2D Graphics

Release 10.0

The Sage Development Team

May 25, 2023
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1.1 2D plotting

Sage provides extensive 2D plotting functionality. The underlying rendering is done using the matplotlib Python library. The following graphics primitives are supported:

- arrow() - an arrow from a min point to a max point.
- circle() - a circle with given radius
- ellipse() - an ellipse with given radii and angle
- arc() - an arc of a circle or an ellipse
- disk() - a filled disk (i.e. a sector or wedge of a circle)
- line() - a line determined by a sequence of points (this need not be straight!)
- point() - a point
- text() - some text
- polygon() - a filled polygon

The following plotting functions are supported:

- plot() - plot of a function or other Sage object (e.g., elliptic curve).
- parametric_plot()
- implicit_plot()
- polar_plot()
- region_plot()
- list_plot()
- scatter_plot()
- bar_chart()
- contour_plot()
- density_plot()
- plot_vector_field()
- plot_slope_field()
- matrix_plot()
- complex_plot()
• \texttt{graphics_array()}
• \texttt{multi_graphics()}

• The following log plotting functions:
  – \texttt{plot\_loglog()}
  – \texttt{plot\_semilogx()} and \texttt{plot\_semilogy()}
  – \texttt{list\_plot\_loglog()}
  – \texttt{list\_plot\_semilogx()} and \texttt{list\_plot\_semilogy()}

The following miscellaneous Graphics functions are included:

• \texttt{Graphics()}
• \texttt{is\_Graphics()}
• \texttt{hue()}

Type \texttt{?} after each primitive in Sage for help and examples.

EXAMPLES:

We draw a curve:

\begin{verbatim}
\texttt{sage: plot(x^2, (x,0,5))}
\end{verbatim}

Graphics object consisting of 1 graphics primitive
We draw a circle and a curve:

```sage
circle((1,1), 1) + plot(x^2, (x,0,5))
```

Graphics object consisting of 2 graphics primitives

Notice that the aspect ratio of the above plot makes the plot very tall because the plot adopts the default aspect ratio of the circle (to make the circle appear like a circle). We can change the aspect ratio to be what we normally expect for a plot by explicitly asking for an 'automatic' aspect ratio:

```sage
show(circle((1,1), 1) + plot(x^2, (x,0,5)), aspect_ratio='automatic')
```

The aspect ratio describes the apparently height/width ratio of a unit square. If you want the vertical units to be twice as big as the horizontal units, specify an aspect ratio of 2:

```sage
show(circle((1,1), 1) + plot(x^2, (x,0,5)), aspect_ratio=2)
```

The figsize option adjusts the figure size. The default figsize is 4. To make a figure that is roughly twice as big, use figsize=8:

```sage
show(circle((1,1), 1) + plot(x^2, (x,0,5)), figsize=8)
```

You can also give separate horizontal and vertical dimensions. Both will be measured in inches:
\texttt{sage: show(circle((1,1), 1) + plot(x^2, (x,0,5)), figsize=[4,8])}

However, do not make the figsize too big (e.g. one dimension greater than 327 or both in the mid-200s) as this will lead to errors or crashes. See \texttt{show()} for full details.

Note that the axes will not cross if the data is not on both sides of both axes, even if it is quite close:

\texttt{sage: plot(x^3, (x,1,10))}

Graphics object consisting of 1 graphics primitive

When the labels have quite different orders of magnitude or are very large, scientific notation (the \( e \) notation for powers of ten) is used:

\texttt{sage: plot(x^2, (x,480,500))} \quad \# \text{no scientific notation}

Graphics object consisting of 1 graphics primitive

\texttt{sage: plot(x^2, (x,300,500))} \quad \# \text{scientific notation on y-axis}

Graphics object consisting of 1 graphics primitive

But you can fix your own tick labels, if you know what to expect and have a preference:

\texttt{sage: plot(x^2, (x,300,500), ticks=[100,50000])}

Graphics object consisting of 1 graphics primitive
1.1. 2D plotting
To change the ticks on one axis only, use the following notation:

```
\texttt{sage: plot(x^2, (x,300,500), ticks=[None,50000])}
```

Graphics object consisting of 1 graphics primitive

You can even have custom tick labels along with custom positioning.

```
\texttt{sage: plot(x^2, (x,0,3), ticks=[[1,2.5],pi/2], tick_formatter=[["x_1","x_2"],pi])}
```

# long time

Graphics object consisting of 1 graphics primitive

We construct a plot involving several graphics objects:

```
\texttt{sage: G = plot(cos(x), (x, -5, 5), thickness=5, color='green', title='A plot')}
\texttt{sage: P = polygon([[1,2], [5,6], [5,0]], color='red')}
\texttt{sage: G + P}
```

Graphics object consisting of 2 graphics primitives

Next we construct the reflection of the above polygon about the $y$-axis by iterating over the list of first-coordinates of the first graphic element of $P$ (which is the actual Polygon; note that $P$ is a Graphics object, which consists of a single polygon):

```
\texttt{sage: Q = polygon([(-x,y) for x,y in P[0]], color='blue')}
\texttt{sage: Q  \# show it}
```

(continues on next page)
1.1. 2D plotting
We combine together different graphics objects using “+”:

```
sage: H = G + P + Q
sage: print(H)
Graphics object consisting of 3 graphics primitives
sage: type(H)
<class 'sage.plot.graphics.Graphics'>
```

Polygon defined by 3 points
```
sage: H[1]
[(1.0, 2.0), (5.0, 6.0), (5.0, 0.0)]
```

We can put text in a graph:

```
sage: L = [[cos(pi*i/100)^3, sin(pi*i/100)] for i in range(200)]
sage: p = line(L, rgbcolor=(1/4,1/8,3/4))
sage: tt = text('A Bulb', (1.5, 0.25))
sage: tx = text('x axis', (1.5,-0.2))
```

Graphics object consisting of 1 graphics primitive
A plot
sage: ty = text('y axis', (0.4,0.9))
sage: g = p + tt + tx + ty
sage: g.show(xmin=-1.5, xmax=2, ymin=-1, ymax=1)

We can add a graphics object to another one as an inset:

sage: g1 = plot(x^2*sin(1/x), (x, -2, 2), axes_labels=['$x$', '$y$'])
sage: g2 = plot(x^2*sin(1/x), (x, -0.3, 0.3), axes_labels=['$x$', '$y$'],
....:    frame=True)
sage: g1.inset(g2, pos=(0.15, 0.7, 0.25, 0.25))
Multigraphics with 2 elements

We can add a title to a graph:

sage: plot(x^2, (x,-2,2), title='A plot of $x^2$')
Graphics object consisting of 1 graphics primitive

We can set the position of the title:

sage: plot(x^2, (-2,2), title='Plot of $x^2$', title_pos=(0.5,-0.05))
Graphics object consisting of 1 graphics primitive

We plot the Riemann zeta function along the critical line and see the first few zeros:
A plot of $x^2$
Plot of $x^2$
\texttt{sage: } i = 
CDF\.0 \quad \# \text{define } i \text{ this way for maximum speed.}
\texttt{sage: } p1 = \text{plot(} \text{lambda } t: \text{arg(zeta}(0.5+t*i)), 1, 27, \text{rgbcolor}=(0.8,0,0))
\texttt{sage: } p2 = \text{plot(} \text{lambda } t: \text{abs(zeta}(0.5+t*i)), 1, 27, \text{color=hue}(0.7))
\texttt{sage: } \text{print(p1 + p2)}
\text{Graphics object consisting of 2 graphics primitives}
\texttt{sage: } p1 + p2 \quad \# \text{display it}
\text{Graphics object consisting of 2 graphics primitives}

\textbf{Note:} Not all functions in Sage are symbolic. When plotting non-symbolic functions they should be wrapped in \texttt{lambda}:

\texttt{sage: } \text{plot(} \text{lambda } x:\text{fibonacci(round}(x)), (x,1,10))
\text{Graphics object consisting of 1 graphics primitive}

Many concentric circles shrinking toward the origin:

\texttt{sage: } \text{show(sum(circle((i,0), i, hue=sin(i/10)) for i in [10,9,\ldots,0]))} \quad \# \text{long time}

Here is a pretty graph:
Chapter 1. General
1.1. 2D plotting
```python
sage: g = Graphics()
sage: for i in range(60):
    ....:     p = polygon([(i*cos(i),i*sin(i)), (0,i), (i,0)],
    ....:                        color=hue(i/40+0.4), alpha=0.2)
    ....:     g = g + p
sage: g.show(dpi=200, axes=False)
```

Another graph:

```python
sage: x = var('x')
sage: P = plot(sin(x)/x, -4, 4, color='blue') + 
    ....:     plot(x*cos(x), -4, 4, color='red') + 
    ....:     plot(tan(x), -4, 4, color='green')
sage: P.show(ymin=-pi, ymax=pi)
```

PYX EXAMPLES: These are some examples of plots similar to some of the plots in the PyX ([http://pyx.sourceforge.net](http://pyx.sourceforge.net)) documentation:

Symbolline:

```python
sage: y(x) = x*sin(x^2)
sage: v = [(x, y(x)) for x in [-3,-2.95,..,3]]
sage: show(points(v, rgbcolor=(0.2,0.6, 0.1), pointsize=30) + plot(spline(v), -3.1, 3))
```
1.1. 2D plotting
Cycliclink:

```python
sage: g1 = plot(cos(20*x)*exp(-2*x), 0, 1)
sage: g2 = plot(2*exp(-30*x) - exp(-3*x), 0, 1)
sage: show(graphics_array([g1, g2], 2, 1))
```

Pi Axis:

```python
sage: g1 = plot(sin(x), 0, 2*pi)
sage: g2 = plot(cos(x), 0, 2*pi, linestyle="--")
sage: (g1+g2).show(ticks=pi/6, tick_formatter=pi)  # long time # show their sum, nicely formatted
```

An illustration of integration:

```python
sage: f(x) = (x-3)*(x-5)*(x-7)+40
sage: P = line([(2,0),(2,f(2))], color='black')
sage: P += line([(8,0),(8,f(8))], color='black')
sage: P += polygon([(2,0),(2,f(2)) + [(x, f(x)) for x in [2,2.1,...,8]] + [(8,0),(2,0)],
               rgbcolor=(0.8,0.8,0.8),aspect_ratio='automatic')
sage: P += text("$\int_a^b f(x) \, dx$", (5, 20), fontsize=16, color='black')
sage: P += plot(f, (1, 8.5), thickness=3)
sage: P  # show the result
```

Graphics object consisting of 5 graphics primitives
\[ \int_{a}^{b} f(x) \, dx \]
NUMERICAL PLOTTING:

Sage includes Matplotlib, which provides 2D plotting with an interface that is a likely very familiar to people doing numerical computation. You can use `plt.clf()` to clear the current image frame and `plt.close()` to close it. For example,

```python
sage: import pylab as plt
sage: t = plt.arange(0.0, 2.0, 0.01)
sage: s = sin(2*pi*t)
sage: P = plt.plot(t, s, linewidth=1.0)
sage: xl = plt.xlabel('time (s)')
sage: yl = plt.ylabel('voltage (mV)')
sage: t = plt.title('About as simple as it gets, folks')
sage: plt.grid(True)
```

We test that `imshow` works as well, verifying that github issue #2900 is fixed (in Matplotlib).

```python
sage: plt.imshow([[1,2], [0,1]])
<matplotlib.image.AxesImage object at ...>
```

Since the above overwrites many Sage plotting functions, we reset the state of Sage, so that the examples below work!

```python
sage: reset()
```

See http://matplotlib.sourceforge.net for complete documentation about how to use Matplotlib.

AUTHORS:

- Alex Clemesha and William Stein (2006-04-10): initial version
- David Joyner: examples
- Alex Clemesha (2006-05-04) major update
- William Stein (2006-05-29): fine tuning, bug fixes, better server integration
- Alex Clemesha (2006-09-29): added contour_plot, frame axes, misc polishing
- Robert Miller (2006-10-30): tuning, NetworkX primitive
- Alex Clemesha (2006-11-25): added plot_vector_field, matrix_plot, arrow, bar_chart, Axes class usage (see axes.py)
- Bobby Moretti and William Stein (2008-01): Change plot to specify ranges using the (varname, min, max) notation.
• William Stein (2008-01-19): raised the documentation coverage from a miserable 12 percent to a ‘wopping’ 35 percent, and fixed and clarified numerous small issues.

• Jason Grout (2009-09-05): shifted axes and grid functionality over to matplotlib; fixed a number of smaller issues.

• Jason Grout (2010-10): rewrote aspect ratio portions of the code

• Jeroen Demeyer (2012-04-19): move parts of this file to graphics.py (github issue #12857)

• Aaron Lauve (2016-07-13): reworked handling of ‘color’ when passed a list of functions; now more in-line with other CAS’s. Added list functionality to linestyle and legend_label options as well. (github issue #12962)

• Eric Gourgoulhon (2019-04-24): add multi_graphics() and insets

`sage.plot.plot.SelectiveFormatter(formatter, skip_values)`

This matplotlib formatter selectively omits some tick values and passes the rest on to a specified formatter.

**EXAMPLES:**

This example is almost straight from a matplotlib example.

```python
sage: from sage.plot.plot import SelectiveFormatter
sage: import matplotlib.pyplot as plt
sage: import numpy
sage: fig=plt.figure()
sage: ax=fig.add_subplot(111)
sage: t = numpy.arange(0.0, 2.0, 0.01)
sage: s = numpy.sin(2*numpy.pi*t)
sage: p = ax.plot(t, s)
sage: formatter=SelectiveFormatter(ax.xaxis.get_major_formatter(),skip_values=[0,1])
sage: ax.xaxis.set_major_formatter(formatter)
```

`sage.plot.plot.adaptive_refinement(f, p1, p2, adaptive_tolerance, adaptive_recursion=0.01, level=5, excluded=0)`

The adaptive refinement algorithm for plotting a function $f$. See the docstring for plot for a description of the algorithm.

**INPUT:**

• $f$ – a function of one variable

• $p1$, $p2$ – two points to refine between

• `adaptive_recursion` – (default: 5); how many levels of recursion to go before giving up when doing adaptive refinement. Setting this to 0 disables adaptive refinement.

• `adaptive_tolerance` – (default: 0.01); how large a relative difference should be before the adaptive refinement code considers it significant; see documentation for `generate_plot_points` for more information. See the documentation for `plot()` for more information on how the adaptive refinement algorithm works.

• `excluded` – (default: False); also return locations where it has been discovered that the function is not defined (y-value will be 'NaN' in this case)

**OUTPUT:**

A list of points to insert between $p1$ and $p2$ to get a better linear approximation between them. If `excluded`, also x-values for which the calculation failed are given with 'NaN' as y-value.
sage.plot.plot.generate_plot_points(f, xrange, plot_points, adaptive_tolerance, adaptive_recursion=5, randomize=0.01, initial_points=5, excluded=True, imaginary_tolerance=None)

Calculate plot points for a function f in the interval xrange. The adaptive refinement algorithm is also automatically invoked with a relative adaptive tolerance of adaptive_tolerance; see below.

INPUT:

• f – a function of one variable
• p1, p2 – two points to refine between
• plot_points – (default: 5); the minimal number of plot points. (Note however that in any actual plot a number is passed to this, with default value 200.)
• adaptive_recursion – (default: 5); how many levels of recursion to go before giving up when doing adaptive refinement. Setting this to 0 disables adaptive refinement.
• adaptive_tolerance – (default: 0.01); how large the relative difference should be before the adaptive refinement code considers it significant. If the actual difference is greater than adaptive_tolerance*delta, where delta is the initial subinterval size for the given xrange and plot_points, then the algorithm will consider it significant.
• initial_points – (default: None); a list of x-values that should be evaluated.
• excluded – (default: False); add a list of discovered x-values, for which f is not defined
• imaginary_tolerance – (default: 1e-8); if an imaginary number arises (due, for example, to numerical issues), this tolerance specifies how large it has to be in magnitude before we raise an error. In other words, imaginary parts smaller than this are ignored in your plot points.

OUTPUT:

• a list of points (x, f(x)) in the interval xrange, which approximate the function f.
• if excluded a tuple consisting of the above and a list of x-values at which f is not defined

sage.plot.plot.graphics_array(array, nrows=None, ncols=None)

Plot a list of lists (or tuples) of graphics objects on one canvas, arranged as an array.

INPUT:

• array – either a list of lists of Graphics elements or a single list of Graphics elements
• nrows, ncols – (optional) integers. If both are given then the input array is flattened and turned into an nrows x ncols array, with blank graphics objects padded at the end, if necessary. If only one is specified, the other is chosen automatically.

OUTPUT: an instance of GraphicsArray

EXAMPLES:

Make some plots of sin functions:

```python
sage: f(x) = sin(x)
sage: g(x) = sin(2*pi*x)
sage: h(x) = sin(4*pi*x)
sage: p1 = plot(f, (-2*pi,2*pi), color=hue(0.5)) # long time
sage: p2 = plot(g, (-2*pi,2*pi), color=hue(0.9)) # long time
sage: p3 = parametric_plot((f,g), (0,2*pi), color=hue(0.6)) # long time
sage: p4 = parametric_plot((f,h), (0,2*pi), color=hue(1.0)) # long time
```

Now make a graphics array out of the plots:
sage: graphics_array(((p1,p2), (p3,p4))) # long time
Graphics Array of size 2 x 2

One can also name the array, and then use show() or save():

sage: ga = graphics_array(((p1,p2), (p3,p4))) # long time
sage: ga.show() # long time; same output as above

Here we give only one row:

sage: p1 = plot(sin,(-4,4))
sage: p2 = plot(cos,(-4,4))
sage: ga = graphics_array([p1, p2])
sage: ga
Graphics Array of size 1 x 2
sage: ga.show()

It is possible to use figsize to change the size of the plot as a whole:

sage: L = [plot(sin(k*x), (x,-pi,pi)) for k in [1..3]]
sage: ga = graphics_array(L)
sage: ga.show(figsize=[5,3]) # smallish and compact

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sage: ga.show(figsize=[5,7])  # tall and thin; long time

Specifying only the number of rows or the number of columns computes the other dimension automatically:

sage: ga = graphics_array([plot(sin)] * 10, nrows=3)
sage: ga.nrows(), ga.ncols()
(3, 4)
The options like fontsize, scale or frame passed to individual plots are preserved:

```
sage: p1 = plot(sin(x^2), (x, 0, 6),
...:          axes_labels=[r'\theta', r'sin(\theta^2)'], fontsize=16)
sage: p2 = plot(x^3, (x, 1, 100), axes_labels=[r'x', r'y'],
...:          scale='semilogy', frame=True, gridlines='minor')
sage: ga = graphics_array([p1, p2])
sage: ga.show()
```

See also:

`GraphicsArray` for more examples

`sage.plot.plot.list_plot(data, plotjoined=False, aspect_ratio='automatic', **kwargs)`

`list_plot` takes either a list of numbers, a list of tuples, a numpy array, or a dictionary and plots the corresponding points.

If given a list of numbers (that is, not a list of tuples or lists), `list_plot` forms a list of tuples \((i, x_i)\) where \(i\) goes from 0 to \(\text{len(data)}-1\) and \(x_i\) is the \(i\)-th data value, and puts points at those tuple values.

`list_plot` will plot a list of complex numbers in the obvious way; any numbers for which `CC()` makes sense will work.

`list_plot` also takes a list of tuples \((x_i, y_i)\) where \(x_i\) and \(y_i\) are the \(i\)-th values representing the \(x\)- and \(y\)-values, respectively.
\[ \sin(\theta^2) \]
If given a dictionary, `list_plot` interprets the keys as $x$-values and the values as $y$-values.

The `plotjoined=True` option tells `list_plot` to plot a line joining all the data.

For other keyword options that the `list_plot` function can take, refer to `plot()`.

It is possible to pass empty dictionaries, lists, or tuples to `list_plot`. Doing so will plot nothing (returning an empty plot).

**EXAMPLES:**

```
sage: list_plot([i^2 for i in range(5)]) # long time
Graphics object consisting of 1 graphics primitive
```

Here are a bunch of random red points:

```
sage: r = [(random(), random()) for _ in range(20)]
sage: list_plot(r, color='red')
Graphics object consisting of 1 graphics primitive
```

This gives all the random points joined in a purple line:

```
sage: list_plot(r, plotjoined=True, color='purple')
Graphics object consisting of 1 graphics primitive
```

You can provide a numpy array:
1.1. 2D plotting
sage: import numpy
sage: list_plot(numpy.arange(10))
Graphics object consisting of 1 graphics primitive

Plot a list of complex numbers:

sage: list_plot([1, I, pi + I/2, CC(.25, .25)])
Graphics object consisting of 1 graphics primitive

Note that if your list of complex numbers are all actually real, they get plotted as real values, so this

sage: list_plot([CDF(1), CDF(1/2), CDF(1/3)])
Graphics object consisting of 1 graphics primitive

is the same as list_plot([1, 1/2, 1/3]) – it produces a plot of the points (0, 1), (1, 1/2), and (2, 1/3).

If you have separate lists of \( x \) values and \( y \) values which you want to plot against each other, use the zip command to make a single list whose entries are pairs of \((x, y)\) values, and feed the result into list_plot:
1.1. 2D plotting
\begin{verbatim}
sage: x_coords = [cos(t)^3 for t in srange(0, 2*pi, 0.02)]
sage: y_coords = [sin(t)^3 for t in srange(0, 2*pi, 0.02)]
sage: list_plot(list(zip(x_coords, y_coords)))
Graphics object consisting of 1 graphics primitive
\end{verbatim}

If instead you try to pass the two lists as separate arguments, you will get an error message:

\begin{verbatim}
sage: list_plot(x_coords, y_coords)
Traceback (most recent call last):
  ...
TypeError: The second argument 'plotjoined' should be boolean (True or False). If you meant to plot two lists 'x' and 'y' against each other, use 'list_plot(list(zip(x,y)))'.
\end{verbatim}

Dictionaries with numeric keys and values can be plotted:

\begin{verbatim}
Graphics object consisting of 1 graphics primitive
\end{verbatim}

Plotting in logarithmic scale is possible for 2D list plots. There are two different syntaxes available:
1.1. 2D plotting
sage: yl = [2**k for k in range(20)]
sage: list_plot(yl, scale='semilogy')  # long time # log axis on vertical
Graphics object consisting of 1 graphics primitive

sage: list_plot_semilogy(yl)  # same
Graphics object consisting of 1 graphics primitive

Warning: If plotjoined is False then the axis that is in log scale must have all points strictly positive. For instance, the following plot will show no points in the figure since the points in the horizontal axis starts from (0, 1). Further, matplotlib will display a user warning.

sage: list_plot(yl, scale='loglog')  # both axes are log
doctest:warning
...
Graphics object consisting of 1 graphics primitive

Instead this will work. We drop the point (0, 1):

sage: list_plot(list(zip(range(1,len(yl)), yl[1:])), scale='loglog')  # long time
Graphics object consisting of 1 graphics primitive

We use list_plot_loglog() and plot in a different base.:
We can also change the scale of the axes in the graphics just before displaying:

```python
sage: G = list_plot(yl)  # long time
sage: G.show(scale=('semilogy', 2))  # long time
```

```
sage.plot.plot.list_plot_loglog(data, plotjoined=False, base=10, **kwds)
```

Plot the data in ‘loglog’ scale, that is, both the horizontal and the vertical axes will be in logarithmic scale.

**INPUT:**
- `base` – (default: 10); the base of the logarithm. This must be greater than 1. The base can be also given as a list or tuple (basex, basey). basex sets the base of the logarithm along the horizontal axis and basey sets the base along the vertical axis.

For all other inputs, look at the documentation of `list_plot()`.

