steps:
`integrate(tan(x), x)`

Fullscreen

1. Rewrite the integrand:

$$\tan(x) = \frac{\sin(x)}{\cos(x)}$$

2. Let $u = \cos(x)$.

Then let $du = -\sin(x)dx$ and substitute du :

$$\int -\frac{1}{u} du$$

A. The integral of a constant times a function is the constant times the integral of the function:

$$\int -\frac{1}{u} du = - \int \frac{1}{u} du$$

I. The integral of $\frac{1}{u}$ is $\log(u)$.

So, the result is: $-\log(u)$

Now substitute u back in:

$$-\log(\cos(x))$$

3. Add the constant of integration:

$$-\log(\cos(x)) + \text{constant}$$

The answer is:

$$-\log(\cos(x)) + \text{constant}$$

Fig. 1: Integral steps of $\tan(x)$

- 854 • It also displays the factor tree diagrams for different numbers.

• SymPy Gamma also saves user search queries, and offers many such similar features for free, which Wolfram|Alpha only offers to its paid users.

Every input query from the user on SymPy Gamma is first, parsed by its own parser, which handles several different forms of function names, which SymPy as a library doesn't support. For instance, SymPy Gamma supports queries like `sin x`, whereas SymPy doesn't support this, and supports only `sin(x)`.

This parser converts the input query to the equivalent SymPy readable code, which is then eventually processed by SymPy and the result is finally formatted in LaTeX and displayed on the SymPy Gamma web-application.

9.4. SymPy Live. SymPy Live is an online Python shell, which runs on Google App Engine, that executes SymPy code. It is integrated in the SymPy documentation examples, located at this [link](#).

This is accomplished by providing a HTML/JavaScript GUI for entering source code and visualization of output, and a server part which evaluates the requested source code. It's an interactive AJAX shell, that runs SymPy code using Python on the server.

Certain Features of SymPy Live:

- It supports the exact same syntax as SymPy, hence it can be used easily, to test for outputs of various SymPy expressions.
- It can be run as a standalone app or in an existing app as an admin-only handler, and can also be used for system administration tasks, as an interactive way to try out APIs, or as a debugging aid during development.
- It can also be used to plot figures ([link](#)), and execute all kinds of expressions that SymPy can evaluate.
- SymPy Live also formats the output in LaTeX for pretty-printing the output.

9.5. Comparison with Mathematica. Wolfram Mathematica is a popular proprietary CAS. It features highly advanced algorithms. Mathematica has a core implemented in C++ [2] which interprets its own programming language (known as Wolfram language).

Analogously to Lisp's S-expressions, Mathematica uses its own style of M-expressions, which are arrays of either atoms or other M-expression. The first element of the expression identifies the type of the expression and is indexed by zero, whereas the first argument is indexed by one. Notice that SymPy expression arguments are stored in a Python tuple (that is, an immutable array), while the expression type is identified by the type of the object storing the expression.

Mathematica can associate attributes to its atoms.

Unlike SymPy, Mathematica's expressions are mutable, that is one can change parts of the expression tree without the need of creating a new object. The reactivity of Mathematica allows for a lazy updating of any references to that data structure.

Products in Mathematica are determined by some builtin node types, such as `Times`, `Dot`, and others. `Times` is overloaded by the `*` operator, and is always meant to represent a commutative operator. The other notable product is `Dot`, overloaded by the `.` operator. This product represents matrix multiplication, it is not commutative. SymPy uses the same node for both scalar and matrix multiplication, the only exception being with abstract matrix symbols. Unlike Mathematica, SymPy determines commutativity with respect to multiplication from the factor's expression type. Mathematica puts the `Orderless` attribute on the expression type.

Regarding associative expressions, SymPy handles associativity by making associative expressions inherit the class `AssocOp`, while Mathematica specifies the `Flat`

904 attribute on the expression type.