**EXAMPLES:**

```python
sage: yl = [5**k for k in range(10)]; xl = [2**k for k in range(10)]
sage: list_plot_loglog(list(zip(xl, yl)))  # long time # plot in loglog scale with base 10
Graphics object consisting of 1 graphics primitive
```
sage: list_plot_loglog(list(zip(xl, yl)), base=2.1)  # long time # with base 2.1 on both axes
Graphics object consisting of 1 graphics primitive

Warning: If plotjoined is False then the axis that is in log scale must have all points strictly positive. For instance, the following plot will show no points in the figure since the points in the horizontal axis starts from (0, 1).

sage: yl = [2**k for k in range(20)]
sage: list_plot_loglog(yl)
Graphics object consisting of 1 graphics primitive

Instead this will work. We drop the point (0, 1):

sage: list_plot_loglog(list(zip(range(1,len(yl)), yl[1:])))
Graphics object consisting of 1 graphics primitive

sage.plot.plot.list_plot_semilogx(data, plotjoined=False, base=10, **kwds)

Plot data in ‘semilogx’ scale, that is, the horizontal axis will be in logarithmic scale.
INPUT:

- base – (default: 10); the base of the logarithm. This must be greater than 1.

For all other inputs, look at the documentation of `list_plot()`.

EXAMPLES:

```
sage: yl = [2**k for k in range(12)]
sage: list_plot_semilogx(list(zip(yl,yl)))
```

Graphics object consisting of 1 graphics primitive

```
Warning: If plotjoined is False then the horizontal axis must have all points strictly positive. Otherwise the plot will come up empty. For instance the following plot contains a point at (0, 1).

sage: yl = [2**k for k in range(12)]
sage: list_plot_semilogx(yl) # plot empty due to (0,1)
```

Graphics object consisting of 1 graphics primitive

```
We remove (0, 1) to fix this:

sage: list_plot_semilogx(list(zip(range(1, len(yl)), yl[1:])))
```

Graphics object consisting of 1 graphics primitive
```python
sage: list_plot_semilogx([(1,2),(3,4),(3,-1),(25,3)], base=2) # with base 2
Graphics object consisting of 1 graphics primitive
```

```
sage: yl = [2**k for k in range(12)]
sage: list_plot_semilogy(yl) # plot in semilogy scale, base 10
Graphics object consisting of 1 graphics primitive
```

**sage.plot.plot.list_plot_semilogy**(data, plotjoined=False, base=10, **kwds)

Plot data in ‘semilogy’ scale, that is, the vertical axis will be in logarithmic scale.

**INPUT:**

- `base` – (default: 10); the base of the logarithm. This must be greater than 1.

For all other inputs, look at the documentation of `list_plot()`.

**EXAMPLES:**

```python
sage: xl = [2**k for k in range(12)]; yl = range(len(xl))
sage: list_plot_semilogy(list(zip(xl,yl))) # plot empty due to (1,0)
```

**Warning:** If `plotjoined` is `False` then the vertical axis must have all points strictly positive. Otherwise the plot will come up empty. For instance the following plot contains a point at (1,0). Further, matplotlib will display a user warning.

```python
sage: xl = [2**k for k in range(12)]; yl = range(len(xl))
sage: list_plot_semilogy(list(zip(xl,yl))) # plot empty due to (1,0)
```
Graphics object consisting of 1 graphics primitive

We remove (1, 0) to fix this:

```
sage: list_plot_semilogy(list(zip(xl[1:], yl[1:])))
```

Graphics object consisting of 1 graphics primitive

```
sage: list_plot_semilogy([2, 4, 6, 8, 16, 31], base=2) # with base 2
```

Graphics object consisting of 1 graphics primitive

```
sage.plot.plot.minmax_data(xdata, ydata, dict=False)
Return the minimums and maximums of xdata and ydata.

If dict is False, then minmax_data returns the tuple (xmin, xmax, ymin, ymax); otherwise, it returns a dictionary whose keys are ‘xmin’, ‘xmax’, ‘ymin’, and ‘ymax’ and whose values are the corresponding values.

EXAMPLES:
```
sage: from sage.plot.plot import minmax_data
dsage: minmax_data([], [])
(-1, 1, -1, 1)
```

(continues on next page)
sage: minmax_data([-1, 2], [4, -3])
(-1, 2, -3, 4)
sage: minmax_data([1, 2], [4, -3])
(1, 2, -3, 4)
sage: d = minmax_data([-1, 2], [4, -3], dict=True)
sage: list(sorted(d.items()))
[('xmin', -1), ('xmax', 2), ('ymin', -3), ('ymax', 4)]
sage: d = minmax_data([1, 2], [3, 4], dict=True)
sage: list(sorted(d.items()))
[('xmin', 1), ('xmax', 2), ('ymin', 3), ('ymax', 4)]

sage.plot.plot.multi_graphics(graphics_list)

Plot a list of graphics at specified positions on a single canvas.

If the graphics positions define a regular array, use graphics_array() instead.

INPUT:

• graphics_list – a list of graphics along with their positions on the canvas; each element of graphics_list is either
  
  – a pair (graphics, position), where graphics is a Graphics object and position is the 4-tuple (left, bottom, width, height) specifying the location and size of the graphics on the canvas, all quantities being in fractions of the canvas width and height
  
  – or a single Graphics object; its position is then assumed to occupy the whole canvas, except for some padding; this corresponds to the default position (left, bottom, width, height) = (0.125, 0.11, 0.775, 0.77)

OUTPUT: an instance of MultiGraphics

EXAMPLES:

multi_graphics is to be used for plot arrangements that cannot be achieved with graphics_array(), for instance:

sage: g1 = plot(sin(x), (x, -10, 10), frame=True)
sage: g2 = EllipticCurve([0,1,-1,0]).plot(color='red', thickness=2, 
  ....:                     axes_labels=['$x$', '$y$']) \
  ....:                     + text(r'$y^2 + y = x^3 - x$', (1.2, 2), color='red')
sage: g3 = matrix_plot(matrix([[1,3,5,1], [2,4,5,6], [1,3,5,7]]))
sage: G = multi_graphics([(g1, (0.125, 0.65, 0.775, 0.3)), 
  ....:                     (g2, (0.125, 0.11, 0.4, 0.4)),
  ....:                     (g3, (0.55, 0.18, 0.4, 0.3))])
sage: G
Multigraphics with 3 elements

An example with a list containing a graphics object without any specified position (the graphics, here g3, occupies then the whole canvas):

sage: G = multi_graphics([g3, (g1, (0.4, 0.4, 0.2, 0.2))])
sage: G
Multigraphics with 2 elements

See also:

MultiGraphics for more examples
\[ y^2 + y = x^3 - x \]
sage.plot.plot.parametric_plot(funcs, aspect_ratio=1.0, *args, **kwargs)

Plot a parametric curve or surface in 2d or 3d.

parametric_plot() takes two or three functions as a list or a tuple and makes a plot with the first function giving the $x$ coordinates, the second function giving the $y$ coordinates, and the third function (if present) giving the $z$ coordinates.

In the 2d case, parametric_plot() is equivalent to the plot() command with the option parametric=True. In the 3d case, parametric_plot() is equivalent to parametric_plot3d(). See each of these functions for more help and examples.

INPUT:

- `funcs` – 2 or 3-tuple of functions, or a vector of dimension 2 or 3.
- `other options` – passed to plot() or parametric_plot3d()

EXAMPLES: We draw some 2d parametric plots. Note that the default aspect ratio is 1, so that circles look like circles.

```python
sage: t = var('t')
sage: parametric_plot( (cos(t), sin(t)), (t, 0, 2*pi))
Graphics object consisting of 1 graphics primitive
```

![Circular Plot](image)

```python
sage: parametric_plot( (sin(t), sin(2*t)), (t, 0, 2*pi), color=hue(0.6))
Graphics object consisting of 1 graphics primitive
```

![Circular Lissajous Curve](image)
Note that in parametric_plot, there is only fill or no fill.

```
sage: parametric_plot((t, t^2), (t, -4, 4), fill=True)
Graphics object consisting of 2 graphics primitives
```

A filled Hypotrochoid:

```
sage: parametric_plot([cos(x) + 2 * cos(x/4), sin(x) - 2 * sin(x/4)], (x,0, 8*pi), fill=True)
Graphics object consisting of 2 graphics primitives
```

```
sage: parametric_plot((5*cos(x), 5*sin(x), x), (x,-12, 12), plot_points=150, color="red") # long time
Graphics3d Object
```

```
sage: y=var('y')
sage: parametric_plot( (5*cos(x), x*y, cos(x*y)), (x, -4,4), (y,-4,4)) # long time
Graphics3d Object
```
sage: t=var('t')
sage: parametric_plot( vector((sin(t), sin(2*t))), (t, 0, 2*pi), color='green') # long time
Graphics object consisting of 1 graphics primitive

Plotting in logarithmic scale is possible with 2D plots. The keyword aspect_ratio will be ignored if the scale is not 'loglog' or 'linear':

sage: parametric_plot((x, x**2), (x, 1, 10), scale='loglog')
Graphics object consisting of 1 graphics primitive

We can also change the scale of the axes in the graphics just before displaying. In this case, the aspect_ratio must be specified as 'automatic' if the scale is set to 'semilogx' or 'semilogy'. For other values of the scale parameter, any aspect_ratio can be used, or the keyword need not be provided:

sage: p = parametric_plot((x, x**2), (x, 1, 10))
sage: p.show(scale='semilogy', aspect_ratio='automatic')
1.1. 2D plotting
sage.plot.plot.plot(funcs, alpha=1, thickness=1, fill=False, fillcolor='automatic', fillalpha=0.5,
plot_points=200, adaptive_tolerance=0.01, adaptive_recursion=5, detect_poles=False,
exclude=None, legend_label=None, aspect_ratio='automatic',
imaginary_tolerance=1e-08, *args, **kwds)

Use plot by writing

plot(X, ...)

where X is a Sage object (or list of Sage objects) that either is callable and returns numbers that can be coerced to floats, or has a plot method that returns a GraphicPrimitive object.

There are many other specialized 2D plot commands available in Sage, such as plot_slope_field, as well as various graphics primitives like Arrow; type sage.plot.plot? for a current list.

Type plot.options for a dictionary of the default options for plots. You can change this to change the defaults for all future plots. Use plot.reset() to reset to the default options.

PLOT OPTIONS:

- **plot_points** – (default: 200); the minimal number of plot points.
- **adaptive_recursion** – (default: 5); how many levels of recursion to go before giving up when doing adaptive refinement. Setting this to 0 disables adaptive refinement.
- **adaptive_tolerance** – (default: 0.01); how large a difference should be before the adaptive refinement code considers it significant. See the documentation further below for more information, starting at “the algorithm used to insert”.
- **imaginary_tolerance** – (default: 1e-8); if an imaginary number arises (due, for example, to numerical issues), this tolerance specifies how large it has to be in magnitude before we raise an error. In other words, imaginary parts smaller than this are ignored in your plot points.
- **base** – (default: 10); the base of the logarithm if a logarithmic scale is set. This must be greater than 1. The base can be also given as a list or tuple (basex, basey). basex sets the base of the logarithm along the horizontal axis and basey sets the base along the vertical axis.
- **scale** – string (default: "linear"); scale of the axes. Possible values are "linear", "loglog", "semilogx", "semilogy".
  The scale can be also be given as single argument that is a list or tuple (scale, base) or (scale, basex, basey).
  The "loglog" scale sets both the horizontal and vertical axes to logarithmic scale. The "semilogx" scale sets the horizontal axis to logarithmic scale. The "semilogy" scale sets the vertical axis to logarithmic scale. The "linear" scale is the default value when Graphics is initialized.
- **xmin** – starting x value in the rendered figure. This parameter is passed directly to the show procedure and it could be overwritten.
- **xmax** – ending x value in the rendered figure. This parameter is passed directly to the show procedure and it could be overwritten.
- **ymin** – starting y value in the rendered figure. This parameter is passed directly to the show procedure and it could be overwritten.
- **ymax** – ending y value in the rendered figure. This parameter is passed directly to the show procedure and it could be overwritten.
- **detect_poles** – (default: False) If set to True poles are detected. If set to “show” vertical asymptotes are drawn.
• **legend_label** – a (TeX) string serving as the label for \( X \) in the legend. If \( X \) is a list, then this option can be a single string, or a list or dictionary with strings as entries/values. If a dictionary, then keys are taken from `range(len(X))`.

---

**Note:**

• If the *scale* is "linear", then irrespective of what *base* is set to, it will default to 10 and will remain unused.

• If you want to limit the plot along the horizontal axis in the final rendered figure, then pass the `xmin` and `xmax` keywords to the `show()` method. To limit the plot along the vertical axis, `ymin` and `ymax` keywords can be provided to either this `plot` command or to the `show` command.

• This function does NOT simply sample equally spaced points between `xmin` and `xmax`. Instead it computes equally spaced points and adds small perturbations to them. This reduces the possibility of, e.g., sampling \( \sin \) only at multiples of \( 2\pi \), which would yield a very misleading graph.

• If there is a range of consecutive points where the function has no value, then those points will be excluded from the plot. See the example below on automatic exclusion of points.

• For the other keyword options that the `plot` function can take, refer to the method `show()` and the further options below.

---

**COLOR OPTIONS:**

• **color** - (Default: ‘blue’) One of:
  - an RGB tuple (r,g,b) with each of r,g,b between 0 and 1.
  - a color name as a string (e.g., ‘purple’).
  - an HTML color such as ‘#aaff0b’.
  - a list or dictionary of colors (valid only if \( X \) is a list): if a dictionary, keys are taken from `range(len(X))`; the entries/values of the list/dictionary may be any of the options above.
  - ‘automatic’ – maps to default (‘blue’) if \( X \) is a single Sage object; and maps to a fixed sequence of regularly spaced colors if \( X \) is a list.

• **legend_color** - the color of the text for \( X \) (or each item in \( X \)) in the legend.
  Default color is ‘black’. Options are as in `color` above, except that the choice ‘automatic’ maps to ‘black’ if \( X \) is a single Sage object.

• **fillcolor** - The color of the fill for the plot of \( X \) (or each item in \( X \)).
  Default color is ‘gray’ if \( X \) is a single Sage object or if `color` is a single color. Otherwise, options are as in `color` above.

**APPEARANCE OPTIONS:**

The following options affect the appearance of the line through the points on the graph of \( X \) (these are the same as for the line function):

**INPUT:**

• **alpha** – how transparent the line is

• **thickness** – how thick the line is

• **rgbcolor** – the color as an RGB tuple

• **hue** – the color given as a hue
LINE OPTIONS:

Any MATPLOTLIB line option may also be passed in. E.g.,

- **linestyle** - (default: "-") The style of the line, which is one of
  - "-" or "solid"
  - "--" or "dashed"
  - ".-" or "dash dot"
  - ":" or "dotted"
  - "None" or " " or "" (nothing)
  - a list or dictionary (see below)

The linestyle can also be prefixed with a drawing style (e.g., "steps--")

- "default" (connect the points with straight lines)
- "steps" or "steps-pre" (step function; horizontal line is to the left of point)
- "steps-mid" (step function; points are in the middle of horizontal lines)
- "steps-post" (step function; horizontal line is to the right of point)

If \( X \) is a list, then linestyle may be a list (with entries taken from the strings above) or a dictionary (with keys in range(len(\( X \))) and values taken from the strings above).

- **marker** - The style of the markers, which is one of
  - "None" or " " or "" (nothing) – default
  - ",", "(pixel), "." (point)
  - "-" (horizontal line), "|" (vertical line)
  - "o" (circle), "+" (pentagon), "s" (square), "x" (x), "+" (plus), "*" (star)
  - "D" (diamond), "d" (thin diamond)
  - "H" (hexagon), "h" (alternative hexagon)
  - "<" (triangle left), ">" (triangle right), ">" (triangle up), "v" (triangle down)
  - "1" (tri down), "2" (tri up), "3" (tri left), "4" (tri right)
  - 0 (tick left), 1 (tick right), 2 (tick up), 3 (tick down)
  - 4 (caret left), 5 (caret right), 6 (caret up), 7 (caret down), 8 (octagon)
  - "$...$" (math TeX string)

  (numsides, style, angle) to create a custom, regular symbol
  * numsides – the number of sides
  * style – 0 (regular polygon), 1 (star shape), 2 (asterisk), 3 (circle)
  * angle – the angular rotation in degrees

- **markersize** - the size of the marker in points
- **markeredgecolor** – the color of the marker edge
- **markerfacecolor** – the color of the marker face
- **markeredgewidth** - the size of the marker edge in points
• **exclude** - (Default: None) values which are excluded from the plot range. Either a list of real numbers, or an equation in one variable.

**FILLING OPTIONS:**

• **fill** - (default: False) One of:
  - “axis” or True: Fill the area between the function and the x-axis.
  - “min”: Fill the area between the function and its minimal value.
  - “max”: Fill the area between the function and its maximal value.
  - a number c: Fill the area between the function and the horizontal line y = c.
  - a function g: Fill the area between the function that is plotted and g.
  - a dictionary d (only if a list of functions are plotted): The keys of the dictionary should be integers. The value of d[i] specifies the fill options for the i-th function in the list. If d[i] == [j]: Fill the area between the i-th and the j-th function in the list. (But if d[i] == j: Fill the area between the i-th function in the list and the horizontal line y = j.)

• **fillalpha** - (default: 0.5) How transparent the fill is. A number between 0 and 1.

**MATPLOTLIB STYLE SHEET OPTION:**

• **stylesheet** - (Default: classic) Support for loading a full matplotlib style sheet. Any style sheet listed in matplotlib.pyplot.style.available is acceptable. If a non-existing style is provided the default classic is applied.

**EXAMPLES:**

We plot the sin function:

```sage
sage: P = plot(sin, (0,10)); print(P)
Graphics object consisting of 1 graphics primitive
sage: len(P)  # number of graphics primitives
1
sage: len(P[0])  # how many points were computed (random)
225
sage: P  # render
Graphics object consisting of 1 graphics primitive
```

```sage
sage: P = plot(sin, (0,10), plot_points=10); print(P)
Graphics object consisting of 1 graphics primitive
sage: len(P[0])  # random output
32
sage: P  # render
Graphics object consisting of 1 graphics primitive
```

We plot with `randomize=False`, which makes the initial sample points evenly spaced (hence always the same). Adaptive plotting might insert other points, however, unless `adaptive_recursion=0`.

```sage
sage: p=plot(1, (x,0,3), plot_points=4, randomize=False, adaptive_recursion=0)
sage: list(p[0])
[(0.0, 1.0), (1.0, 1.0), (2.0, 1.0), (3.0, 1.0)]
```

Some colored functions:
1.1. 2D plotting
We plot several functions together by passing a list of functions as input:

```
sage: plot([x*exp(-n*x^2)/.4 for n in [1..5]], (0, 2), aspect_ratio=.8)
```
Graphics object consisting of 5 graphics primitives

By default, color will change from one primitive to the next. This may be controlled by modifying color option:

```
sage: g1 = plot([x*exp(-n*x^2)/.4 for n in [1..3]], (0, 2), color='blue', aspect_ratio=.8); g1
Graphics object consisting of 3 graphics primitives
sage: g2 = plot([x*exp(-n*x^2)/.4 for n in [1..3]], (0, 2), color=['red','red','green'], linestyle=['-','-','-'], aspect_ratio=.8); g2
```
Graphics object consisting of 3 graphics primitives

While plotting real functions, imaginary numbers that are “almost real” will inevitably arise due to numerical issues. By tweaking the `imaginary_tolerance`, you can decide how large of an imaginary part you’re willing to sweep under the rug in order to plot the corresponding point. If a particular value’s imaginary part has
1.1. 2D plotting
1.1. 2D plotting
magnitude larger than `imaginary_tolerance`, that point will not be plotted. The default tolerance is $1e^{-8}$, so the imaginary part in the first example below is ignored, but the second example “fails,” emits a warning, and produces an empty graph:

```python
sage: f = x + I*1e-12
sage: plot(f, x, -1, 1)
Graphics object consisting of 1 graphics primitive
sage: plot(f, x, -1, 1, imaginary_tolerance=0)
...WARNING: ...Unable to compute ...
Graphics object consisting of 0 graphics primitives
```

We can also build a plot step by step from an empty plot:

```python
sage: a = plot([]); a  # passing an empty list returns an empty plot
     # passing (Graphics()) object
Graphics object consisting of 0 graphics primitives
sage: a += plot(x**2); a  # append another plot
Graphics object consisting of 1 graphics primitive
sage: a += plot(x**3); a  # append yet another plot
Graphics object consisting of 2 graphics primitives
```

The function $\sin(1/x)$ wiggles wildly near 0. Sage adapts to this and plots extra points near the origin.
Via the matplotlib library, Sage makes it easy to tell whether a graph is on both sides of both axes, as the axes only cross if the origin is actually part of the viewing area:

```sage
plot(x^3,(x,0,2)) # this one has the origin
Graphics object consisting of 1 graphics primitive
```

```sage
plot(x^3,(x,1,2)) # this one does not
Graphics object consisting of 1 graphics primitive
```

Another thing to be aware of with axis labeling is that when the labels have quite different orders of magnitude or are very large, scientific notation (the $e$ notation for powers of ten) is used:

```sage
plot(x^2,(x,480,500)) # this one has no scientific notation
Graphics object consisting of 1 graphics primitive
```

```sage
plot(x^2,(x,300,500)) # this one has scientific notation on y-axis
Graphics object consisting of 1 graphics primitive
```

You can put a legend with `legend_label` (the legend is only put once in the case of multiple functions):
1.1. 2D plotting
Chapter 1. General
1.1. 2D plotting
Sage understands TeX, so these all are slightly different, and you can choose one based on your needs:

```sage
sage: plot(sin, legend_label='sin')
Graphics object consisting of 1 graphics primitive
```

```sage
sage: plot(sin, legend_label='$\sin$')
Graphics object consisting of 1 graphics primitive
```

```sage
sage: plot(sin, legend_label=r'$\sin$')
Graphics object consisting of 1 graphics primitive
```

It is possible to use a different color for the text of each label:

```sage
sage: p1 = plot(sin, legend_label='sin', legend_color='red')
sage: p2 = plot(cos, legend_label='cos', legend_color='green')
sage: p1 + p2
Graphics object consisting of 2 graphics primitives
```

Prior to github issue #19485, legends by default had a shadowless gray background. This behavior can be recovered by setting the legend options on your plot object:
Chapter 1. General
1.1. 2D plotting

\[ \sin \]
1.1. 2D plotting
If \( X \) is a list of Sage objects and \texttt{legend\_label} is ‘automatic’, then Sage will create labels for each function according to their internal representation:

\begin{verbatim}
sage: plot([sin(x), tan(x), 1-x^2], legend_label='automatic')
Graphics object consisting of 3 graphics primitives
\end{verbatim}

If \texttt{legend\_label} is any single string other than ‘automatic’, then it is repeated for all members of \( X \):

\begin{verbatim}
sage: plot([sin(x), tan(x)], color='blue', legend_label='trig')
Graphics object consisting of 2 graphics primitives
\end{verbatim}

Note that the independent variable may be omitted if there is no ambiguity:

\begin{verbatim}
sage: plot(sin(1.0/x), (-1, 1))
Graphics object consisting of 1 graphics primitive
\end{verbatim}

Plotting in logarithmic scale is possible for 2D plots. There are two different syntaxes supported:

\begin{verbatim}
sage: plot(exp, (1, 10), scale='semilogy') # log axis on vertical
Graphics object consisting of 1 graphics primitive
\end{verbatim}
1.1. 2D plotting
Chapter 1. General
We can also change the scale of the axes in the graphics just before displaying:

```
sage: G = plot(exp, 1, 10) # long time
sage: G.show(scale=('semilogy', 2)) # long time
```

The algorithm used to insert extra points is actually pretty simple. On the picture drawn by the lines below:

```
sage: p = plot(x^2, (-0.5, 1.4)) + line([(0,0), (1,1)], color='green')
sage: p += line([(0.5, 0.5), (0.5, 0.5^2)], color='purple')
sage: p += point(((0, 0), (0.5, 0.5), (0.5, 0.5^2), (1, 1)), color='red', pointsize=20)
sage: p += text('A', (-0.05, 0.1), color='red')
sage: p += text('B', (1.01, 1.1), color='red')
```

(continues on next page)
1.1. 2D plotting
You have the function (in blue) and its approximation (in green) passing through the points A and B. The algorithm finds the midpoint C of AB and computes the distance between C and D. If that distance exceeds the adaptive_tolerance threshold (relative to the size of the initial plot subintervals), the point D is added to the curve. If D is added to the curve, then the algorithm is applied recursively to the points A and D, and D and B. It is repeated adaptive_recursion times (5, by default).

The actual sample points are slightly randomized, so the above plots may look slightly different each time you draw them.

We draw the graph of an elliptic curve as the union of graphs of 2 functions.

It is important to mention that when we draw several graphs at the same time, parameters xmin, xmax, ymin and ymax are just passed directly to the show procedure. In fact, these parameters would be overwritten:
1.1. 2D plotting
sage: p=plot(x^3, x, xmin=-1, xmax=1, ymin=-1, ymax=1)
sage: q=plot(exp(x), x, xmin=-2, xmax=2, ymin=0, ymax=4)
sage: (p+q).show()

As a workaround, we can perform the trick:

sage: p1 = line([(a,b) for a,b in zip(p[0].xdata, p[0].ydata) if (b>=-1 and b<=1)])
sage: q1 = line([(a,b) for a,b in zip(q[0].xdata, q[0].ydata) if (b>=0 and b<=4)])
sage: (p1+q1).show()

We can also directly plot the elliptic curve:

sage: E = EllipticCurve([0,-1])
sage: plot(E, (1, 4), color=hue(0.6))

Graphics object consisting of 1 graphics primitive

We can change the line style as well:

sage: plot(sin(x), (x, 0, 10), linestyle='-.')

Graphics object consisting of 1 graphics primitive

If we have an empty linestyle and specify a marker, we can see the points that are actually being plotted:
1.1. 2D plotting
sage: plot(sin(x), (x, 0, 10), plot_points=20, linestyle='', marker='.
Graphics object consisting of 1 graphics primitive

The marker can be a TeX symbol as well:

sage: plot(sin(x), (x, 0, 10), plot_points=20, linestyle='', marker=r'$\checkmark$
Graphics object consisting of 1 graphics primitive

Sage currently ignores points that cannot be evaluated

sage: from sage.misc.verbose import set_verbose
sage: set_verbose(-1)
sage: plot(-x*log(x), (x, 0, 1))  # this works fine since the failed endpoint is.
˓→just skipped.
Graphics object consisting of 1 graphics primitive
sage: set_verbose(0)

This prints out a warning and plots where it can (we turn off the warning by setting the verbose mode temporarily to -1.)

sage: set_verbose(-1)
sage: plot(x^(1/3), (x, -1, 1))
Graphics object consisting of 1 graphics primitive

(continues on next page)
1.1. 2D plotting
Plotting the real cube root function for negative input requires avoiding the complex numbers one would usually get. The easiest way is to use \texttt{real_nth_root(x, n)}

\begin{verbatim}
sage: plot(real_nth_root(x, 3), (x, -1, 1))
Graphics object consisting of 1 graphics primitive
\end{verbatim}

We can also get the same plot in the following way:

\begin{verbatim}
sage: plot(sign(x)*abs(x)^(1/3), (x, -1, 1))
Graphics object consisting of 1 graphics primitive
\end{verbatim}

A way to plot other functions without symbolic variants is to use lambda functions:

\begin{verbatim}
sage: plot(lambda x : RR(x).nth_root(3), (x, -1, 1))
Graphics object consisting of 1 graphics primitive
\end{verbatim}

We can detect the poles of a function:

\begin{verbatim}
sage: plot(gamma, (-3, 4), detect_poles=True).show(ymin=-5, ymax=5)
\end{verbatim}

We draw the Gamma-Function with its poles highlighted:
1.1. 2D plotting
1.1. 2D plotting
The basic options for filling a plot:

```python
sage: p1 = plot(sin(x), -pi, pi, fill='axis')
sage: p2 = plot(sin(x), -pi, pi, fill='min', fillalpha=1)
sage: p3 = plot(sin(x), -pi, pi, fill='max')
sage: p4 = plot(sin(x), -pi, pi, fill=(1-x)/3, fillcolor='blue', fillalpha=.2)
sage: graphics_array([p1, p2], [p3, p4]).show(frame=True, axes=False) # long time
```

The basic options for filling a list of plots:

```python
sage: (f1, f2) = x*exp(-1*x^2)/.35, x*exp(-2*x^2)/.35
sage: p1 = plot([f1, f2], -pi, pi, fill={1: [0]}, fillcolor='blue', fillalpha=.25, color='blue')
sage: p2 = plot([f1, f2], -pi, pi, fill={0: x/3, 1:[0]}, color=['blue'])
sage: p3 = plot([f1, f2], -pi, pi, fill=[0, [0]], fillcolor=\['orange','red'\], fillalpha=1, color={1: 'blue'})
sage: p4 = plot([f1, f2], (x,-pi, pi), fill=[x/3, 0], fillcolor=['grey'], color=['red', 'blue'])
sage: graphics_array([[p1, p2], [p3, p4]]).show(frame=True, axes=False) # long time
```

A example about the growth of prime numbers:
1.1. 2D plotting
Fill the area between a function and its asymptote:

```
sage: f = (2*x^3+2*x-1)/((x-2)^*(x+1))
sage: plot([f, 2*x+2], -7,7, fill={0: [1]}, fillcolor='#ccc').show(ymin=-20, ymax=20)
```

Fill the area between a list of functions and the x-axis:

```
sage: def b(n): return lambda x: bessel_J(n, x)
sage: plot([b(n) for n in [1..5]], 0, 20, fill='axis')
```

Note that to fill between the ith and jth functions, you must use the dictionary key-value syntax i:j; using key-value pairs like i:j will fill between the ith function and the line y=j:

```
sage: def b(n): return lambda x: bessel_J(n, x) + 0.5*(n-1)
sage: plot([b(c) for c in [1..5]], 0, 20, fill={i:[i-1] for i in [1..4]}, color={i: 'blue' for i in [1..5]}, aspect_ratio=3, ymax=3)
```

Graphics object consisting of 10 graphics primitives
1.1. 2D plotting
Extra options will get passed on to \texttt{show()}, as long as they are valid:

\begin{verbatim}
sage: plot(sin(x^2), (x, -3, 3), title=r'Plot of $\sin(x^2)$', axes_labels=['$x$', '$y$'])  # These labels will be nicely typeset
Graphics object consisting of 1 graphics primitive
\end{verbatim}

\begin{verbatim}
sage: plot(sin(x^2), (x, -3, 3), title='Plot of \sin(x^2)', axes_labels=['x', 'y'])  # These will not
Graphics object consisting of 1 graphics primitive
\end{verbatim}

\begin{verbatim}
sage: plot(sin(x^2), (x, -3, 3), axes_labels=['x', 'y'], axes_labels_size=2.5)  # Large axes labels (w.r.t. the tick marks)
Graphics object consisting of 1 graphics primitive
\end{verbatim}

\begin{verbatim}
sage: plot(sin(x^2), (x, -3, 3), figsize=[8,2])
Graphics object consisting of 1 graphics primitive
\end{verbatim}

\begin{verbatim}
sage: plot(sin(x^2), (x, -3, 3)).show(figsize=[8,2])  # These are equivalent
\end{verbatim}
Plot of $\sin(x^2)$
Plot of $\sin(x^2)$
Chapter 1. General
This includes options for custom ticks and formatting. See documentation for `show()` for more details.

```sage
plot(sin(pi*x), (x, -8, 8), ticks=[[-7,-3,0,3,7],[-1/2,0,1/2]])
```

Graphics object consisting of 1 graphics primitive

This is particularly useful when setting custom ticks in multiples of $\pi$.

```sage
plot(2*x + 1, (x, 0, 5), ticks=[[0, 1, e, pi, sqrt(20)], [1, 3, 2*e + 1, 2*pi - 1, 2*sqrt(20) + 1]], tick_formatter="latex")
```

Graphics object consisting of 1 graphics primitive

You can even have custom tick labels along with custom positioning.

```sage
plot(x**2, (x,0,3), ticks=[[1,2.5],[0.5,1,2]], tick_formatter=["$x_1$","x_2"],["$y_1$","y_2$","y_3$"])
```

Graphics object consisting of 1 graphics primitive

You can force Type 1 fonts in your figures by providing the relevant option as shown below. This also requires that LaTeX, dvipng and Ghostscript be installed:

1.1. 2D plotting
1.1. 2D plotting
A example with excluded values:

```python
sage: plot(floor(x), (x, 1, 10), exclude=[1..10])
```

Graphics object consisting of 11 graphics primitives

We exclude all points where PrimePi makes a jump:

```python
sage: jumps = [n for n in [1..100] if prime_pi(n) != prime_pi(n-1)]
sage: plot(lambda x: prime_pi(x), (x, 1, 100), exclude=jumps)
```

Graphics object consisting of 26 graphics primitives

Excluded points can also be given by an equation:

```python
sage: g(x) = x^2-2*x-2
sage: plot(1/g(x), (x, -3, 4), exclude=g(x)==0, ymin=-5, ymax=5) # long time
```

Graphics object consisting of 3 graphics primitives

exclude and detect_poles can be used together:
\textbf{sage: } f(x) = (\text{floor}(x)+0.5) / (1-(x-0.5)^2) \\
\textbf{sage: } \text{plot}(f, (x, -3.5, 3.5), \text{detect_poles}='\text{show}', \text{exclude}=[-3..3], \text{ymin}=-5, \text{ymax}=5) \\
\text{Graphics object consisting of 12 graphics primitives}

Regions in which the plot has no values are automatically excluded. The regions thus excluded are in addition to the exclusion points present in the \texttt{exclude} keyword argument.: 

\textbf{sage: } \text{set\_verbose(-1)} \\
\textbf{sage: } \text{plot}((\text{arcsec}, (x, -2, 2))) \quad \# \ [-1, 1] \ is \ excluded \ automatically \\
\text{Graphics object consisting of 2 graphics primitives}

\textbf{sage: } \text{plot}((\text{arcsec}, (x, -2, 2), \text{exclude}=[1.5])) \quad \# \ x=1.5 \ is \ also \ excluded \\
\text{Graphics object consisting of 3 graphics primitives}

\textbf{sage: } \text{plot}((\text{arcsec}(x/2), -2, 2)) \quad \# \ \text{plot} \ \text{should} \ \text{be} \ \text{empty}; \ \text{no} \ \text{valid} \ \text{points} \\
\text{Graphics object consisting of 0 graphics primitives} \\
\textbf{sage: } \text{plot}((\text{sqrt}(x^2-1), -2, 2)) \quad \# \ [-1, 1] \ is \ excluded \ automatically \\
\text{Graphics object consisting of 2 graphics primitives}

\textbf{sage: } \text{plot}((\text{arccsc}, -2, 2)) \quad \# \ [-1, 1] \ is \ excluded \ automatically \\
\text{Graphics object consisting of 2 graphics primitives} \\
\textbf{sage: } \text{set\_verbose(0)}
1.1. 2D plotting
1.1. 2D plotting
sage.plot.plot.plot_loglog(funcs, base=10, *args, **kwds)

Plot graphics in ‘loglog’ scale, that is, both the horizontal and the vertical axes will be in logarithmic scale.

INPUT:

• base – (default: 10); the base of the logarithm. This must be greater than 1. The base can be also given as a list or tuple (basex, basey). basex sets the base of the logarithm along the horizontal axis and basey sets the base along the vertical axis.

• funcs – any Sage object which is acceptable to the plot().

For all other inputs, look at the documentation of plot().

EXAMPLES:

```python
sage: plot_loglog(exp, (1,10))  # plot in loglog scale with base 10
Graphics object consisting of 1 graphics primitive
```

```python
sage: plot_loglog(exp, (1,10), base=2.1)  # long time # with base 2.1 on both axes
Graphics object consisting of 1 graphics primitive
```

```python
sage: plot_loglog(exp, (1,10), base=(2,3))
Graphics object consisting of 1 graphics primitive
```

sage.plot.plot.plot_semilogx(funcs, base=10, *args, **kwds)

Plot graphics in ‘semilogx’ scale, that is, the horizontal axis will be in logarithmic scale.
1.1. 2D plotting
INPUT:

- **base** – (default: 10); the base of the logarithm. This must be greater than 1.
- **funcs** – any Sage object which is acceptable to the `plot()`.

For all other inputs, look at the documentation of `plot()`.

EXAMPLES:

```python
sage: plot_semilogx(exp, (1,10))  # long time # plot in semilogx scale, base 10
Graphics object consisting of 1 graphics primitive
```

```python
sage: plot_semilogx(exp, (1,10), base=2)  # with base 2
```

```python
sage: s = var('s')  # Samples points logarithmically so graph is smooth
sage: f = 4000000/(4000000 + 4000*s*i - s*s)
```

```python
sage: plot_semilogx(20*log(abs(f), 10), (s, 1, 1e6))
```

```python
sage: plot_semilogy(funcs, base=10, *args, **kwds)
```

Plot graphics in ‘semilogy’ scale, that is, the vertical axis will be in logarithmic scale.

INPUT:
1.1. 2D plotting
• base – (default: 10); the base of the logarithm. This must be greater than 1.
• funcs – any Sage object which is acceptable to the plot().

For all other inputs, look at the documentation of plot().

EXAMPLES:

```
sage: plot_semilogy(exp, (1,10)) # long time # plot in semilogy scale, base 10
Graphics object consisting of 1 graphics primitive
```

```
sage: plot_semilogy(exp, (1,10), base=2) # long time # with base 2
Graphics object consisting of 1 graphics primitive
```

sage.plot.plot.polar_plot(funcs, aspect_ratio=1.0, *args, **kwds)
polar_plot takes a single function or a list or tuple of functions and plots them with polar coordinates in the given domain.

This function is equivalent to the plot() command with the options polar=True and aspect_ratio=1. For more help on options, see the documentation for plot().

INPUT:
• funcs – a function
• other options are passed to plot
Chapter 1. General
EXAMPLES:

Here is a blue 8-leaved petal:

```
sage: polar_plot(sin(5*x)^2, (x, 0, 2*pi), color='blue')
```

Graphics object consisting of 1 graphics primitive

A red figure-8:

```
sage: polar_plot(abs(sqrt(1 - sin(x)^2)), (x, 0, 2*pi), color='red')
```

Graphics object consisting of 1 graphics primitive

A green limacon of Pascal:

```
sage: polar_plot(2 + 2*cos(x), (x, 0, 2*pi), color=hue(0.3))
```

Graphics object consisting of 1 graphics primitive

Several polar plots:

```
sage: polar_plot([2*sin(x), 2*cos(x)], (x, 0, 2*pi))
```

Graphics object consisting of 2 graphics primitives

A filled spiral:
1.1. 2D plotting
Chapter 1. General
Fill the area between two functions:

```python
sage: polar_plot(cos(4*x) + 1.5, 0, 2*pi, fill=0.5 * cos(4*x) + 2.5, fillcolor='orange')
```

Fill the area between several spirals:

```python
sage: polar_plot([(1.2+k*0.2)*log(x) for k in range(6)], 1, 3*pi, fill={0: [1], 2: [3], 4: [5]})
```

Exclude points at discontinuities:

```python
sage: polar_plot(log(floor(x)), (x, 1, 4*pi), exclude=[1..12])
```

`sage.plot.plot.reshape(v, n, m)`

Helper function for creating graphics arrays.

The input array is flattened and turned into an `n x m` array, with blank graphics object padded at the end, if
1.1. 2D plotting
necessary.

INPUT:

• v – a list of lists or tuples
• n, m – integers

OUTPUT: a list of lists of graphics objects

EXAMPLES:

```sage
L = [plot(sin(k*x),(x,-pi,pi)) for k in range(10)]
sage: graphics_array(L,3,4)  # long time (up to 4s on sage.math, 2012)
Graphics Array of size 3 x 4
```

```sage
M = [[plot(sin(k*x),(x,-pi,pi)) for k in range(3)],
     [plot(cos(j*x),(x,-pi,pi)) for j in [3..5]]]
sage: graphics_array(M,6,1)  # long time (up to 4s on sage.math, 2012)
Graphics Array of size 6 x 1
```

`sage.plot.plot.to_float_list(v)`

Given a list or tuple or iterable v, coerce each element of v to a float and make a list out of the result.

EXAMPLES:

```sage
from sage.plot.plot import to_float_list
to_float_list([1,1/2,3])
[1.0, 0.5, 3.0]
```

`sage.plot.plot.xydata_from_point_list(points)`

Return two lists (xdata, ydata), each coerced to a list of floats, which correspond to the x-coordinates and the y-coordinates of the points.

The points parameter can be a list of 2-tuples or some object that yields a list of one or two numbers.

This function can potentially be very slow for large point sets.

### 1.2 Text in plots

**class** `sage.plot.text.Text(string, point, options)`

Bases: `GraphicPrimitive`

Base class for Text graphics primitive.

**get_minmax_data()**

Return a dictionary with the bounding box data. Notice that, for text, the box is just the location itself.

EXAMPLES:

```sage
T = text("Where am I?",(1,1))
t=T[0]
t.get_minmax_data() ['ymin']
1.0
t.get_minmax_data() ['ymax']
1.0
```
plot3d(**kwds)

Plot 2D text in 3D.

EXAMPLES:

```python
sage: T = text("ABC", (1, 1))
sage: t = T[0]
sage: s = t.plot3d()
sage: s.jmol_repr(s.testing_render_params())[0][2]
'label "ABC"
sage: s._trans(1.0, 1.0, 0)
```

```
sage.plot.text.text(string, xy, fontsize=10, rgbcolor=(0, 0, 1), horizontal_alignment='center', vertical_alignment='center', axis_coords=False, clip=False, **options)
```

Return a 2D text graphics object at the point \((x, y)\).

Type `text.options` for a dictionary of options for 2D text.

2D OPTIONS:

- `fontsize` - How big the text is. Either an integer that specifies the size in points or a string which specifies a size (one of ‘xx-small’, ‘x-small’, ‘small’, ‘medium’, ‘large’, ‘x-large’, ‘xx-large’)
- `fontstyle` - A string either ‘normal’, ‘italic’ or ‘oblique’
- `rgbcolor` - The color as an RGB tuple
- `hue` - The color given as a hue
- `alpha` - A float (0.0 transparent through 1.0 opaque)
- `background_color` - The background color
- `rotation` - How to rotate the text: angle in degrees, vertical, horizontal
- `vertical_alignment` - How to align vertically: top, center, bottom
- `horizontal_alignment` - How to align horizontally: left, center, right
- `zorder` - The layer level in which to draw
- `clip` - (default: False) Whether to clip or not
- `axis_coords` - (default: False) If True, use axis coordinates, so that (0,0) is the lower left and (1,1) upper right, regardless of the x and y range of plotted values.
- `bounding_box` - A dictionary specifying a bounding box. Currently the text location.

EXAMPLES:

```python
sage: text("Sage graphics are really neat because they use matplotlib!", (2,12))
```

Graphics object consisting of 1 graphics primitive

Larger font, bold, colored red and transparent text:

```python
sage: text("I had a dream!", (2,12), alpha=0.3, fontsize='large', fontweight='bold', color='red')
```

Graphics object consisting of 1 graphics primitive
Sage graphics are really neat because they use matplotlib!
I had a dream!
By setting `horizontal_alignment` to ‘left’ the text is guaranteed to be in the lower left no matter what:

```
sage: text("I got a horse and he lives in a tree", (0,0), axis_coords=True,
       horizontal_alignment='left')
```

Graphics object consisting of 1 graphics primitive

Various rotations:

```
sage: text("noitator", (0,0), rotation=45.0, horizontal_alignment='left',
       vertical_alignment='bottom')
```

Graphics object consisting of 1 graphics primitive

```
sage: text("Sage is really neat!!",(0,0), rotation="vertical")
```

Graphics object consisting of 1 graphics primitive

You can also align text differently:

```
sage: t1 = text("Hello",(1,1), vertical_alignment="top")
sage: t2 = text("World", (1,0.5), horizontal_alignment="left")
```

```
sage: t1 + t2  # render the sum
```

Graphics object consisting of 2 graphics primitives

You can save text as part of PDF output:
1.2. Text in plots
Hello
World

1.2. Text in plots
sage: import tempfile
sage: with tempfile.NamedTemporaryFile(suffix=".pdf") as f:
    ....:
    text("sage", (0,0), rgbcolor=(0,0,0)).save(f.name)

Some examples of bounding box:

```python
sage: bbox = {'boxstyle': 'rarrow,pad=0.3', 'fc': 'cyan', 'ec': 'b', 'lw': 2}
sage: text("I feel good", (1, 2), bounding_box=bbox)
Graphics object consisting of 1 graphics primitive
```

```
I feel good
```

The possible options of the bounding box are 'boxstyle' (one of 'larrow', 'rarrow', 'round', 'round4', 'roundtooth', 'sawtooth', 'square'), 'fc' or 'facecolor', 'ec' or 'edgecolor', 'ha' or 'horizontalalignment', 'va' or 'verticalalignment', 'lw' or 'linewidth'.

A text with a background color:

```python
sage: text("So good", (0, 0), bounding_box={'boxstyle': 'round', 'fc': 'w'})
Graphics object consisting of 1 graphics primitive
```

Use dollar signs for LaTeX and raw strings to avoid having to escape backslash characters:
1.2. Text in plots
So good
sage: A = arc((0, 0), 1, sector=(0.0, RDF.pi()))
sage: a = sqrt(1./2.)
sage: PQ = point2d([(-a, a), (a, a)])
sage: botleft = dict(horizontal_alignment='left', vertical_alignment='bottom')
sage: botright = dict(horizontal_alignment='right', vertical_alignment='bottom')
sage: tp = text(r'$z_P = e^{3i\pi/4}$', (-a, a), **botright)
sage: tq = text(r'$Q = (\frac{\sqrt{2}}{2}, \frac{\sqrt{2}}{2})$', (a, a), **botleft)
sage: A + PQ + tp + tq
Graphics object consisting of 4 graphics primitives

Text coordinates must be 2D, an error is raised if 3D coordinates are passed:

```
sage: t = text("hi", (1, 2, 3))
Traceback (most recent call last):
...
ValueError: use text3d instead for text in 3d
```

Use the text3d function for 3D text:

```
sage: t = text3d("hi", (1, 2, 3))
```

Or produce 2D text with coordinates \((x, y)\) and plot it in 3D (at \(z = 0\)):

1.2. Text in plots
sage: t = text("hi", (1, 2))
sage: t.plot3d() # text at position (1, 2, 0)
Graphics3d Object

Extra options will get passed on to show(), as long as they are valid. Hence this

sage: text("MATH IS AWESOME", (0, 0), fontsize=40, axes=False)
Graphics object consisting of 1 graphics primitive

is equivalent to

sage: text("MATH IS AWESOME", (0, 0), fontsize=40).show(axes=False)

1.3 Colors

This module defines a Color object and helper functions (see, e.g., hue(), rainbow()), as well as a set of colors and colormaps to use with Graphics objects in Sage.

For a list of pre-defined colors in Sage, evaluate:

sage: sorted(colors)
['aliceblue', 'antiquewhite', 'aqua', 'aquamarine', 'automatic', ...]

Apart from ‘automatic’ which just an alias for ‘lightblue’, this list comprises the “official” W3C CSS3 / SVG colors.

For a list of color maps in Sage, evaluate:

sage: sorted(colormaps)
['Accent', ...]

These are imported from matplotlib’s colormaps collection.

class sage.plot.colors.Color(r=#0000ff, g=None, b=None, space='rgb')

Bases: object

An Red-Green-Blue (RGB) color model color object. For most consumer-grade devices (e.g., CRTs, LCDs, and printers), as well as internet applications, this is a point in the sRGB absolute color space. The Hue-Saturation-Lightness (HSL), Hue-Lightness-Saturation (HLS), and Hue-Saturation-Value (HSV) spaces are useful alternate representations, or coordinate transformations, of this space. Coordinates in all of these spaces are floating point values in the interval [0.0, 1.0].

Note: All instantiations of Color are converted to an internal RGB floating point 3-tuple. This is likely to degrade precision.

INPUT:

• r, g, b - either a triple of floats between 0 and 1, OR r - a color name string or HTML color hex string

• space - a string (default: ‘rgb’); the coordinate system (other choices are ‘hsl’, ‘hls’, and ‘hsv’) in which to interpret a triple of floats

EXAMPLES:
sage: Color('purple')
RGB color (0.5019607843137255, 0.0, 0.5019607843137255)
sage: Color('#8000ff')
RGB color (0.5019607843137255, 0.0, 1.0)
sage: Color(0.5,0,1)
RGB color (0.5, 0.0, 1.0)
sage: Color(0.5, 1.0, 1, space='hsv')
RGB color (0.0, 1.0, 1.0)
sage: Color(0.25, 0.5, 0.5, space='hls')
RGB color (0.5000000000000001, 0.75, 0.25)
sage: Color(1, 0, 1/3, space='hsl')
RGB color (0.3333333333333333, 0.3333333333333333, 0.3333333333333333)
sage: from sage.plot.colors import chocolate
sage: Color(chocolate)
RGB color (0.8235294117647058, 0.4117647058823529, 0.11764705882352941)

blend(color, fraction=0.5)

Return a color blended with the given color by a given fraction. The algorithm interpolates linearly between the colors’ corresponding R, G, and B coordinates.

INPUT:

• color - a Color instance or float-convertible 3-tuple/list; the color with which to blend this color
• fraction - a float-convertible number; the fraction of color to blend with this color

OUTPUT:

• a new Color instance

EXAMPLES:

sage: from sage.plot.colors import red, blue, lime
sage: red.blend(blue)
RGB color (0.5, 0.0, 0.5)
sage: red.blend(blue, fraction=0.0)
RGB color (1.0, 0.0, 0.0)
sage: red.blend(blue, fraction=1.0)
RGB color (0.0, 0.0, 1.0)
sage: lime.blend((0.3, 0.5, 0.7))
RGB color (0.15, 0.75, 0.35)
sage: blue.blend(blue)
RGB color (0.0, 0.0, 1.0)
sage: red.blend(lime, fraction=0.3)
RGB color (0.7, 0.3, 0.0)
sage: blue.blend((0.0, 0.9, 0.2), fraction=0.2)
RGB color (0.0, 0.18000000000000002, 0.8400000000000001)
sage: red.blend(0.2)
Traceback (most recent call last):
...
TypeError: 0.2000000000000000 must be a Color or float-convertible 3-tuple/list

darker(fraction=0.3333333333333333)

Return a darker “shade” of this RGB color by blend()-ing it with black. This is not an inverse of lighter().

INPUT:

1.3. Colors
• fraction - a float (default: 1/3); blending fraction to apply

OUTPUT:

• a new instance of Color

EXAMPLES:

```
sage: from sage.plot.colors import black
sage: vector(black.darker().rgb()) == vector(black.rgb())
True
sage: Color(0.4, 0.6, 0.8).darker(0.1)
RGB color (0.36000000000000004, 0.54, 0.72000000000000001)
sage: Color(.1,.2,.3,space='hsl').darker()
RGB color (0.24000000000000002, 0.20800000000000002, 0.16)
```

hls()

Return the Hue-Lightness-Saturation (HLS) coordinates of this color.

OUTPUT:

• a 3-tuple of floats

EXAMPLES:

```
sage: Color(0.3, 0.5, 0.7, space='hls').hls()
(0.30000000000000004, 0.5, 0.7)
sage: Color(0.3, 0.5, 0.7, space='hsl').hls() # abs tol 1e-15
(0.30000000000000004, 0.7, 0.50000000000000001)
sage: Color('#aabbcc').hls() # abs tol 1e-15
(0.5833333333333334, 0.7333333333333334, 0.250000000000000017)
sage: from sage.plot.colors import orchid
sage: orchid.hls() # abs tol 1e-15
(0.8396226415094339, 0.6470588235294117, 0.5888888888888889)
```

hsl()

Return the Hue-Saturation-Lightness (HSL) coordinates of this color.

OUTPUT:

• a 3-tuple of floats

EXAMPLES:

```
sage: Color(1,0,0).hsl()
(0.0, 1.0, 0.5)
sage: from sage.plot.colors import orchid
sage: orchid.hsl() # abs tol 1e-15
(0.8396226415094339, 0.5888888888888889, 0.6470588235294117)
sage: Color('#aabbcc').hsl() # abs tol 1e-15
(0.5833333333333334, 0.250000000000000017, 0.7333333333333334)
```

hsv()

Return the Hue-Saturation-Value (HSV) coordinates of this color.

OUTPUT:

• a 3-tuple of floats

EXAMPLES:
sage: from sage.plot.colors import red
sage: red.hsv()
(0.0, 1.0, 1.0)
sage: Color('red').hsv()
(0.0, 1.0, 1.0)
sage: Color('gray').hsv()
(0.0, 0.0, 0.5)

html_color()
Return a HTML hex representation for this color.
OUTPUT:
• a string of length 7.
EXAMPLES:
sage: Color('yellow').html_color()
'#ffffff'
sage: Color('#fedcba').html_color()
'#fedcba'
sage: Color(0.0, 1.0, 0.0).html_color()
'#ffffff'
sage: from sage.plot.colors import honeydew
sage: honeydew.html_color()
'#ffffff'

lighter(fraction=0.3333333333333333)
Return a lighter “shade” of this RGB color by blend()-ing it with white. This is not an inverse of darker().
INPUT:
• fraction - a float (default: 1/3); blending fraction to apply
OUTPUT:
• a new instance of Color
EXAMPLES:
sage: from sage.plot.colors import khaki
sage: khaki.lighter().darker()
RGB color (0.9607843137254903, 0.934640522875817, 0.6993464052287582)
sage: Color('#ffffff').lighter().darker()
RGB color (0.6666666666666667, 0.6666666666666667, 0.6666666666666667)
sage: Color('#abcdef').lighter(1/4)
RGB color (0.7529411764705882, 0.8529411764705882, 0.9529411764705882)
sage: Color(1, 0, 8/9, space='hsv').lighter()
RGB color (0.9259259259259259, 0.9259259259259259, 0.9259259259259259)

rgb()
Return the underlying Red-Green-Blue (RGB) coordinates of this color.
OUTPUT:
• a 3-tuple of floats
EXAMPLES:
```python
sage: Color(0.3, 0.5, 0.7).rgb()
(0.3, 0.5, 0.7)
sage: Color('#8000ff').rgb()
(0.5019607843137255, 0.0, 1.0)
sage: from sage.plot.colors import orange
sage: orange.rgb()
(1.0, 0.6470588235294118, 0.0)
sage: Color('magenta').rgb()
(1.0, 0.0, 1.0)
sage: Color(1, 0.7, 0.9, space='hsv').rgb()
(0.9, 0.2700000000000001, 0.2700000000000001)
```

**class** `sage.plot.colors.Colormaps`

Bases: `MutableMapping`

A dict-like collection of lazily-loaded matplotlib color maps. For a list of map names, evaluate:

```python
sage: sorted(colormaps)
['Accent', ...]
```

**load_maps()**

If it’s necessary, loads matplotlib’s color maps and adds them to the collection.

**EXAMPLES:**

```python
sage: from sage.plot.colors import Colormaps
sage: maps = Colormaps()
sage: len(maps.maps)
0
sage: maps.load_maps()

sage: 'viridis' in maps
True
```

**class** `sage.plot.colors.ColorsDict`

Bases: `dict`

A dict-like collection of colors, accessible via key or attribute. For a list of color names, evaluate:

```python
sage: sorted(colors)
['aliceblue', 'antiquewhite', 'aquamarine', ...]
```

`sage.plot.colors.check_color_data(cfcm)`

Make sure that the arguments are in order (coloring function, colormap).

This will allow users to use both possible orders.

**EXAMPLES:**

```python
sage: from sage.plot.colors import check_color_data
sage: cf = lambda x,y : (x-y) % 1
sage: cm = colormaps.autumn
sage: check_color_data((cf, cm)) == (cf, cm)
True
```
sage: check_color_data((cm, cf)) == (cf, cm)
True

`sage.plot.colors.float_to_html(r, g, b)`

Convert a Red-Green-Blue (RGB) color tuple to a HTML hex color.

Each input value should be in the interval [0.0, 1.0]; otherwise, the values are first reduced modulo one (see `mod_one()`).

**INPUT:**

- `r` – a real number; the RGB color’s “red” intensity
- `g` – a real number; the RGB color’s “green” intensity
- `b` – a real number; the RGB color’s “blue” intensity

**OUTPUT:**

- a string of length 7, starting with ‘#’

**EXAMPLES:**

```python
sage: from sage.plot.colors import float_to_html
sage: float_to_html(1.,1.,0.)
'#{ffffff}'
sage: float_to_html(.03,.06,.02)
'#{070f05}'
sage: float_to_html(*Color('brown').rgb())
'#{a52a2a}'
```

`sage.plot.colors.float_to_integer(r, g, b)`

Convert a Red-Green-Blue (RGB) color tuple to an integer.

Each input value should be in the interval [0.0, 1.0]; otherwise, the values are first reduced modulo one (see `mod_one()`).

**INPUT:**

- `r` – a real number; the RGB color’s “red” intensity
- `g` – a real number; the RGB color’s “green” intensity
- `b` – a real number; the RGB color’s “blue” intensity

**OUTPUT:**

- the integer $256^2 r \cdot nt + 256 g \cdot nt + b \cdot nt$, where $r \cdot nt, g \cdot nt,$ and $b \cdot nt$ are obtained from $r$, $g$, and $b$ by converting from the real interval [0.0, 1.0] to the integer range 0, 1, ..., 255.

**EXAMPLES:**

```python
sage: from sage.plot.colors import float_to_integer
sage: float_to_integer(1.,1.,0.)
16776960
sage: float_to_integer(.03,.06,.02)
462597
sage: float_to_integer(*Color('brown').rgb())
10824234
```
sage.plot.colors.get_cmap(cmap)

Returns a color map (actually, a matplotlib Colormap object), given its name or a [mixed] list/tuple of RGB list/tuples and color names. For a list of map names, evaluate:

```
sage: sorted(colormaps)
['Accent', ...]
```

See rgbcolor() for valid list/tuple element formats.

**INPUT:**

- `cmap` - a string, list, tuple, or matplotlib.colors.Colormap; a string must be a valid color map name

**OUTPUT:**

- a matplotlib.colors.Colormap instance

**EXAMPLES:**

```
sage: from sage.plot.colors import get_cmap
sage: get_cmap('jet')
<matplotlib.colors.LinearSegmentedColormap object at 0x...>
sage: get_cmap([[0,0,0], (0.5,0.5,0.5), (1,1,1)])
<matplotlib.colors.ListedColormap object at 0x...>
sage: get_cmap(['green', 'lightblue', 'blue'])
<matplotlib.colors.ListedColormap object at 0x...>
sage: get_cmap(((0.5, 0.3, 0.2), [1.0, 0.0, 0.5], 'purple', Color(0.5,0.5,1, space='hsv')))
<matplotlib.colors.ListedColormap object at 0x...>
sage: get_cmap('jolies')
Traceback (most recent call last):
...  RuntimeError: Color map jolies not known (type "import matplotlib; list(matplotlib.colormaps.keys())" for valid names)
sage: get_cmap('mpl')
Traceback (most recent call last):
...  RuntimeError: Color map mpl not known (type "import matplotlib; list(matplotlib.colormaps.keys())" for valid names)
```

sage.plot.colors.html_to_float(c)

Convert a HTML hex color to a Red-Green-Blue (RGB) tuple.

**INPUT:**

- `c` - a string; a valid HTML hex color

**OUTPUT:**

- a RGB 3-tuple of floats in the interval [0.0, 1.0]

**EXAMPLES:**

```
sage: from sage.plot.colors import html_to_float
sage: html_to_float('#fff')
(1.0, 1.0, 1.0)
sage: html_to_float('#abcdef')
(0.6705882352941176, 0.803921568627451, 0.9372549019607843)
```
sage.plot.colors.hue(h, s=1, v=1)

Convert a Hue-Saturation-Value (HSV) color tuple to a valid Red-Green-Blue (RGB) tuple. All three inputs should lie in the interval [0.0, 1.0]; otherwise, they are reduced modulo 1 (see \texttt{mod_one()}). In particular $h=0$ and $h=1$ yield red, with the intermediate hues orange, yellow, green, cyan, blue, and violet as $h$ increases.

This function makes it easy to sample a broad range of colors for graphics:

\begin{verbatim}
sage: p = Graphics()
sage: for phi in xsrange(0, 2 * pi, 1 / pi):
....:     p += plot(sin(x + phi), (x, -7, 7), rgbcolor = hue(phi))
sage: p
Graphics object consisting of 20 graphics primitives
\end{verbatim}

INPUT:

\begin{itemize}
  \item $h$ - a number; the color’s hue
  \item $s$ - a number (default: 1); the color’s saturation
  \item $v$ - a number (default: 1); the color’s value
\end{itemize}

OUTPUT:

\begin{itemize}
  \item a RGB 3-tuple of floats in the interval [0.0, 1.0]
\end{itemize}

EXAMPLES:

\begin{verbatim}
sage: hue(0.6)
(0.0, 0.40000000000000036, 1.0)
sage: from sage.plot.colors import royalblue
sage: royalblue
RGB color (0.2549019607843137, 0.4117647058823529, 0.8823529411764706)
sage: hue(*royalblue.hsv())
(0.2549019607843137, 0.4117647058823529, 0.8823529411764706)
sage: hue(.5, .5, .5)
(0.25, 0.5, 0.5)
\end{verbatim}

\textbf{Note}: The HSV to RGB coordinate transformation itself is given in the source code for the Python library’s \texttt{colorsys} module:

\begin{verbatim}
sage: from colorsys import hsv_to_rgb  # not tested
sage: hsv_to_rgb
\end{verbatim}

sage.plot.colors.mod_one(x)

Reduce a number modulo 1.

INPUT:

\begin{itemize}
  \item $x$ - an instance of Integer, int, RealNumber, etc.; the number to reduce
\end{itemize}

OUTPUT:
• a float

EXAMPLES:

```
sage: from sage.plot.colors import mod_one
sage: mod_one(1)
1.0
sage: mod_one(7.0)
0.0
sage: mod_one(-11/7)
0.4285714285714286
sage: mod_one(pi) + mod_one(-pi)
1.0
```

`sage.plot.colors.rainbow(n, format='hex')`

Returns a list of colors sampled at equal intervals over the spectrum, from Hue-Saturation-Value (HSV) coordinates (0, 1, 1) to (1, 1, 1). This range is red at the extremes, but it covers orange, yellow, green, cyan, blue, violet, and many other hues in between. This function is particularly useful for representing vertex partitions on graphs.

**INPUT:**

- n - a number; the length of the list

- format - a string (default: ‘hex’); the output format for each color in the list; the other choice is ‘rgbtuple’

**OUTPUT:**

- a list of strings or RGB 3-tuples of floats in the interval [0.0, 1.0]

**EXAMPLES:**

```
sage: from sage.plot.colors import rainbow
sage: rainbow(7)
['#ff0000', '#ffda00', '#48ff00', '#00ff91', '#0091ff', '#4800ff', '#ff00da']
sage: rainbow(int(7))
['#ff0000', '#ffda00', '#48ff00', '#00ff91', '#0091ff', '#4800ff', '#ff00da']
sage: rainbow(7, 'rgbtuple')
[(1.0, 0.0, 0.0), (1.0, 0.5714285714285716, 0.0), (0.0, 0.5714285714285714, 1.0), (0.0, 1.0, 0.0), (0.5714285714285714, 1.0, 0.0), (0.0, 1.0, 0.5714285714285712), (0.0, 0.8571428571428571, 1.0), (0.0, 0.0, 0.8571428571428577)]
```

**AUTHORS:**

- Robert L. Miller
- Karl-Dieter Crisman (directly use `hsv_to_rgb()` for hues)

`sage.plot.colors.rgbcolor(c, space='rgb')`

Convert a color (string, tuple, list, or `Color`) to a mod-one reduced (see `mod_one()`) valid Red-Green-Blue (RGB) tuple. The returned tuple is also a valid matplotlib RGB color.

**INPUT:**

- c - a `Color` instance, string (name or HTML hex), 3-tuple, or 3-list; the color to convert

- space - a string (default: ‘rgb’); the color space coordinate system (other choices are ‘hsl’, ‘hls’, and ‘hsv’) in which to interpret a 3-tuple or 3-list

**OUTPUT:**

- a RGB 3-tuple of floats in the interval [0.0, 1.0]
EXAMPLES:

```python
sage: from sage.plot.colors import rgbcolor
sage: rgbcolor(Color(0.25, 0.4, 0.9))
(0.25, 0.4, 0.9)
sage: rgbcolor('purple')
(0.5019607843137255, 0.0, 0.5019607843137255)
sage: rgbcolor('#fa0')
(1.0, 0.6666666666666666, 0.0)
sage: rgbcolor('#ffffff')
(1.0, 1.0, 1.0)
sage: rgbcolor((1,1/2,1/3), space='hsv')
(1.0, 0.0, 0.0)
sage: rgbcolor((0.5,0.75,1), space='hls')
(0.5, 0.9999999999999999, 1.0)
sage: rgbcolor((0.5,1.0,0.75), space='hsl')
(0.5, 0.9999999999999999, 1.0)
sage: rgbcolor([1,2,255]) # WARNING -- numbers are reduced mod 1!!
(1.0, 0.0, 0.0)
sage: rgbcolor('#abcd')
Traceback (most recent call last):
...
ValueError: color hex string (= 'abcd') must have length 3 or 6
sage: rgbcolor('fff')
Traceback (most recent call last):
...
ValueError: unknown color 'fff'
```

```
sage: rgbcolor(1)
Traceback (most recent call last):
...
TypeError: '1' must be a Color, list, tuple, or string
sage: rgbcolor((0.2,0.8,1), space='grassmann')
Traceback (most recent call last):
...
ValueError: space must be one of 'rgb', 'hsv', 'hsl', 'hls'
```

```
sage: rgbcolor([0.4])
Traceback (most recent call last):
...
ValueError: color list or tuple '[0.400000000000000, 0.100000000000000]' must have
→3 entries, one for each RGB, HSV, HLS, or HSL channel
```

```
sage.plot.colors.to_mpl_color(c, space='rgb')

Convert a color (string, tuple, list, or Color) to a mod-one reduced (see mod_one()) valid Red-Green-Blue (RGB) tuple. The returned tuple is also a valid matplotlib RGB color.

INPUT:

- c - a Color instance, string (name or HTML hex), 3-tuple, or 3-list; the color to convert
- space - a string (default: 'rgb'); the color space coordinate system (other choices are 'hsl', 'hls', and 'hsv') in which to interpret a 3-tuple or 3-list
```
OUTPUT:

- a RGB 3-tuple of floats in the interval [0.0, 1.0]

EXAMPLES:

```python
sage: from sage.plot.colors import rgbcolor
sage: rgbcolor(Color(0.25, 0.4, 0.9))
(0.25, 0.4, 0.9)
sage: rgbcolor('purple')
(0.5019607843137255, 0.0, 0.5019607843137255)
sage: rgbcolor('#fa0')
(1.0, 0.6666666666666666, 0.0)
sage: rgbcolor('#ffffff')
(1.0, 1.0, 1.0)
sage: rgbcolor((1,1/2,1/3))
(1.0, 0.5, 0.3333333333333333)
sage: rgbcolor([1,1/2,1/3])
(1.0, 0.5, 0.3333333333333333)
sage: rgbcolor((1,1,1), space='hsv')
(1.0, 0.0, 0.0)
sage: rgbcolor((0.5,0.75,1), space='hls')
(0.5, 0.9999999999999999, 1.0)
sage: rgbcolor((0.5,1.0,0.75), space='hsl')
(0.5, 0.9999999999999999, 1.0)
sage: rgbcolor([1,2,255])  # WARNING -- numbers are reduced mod 1!!
(1.0, 0.0, 0.0)
sage: rgbcolor('#abcd')
Traceback (most recent call last):
    ...
ValueError: color hex string (= 'abcd') must have length 3 or 6
sage: rgbcolor('fff')
Traceback (most recent call last):
    ...
ValueError: unknown color 'fff'
sage: rgbcolor(1)
Traceback (most recent call last):
    ...
TypeError: 1 must be a Color, list, tuple, or string
sage: rgbcolor((0.2,0.8,1), space='grassmann')
Traceback (most recent call last):
    ...
ValueError: space must be one of 'rgb', 'hsv', 'hsl', 'hls'
sage: rgbcolor([0.4, 0.1])
Traceback (most recent call last):
    ...
ValueError: color list or tuple '[0.4000000000000000, 0.1000000000000000]' must have 3 entries, one for each RGB, HSV, HLS, or HSL channel
```
1.4 Animated plots

Animations are generated from a list (or other iterable) of graphics objects. Images are produced by calling the `save_image` method on each input object, creating a sequence of PNG files. These are then assembled to various target formats using different tools. In particular, the `convert` program from ImageMagick can be used to generate an animated GIF file. FFmpeg (with the command line program `ffmpeg`) provides support for various video formats, but also an alternative method of generating animated GIFs. For browsers which support it, APNG can be used as another alternative which works without any extra dependencies.

**Warning:** Note that ImageMagick and FFmpeg are not included with Sage, and must be installed by the user. On unix systems, type `which convert` at a command prompt to see if `convert` (part of the ImageMagick suite) is installed. If it is, you will be given its location. Similarly, you can check for `ffmpeg` with `which ffmpeg`. See the websites of ImageMagick or FFmpeg for installation instructions.

EXAMPLES:

The sine function:

```python
sage: x = SR.var("x")
sage: sines = [plot(c*sin(x), (-2*pi,2*pi), color=Color(c,0,0), ymin=-1, ymax=1) for c in sxrange(0,1,.2)]
sage: a = animate(sines)
sage: print(a)
Animation with 5 frames
sage: a.show()  # long time # optional -- ImageMagick
```

Animate using FFmpeg instead of ImageMagick:

```python
sage: a.show(use_ffmpeg=True)  # long time # optional -- FFmpeg
```

Animate as an APNG:

```python
sage: a.apng(show_path=True)  # long time
Animation saved to ....png.
```

An animated `sage.plot.multigraphics.GraphicsArray` of rotating ellipses:

```python
sage: E = animate((graphics_array([[ellipse((0,0),a,b,angle=t,xmin=-3,xmax=3)+circle((0,0),3,color='blue') for a in range(1,3)] for b in range(2,4)]) for t in sxrange(0,pi/4,.15)))
sage: str(E)  # animations produced from a generator do not have a known length
'Animation with unknown number of frames'
sage: E.show()  # long time # optional -- ImageMagick
```

A simple animation of a circle shooting up to the right:

```python
sage: c = animate([circle((i,i), 1-1/(i+1), hue=i/10) for i in srange(0,2,0.2)],
                      xmin=0,ymin=0,xmax=2,ymax=2,figsize=[2,2])
sage: c.show()  # long time # optional -- ImageMagick
```

Animations of 3d objects:
```python
sage: s, t = SR.var("s,t")
sage: def sphere_and_plane(x):
    ....:     return sphere((0,0,0),1,color='red',opacity=.5)+parametric_plot3d([t,x,s],(s,-1,1),(t,-1,1),color='green',opacity=.7)
sage: sp = animate([sphere_and_plane(x) for x in sxrange(-1,1,.3)])
sage: sp[0]  # first frame
Graphics3d Object
sage: sp[-1]  # last frame
Graphics3d Object
sage: sp.show()  # long time # optional -- ImageMagick

sage: (x,y,z) = SR.var("x,y,z")
sage: def frame(t):
    ....:     return implicit_plot3d((x^2 + y^2 + z^2), (x, -2, 2), (y, -2, 2), (z, -2, 2),
                                plot_points=60, contour=[1,3,5], region=lambda x,y,z: x<=t or y>=t or z<=t)
sage: a = animate([frame(t) for t in srange(.01,1.5,.2)])
sage: a[0]  # long time
Graphics3d Object
sage: a.show()  # long time # optional -- ImageMagick
```

If the input objects do not have a `save_image` method, then the animation object attempts to make an image by calling its internal method `sage.plot.animate.Animation.make_image()`. This is illustrated by the following example:

```python
sage: t = SR.var("t")
sage: a = animate((sin(c*pi*t) for c in sxrange(1,2,.2)))
sage: a.show()  # long time # optional -- ImageMagick
```

AUTHORS:

- William Stein
- John Palmieri
- Niles Johnson (2013-12): Expand to animate more graphics objects
- Martin von Gagern (2014-12): Added APNG support
- Joshua Campbell (2020): interactive animation via Three.js viewer

REFERENCES:

- ImageMagick
- FFmpeg
- APNG
- browsers which support it

**class** `sage.plot.animate.APngAssembler(out, num_frames, num_plays=0, delay=200, delay_denominator=100)`

**Bases:** `object`

Builds an APNG (Animated PNG) from a sequence of PNG files. This is used by the `sage.plot.animate.Animation.apng()` method.

This code is quite simple; it does little more than copying chunks from input PNG files to the output file. There is no optimization involved. This does not depend on external programs or libraries.

**INPUT:**
• out – a file opened for binary writing to which the data will be written
• num_frames – the number of frames in the animation
• num_plays – how often to iterate, 0 means infinitely
• delay – numerator of the delay fraction in seconds
• delay_denominator – denominator of the delay in seconds

EXAMPLES:

```python
sage: from sage.plot.animate import APngAssembler
sage: x = SR.var("x")
sage: def assembleAPNG():
    ....: a = animate([sin(x + float(k)) for k in srange(0,2*pi,0.7)],
    ....:     xmin=0, xmax=2*pi, figsize=[2,1])
    ....: pngdir = a.png()
    ....: outfile = sage.misc.temporary_file.tmp_filename(ext='.png')
    ....: with open(outfile, "wb") as f:
    ....:     apng = APngAssembler(f, len(a))
    ....:     for i in range(len(a)):
    ....:         png = os.path.join(pngdir, "{:08d}.png".format(i))
    ....:         apng.add_frame(png, delay=10*i + 10)
    ....: return outfile
sage: assembleAPNG()  # long time '...png'
```

```python
add_frame(pngfile, delay=None, delay_denominator=None)
```

Adds a single frame to the APNG file.

INPUT:

• pngfile – file name of the PNG file with data for this frame
• delay – numerator of the delay fraction in seconds
• delay_denominator – denominator of the delay in seconds

If the delay is not specified, the default from the constructor applies.

```python
magic = b'\x89PNG\r\n\x1a\n'
mustmatch = frozenset({b'IHDR', b'PLTE', b'BGD', b'cHRM', b'gAMA', b'pHYs',
    b'sBIT', b'tRNS'})
```

```python
set_default(pngfile)
```

Adds a default image for the APNG file.

This image is used as a fallback in case some application does not understand the APNG format. This method must be called prior to any calls to the add_frame method, if it is called at all. If it is not called, then the first frame of the animation will be the default.

INPUT:

• pngfile – file name of the PNG file with data for the default image

```python
class sage.plot.animate.Animation(v=None, **kwds)
```

Bases: WithEqualityById, SageObject

Return an animation of a sequence of plots of objects.

INPUT:
• v - iterable of Sage objects. These should preferably be graphics objects, but if they aren’t then `make_image()` is called on them.

• xmin, xmax, ymin, ymax - the ranges of the x and y axes.

• **kwds - all additional inputs are passed onto the rendering command. E.g., use figsize to adjust the resolution and aspect ratio.

EXEMPLARY:

```
sage: x = SR.var("x")
sage: a = animate([sin(x + float(k)) for k in srange(0,2*pi,0.3)],
                   xmin=0, xmax=2*pi, figsize=[2,1])
sage: print(a)
Animation with 21 frames
sage: print(a[:5])
Animation with 5 frames
sage: a.show() # long time # optional -- ImageMagick
sage: a[:5].show() # long time # optional -- ImageMagick
```

The `show()` method takes arguments to specify the delay between frames (measured in hundredths of a second, default value 20) and the number of iterations (default value 0, which means to iterate forever). To iterate 4 times with half a second between each frame:

```
sage: a.show(delay=50, iterations=4) # long time # optional -- ImageMagick
```

An animation of drawing a parabola:

```
sage: step = 0.1
sage: L = Graphics()
sage: v = []
sage: for i in srange(0,1,step):
    ....:     L += line([(i,i^2),(i+step,(i+step)^2)], rgbcolor=(1,0,0), thickness=2)
    ....:     v.append(L)
sage: a = animate(v, xmin=0, ymin=0)
sage: a.show() # long time # optional -- ImageMagick
sage: show(L)
```

`apng(savefile=None, show_path=False, delay=20, iterations=0)`

Creates an animated PNG composed from rendering the graphics objects in self. Return the absolute path to that file.

Notice that not all web browsers are capable of displaying APNG files, though they should still present the first frame of the animation as a fallback.

The generated file is not optimized, so it may be quite large.

Input:

• delay - (default: 20) delay in hundredths of a second between frames

• savefile - file that the animated gif gets saved to

• iterations - integer (default: 0); number of iterations of animation. If 0, loop forever.

• show_path - boolean (default: False); if True, print the path to the saved file

EXEMPLARY:
```python
sage: x = SR.var("x")
sage: a = animate([sin(x + float(k)) for k in srange(0, 2*pi, 0.7)],
....:     xmin=0, xmax=2*pi, figsize=[2, 1])
sage: dir = tmp_dir()
sage: a.apng(show_path=True)  # long time
Animation saved to ...png.
sage: a.apng(savefile=dir + 'my_animation.png', delay=35, iterations=3)  # long...
Animation saved to .../my_animation.png.
```

If the individual frames have different sizes, an error will be raised:

```python
sage: a = animate([plot(sin(x), (x, 0, k)) for k in range(1, 4)],
....:     ymin=-1, ymax=1, aspect_ratio=1, figsize=[2, 1])
sage: a.apng()  # long time
Traceback (most recent call last):
  ...
ValueError: Chunk IHDR mismatch
```

**ffmpeg**(savefile=None, show_path=False, output_format=None, ffmpeg_options='', delay=None, iterations=0, pix_fmt='rgb24')

Return a movie showing an animation composed from rendering the frames in self.

This method will only work if ffmpeg is installed. See https://www.ffmpeg.org for information about ffmpeg.

**INPUT:**

- savefile – file that the mpeg gets saved to.

**Warning:** This will overwrite savefile if it already exists.

- show_path – boolean (default: False); if True, print the path to the saved file
- output_format - string (default: None); format and suffix to use for the video. This may be 'mpg', 'mpeg', 'avi', 'gif', or any other format that ffmpeg can handle. If this is None and the user specifies savefile with a suffix, say savefile='animation.avi', try to determine the format ('avi' in this case) from that file name. If no file is specified or if the suffix cannot be determined, 'mpg' is used.
- ffmpeg_options - string (default: ''); this string is passed directly to ffmpeg.
- delay - integer (default: None); delay in hundredths of a second between frames. The framerate is 100/delay. This is not supported for mpeg files: for mpegs, the frame rate is always 25 fps.
- iterations - integer (default: 0); number of iterations of animation. If 0, loop forever. This is only supported for animated gif output and requires ffmpeg version 0.9 or later. For older versions, set iterations=None.
- pix_fmt - string (default: 'rgb24'); used only for gif output. Different values such as 'rgb8' or 'pal8' may be necessary depending on how ffmpeg was installed. Set pix_fmt=None to disable this option.

If savefile is not specified: in notebook mode, display the animation; otherwise, save it to a default file name. Use sage.misc.verbose.set_verbose() with level=1 to see additional output.
EXAMPLES:

```python
sage: x = SR.var("x")
sage: a = animate([[sin(x + float(k)) for k in srange(0,2*pi,0.7)], ....: xmin=0, xmax=2*pi, ymin=-1, ymax=1, figsize=[2,1])
sage: td = tmp_dir()
sage: a.gif()                           # not tested
sage: a.gif(savefile=td + 'new.gif')  # long time #
```

Note: If ffmpeg is not installed, you will get an error message like this:

```
Exception: ffmpeg is not available.
Executable 'ffmpeg' not found on PATH.
Further installation instructions might be available at https://www.ffmpeg.org/.
```

\[gif(\text{delay}=20, \text{savefile}=\text{None}, \text{iterations}=0, \text{show_path}=\text{False}, \text{use_ffmpeg}=\text{False})\]

Returns an animated gif composed from rendering the graphics objects in self.

This method will only work if either (a) the ImageMagick software suite is installed, i.e., you have the `convert` command or (b) ffmpeg is installed. See the web sites of ImageMagick and FFmpeg for more details. By default, this produces the gif using `convert` if it is present. If this can’t find `convert` or if `use_ffmpeg` is True, then it uses ffmpeg instead.

INPUT:

- delay - (default: 20) delay in hundredths of a second between frames
- savefile - file that the animated gif gets saved to
- iterations - integer (default: 0); number of iterations of animation. If 0, loop forever.
- show_path - boolean (default: False); if True, print the path to the saved file
- use_ffmpeg - boolean (default: False); if True, use ‘ffmpeg’ by default instead of ‘convert’.

If savefile is not specified: in notebook mode, display the animation; otherwise, save it to a default file name.

EXAMPLES:

```python
sage: with open(td + 'my_animation.gif', 'rb') as f: print(b'GIF89' in f.read())
```

(continues on next page)
True

```python
sage: a.gif(savefile=td + 'my_animation.gif', show_path=True)  # long time # optional -- ImageMagick
Animation saved to .../my_animation.gif.
```

```python
sage: a.gif(savefile=td + 'my_animation_2.gif', show_path=True, use_ffmpeg=True)  # long time # optional -- ffmpeg
Animation saved to .../my_animation_2.gif.
```

**Note:** If neither ffmpeg nor ImageMagick is installed, you will get an error message like this:

```python
Error: Neither ImageMagick nor ffmpeg appears to be installed. Saving an animation to a GIF file or displaying an animation requires one of these packages, so please install one of them and try again.
```

See [www.imagemagick.org](http://www.imagemagick.org) and [www.ffmpeg.org](http://www.ffmpeg.org) for more information.

---

**graphics_array**(ncols=3)

Return a `sage.plot.multigraphics.GraphicsArray` with plots of the frames of this animation, using the given number of columns. The frames must be acceptable inputs for `sage.plot.multigraphics.GraphicsArray`.

**EXAMPLES:**

```python
sage: E = EllipticCurve('37a')
sage: v = [E.change_ring(GF(p)).plot(pointsize=30) for p in [97, 101, 103]]
sage: a = animate(v, xmin=0, ymin=0, axes=False)
sage: print(a)
Animation with 3 frames
sage: a.show()  # optional -- ImageMagick
```

Modify the default arrangement of array:

```python
sage: g = a.graphics_array(); print(g)
Graphics Array of size 1 x 3
sage: g.show(figsize=[6,3])
```

Specify different arrangement of array and save it with a given file name:

```python
sage: g = a.graphics_array(ncols=2); print(g)
Graphics Array of size 2 x 2
sage: f = tmp_filename(ext='.png'); print(f)
...png
sage: g.save(f)
```

Frames can be specified as a generator too; it is internally converted to a list:

```python
sage: t = SR.var("t")
sage: b = animate((plot(sin(c*pi*t)) for c in sxrange(1,2,.2)))
sage: g = b.graphics_array()
sage: print(g)
Graphics Array of size 2 x 3
```
**interactive(**kwds\)**

Create an interactive depiction of the animation.

**INPUT:**

- **kwds** – any of the viewing options accepted by show() are valid as keyword arguments to this function and they will behave in the same way. Those that are animation-related and recognized by the Three.js viewer are: animate, animation_controls, auto_play, delay, and loop.

**OUTPUT:**

A 3D graphics object which, by default, will use the Three.js viewer.

**EXAMPLES:**

```sage
x = SR.var("x")
sage: frames = [point3d((sin(x), cos(x), x)) for x in (0, pi/16, ..., 2*pi)]
sage: animate(frames).interactive(online=True)
```

Works with frames that are 2D or 3D graphics objects or convertible to 2D or 3D graphics objects via a plot or plot3d method:

```sage
frames = [dodecahedron(), circle(center=(0, 0), radius=1), x^2]
sage: animate(frames).interactive(online=True, delay=100)
```

**See also:**

Three.js JavaScript WebGL Renderer

**make_image**(frame, filename, **kwds)**

Given a frame which has no save_image() method, make a graphics object and save it as an image with the given filename. By default, this is `sage.plot.plot.plot()`. To make animations of other objects, override this method in a subclass.

**EXAMPLES:**

```sage
from sage.plot.animate import Animation
class MyAnimation(Animation):
    def make_image(self, frame, filename, **kwds):
        P = parametric_plot(frame[0], frame[1], **frame[2])
        P.save_image(filename, **kwds)

t = SR.var("t")
x = lambda t: cos(t)
y = lambda n,t: sin(t)/n
B = MyAnimation([[x(t), y(i+1,t)],(t,0,1)], {'color':Color((1,0,i/4)),
            'aspect_ratio':1, 'ymax':1}) for i in range(4])

d = B.png(); v = os.listdir(d); v.sort(); v # long time
['00000000.png', '00000001.png', '00000002.png', '00000003.png']
sage: B.show() # not tested

class MyAnimation(Animation):
    def make_image(self, frame, filename, **kwds):
        G = frame.plot()
```
....: G.set_axes_range(floor(G.xmin()), ceil(G.xmax()), floor(G.ymin()),
            ceil(G.ymax()))
....: G.save_image(filename, **kwds)

```
sage: B = MyAnimation([[graphs.CompleteGraph(n) for n in range(7,11)], figsize=5]
sage: d = B.png()
sage: v = os.listdir(d); v.sort(); v
['00000000.png', '00000001.png', '00000002.png', '00000003.png']
sage: B.show()  # not tested
```

### save(filename=None, show_path=False, use_ffmpeg=False, **kwds)

Save this animation.

**INPUT:**

- `filename` - (default: None) name of save file
- `show_path` - boolean (default: False); if True, print the path to the saved file
- `use_ffmpeg` - boolean (default: False); if True, use ‘ffmpeg’ by default instead of ‘convert’ when creating GIF files.

If filename is None, then in notebook mode, display the animation; otherwise, save the animation to a GIF file. If filename ends in ‘.html’, save an interactive() version of the animation to an HTML file that uses the Three.js viewer. If filename ends in ‘.sobj’, save to an sobj file. Otherwise, try to determine the format from the filename extension (‘.mpg’, ‘.gif’, ‘.avi’, etc.). If the format cannot be determined, default to GIF.

For GIF files, either ffmpeg or the ImageMagick suite must be installed. For other movie formats, ffmpeg must be installed. sobj and HTML files can be saved with no extra software installed.

**EXAMPLES:**

```
sage: x = SR.var("x")
sage: a = animate([sin(x + float(k)) for k in srange(0,2*pi,0.7)],
```
show(delay=None, iterations=None, **kwds)

Show this animation immediately.

This method attempts to display the graphics immediately, without waiting for the currently running code (if any) to return to the command line. Be careful, calling it from within a loop will potentially launch a large number of external viewer programs.

INPUT:

- delay – (default: 20) delay in hundredths of a second between frames.
- iterations – integer (default: 0); number of iterations of animation. If 0, loop forever.
- format - (default: gif) format to use for output. Currently supported formats are: gif, ogg, webm, mp4, flash, matroska, avi, wmv, quicktime.

OUTPUT:

This method does not return anything. Use save() if you want to save the figure as an image.

Note: Currently this is done using an animated gif, though this could change in the future. This requires that either ffmpeg or the ImageMagick suite (in particular, the convert command) is installed.

See also the ffmpeg() method.

EXAMPLES:

```
sage: x = SR.var("x")
sage: a = animate([sin(x + float(k)) for k in srange(0, 2*pi, 0.7)],
        ....:  xmin=0, xmax=2*pi, figsize=[2,1])
sage: a.show()  # long time # optional -- ImageMagick
```

The preceding will loop the animation forever. If you want to show only three iterations instead:

```
sage: a.show(iterations=3)  # long time # optional -- ImageMagick
```
To put a half-second delay between frames:

```
sage: a.show(delay=50)    # long time # optional -- ImageMagick
```

You can also make use of the HTML5 video element in the Sage Notebook:

```
sage: a.show(format="ogg")    # long time # optional -- ffmpeg
sage: a.show(format="mp4")    # long time # optional -- ffmpeg
sage: a.show(format="webm", iterations=1)    # long time # optional -- ffmpeg
```

Other backends may support other file formats as well:

```
sage: a.show(format="flash")    # long time # optional -- ffmpeg
sage: a.show(format="matroska")    # long time # optional -- ffmpeg
sage: a.show(format="avi")    # long time # optional -- ffmpeg
sage: a.show(format="wmv")    # long time # optional -- ffmpeg
sage: a.show(format="quicktime")    # long time # optional -- ffmpeg
```

**Note:** If you don’t have ffmpeg or ImageMagick installed, you will get an error message like this:

```
Error: Neither ImageMagick nor ffmpeg appears to be installed. Saving an animation to a GIF file or displaying an animation requires one of these packages, so please install one of them and try again.
```

```sage
sage.plot.animate.animate(frames, **kwds)
```

Animate a list of frames by creating a `sage.plot.animate.Animation` object.

**EXAMPLES:**

```
sage: t = SR.var("t")
sage: a = animate(((cos(c*pi*t) for c in sxrange(1,2,.2)))
sage: a.show()    # long time # optional -- ImageMagick
```

See also `sage.plot.animate` for more examples.
2.1 Complex plots

AUTHORS:

• Robert Bradshaw (2009): initial version
• David Lowry-Duda (2022): incorporate matplotlib colormaps

class sage.plot.complex_plot.ComplexPlot(rgb_data, x_range, y_range, options)
    Bases: GraphicPrimitive

The GraphicsPrimitive to display complex functions in using the domain coloring method

INPUT:

• rgb_data – An array of colored points to be plotted.
• x_range – A minimum and maximum x value for the plot.
• y_range – A minimum and maximum y value for the plot.

get_minmax_data()
    Return a dictionary with the bounding box data.

EXAMPLES:

```sage
sage: p = complex_plot(lambda z: z, (-1, 2), (-3, 4))
sage: sorted(p.get_minmax_data().items())
[('xmax', 2.0), ('xmin', -1.0), ('ymax', 4.0), ('ymin', -3.0)]
sage: p = complex_plot(lambda z: z, (1, 2), (3, 4))
sage: sorted(p.get_minmax_data().items())
[('xmax', 2.0), ('xmin', 1.0), ('ymax', 4.0), ('ymin', 3.0)]
```

sage.plot.complex_plot.add_contours_to_rgb(rgb, delta, dark_rate=0.5)

Return an rgb array from given array of \((r, g, b)\) and \((\text{delta})\).

Each input \((r, g, b)\) is modified by \(\text{delta}\) to be lighter or darker depending on the size of \(\text{delta}\). Negative \(\text{delta}\) values darken the color, while positive \(\text{delta}\) values lighten the pixel.

We assume that the \(\text{delta}\) values come from a function like `sage.plot.complex_plot.mag_to_lightness()`, which maps magnitudes to the range \([-1, +1]\).

INPUT:

• rgb – a grid of length 3 tuples \((r, g, b)\), as an \(N \times M \times 3\) numpy array.
2D Graphics, Release 10.0

- **delta** – a grid of values as an \( N \times M \) numpy array; these represent how much to change the lightness of each \((r, g, b)\). Values should be in \([-1, 1]\).

- **dark_rate** – a positive number (default: 0.5); affects how strongly visible the contours appear.

**OUTPUT:**
An \( N \times M \times 3 \) floating point Numpy array \( X \), where \( X[i,j] \) is an \((r, g, b)\) tuple.

**See also:**
- `sage.plot.complex_plot.complex_to_rgb()`
- `sage.plot.complex_plot.add_lightness_smoothing_to_rgb()`

**ALGORITHM:**
Each pixel and lightness-delta is mapped from \((r, g, b, \text{delta}) \rightarrow (h, l, s, \text{delta})\) using the standard RGB-to-HLS formula.

Then the lightness is adjusted via \( l \rightarrow l' = l + 0.5 \cdot \text{delta} \).

Finally map \((h, l', s) \rightarrow (r, g, b)\) using the standard HLS-to-RGB formula.

**EXAMPLES:**

```python
sage: import numpy as np
sage: from sage.plot.complex_plot import add_contours_to_rgb
sage: add_contours_to_rgb(np.array([[[0, 0, 0.25, 0.5]]]), np.array([[0.75]])) # abs tol 1e-4
array([[[0.25, 0.625, 1.]]])
sage: add_contours_to_rgb(np.array([[[0, 0, 0]]]), np.array([[1]])) # abs tol 1e-4
array([[[0.5, 0.5, 0.5]]])
sage: add_contours_to_rgb(np.array([[[1, 1, 1]]]), np.array([[-0.5]])) # abs tol 1e-4
array([[[0.75, 0.75, 0.75]]])
```

Raising **dark_rate** leads to bigger adjustments:

```python
sage: add_contours_to_rgb(np.array([[[0.5, 0.5, 0.5]]]), # abs tol 1e-4
                      ....: np.array([[0.5]]), dark_rate=0.1)
array([[[0.55, 0.55, 0.55]]])
sage: add_contours_to_rgb(np.array([[[0.5, 0.5, 0.5]]]), # abs tol 1e-4
                      ....: np.array([[0.5]]), dark_rate=0.5)
array([[[0.75, 0.75, 0.75]]])
```

**sage.plot.complex_plot.add_lightness_smoothing_to_rgb(rgb, delta)**

Return an rgb array from given array of colors and lightness adjustments.

This smoothly adds lightness from black (when delta is \(-1\)) to white (when delta is \(1\)).

Each input \((r, g, b)\) is modified by delta to be lighter or darker depending on the size of delta. When delta is \(-1\), the output is black. When delta is \(+1\), the output is white. Colors piecewise-linearly vary from black to the initial \((r, g, b)\) to white.

We assume that the delta values come from a function like `sage.plot.complex_plot.mag_to_lightness()`, which maps magnitudes to the range \([-1, +1]\).

**INPUT:**
- **rgb** – a grid of length 3 tuples \((r, g, b)\), as an \(N \times M \times 3\) numpy array.
• **delta** – a grid of values as an $N \times M$ numpy array; these represent how much to change the lightness of each $(r, g, b)$. Values should be in $[-1, 1]$.

**OUTPUT:**

An $N \times M \times 3$ floating point Numpy array $X$, where $X[i, j]$ is an $(r, g, b)$ tuple.

**See also:**

• `sage.plot.complex_plot.complex_to_rgb()`
• `sage.plot.complex_plot.add_contours_to_rgb()`

**EXAMPLES:**

We can call this on grids of values:

```python
sage: import numpy as np
sage: from sage.plot.complex_plot import add_lightness_smoothing_to_rgb
sage: add_lightness_smoothing_to_rgb(np.array([[0, 0.25, 0.5]]), np.array([[0.075, 0.125, 0.875]])) # abs tol 1e-4
array([[0.75, 0.8125, 0.875]])
```

`sage.plot.complex_plot.complex_plot(f, x_range, y_range, contoured=False, tiled=False, cmap=None, ...)`

`complex_plot` takes a complex function of one variable, $f(z)$ and plots output of the function over the specified $x$ range and $y$ range as demonstrated below. The magnitude of the output is indicated by the brightness and the argument is represented by the hue.

By default, zero magnitude corresponds to black output, infinite magnitude corresponds to white output. The options `contoured`, `tiled`, and `cmap` affect the output.

`complex_plot(f, (xmin, xmax), (ymin, ymax), contoured, tiled, cmap, ...)`

**INPUT:**

• $f$ – a function of a single complex value $x + iy$
• $(xmin, xmax)$ – 2-tuple, the range of $x$ values
• $(ymin, ymax)$ – 2-tuple, the range of $y$ values
• `cmap` – None, or the string name of a matplotlib colormap, or an instance of a matplotlib Colormap, or the special string 'matplotlib' (default: None); If None, then hues are chosen from a standard color wheel, cycling from red to yellow to blue. If matplotlib, then hues are chosen from a preset matplotlib colormap.

The following named parameter inputs can be used to add contours and adjust their distribution:

• `contoured` – boolean (default: False); causes the magnitude to be indicated by logarithmically spaced ‘contours’. The magnitude along one contour is either twice or half the magnitude along adjacent contours.
• `dark_rate` – a positive number (default: 0.5); affects how quickly magnitudes affect how light/dark the image is. When there are contours, this affects how visible each contour is. Large values (near 1.0) have very strong, immediate effects, while small values (near 0.0) have gradual effects.
• `tiled` – boolean (default: False); causes the magnitude to be indicated by logarithmically spaced ‘contours’ as in `contoured`, and in addition for there to be 10 evenly spaced phase contours.
• `nphases` – a positive integer (default: 10); when `tiled=True`, this is the number of divisions the phase is divided into.

• `contour_type` – either 'logarithmic', or 'linear' (default: 'logarithmic'); causes added contours to be of given type when `contoured=True`.

• `contour_base` – a positive integer; when `contour_type` is 'logarithmic', this sets logarithmic contours at multiples of `contour_base` apart. When `contour_type` is 'linear', this sets contours at distances of `contour_base` apart. If None, then a default is chosen depending on `contour_type`.

The following inputs may also be passed in as named parameters:

• `plot_points` – integer (default: 100); number of points to plot in each direction of the grid

• `interpolation` – string (default: 'catrom'); the interpolation method to use: 'bilinear', 'bicubic', 'spline16', 'spline36', 'quadric', 'gaussian', 'sinc', 'bessel', 'mitchell', 'lanczos', 'catrom', 'hermite', 'hanning', 'hamming', 'kaiser'

Any additional parameters will be passed to `show()`, as long as they're valid.

**Note:** Matplotlib colormaps can be chosen or customized to cater to different types of vision. The colormaps 'cividis' and 'viridis' in matplotlib are designed to be perceptually uniform to a broader audience. The colormap 'turbo' is similar to the default but with more even contrast. See [NAR2018] for more information about colormap choice for scientific visualization.

**EXAMPLES:**

Here we plot a couple of simple functions:

```sage
sage: complex_plot(sqrt(x), (-5, 5), (-5, 5))
Graphics object consisting of 1 graphics primitive
```

```sage
sage: complex_plot(sin(x), (-5, 5), (-5, 5))
Graphics object consisting of 1 graphics primitive
```

```sage
sage: complex_plot(log(x), (-10, 10), (-10, 10))
Graphics object consisting of 1 graphics primitive
```

```sage
sage: complex_plot(exp(x), (-10, 10), (-10, 10))
Graphics object consisting of 1 graphics primitive
```

A plot with a different choice of colormap:

```sage
sage: complex_plot(exp(x), (-10, 10), (-10, 10), cmap='viridis')
Graphics object consisting of 1 graphics primitive
```

A function with some nice zeros and a pole:

```sage
sage: f(z) = z^5 + z - 1 + 1/z
sage: complex_plot(f, (-3, 3), (-3, 3))
Graphics object consisting of 1 graphics primitive
```

The same function as above, but with contours. Contours render poorly with few plot points, so we use 300 here:
2.1. Complex plots
2.1. Complex plots
2.1. Complex plots
\begin{Verbatim}
sage: f(z) = z^5 + z - 1 + 1/z
sage: complex_plot(f, (-3, 3), (-3, 3), plot_points=300, contoured=True)
Graphics object consisting of 1 graphics primitive
\end{Verbatim}

The same function as above, but tiled and with the \textit{plasma} colormap:

\begin{Verbatim}
sage: f(z) = z^5 + z - 1 + 1/z
sage: complex_plot(f, (-3, 3), (-3, 3),
....: plot_points=300, tiled=True, cmap='plasma')
Graphics object consisting of 1 graphics primitive
\end{Verbatim}

When using \texttt{tiled=True}, the number of phase subdivisions can be controlled by adjusting \texttt{nphases}. We make the same plot with fewer tilings:

\begin{Verbatim}
sage: f(z) = z^5 + z - 1 + 1/z
sage: complex_plot(f, (-3, 3), (-3, 3), plot_points=300,
....: tiled=True, nphases=5, cmap='plasma')
Graphics object consisting of 1 graphics primitive
\end{Verbatim}

It is also possible to use \textit{linear} contours. We plot the same function above on an inset, setting contours to appear 1 apart:

\begin{Verbatim}
\end{Verbatim}
2.1. Complex plots
\texttt{sage: f(z) = z^5 + z - 1 + 1/z}
\texttt{sage: complex_plot(f, (0, 1), (0, 1), plot_points=300, ....: contoured=True, contour_type='linear', contour_base=1)}
Graphics object consisting of 1 graphics primitive

Note that tightly spaced contours can lead to Moiré patterns and aliasing problems. For example:

\texttt{sage: f(z) = z^5 + z - 1 + 1/z}
\texttt{sage: complex_plot(f, (-3, 3), (-3, 3), plot_points=300, ....: contoured=True, contour_type='linear', contour_base=1)}
Graphics object consisting of 1 graphics primitive

When choosing colormaps, cyclic colormaps such as \textit{twilight} or \textit{hsv} might be considered more appropriate for showing changes in phase without sharp color contrasts:

\texttt{sage: f(z) = z^5 + z - 1 + 1/z}
\texttt{sage: complex_plot(f, (-3, 3), (-3, 3), plot_points=300, cmap='twilight')}
Graphics object consisting of 1 graphics primitive

Passing \textit{matplotlib} as the colormap gives a special colormap that is similar to the default:

\texttt{sage: f(z) = z^5 + z - 1 + 1/z}
\texttt{sage: complex_plot(f, (-3, 3), (-3, 3), cmap=matplotlib)}

(continues on next page)
2.1. Complex plots
Here is the identity, useful for seeing what values map to what colors:

```
sage: complex_plot(lambda z: z, (-3, 3), (-3, 3))
```

The Riemann Zeta function:

```
sage: complex_plot(zeta, (-30, 30), (-30, 30))
```

For advanced usage, it is possible to tweak many parameters. Increasing `dark_rate` will make regions become darker/lighter faster when there are no contours:

```
sage: complex_plot(zeta, (-30, 30), (-30, 30), dark_rate=1.0)
```

Decreasing `dark_rate` has the opposite effect. When there are contours, adjust `dark_rate` affects how visible contours are. Compare:
2.1. Complex plots
Chapter 2. Function and Data Plots
and:

```python
sage: complex_plot(zeta, (-1, 9), (10, 20), plot_points=200, # long time
                  ....:     contoured=True, cmap='twilight', dark_rate=0.75)
Graphics object consisting of 1 graphics primitive
```

In practice, different values of `dark_rate` will work well with different colormaps.

Extra options will get passed on to `show()`, as long as they are valid:

```python
sage: complex_plot(lambda z: z, (-3, 3), (-3, 3), figsize=[1,1])
Graphics object consisting of 1 graphics primitive
```

```python
sage: complex_plot(lambda z: z, (-3, 3), (-3, 3)).show(figsize=[1,1]) # These are equivalent
```

REFERENCES:

Plotting complex functions with colormaps follows the strategy from [LD2021] and incorporates contour techniques described in [WegSem2010].
Convert a grid of complex numbers to a grid of rgb values using colors taken from given colormap.

INPUT:
- `z_values` – A grid of complex numbers, as a list of lists
- `cmap` – the string name of a matplotlib colormap, or an instance of a matplotlib Colormap (default: 'turbo').
- `contoured` – boolean (default: False); causes magnitude to be indicated through contour-like adjustments to lightness.
- `tiled` – boolean (default: False); causes magnitude and argument to be indicated through contour-like adjustments to lightness.
- `nphases` – a positive integer (default: 10); when `tiled=True`, this is the number of divisions the phase is divided into.
- `contour_type` – either 'logarithmic', or 'linear' (default: 'logarithmic'); causes added contours to be of given type when `contoured=True`.
- `contour_base` – a positive integer; when `contour_type` is 'logarithmic', this sets logarithmic contours at multiples of `contour_base` apart. When `contour_type` is 'linear', this sets contours at distances of `contour_base` apart. If None, then a default is chosen depending on `contour_type`.
- `dark_rate` – a positive number (default: 0.5); affects how quickly magnitudes affect how light/dark the image is. When there are contours, this affects how visible each contour is. Large values (near 1.0) have very strong, immediate effects, while small values (near 0.0) have gradual effects.

OUTPUT:
An $N \times M \times 3$ floating point Numpy array $X$, where $X[i,j]$ is an (r, g, b) tuple.

See also:
`sage.plot.complex_plot.complex_to_rgb()`

EXAMPLES:
We can call this on grids of complex numbers:

```
sage: from sage.plot.complex_plot import complex_to_cmap_rgb
sage: complex_to_cmap_rgb([[0, 1, 1000]]) # abs tol 1e-4
array([[0. , 0. , 0. ],
       [0.49669808, 0.76400071, 0.18024425],
       [0.87320419, 0.99643856, 0.72730967]])
sage: complex_to_cmap_rgb([[0, 1, 1000]], cmap='viridis') # abs tol 1e-4
array([[0.0984475 , 0.4375291 , 0.42487821],
       [0.68959896, 0.84592555, 0.84009311]])
```

We can change contour types and the distances between contours:

```
sage: complex_to_cmap_rgb([[0, 1 + j, 3 + 4j], contoured=True, # abs tol 1e-4
......:                     contour_type="logarithmic", contour_base=3)
array([[0.64362 , 0.98999 , 0.23356 ],
       [0.93239357, 0.81063338, 0.21955399],
       [0.95647342, 0.74861225, 0.14963982]])
```

(continues on next page)
We see that changing `dark_rate` affects how visible contours are. In this example, we set `contour_base=5` and note that the points 0 and $1 + i$ are far away from contours, but $2.9 + 4i$ is near (and just below) a contour. Raising `dark_rate` should have strong effects on the last coloration and weaker effects on the others:

```python
sage: complex_to_cmap_rgb([[0, 1 + 1j, 2.9 + 4j]], cmap='turbo', # abs tol 1e-4
                          contoured=True, dark_rate=0.05, contour_base=5)
array([[0.6436203, 0.98999, 0.23356],
       [0.9334746, 0.8133052, 0.2305656],
       [0.9635718, 0.7533774, 0.1944091]])
```

```python
sage: complex_to_cmap_rgb([[0, 1 + 1j, 2.9 + 4j]], cmap='turbo', # abs tol 1e-4
                          contoured=True, dark_rate=0.85, contour_base=5)
array([[0.6436203, 0.98999, 0.23356],
       [0.9387468, 0.8284289, 0.2928956],
       [0.5778954, 0.4270329, 0.0261272]])
```

Convert a grid of complex numbers to a grid of rgb values using a default choice of colors.

**INPUT:**

- `z_values` – A grid of complex numbers, as a list of lists
- `contoured` – boolean (default: False); causes magnitude to be indicated through contour-like adjustments to lightness.
- `tiled` – boolean (default: False); causes magnitude and argument to be indicated through contour-like adjustments to lightness.
- `nphases` – a positive integer (default: 10); when `tiled=True`, this is the number of divisions the phase is divided into.
- `contour_type` – either 'logarithmic', or 'linear' (default: 'logarithmic'); causes added contours to be of given type when `contoured=True`.
- `contour_base` – a positive integer; when `contour_type` is 'logarithmic', this sets logarithmic contours at multiples of `contour_base` apart. When `contour_type` is 'linear', this sets contours at distances of `contour_base` apart. If None, then a default is chosen depending on `contour_type`.
- `dark_rate` – a positive number (default: 0.5); affects how quickly magnitudes affect how light/dark the image is. When there are contours, this affects how visible each contour is. Large values (near 1.0) have very strong, immediate effects, while small values (near 0.0) have gradual effects.

**OUTPUT:**

An $N \times M \times 3$ floating point Numpy array $X$, where $X[i,j]$ is an (r,g,b) tuple.

**See also:**

`sage.plot.complex_plot.complex_to_cmap_rgb()`
We can call this on grids of complex numbers:

```python
sage: from sage.plot.complex_plot import complex_to_rgb
sage: complex_to_rgb([[0, 1, 1000]]) # abs tol 1e-4
array([[0., 0., 0.],
        [0.77172568, 0., 0.],
        [1., 0.64421177, 0.64421177]])
sage: complex_to_rgb([[0, 1j, 1000j]]) # abs tol 1e-4
array([[0., 0., 0.],
        [0.38586284, 0.77172568, 0.],
        [0.82210588, 1., 0.64421177]])
sage: complex_to_rgb([[0, 1, 1000]], contoured=True) # abs tol 1e-4
array([[1., 0., 0.],
        [1., 0.15, 0.15],
        [0.66710786, 0., 0.]])
sage: complex_to_rgb([[0, 1, 1000]], tiled=True) # abs tol 1e-4
array([[1., 0., 0.],
        [1., 0.15, 0.15],
        [0.90855393, 0., 0.]])
```

We can change contour types and the distances between contours:

```python
sage: complex_to_rgb([[0, 1 + 1j, 3 + 4j]], # abs tol 1e-4
           contoured=True, contour_type="logarithmic", contour_base=3)  
array([[1., 0.99226756, 0.74420067, 0.],
        [0.91751324, 0.81245954, 0.]])
sage: complex_to_rgb([[0, 1 + 1j, 3 + 4j]], # abs tol 1e-4
           contoured=True, contour_type="linear", contour_base=3)  
array([[1., 0.91429774, 0.6857233, 0.],
        [0.81666667, 0.72315973, 0.]])
```

Lowering `dark_rate` causes colors to go to black more slowly near 0:

```python
sage: complex_to_rgb([[0, 0.5, 1]], dark_rate=0.4) # abs tol 1e-4
array([[0., 0.65393731, 0.],
        [0.65393731, 0., 0.],
        [0.77172568, 0., 0.]])
sage: complex_to_rgb([[0, 0.5, 1]], dark_rate=0.2) # abs tol 1e-4
array([[0., 0.71235886, 0.],
        [0.71235886, 0., 0.],
        [0.77172568, 0., 0.]])
```

`sage.plot.complex_plot.hls_to_rgb(hls)`

Convert array of hls values (each in the range [0, 1]) to a numpy array of rgb values (each in the range [0, 1])

**INPUT:**

- `hls` – an $N \times 3$ array of floats in the range $[0, 1]$; the hls values at each point. (Note that the input can actually be of any dimension, such as $N \times M \times 3$, as long as the last dimension has length 3).

**OUTPUT:**

An $N \times 3$ Numpy array of floats in the range $[0, 1]$, with the same dimensions as the input array.
See also:

`sage.plot.complex_plot.rgb_to_hls()`

EXAMPLES:

We convert a row of floats and verify that we can convert back using `rgb_to_hls`:

```python
sage: from sage.plot.complex_plot import rgb_to_hls, hls_to_rgb
sage: hls = [[0.2, 0.4, 0.5], [0.1, 0.3, 1.0]]
sage: rgb = hls_to_rgb(hls)
sage: rgb # abs tol 1e-4
array([[0.52, 0.6 , 0.2 ],
        [0.6 , 0.36, 0. ]])
sage: rgb_to_hls(rgb) # abs tol 1e-4
array([[0.2, 0.4, 0.5],
        [0.1, 0.3, 1. ]])
```

Multidimensional inputs can be given as well:

```python
sage: multidim_arr = [[[0, 0.2, 0.4], [0, 1, 0]], [[0, 0, 0], [0.5, 0.6, 0.9]]
sage: hls_to_rgb(multidim_arr) # abs tol 1e-4
array([[0.28, 0.12, 0.12],
        [1. , 1. , 1. ]],
      [[0. , 0. , 0. ],
       [0.24, 0.96, 0.96]])
```

`sage.plot.complex_plot.rgb_to_hls(rgb)`

Convert array of rgb values (each in the range [0, 1]) to a numpy array of hls values (each in the range [0, 1])

INPUT:

- `rgb` – an \( N \times 3 \) array of floats with values in the range [0, 1]; the rgb values at each point. (Note that the input can actually be of any dimension, such as \( N \times M \times 3 \), as long as the last dimension has length 3).

OUTPUT:

An \( N \times 3 \) Numpy array of floats in the range [0, 1], with the same dimensions as the input array.

See also:

`sage.plot.complex_plot.hls_to_rgb()`

EXAMPLES:

We convert a row of floats and verify that we can convert back using `hls_to_rgb`:

```python
sage: from sage.plot.complex_plot import rgb_to_hls, hls_to_rgb
sage: rgb = [[0.2, 0.4, 0.5], [0.1, 0.3, 1.0]]
sage: hls = rgb_to_hls(rgb)
sage: hls # abs tol 1e-4
array([[0.55555556, 0.35 , 0.42857143],
      [0.62962963, 0.55 , 1. ]])
sage: hls_to_rgb(hls) # abs tol 1e-4
array([[0.2, 0.4, 0.5],
        [0.1, 0.3, 1. ]])
```

Multidimensional inputs can be given as well:
2.2 Contour plots

class sage.plot.contour_plot.ContourPlot(xy_data_array, xrange, yrange, options)
   Bases: GraphicPrimitive
   
   Primitive class for the contour plot graphics type.

   See contour_plot? for help actually doing contour plots.

   INPUT:

   • **xy_data_array** - list of lists giving evaluated values of the function on the grid
   • **xrange** - tuple of 2 floats indicating range for horizontal direction
   • **yrange** - tuple of 2 floats indicating range for vertical direction
   • **options** - dict of valid plot options to pass to constructor

   EXAMPLES:

   Note this should normally be used indirectly via contour_plot:

   \[
   \text{sage: from sage.plot.contour_plot import ContourPlot} \\
   \text{sage: C = ContourPlot([[1,3],[2,4]], (1,2), (2,3), options={})} \\
   \text{sage: C} \\
   \text{ContourPlot defined by a 2 x 2 data grid} \\
   \text{sage: C.xrange} \\
   (1, 2)
   \]

   get_minmax_data()
   
   Return a dictionary with the bounding box data.

   EXAMPLES:

   \[
   \text{sage: x, y = var('x, y')} \\
   \text{sage: f(x,y) = x^2 + y^2} \\
   \text{sage: d = contour_plot(f, (3,6), (3,6))[0].get_minmax_data()} \\
   \text{sage: d['xmin']} \\
   3.0 \\
   \text{sage: d['ymin']} \\
   3.0
   \]

sage.plot.contour_plot.contour_plot(f, xrange, yrange, plot_points=100, fill=True, contours=None, linewidths=None, linestyles=None, labels=False, frame=True, axes=False, colorbar=False, legend_label=None, aspect_ratio=1, region=None, label_fontsize=9, label_colors='blue', label_inline=False, label_inline_spacing=3, label_fmt='%1.2f', colorbar_orientation='vertical', colorbar_format=None, colorbar_spacing='uniform', **options)
contour_plot takes a function of two variables, \( f(x, y) \) and plots contour lines of the function over the specified \( x\text{range} \) and \( y\text{range} \) as demonstrated below.

\[
\text{contour}_{-}\text{plot}(f, (\text{xmin, xmax}), (\text{ymin, ymax}), \ldots)
\]

**INPUT:**
- \( f \) – a function of two variables
- \( (\text{xmin, xmax}) \) – 2-tuple, the range of \( x \) values OR 3-tuple \((x, \text{xmin, xmax})\)
- \( (\text{ymin, ymax}) \) – 2-tuple, the range of \( y \) values OR 3-tuple \((y, \text{ymin, ymax})\)

The following inputs must all be passed in as named parameters:
- **plot_points** – integer (default: 100); number of points to plot in each direction of the grid. For old computers, 25 is fine, but should not be used to verify specific intersection points.
- **fill** – bool (default: True), whether to color in the area between contour lines
- **cmap** – a colormap (default: 'gray'), the name of a predefined colormap, a list of colors or an instance of a matplotlib Colormap. Type: `import matplotlib.cm; matplotlib.cm.dalad.keys()` for available colormap names.
- **contours** – integer or list of numbers (default: None): If a list of numbers is given, then this specifies the contour levels to use. If an integer is given, then these many contour lines are used, but the exact levels are determined automatically. If None is passed (or the option is not given), then the number of contour lines is determined automatically, and is usually about 5.
- **linewidths** – integer or list of integer (default: None), if a single integer all levels will be of the width given, otherwise the levels will be plotted with the width in the order given. If the list is shorter than the number of contours, then the widths will be repeated cyclically.
- **linestyles** – string or list of strings (default: None), the style of the lines to be plotted, one of: "solid", "dashed", "dashdot", "dotted", respectively "-", "--", "-.", ":". If the list is shorter than the number of contours, then the styles will be repeated cyclically.
- **labels** – boolean (default: False) Show level labels or not.

The following options are to adjust the style and placement of labels, they have no effect if no labels are shown.
- **label_fontsize** – integer (default: 9), the font size of the labels.
- **label_colors** – string or sequence of colors (default: None) If a string, gives the name of a single color with which to draw all labels. If a sequence, gives the colors of the labels. A color is a string giving the name of one or a 3-tuple of floats.
- **label_inline** – boolean (default: False if fill is True, otherwise True), controls whether the underlying contour is removed or not.
- **label_inline_spacing** – integer (default: 3), When inline, this is the amount of contour that is removed from each side, in pixels.
- **label_fmt** – a format string (default: "%.1f"), this is used to get the label text from the level. This can also be a dictionary with the contour levels as keys and corresponding text string labels as values. It can also be any callable which returns a string when called with a numeric contour level.
- **colorbar** – boolean (default: False) Show a colorbar or not.

The following options are to adjust the style and placement of colorbars. They have no effect if a colorbar is not shown.
- `colorbar_orientation` – string (default: ‘vertical’), controls placement of the colorbar, can be either ‘vertical’ or ‘horizontal’

- `colorbar_format` – a format string, this is used to format the colorbar labels.

- `colorbar_spacing` – string (default: ‘proportional’). If ‘proportional’, make the contour divisions proportional to values. If ‘uniform’, space the colorbar divisions uniformly, without regard for numeric values.

- `legend_label` – the label for this item in the legend

- `region` - (default: None) If region is given, it must be a function of two variables. Only segments of the surface where region(x,y) returns a number >0 will be included in the plot.

**Warning:** Due to an implementation detail in matplotlib, single-contour plots whose data all lie on one side of the sole contour may not be plotted correctly. We attempt to detect this situation and to produce something better than an empty plot when it happens; a `UserWarning` is emitted in that case.

**EXAMPLES:**

Here we plot a simple function of two variables. Note that since the input function is an expression, we need to explicitly declare the variables in 3-tuples for the range:

```python
sage: x,y = var('x,y')
sage: contour_plot(cos(x^2 + y^2), (x,-4,4), (y,-4,4))
Graphics object consisting of 1 graphics primitive
```

Here we change the ranges and add some options:

```python
sage: x,y = var('x,y')
sage: contour_plot((x^2) * cos(x*y), (x,-10,5), (y,-5,5), fill=False, plot_˓→points=150)
Graphics object consisting of 1 graphics primitive
```

An even more complicated plot:

```python
sage: x,y = var('x,y')
sage: contour_plot(sin(x^2+y^2) * cos(x) * sin(y), (x,-4,4), (y,-4,4), plot_˓→points=150)
Graphics object consisting of 1 graphics primitive
```

Some elliptic curves, but with symbolic endpoints. In the first example, the plot is rotated 90 degrees because we switch the variables $x, y$:

```python
sage: x,y = var('x,y')
sage: contour_plot(y^2 + 1 - x^3 - x, (y,-pi,pi), (x,-pi,pi))
Graphics object consisting of 1 graphics primitive
```

```python
sage: contour_plot(y^2 + 1 - x^3 - x, (x,-pi,pi), (y,-pi,pi))
Graphics object consisting of 1 graphics primitive
```

We can play with the contour levels:
2.2. Contour plots
Chapter 2. Function and Data Plots
2.2. Contour plots
sage: x, y = var('x, y')
sage: f(x, y) = x^2 + y^2
sage: contour_plot(f, (-2, 2), (-2, 2))
Graphics object consisting of 1 graphics primitive

sage: contour_plot(f, (-2, 2), (-2, 2), contours=2, cmap=[(1,0,0), (0,1,0), (0,0,1)])
Graphics object consisting of 1 graphics primitive

sage: contour_plot(f, (-2, 2), (-2, 2), contours=(0.1, 1.0, 1.2, 1.4), cmap='hsv')
Graphics object consisting of 1 graphics primitive

sage: contour_plot(x - y^2, (x,-5,5), (y,-3,3), contours=[-4,0,1])
Graphics object consisting of 1 graphics primitive

We can change the style of the lines:

sage: contour_plot(f, (-2, 2), (-2, 2), fill=False, linewidths=10)
Graphics object consisting of 1 graphics primitive

2.2. Contour plots
Chapter 2. Function and Data Plots
2.2. Contour plots
2.2. Contour plots
We can add labels and play with them:
2.2. Contour plots
sage: contour_plot(y^2 + 1 - x^3 - x, (x,-pi,pi), (y,-pi,pi),
....: fill=False, cmap='hsv', labels=True)
Graphics object consisting of 1 graphics primitive

sage: P = contour_plot(y^2 + 1 - x^3 - x, (x,-pi,pi), (y,-pi,pi),
....: fill=False, cmap='hsv', labels=True, label_fmt="%1.0f",
....: label_colors='black')
sage: P
Graphics object consisting of 1 graphics primitive

sage: P = contour_plot(y^2 + 1 - x^3 - x, (x,-pi,pi), (y,-pi,pi),
....: fill=False, cmap='hsv', labels=True, contours=[-4,0,4],
....: label_fmt={-4:"low", 0:"medium", 4: "hi"},
....: label_colors='black')
sage: P
Graphics object consisting of 1 graphics primitive
2.2. Contour plots
Sage: P
Graphics object consisting of 1 graphics primitive

Sage: P = contour_plot(y^2 + 1 - x^3 - x, (x,-pi,pi), (y,-pi,pi),
    fill=False, cmap='hsv', labels=True,
    label_inline_spacing=1)
Sage: P
Graphics object consisting of 1 graphics primitive

Sage: P = contour_plot(y^2 + 1 - x^3 - x, (x,-pi,pi), (y,-pi,pi),
    fill=False, cmap='hsv', labels=True,
    label_inline=False)
Sage: P
(Graphics object consisting of 1 graphics primitive) (continues on next page)
2.2. Contour plots
We can change the color of the labels if so desired:

```sage
sage: contour_plot(f, (-2,2), (-2,2), labels=True, label_colors='red')
Graphics object consisting of 1 graphics primitive
```

We can add a colorbar as well:

```sage
sage: f(x, y) = x^2 + y^2
sage: contour_plot(f, (x,-3,3), (y,-3,3), colorbar=True)
Graphics object consisting of 1 graphics primitive
```

```sage
sage: contour_plot(f, (x,-3,3), (y,-3,3), colorbar=True, colorbar_orientation='horizontal')
Graphics object consisting of 1 graphics primitive
```

```sage
sage: contour_plot(f, (x,-3,3), (y,-3,3), contours=[-2,-1,4], colorbar=True)
Graphics object consisting of 1 graphics primitive
```
2.2. Contour plots
2.2. Contour plots
sage: contour_plot(f, (x,-3,3), (y,-3,3), contours=[-2,-1,4],
....:       colorbar=True, colorbar_spacing='uniform')
Graphics object consisting of 1 graphics primitive

This should plot concentric circles centered at the origin:

sage: x,y = var('x,y')
sage: contour_plot(x^2 + y^2-2,(x,-1,1), (y,-1,1))
Graphics object consisting of 1 graphics primitive
2.2. Contour plots
2.2. Contour plots
Extra options will get passed on to show(), as long as they are valid:

```
sage: f(x,y) = cos(x) + sin(y)
sage: contour_plot(f, (0,pi), (0,pi), axes=True)
```
Graphics object consisting of 1 graphics primitive

```
sage: contour_plot(f, (0,pi), (0,pi)).show(axes=True) # These are equivalent
```

One can also plot over a reduced region:

```
sage: contour_plot(x**2 - y**2, (x,-2,2), (y,-2,2), region=x - y, plot_points=300)
```
Graphics object consisting of 1 graphics primitive

Note that with fill=False and grayscale contours, there is the possibility of confusion between the contours and the axes, so use fill=False together with axes=True with caution:

```
sage: contour_plot(f, (-pi,pi), (-pi,pi), fill=False, axes=True)
```
Graphics object consisting of 1 graphics primitive

If you are plotting a sole contour and if all of your data lie on one side of it, then (as part of github issue #21042) a heuristic may be used to improve the result; in that case, a warning is emitted:

```
sage: contour_plot(lambda x,y: abs(x^2-y^2), (-1,1), (-1,1), ....: contours=[0], fill=False, cmap=['blue'])
```

(continues on next page)
2.2. Contour plots
... UserWarning: pathological contour plot of a function whose values all lie on one side of the sole contour; we are adding more plot points and perturbing your function values. Graphics object consisting of 1 graphics primitive

Constant functions (with a single contour) can be plotted as well; this was not possible before github issue #21042:

```python
sage: contour_plot(lambda x, y: 0, (-1, 1), (-1, 1),
                contours=[0], fill=False, cmap=['blue'])
```

Return the equation rewritten as a symbolic function to give negative values when True, positive when False.

EXAMPLES:

```python
sage: from sage.plot.contour_plot import equify
sage: var('x, y')
(x, y)
sage: equify(x^2 < 2)
x^2 - 2
```

(continues on next page)
2.2. Contour plots
sage: equify(x^2 > 2)
-x^2 + 2
sage: equify(x*y > 1)
-x*y + 1
sage: equify(y > 0)
-y
sage: f = equify(lambda x, y: x > y)
sage: f(1, 2)
1
sage: f(2, 1)
-1

sage.plot.contour_plot.implicit_plot(f, xrange, yrange, plot_points=150, contours=(0, ), fill=False, cmap=['blue'], **options)

implicit_plot takes a function of two variables, \( f(x, y) \) and plots the curve \( f(x, y) = 0 \) over the specified \( x \)range and \( y \)range as demonstrated below.

\[
\text{implicit_plot}(f, (xmin,xmax), (ymin,ymax), ...)
\]

\[
\text{implicit_plot}(f, (x,xmin,xmax), (y,ymin,ymax), ...)
\]

**INPUT:**

- \( f \) – a function of two variables or equation in two variables
- \((xmin,xmax)\) – 2-tuple, the range of \( x \) values or \((x,xmin,xmax)\)
- \((ymin,ymax)\) – 2-tuple, the range of \( y \) values or \((y,ymin,ymax)\)

The following inputs must all be passed in as named parameters:

- \( \text{plot_points} \) – integer (default: 150); number of points to plot in each direction of the grid
- \( \text{fill} \) – boolean (default: False); if True, fill the region \( f(x, y) < 0 \).
- \( \text{fillcolor} \) – string (default: 'blue'), the color of the region where \( f(x, y) < 0 \) if \( \text{fill} = \text{True} \). Colors are defined in \texttt{sage.plot.colors}; try \texttt{colors?} to see them all.
- \( \text{linewidth} \) – integer (default: None), if a single integer all levels will be of the width given, otherwise the levels will be plotted with the widths in the order given.
- \( \text{linestyle} \) – string (default: None), the style of the line to be plotted, one of: "solid", "dashed", "dashdot" or "dotted", respectively "$-"", "$-\text{-}\$", "$--\$", or "$:\$".
- \( \text{color} \) – string (default: 'blue'), the color of the plot. Colors are defined in \texttt{sage.plot.colors}; try \texttt{colors?} to see them all. If \( \text{fill} = \text{True} \), then this sets only the color of the border of the plot. See \texttt{fillcolor} for setting the color of the fill region.
- \( \text{legend_label} \) – the label for this item in the legend
- \( \text{base} \) – (default: 10) the base of the logarithm if a logarithmic scale is set. This must be greater than 1. The base can be also given as a list or tuple \((\text{basex, basey})\). \texttt{basex} sets the base of the logarithm along the horizontal axis and \texttt{basey} sets the base along the vertical axis.
- \( \text{scale} \) – (default: "linear") string. The scale of the axes. Possible values are "linear", "loglog", "semilogx", "semilogy".

The scale can be also be given as single argument that is a list or tuple \((\text{scale, base})\) or \((\text{scale, base}, \text{base})\).
The "loglog" scale sets both the horizontal and vertical axes to logarithmic scale. The "semilogx" scale sets the horizontal axis to logarithmic scale. The "semilogy" scale sets the vertical axis to logarithmic scale. The "linear" scale is the default value when Graphics is initialized.

**Warning:** Due to an implementation detail in matplotlib, implicit plots whose data are all nonpositive or nonnegative may not be plotted correctly. We attempt to detect this situation and to produce something better than an empty plot when it happens; a UserWarning is emitted in that case.

**EXAMPLES:**

A simple circle with a radius of 2. Note that since the input function is an expression, we need to explicitly declare the variables in 3-tuples for the range:

```
sage: var("x y")
(x, y)
sage: implicit_plot(x^2 + y^2 - 2, (x,-3,3), (y,-3,3))
```

We can do the same thing, but using a callable function so we do not need to explicitly define the variables in the ranges. We also fill the inside:

```
sage: f(x,y) = x^2 + y^2 - 2
```

(continues on next page)
The same circle but with a different line width:

```
sage: implicit_plot(f, (-3,3), (-3,3), linewidth=6)
```

Again the same circle but this time with a dashdot border:

```
sage: implicit_plot(f, (-3,3), (-3,3), linestyle='dashdot')
```

The same circle with different line and fill colors:

```
sage: implicit_plot(f, (-3,3), (-3,3), color='red', # long time
...... fill=True, fillcolor='green',
...... plot_points=500)
```

You can also plot an equation:
2.2. Contour plots
2.2. Contour plots
You can even change the color of the plot:

```sage
sage: implicit_plot(x^2 + y^2 == 2, (x,-3,3), (y,-3,3), color="red")
Graphics object consisting of 1 graphics primitive
```

The color of the fill region can be changed:

```sage
sage: implicit_plot(x**2 + y**2 == 2, (x,-3,3), (y,-3,3), fill=True, fillcolor='red')
Graphics object consisting of 2 graphics primitives
```

Here is a beautiful (and long) example which also tests that all colors work with this:

```sage
sage: G = Graphics()
sage: counter = 0
sage: for col in colors.keys():   # long time
    ....:     G += implicit_plot(x^2 + y^2 == 1 + counter*.1, (x,-4,4),(y,-4,4),
    ....:                       color=col)
```

(continues on next page)
2.2. Contour plots
We can define a level-\(n\) approximation of the boundary of the Mandelbrot set:

```python
sage: def mandel(n):
    c = polygen(CDF, 'c')
    z = 0
    for i in range(n):
        z = z^2 + c
    def f(x,y):
        val = z(CDF(x, y))
        return val.norm() - 4
    return f
```

The first-level approximation is just a circle:

```python
sage: implicit_plot(mandel(1), (-3,3), (-3,3))
```

A third-level approximation starts to get interesting:

```python
sage: implicit_plot(mandel(3), (-3,3), (-3,3))
```

2.2. Contour plots
The seventh-level approximation is a degree 64 polynomial, and `implicit_plot` does a pretty good job on this part of the curve. (plot_points=200 looks even better, but it takes over a second.)

```sage
sage: implicit_plot(mandel(7), (-0.3, 0.05), (-1.15, -0.9), plot_points=50)
```

When making a filled implicit plot using a python function rather than a symbolic expression the user should increase the number of plot points to avoid artifacts:

```sage
sage: implicit_plot(lambda x, y: x^2 + y^2 - 2, (x,-3,3), (y,-3,3), fill=True, plot_points=500)
```

An example of an implicit plot on ‘loglog’ scale:

```sage
sage: implicit_plot(x^2 + y^2 == 200, (x,1,200), (y,1,200), scale='loglog')
```

2.2. Contour plots
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2.2. Contour plots
region_plot takes a boolean function of two variables, $f(x, y)$ and plots the region where $f$ is True over the specified xrange and yrange as demonstrated below.

region_plot($f$, (xmin, xmax), (ymin, ymax), ...)

INPUT:
- $f$ – a boolean function or a list of boolean functions of two variables
- (xmin, xmax) – 2-tuple, the range of $x$ values OR 3-tuple $(x, xmin, xmax)$
- (ymin, ymax) – 2-tuple, the range of $y$ values OR 3-tuple $(y, ymin, ymax)$
- plot_points – integer (default: 100); number of points to plot in each direction of the grid
- incol – a color (default: 'blue'), the color inside the region
- outcol – a color (default: None), the color of the outside of the region

If any of these options are specified, the border will be shown as indicated, otherwise it is only implicit (with color incol) as the border of the inside of the region.

- bordercol – a color (default: None), the color of the border
  ('black' if borderwidth or borderstyle is specified but not bordercol)
- borderstyle – string (default: 'solid'), one of 'solid', 'dashed', 'dotted', 'dashdot', respectively '-', '--', ':', '-.'.
- borderwidth – integer (default: None), the width of the border in pixels
- alpha – (default: 1) how transparent the fill is; a number between 0 and 1
- legend_label – the label for this item in the legend
- base - (default: 10) the base of the logarithm if a logarithmic scale is set. This must be greater than 1. The base can be also given as a list or tuple (basex, basey). basex sets the base of the logarithm along the horizontal axis and basey sets the base along the vertical axis.
- scale – (default: "linear") string. The scale of the axes. Possible values are "linear", "loglog", "semilogx", "semilogy".
  The scale can be also be given as single argument that is a list or tuple (scale, base) or (scale, basex, basey).
  The "loglog" scale sets both the horizontal and vertical axes to logarithmic scale. The "semilogx" scale sets the horizontal axis to logarithmic scale. The "semilogy" scale sets the vertical axis to logarithmic scale. The "linear" scale is the default value when Graphics is initialized.

EXAMPLES:
Here we plot a simple function of two variables:

```
sage: x,y = var('x,y')
sage: region_plot(cos(x^2 + y^2) <= 0, (x,-3,3), (y,-3,3))
Graphics object consisting of 1 graphics primitive
```

Here we play with the colors:

```
sage: region_plot(x^2 + y^3 < 2, (x,-2,2), (y,-2,2), incol='lightblue', bordercol='gray')
Graphics object consisting of 2 graphics primitives
```

An even more complicated plot, with dashed borders:
2.2. Contour plots
A disk centered at the origin:

\[
\text{sage: region_plot}(x^2 + y^2 < 1, (x,-1,1), (y,-1,1))
\]

Graphics object consisting of 1 graphics primitive

A plot with more than one condition (all conditions must be true for the statement to be true):

\[
\text{sage: region_plot}([x^2 + y^2 < 1, x < y], (x,-2,2), (y,-2,2))
\]

Graphics object consisting of 1 graphics primitive

Since it does not look very good, let us increase \textit{plot\_points}:

\[
\text{sage: region_plot}([x^2 + y^2 < 1, x < y], (x,-2,2), (y,-2,2), \text{plot\_points}=400)
\]

Graphics object consisting of 1 graphics primitive

To get plots where only one condition needs to be true, use a function. Using lambda functions, we definitely need the extra \textit{plot\_points}:
2.2. Contour plots
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2.2. Contour plots
\begin{verbatim}
\texttt{sage: region_plot(lambda x, y: x^2 + y^2 < 1 or x < y, (x,-2,2), (y,-2,2), plot_points=400)}
Graphics object consisting of 1 graphics primitive
\end{verbatim}

The first quadrant of the unit circle:
\begin{verbatim}
\texttt{sage: region_plot([y > 0, x > 0, x^2 + y^2 < 1], (x,-1.1,1.1), (y,-1.1,1.1), plot_points=400)}
Graphics object consisting of 1 graphics primitive
\end{verbatim}

Here is another plot, with a huge border:
\begin{verbatim}
\texttt{sage: region_plot(x*(x-1)*(x+1) + y^2 < 0, (x,-3,2), (y,-3,3),
.....: incol='lightblue', bordercol='gray', borderwidth=10,
.....: plot_points=50)}
Graphics object consisting of 2 graphics primitives
\end{verbatim}

If we want to keep only the region where x is positive:
\begin{verbatim}
\texttt{sage: region_plot([x*(x-1)*(x+1) + y^2 < 0, x > -1], (x,-3,2), (y,-3,3),
.....: incol='lightblue', plot_points=50)}
Graphics object consisting of 1 graphics primitive
\end{verbatim}

Here we have a cut circle:
2.2. Contour plots
\texttt{sage: region_plot([x^2 + y^2 < 4, x > -1], (x,-2,2), (y,-2,2),
....: incol='lightblue', bordercol='gray', plot_points=200)
Graphics object consisting of 2 graphics primitives}

The first variable range corresponds to the horizontal axis and the second variable range corresponds to the vertical axis:

\texttt{sage: s, t = var('s, t')
\texttt{sage: region_plot(s > 0, (t,-2,2), (s,-2,2))
Graphics object consisting of 1 graphics primitive

\texttt{sage: region_plot(s>0,(s,-2,2),(t,-2,2))
Graphics object consisting of 1 graphics primitive}

An example of a region plot in ‘loglog’ scale:

\texttt{sage: region_plot(x^2 + y^2 < 100, (x,1,10), (y,1,10), scale='loglog')
Graphics object consisting of 1 graphics primitive}
2.2. Contour plots
2.3 Density plots

class sage.plot.density_plot.DensityPlot(xy_data_array, xrange, yrange, options)

Primitive class for the density plot graphics type. See density_plot? for help actually doing density plots.

INPUT:

• xy_data_array - list of lists giving evaluated values of the function on the grid
• xrange - tuple of 2 floats indicating range for horizontal direction
• yrange - tuple of 2 floats indicating range for vertical direction
• options - dict of valid plot options to pass to constructor

EXAMPLES:

Note this should normally be used indirectly via density_plot:

```python
sage: from sage.plot.density_plot import DensityPlot
sage: D = DensityPlot([[1,3],[2,4]], (1,2), (2,3),options={})
```

get_minmax_data()

Returns a dictionary with the bounding box data.

EXAMPLES:

```python
sage: x,y = var('x,y')
sage: f(x, y) = x^2 + y^2
sage: d = density_plot(f, (3,6), (3,6))[0].get_minmax_data()
sage: d['xmin']
3.0
sage: d['ymin']
3.0
```

sage.plot.density_plot.density_plot(f, xrange, yrange, plot_points=25, cmap='gray', interpolation='catrom', **options)

density_plot takes a function of two variables, \( f(x, y) \) and plots the height of the function over the specified xrange and yrange as demonstrated below.

density_plot(f, (xmin,xmax), (ymin,ymax), ...)

INPUT:

• \( f \) – a function of two variables
• (xmin,xmax) – 2-tuple, the range of x values OR 3-tuple \((x,xmin,xmax)\)
• (ymin,ymax) – 2-tuple, the range of y values OR 3-tuple \((y,ymin,ymax)\)

The following inputs must all be passed in as named parameters:

• plot_points – integer (default: 25); number of points to plot in each direction of the grid
• **cmap** – a colormap (default: 'gray'), the name of a predefined colormap, a list of colors or an instance of a matplotlib Colormap. Type: `import matplotlib.cm; matplotlib.cm.datad.keys()` for available colormap names.

• **interpolation** – string (default: 'catrom'), the interpolation method to use: 'bilinear', 'bicubic', 'spline16', 'spline36', 'quadric', 'gaussian', 'sinc', 'bessel', 'mitchell', 'lanczos', 'catrom', 'hermite', 'hanning', 'hamming', 'kaiser'

**EXAMPLES:**

Here we plot a simple function of two variables. Note that since the input function is an expression, we need to explicitly declare the variables in 3-tuples for the range:

```
sage: x, y = var('x, y')
sage: density_plot(sin(x) * sin(y), (x,-2,2), (y,-2,2))
```

Graphics object consisting of 1 graphics primitive

![Graph of a simple function](image)

Here we change the ranges and add some options; note that here f is callable (has variables declared), so we can use 2-tuple ranges:

```
sage: x, y = var('x, y')
sage: f(x,y) = x^2 * cos(x*y)
sage: density_plot(f, (x,-10,5), (y,-5,5), interpolation='sinc', plot_points=100)
```

Graphics object consisting of 1 graphics primitive

![Graph of a more complicated function](image)

An even more complicated plot:

2.3. Density plots
sage: x,y = var('x,y')
sage: density_plot(sin(x^2+y^2) * cos(x) * sin(y), (x,-4,4), (y,-4,4), cmap='jet',
    plot_points=100)
Graphics object consisting of 1 graphics primitive

This should show a “spotlight” right on the origin:

sage: x,y = var('x,y')
sage: density_plot(1/(x^10 + y^10), (x,-10,10), (y,-10,10))
Graphics object consisting of 1 graphics primitive

Some elliptic curves, but with symbolic endpoints. In the first example, the plot is rotated 90 degrees because we switch the variables $x, y$:

sage: density_plot(y^2 + 1 - x^3 - x, (y,-pi,pi), (x,-pi,pi))
Graphics object consisting of 1 graphics primitive

Extra options will get passed on to show(), as long as they are valid:

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2.3. Density plots
Chapter 2. Function and Data Plots
2.4 Plotting fields

```python
sage: density_plot(log(x) + log(y), (x,1,10), (y,1,10), aspect_ratio=1)
Graphics object consisting of 1 graphics primitive
```

These are equivalent

```python
sage: density_plot(log(x) + log(y), (x,1,10), (y,1,10)).show(aspect_ratio=1)
```

```python
class sage.plot.plot_field.PlotField(xpos_array, ypos_array, xvec_array, yvec_array, options)

Bases: GraphicPrimitive

Primitive class that initializes the PlotField graphics type

get_minmax_data()

Returns a dictionary with the bounding box data.

EXAMPLES:

```python
sage: x,y = var('x,y')
sage: d = plot_vector_field((.01*x,x+y), (x,10,20), (y,10,20))[0].get_minmax_data()
```
sage: d['xmin']
10.0
sage: d['ymin']
10.0

sage.plot.plot_field.plot_slope_field(f, xrange, yrange, **kwds)

plot_slope_field takes a function of two variables xvar and yvar (for instance, if the variables are \(x\) and \(y\), take \(f(x, y)\)), and at representative points \((x_i, y_i)\) between xmin, xmax, and ymin, ymax respectively, plots a line with slope \(f(x_i, y_i)\) (see below).

plot_slope_field(f, (xvar,xmin,xmax), (yvar,ymin,ymax))

EXAMPLES:

A logistic function modeling population growth:

```
sage: x,y = var('x y')
sage: capacity = 3 # thousand
sage: growth_rate = 0.7 # population increases by 70% per unit of time
sage: plot_slope_field(growth_rate * (1-y/capacity) * y, (x,0,5), (y,0,capacity*2))
```

Graphics object consisting of 1 graphics primitive

Plot a slope field involving sin and cos:

```
```

Plot a slope field involving sin and cos:
sage: x, y = var('x y')
sage: plot_slope_field(sin(x+y) + cos(x+y), (x,-3,3), (y,-3,3))
Graphics object consisting of 1 graphics primitive

Plot a slope field using a lambda function:

```python
sage: plot_slope_field(lambda x,y: x + y, (-2,2), (-2,2))
Graphics object consisting of 1 graphics primitive
```

Sage.plot.plot_field.plot_vector_field(f_g, xrange, yrange, plot_points=20, frame=True, **options)

`plot_vector_field` takes two functions of two variables xvar and yvar (for instance, if the variables are $x$ and $y$, take $(f(x, y), g(x, y))$) and plots vector arrows of the function over the specified ranges, with xrange being of xvar between xmin and xmax, and yrange similarly (see below).

```python
sage.plot.plot_field.plot_vector_field((f,g), (xvar,xmin,xmax), (yvar,ymin,ymax))
```

**EXAMPLES:**

Plot some vector fields involving sin and cos:

```python
sage: x,y = var('x y')
sage: plot_vector_field((sin(x),cos(y)), (x,-3,3), (y,-3,3))
Graphics object consisting of 1 graphics primitive
```
2.4. Plotting fields
Plot a gradient field:

\[
\begin{align*}
\text{sage: } & \quad u, v = \text{var('u v')} \\
\text{sage: } & \quad f = \exp(-u^2 + v^2) \\
\text{sage: } & \quad \text{plot_vector_field(f.gradient(), (u,-2,2), (v,-2,2), color='blue')} \\
\end{align*}
\]

Graphics object consisting of 1 graphics primitive

Plot two orthogonal vector fields:

\[
\begin{align*}
\text{sage: } & \quad x, y = \text{var('x,y')} \\
\text{sage: } & \quad a = \text{plot_vector_field((x,y), (x,-3,3), (y,-3,3), color='blue')} \\
\text{sage: } & \quad b = \text{plot_vector_field((y,-x), (x,-3,3), (y,-3,3), color='red')} \\
\text{sage: } & \quad \text{show(a + b)} \\
\end{align*}
\]

We ignore function values that are infinite or NaN:

\[
\begin{align*}
\text{sage: } & \quad x, y = \text{var('x,y')} \\
\text{sage: } & \quad \text{plot_vector_field((-x/sqrt(x^2+y^2),-y/sqrt(x^2+y^2)), (x,-10,10), (y,-10,10))} \\
\end{align*}
\]

Graphics object consisting of 1 graphics primitive
2.4. Plotting fields
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2.4. Plotting fields

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```python
sage: x, y = var('x, y')
sage: plot_vector_field((-x/sqrt(x+y), -y/sqrt(x+y)), (x,-10, 10), (y,-10,10))
Graphics object consisting of 1 graphics primitive
```

Extra options will get passed on to show(), as long as they are valid:

```python
sage: plot_vector_field((x,y), (x,-2,2), (y,-2,2), xmax=10)
Graphics object consisting of 1 graphics primitive
sage: plot_vector_field((x,y), (x,-2,2), (y,-2,2)).show(xmax=10)  # These are equivalent
```

## 2.5 Streamline plots

```python
class sage.plot.streamline_plot.StreamlinePlot(xpos_array, ypos_array, xvec_array, yvec_array, options)

Bases: GraphicPrimitive

Primitive class that initializes the StreamlinePlot graphics type
```

```python
get_minmax_data()

Returns a dictionary with the bounding box data.
```
2.5. Streamline plots
EXAMPLES:

```python
sage: x, y = var('x y')
sage: d = streamline_plot((.01*x, x+y), (x,10,20), (y,10,20))[0].get_minmax_data()
sage: d["xmin"]
10.0
sage: d["ymin"]
10.0
```

```python
sage.plot.streamline_plot.streamline_plot(f_g, xrange, yrange, plot_points=20, density=1.0, frame=True, **options)
```

Return a streamline plot in a vector field.

**streamline_plot** can take either one or two functions. Consider two variables \(x\) and \(y\).

If given two functions \((f(x, y), g(x, y))\), then this function plots streamlines in the vector field over the specified ranges with \(xrange\) being of \(x\), denoted by \(xvar\) below, between \(xmin\) and \(xmax\), and \(yrange\) similarly (see below).

```
streamline_plot(((f, g), (xvar, xmin, xmax), (yvar, ymin, ymax))
```

Similarly, if given one function \(f(x, y)\), then this function plots streamlines in the slope field \(dy/dx = f(x, y)\) over the specified ranges as given above.

**PLOT OPTIONS:**
- `plot_points` – (default: 200) the minimal number of plot points
- `density` – float (default: 1.); controls the closeness of streamlines
- `start_points` – (optional) list of coordinates of starting points for the streamlines; coordinate pairs can be tuples or lists

**EXAMPLES:**

Plot some vector fields involving \(\sin\) and \(\cos\):

```python
sage: x, y = var('x y')
sage: streamline_plot((sin(x), cos(y)), (x,-3,3), (y,-3,3))
Graphics object consisting of 1 graphics primitive
```

```python
sage: streamline_plot((y, (cos(x)-2) * sin(x)), (x,-pi,pi), (y,-pi,pi))
Graphics object consisting of 1 graphics primitive
```

We increase the density of the plot:

```python
sage: streamline_plot((y, (cos(x)-2) * sin(x)), (x,-pi,pi), (y,-pi,pi), density=2)
Graphics object consisting of 1 graphics primitive
```

We ignore function values that are infinite or NaN:

```python
sage: x, y = var('x y')
sage: streamline_plot((-x/sqrt(x^2+y^2), -y/sqrt(x^2+y^2)), (x,-10,10), (y,-10,10))
Graphics object consisting of 1 graphics primitive
```

Extra options will get passed on to `show()`, as long as they are valid:
2.5. Streamline plots
Chapter 2. Function and Data Plots
2.5. Streamline plots
We can also construct streamlines in a slope field:

```python
sage: x, y = var('x y')
sage: streamline_plot((x + y) / sqrt(x^2 + y^2), (x,-3,3), (y,-3,3))
```

Graphics object consisting of 1 graphics primitive

We choose some particular points the streamlines pass through:

```python
sage: pts = [[1, 1], [-2, 2], [1, -3/2]]
sage: g = streamline_plot((x + y) / sqrt(x^2 + y^2), (x,-3,3), (y,-3,3), start_points=pts)
sage: g += point(pts, color='red')
sage: g
```

Graphics object consisting of 2 graphics primitives

**Note:** Streamlines currently pass close to `start_points` but do not necessarily pass directly through them. That is part of the behavior of matplotlib, not an error on your part.
2.5. Streamline plots
2.6 Scatter plots

class sage.plot.scatter_plot.ScatterPlot(xdata, ydata, options)

Bases: GraphicPrimitive

Scatter plot graphics primitive.

Input consists of two lists/arrays of the same length, whose values give the horizontal and vertical coordinates of each point in the scatter plot. Options may be passed in dictionary format.

EXAMPLES:

```python
sage: from sage.plot.scatter_plot import ScatterPlot
sage: ScatterPlot([0,1,2], [3.5,2,5.1], {'facecolor':'white', 'marker':'s'})
Scatter plot graphics primitive on 3 data points
```

get_minmax_data()

Returns a dictionary with the bounding box data.

EXAMPLES:

```python
sage: s = scatter_plot([[0,1],[2,4],[3.2,6]])
sage: d = s.get_minmax_data()
sage: d['xmin']
0.0
sage: d['ymin']
1.0
```

sage.plot.scatter_plot.scatter_plot(datalist, alpha=1, markersize=50, marker='o', zorder=5, facecolor='#fec7b8', edgecolor='black', clip=True, aspect_ratio='automatic', **options)

Returns a Graphics object of a scatter plot containing all points in the datalist. Type scatter_plot.options to see all available plotting options.

INPUT:

- datalist – a list of tuples (x,y)
- alpha – default: 1
- markersize – default: 50
- marker - The style of the markers (default "o"). See the documentation of `plot()` for the full list of markers.
- facecolor – default: '#fec7b8'
- edgecolor – default: 'black'
- zorder – default: 5

EXAMPLES:

```python
sage: scatter_plot([[0,1],[2,2],[4.3,1.1]], marker='s')
Graphics object consisting of 1 graphics primitive
```

Extra options will get passed on to `show()`, as long as they are valid:
2.6. Scatter plots
2.7 Step function plots

`sage.plot.step.plot_step_function(v, vertical_lines=True, **kwds)`

Return the line graphics object that gives the plot of the step function $f$ defined by the list $v$ of pairs $(a, b)$. Here if $(a, b)$ is in $v$, then $f(a) = b$. The user does not have to worry about sorting the input list $v$.

**INPUT:**

- $v$ – list of pairs $(a, b)$
- `vertical_lines` – bool (default: True) if True, draw vertical risers at each step of this step function. Technically these vertical lines are not part of the graph of this function, but they look very nice in the plot so we include them by default

**EXAMPLES:**

We plot the prime counting function:
sage: plot_step_function([(i, prime_pi(i)) for i in range(20)])
Graphics object consisting of 1 graphics primitive

sage: plot_step_function([(i, sin(i)) for i in range(5, 20)])
Graphics object consisting of 1 graphics primitive

We pass in many options and get something that looks like “Space Invaders”:

sage: v = [(i, sin(i)) for i in range(5, 20)]
sage: plot_step_function(v, vertical_lines=False, thickness=30, rgbcolor='purple', axes=False)
Graphics object consisting of 14 graphics primitives
Chapter 2. Function and Data Plots
2.8 Histograms

class sage.plot.histogram.Histogram(datalist, options)

Bases: GraphicPrimitive

Graphics primitive that represents a histogram. This takes quite a few options as well.

EXAMPLES:

```python
sage: from sage.plot.histogram import Histogram
sage: g = Histogram([1,3,2,0], {}); g
Histogram defined by a data list of size 4
sage: type(g)
<class 'sage.plot.histogram.Histogram'>
sage: opts = { 'bins':20, 'label':'mydata' }
sage: g = Histogram([random() for _ in range(500)], opts); g
Histogram defined by a data list of size 500
```

We can accept multiple sets of the same length:

```python
sage: g = Histogram(((1,3,2,0], [4,4,3,3]), {}); g
Histogram defined by 2 data lists
```

get_minmax_data()

Get minimum and maximum horizontal and vertical ranges for the Histogram object.

EXAMPLES:

```python
sage: H = histogram([10,3,5], density=True); h = H[0]
sage: h.get_minmax_data() # rel tol 1e-15
{'xmax': 10.0, 'xmin': 3.0, 'ymax': 0.4761904761904765, 'ymin': 0}
sage: G = histogram([random() for _ in range(500)]); g = G[0]
sage: g.get_minmax_data() # random output
{'xmax': 0.99729312925213209, 'xmin': 0.00013024562219410285, 'ymax': 61, 'ymin': 0}
sage: Y = histogram([random() for _ in range(500)], range=[2,8]); y = Y[0]
sage: ymm = y.get_minmax_data(); ymm['xmax'], ymm['xmin']
(8.0, 2.0)
sage: Z = histogram(((1,3,2,0], [4,4,3,3])); z = Z[0]
sage: z.get_minmax_data()
{'xmax': 4.0, 'xmin': 0, 'ymax': 2, 'ymin': 0}
```

sage.plot.histogram.histogram(datalist, aspect_ratio='automatic', align='mid', weights=None, range=None, bins=10, edgecolor='black', **options)

Computes and draws the histogram for list(s) of numerical data. See examples for the many options; even more customization is available using matplotlib directly.

INPUT:

- **datalist** – A list, or a list of lists, of numerical data
- **align** – (default: “mid”) How the bars align inside of each bin. Acceptable values are “left”, “right” or “mid”
- **alpha** – (float in [0,1], default: 1) The transparency of the plot
• **bins** – The number of sections in which to divide the range. Also can be a sequence of points within the range that create the partition

• **color** – The color of the face of the bars or list of colors if multiple data sets are given

• **cumulative** – (boolean - default: False) If True, then a histogram is computed in which each bin gives the counts in that bin plus all bins for smaller values. Negative values give a reversed direction of accumulation

• **edgecolor** – The color of the border of each bar

• **fill** – (boolean - default: True) Whether to fill the bars

• **hatch** – (default: None) symbol to fill the bars with - one of '/', '\', '|', '-', '+', 'x', 'o', 'O', '.', '*', '*' (or None)

• **hue** – The color of the bars given as a hue. See **hue** for more information on the hue

• **label** – A string label for each data list given

• **linewidth** – (float) width of the lines defining the bars

• **linestyle** – (default: ‘solid’) Style of the line. One of ‘solid’ or ‘-’, ‘dashed’ or ‘--’, ‘dotted’ or ‘:’, ‘dashdot’ or ‘-.’

• **density** – (boolean - default: False) If True, the result is the value of the probability density function at the bin, normalized such that the integral over the range is 1.

• **range** – A list [min, max] which define the range of the histogram. Values outside of this range are treated as outliers and omitted from counts

• **rwidth** – (float in [0,1], default: 1) The relative width of the bars as a fraction of the bin width

• **stacked** – (boolean - default: False) If True, multiple data are stacked on top of each other

• **weights** – (list) A sequence of weights the same length as the data list. If supplied, then each value contributes its associated weight to the bin count

• **zorder** – (integer) the layer level at which to draw the histogram

**Note:** The weights option works only with a single list. List of lists representing multiple data are not supported.

**EXAMPLES:**

A very basic histogram for four data points:

```sage
sage: histogram([1, 2, 3, 4], bins=2)
Graphics object consisting of 1 graphics primitive
```

We can see how the histogram compares to various distributions. Note the use of the density keyword to guarantee the plot looks like the probability density function:

```sage
sage: nv = normalvariate
sage: H = histogram([nv(0, 1) for _ in range(1000)], bins=20, density=True, range=[-5, 5])
sage: P = plot(1/sqrt(2*pi)*e^(-x^2/2), (x, -5, 5), color='red', linestyle='--')
sage: H+P
Graphics object consisting of 2 graphics primitives
```

There are many options one can use with histograms. Some of these control the presentation of the data, even if it is boring:
This includes many usual matplotlib styling options:

```python
sage: T = RealDistribution('lognormal', [0, 1])
sage: histogram([T.get_random_element() for _ in range(100)], alpha=0.3, edgecolor='red', fill=False, linestyle='dashed', hatch='O', linewidth=5)
```

We can do several data sets at once if desired:

```python
sage: histogram([srange(0, 1, .1)*10, [nv(0, 1) for _ in range(100)]], color=['red', 'green'], bins=5)
```

We have the option of stacking the data sets too:
2.8. Histograms
It is possible to use weights with the histogram as well:

```
sage: histogram(list(range(10)), bins=3, weights=[1, 2, 3, 4, 5, 5, 4, 3, 2, 1])
```

Graphics object consisting of 1 graphics primitive

### 2.9 Bar charts

```
class sage.plot.bar_chart.BarChart(ind, datalist, options)
Bases: GraphicPrimitive
```

Graphics primitive that represents a bar chart.

EXAMPLES:

```
sage: from sage.plot.bar_chart import BarChart
sage: g = BarChart(list(range(4)), [1,3,2,0], {}); g
BarChart defined by a 4 datalist
```

(continues on next page)
2.9. Bar charts

![Bar chart diagram]
```
sage: type(g)
<class 'sage.plot.bar_chart.BarChart'>
```

**get_minmax_data()**

Returns a dictionary with the bounding box data.

**EXAMPLES:**

```
sage: b = bar_chart([-2.3,5,-6,12])
sage: d = b.get_minmax_data()
sage: d['xmin']
0
sage: d['xmax']
4
```

```
sage.plot.bar_chart.bar_chart(datalist, width=0.5, rgbcolor=(0, 0, 1), legend_label=None, aspect_ratio='automatic', **options)
```

A bar chart of (currently) one list of numerical data. Support for more data lists in progress.

**EXAMPLES:**

A bar_chart with blue bars:
```
sage: bar_chart([1,2,3,4])
Graphics object consisting of 1 graphics primitive
```

A bar_chart with thinner bars:
```
sage: bar_chart([x^2 for x in range(1,20)], width=0.2)
Graphics object consisting of 1 graphics primitive
```

A bar_chart with negative values and red bars:
```
sage: bar_chart([-3,5,-6,11], rgbcolor=(1,0,0))
Graphics object consisting of 1 graphics primitive
```

A bar chart with a legend (it's possible, not necessarily useful):
```
sage: bar_chart([-1,1,-1,1], legend_label='wave')
Graphics object consisting of 1 graphics primitive
```

Extra options will get passed on to show(), as long as they are valid:
```
sage: bar_chart([-2,8,-7,3], rgbcolor=(1,0,0), axes=False)
Graphics object consisting of 1 graphics primitive
sage: bar_chart([-2,8,-7,3], rgbcolor=(1,0,0)).show(axes=False) # These are...
```
2.9. Bar charts
Chapter 2. Function and Data Plots
2.9. Bar charts
3.1 Graph plotting

(For LaTeX drawings of graphs, see the graph_latex module.)

All graphs have an associated Sage graphics object, which you can display:

```python
sage: G = graphs.WheelGraph(15)
sage: P = G.plot()
sage: P.show()  # long time
```

When plotting a graph created using Sage’s Graph command, node positions are determined using the spring-layout...
algorithm. Special graphs available from graphs.* have preset positions. For example, compare the two plots of the Petersen graph, as obtained using Graph or as obtained from that database:

```python
sage: petersen_spring = Graph('I`ES@obGkqegW~')
sage: petersen_spring.show()  # long time
```

![Graph of Petersen graph using spring layout](image1)

```
sage: petersen_database = graphs.PetersenGraph()
sage: petersen_database.show()  # long time
```

![Graph of Petersen graph from database](image2)

All constructors in this database (except some random graphs) prefill the position dictionary, bypassing the spring-layout positioning algorithm.

**Plot options**

Here is the list of options accepted by plot() and the constructor of GraphPlot. Those two functions also accept all options of sage.plot.graphics.Graphics.show().
3.1. Graph plotting
### Layout Options

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>layout</strong></td>
<td>A layout algorithm – one of: “acyclic”, “circular” (plots the graph with vertices evenly distributed on a circle), “ranked”, “graphviz”, “planar”, “spring” (traditional spring layout, using the graph’s current positions as initial positions), or “tree” (the tree will be plotted in levels, depending on minimum distance for the root).</td>
</tr>
<tr>
<td><strong>iterations</strong></td>
<td>The number of times to execute the spring layout algorithm.</td>
</tr>
<tr>
<td><strong>heights</strong></td>
<td>A dictionary mapping heights to the list of vertices at this height.</td>
</tr>
<tr>
<td><strong>spring</strong></td>
<td>Use spring layout to finalize the current layout.</td>
</tr>
<tr>
<td><strong>tree_root</strong></td>
<td>A vertex designation for drawing trees. A vertex of the tree to be used as the root for the <code>layout='tree'</code> option. If no root is specified, then one is chosen close to the center of the tree. Ignored unless <code>layout='tree'</code>.</td>
</tr>
<tr>
<td><strong>forest_roots</strong></td>
<td>An iterable specifying which vertices to use as roots for the <code>layout='forest'</code> option. If no root is specified for a tree, then one is chosen close to the center of the tree. Ignored unless <code>layout='forest'</code>.</td>
</tr>
<tr>
<td><strong>tree_orientation</strong></td>
<td>The direction of tree branches – ‘up’, ‘down’, ‘left’ or ‘right’.</td>
</tr>
<tr>
<td><strong>save_pos</strong></td>
<td>Whether or not to save the computed position for the graph.</td>
</tr>
<tr>
<td><strong>dim</strong></td>
<td>The dimension of the layout – 2 or 3.</td>
</tr>
<tr>
<td><strong>prog</strong></td>
<td>Which graphviz layout program to use – one of “circo”, “dot”, “fdp”, “neato”, or “twopi”.</td>
</tr>
<tr>
<td><strong>by_component</strong></td>
<td>Whether to do the spring layout by connected component – a boolean.</td>
</tr>
<tr>
<td><strong>pos</strong></td>
<td>The position dictionary of vertices.</td>
</tr>
<tr>
<td><strong>vertex_labels</strong></td>
<td>Vertex labels to draw. This can be True/False to indicate whether to print the vertex string representation of not, a dictionary keyed by vertices and associating to each vertex a label string, or a function taking as input a vertex and returning a label string.</td>
</tr>
<tr>
<td><strong>vertex_color</strong></td>
<td>Default color for vertices not listed in vertex_colors dictionary.</td>
</tr>
<tr>
<td><strong>vertex_colors</strong></td>
<td>A dictionary specifying vertex colors: each key is a color recognizable by matplotlib, and each corresponding value is a list of vertices.</td>
</tr>
<tr>
<td><strong>vertex_size</strong></td>
<td>The size to draw the vertices.</td>
</tr>
<tr>
<td><strong>vertex_shape</strong></td>
<td>The shape to draw the vertices. Currently unavailable for Multi-edged DiGraphs.</td>
</tr>
<tr>
<td><strong>edge_labels</strong></td>
<td>Whether or not to draw edge labels.</td>
</tr>
<tr>
<td><strong>edge_style</strong></td>
<td>The linestyle of the edges. It should be one of “solid”, “dashed”, “dotted”, “dash-dot”, or “-”, “--”, “.-”, “-.”, respectively.</td>
</tr>
<tr>
<td><strong>edge_thickness</strong></td>
<td>The thickness of the edges.</td>
</tr>
<tr>
<td><strong>edge_color</strong></td>
<td>The default color for edges not listed in edge_colors.</td>
</tr>
<tr>
<td><strong>edge_colors</strong></td>
<td>A dictionary specifying edge colors: each key is a color recognized by matplotlib, and each corresponding value is a list of edges.</td>
</tr>
<tr>
<td><strong>color_by_label</strong></td>
<td>Whether to color the edges according to their labels. This also accepts a function or dictionary mapping labels to colors.</td>
</tr>
<tr>
<td><strong>partition</strong></td>
<td>A partition of the vertex set. If specified, plot will show each cell in a different color; vertex_colors takes precedence.</td>
</tr>
<tr>
<td><strong>loop_size</strong></td>
<td>The radius of the smallest loop.</td>
</tr>
<tr>
<td><strong>dist</strong></td>
<td>The distance between multiedges.</td>
</tr>
<tr>
<td><strong>max_dist</strong></td>
<td>The max distance range to allow multiedges.</td>
</tr>
<tr>
<td><strong>talk</strong></td>
<td>Whether to display the vertices in talk mode (larger and white).</td>
</tr>
<tr>
<td><strong>graph_border</strong></td>
<td>Whether or not to draw a frame around the graph.</td>
</tr>
<tr>
<td><strong>edge_labels_background</strong></td>
<td>The color of the background of the edge labels.</td>
</tr>
</tbody>
</table>

### Default Options

This module defines two dictionaries containing default options for the `plot()` and `show()` methods. These two dictionaries are `sage.graphs.graph_plot.DEFAULT_PLOT_OPTIONS` and `sage.graphs.graph_plot.DEFAULT_SHOW_OPTIONS`, respectively.
Obviously, these values are overruled when arguments are given explicitly.

Here is how to define the default size of a graph drawing to be \((6, 6)\). The first two calls to \texttt{show()} use this option, while the third does not (a value for \texttt{figsize} is explicitly given):

\begin{verbatim}
sage: import sage.graphs.graph_plot
sage: sage.graphs.graph_plot.DEFAULT_SHOW_OPTIONS['figsize'] = (6, 6)
sage: graphs.PetersenGraph().show() # long time
sage: graphs.ChvatalGraph().show() # long time
sage: graphs.PetersenGraph().show(figsize=(4, 4)) # long time
\end{verbatim}

We can now reset the default to its initial value, and now display graphs as previously:

\begin{verbatim}
sage: sage.graphs.graph_plot.DEFAULT_SHOW_OPTIONS['figsize'] = (4, 4)
sage: graphs.PetersenGraph().show() # long time
sage: graphs.ChvatalGraph().show() # long time
\end{verbatim}

Note:
- While \texttt{DEFAULT_PLOT_OPTIONS} affects both \texttt{G.show()} and \texttt{G.plot()}, settings from \texttt{DEFAULT_SHOW_OPTIONS} only affects \texttt{G.show()}.
- In order to define a default value permanently, you can add a couple of lines to Sage’s startup scripts. Example:

\begin{verbatim}
sage: import sage.graphs.graph_plot
sage: sage.graphs.graph_plot.DEFAULT_SHOW_OPTIONS['figsize'] = (4, 4)
\end{verbatim}

Index of methods and functions

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<td>Set the position plotting parameters for this GraphPlot.</td>
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<td>GraphPlot.set_vertices()</td>
<td>Set the vertex plotting parameters for this GraphPlot.</td>
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<tr>
<td>GraphPlot.set_edges()</td>
<td>Set the edge (or arrow) plotting parameters for the GraphPlot object.</td>
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<td>Show the (Di)Graph associated with this GraphPlot object.</td>
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\section*{class sage.graphs.graph_plot.GraphPlot(graph, options)}

Bases: \texttt{SageObject}

Return a \texttt{GraphPlot} object, which stores all the parameters needed for plotting (Di)Graphs.

A \texttt{GraphPlot} has a plot and show function, as well as some functions to set parameters for vertices and edges. This constructor assumes default options are set. Defaults are shown in the example below.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: from sage.graphs.graph_plot import GraphPlot
sage: options = {
            'vertex_size': 200,
            'vertex_labels': True,
            'layout': None,
            'edge_style': 'solid',
            'edge_color': 'black',
            'edge_colors': None,
        }
\end{verbatim}

(continues on next page)
layout_tree(root, orientation)

Compute a nice layout of a tree.

INPUT:

• root – the root vertex.

• orientation – whether to place the root at the top or at the bottom:
  – orientation="down" – children are placed below their parent
  – orientation="top" – children are placed above their parent

EXAMPLES:

sage: from sage.graphs.graph_plot import GraphPlot
sage: G = graphs.HoffmanSingletonGraph()
sage: T = Graph()
sage: T.add_edges(G.min_spanning_tree(starting_vertex=0))
sage: T.show(layout='tree', tree_root=0) # indirect doctest

plot(**kwds)

Return a graphics object representing the (di)graph.

INPUT:

The options accepted by this method are to be found in the documentation of the sage.graphs.graph_plot module, and the show() method.

Note: See the module’s documentation for information on default values of this method.

We can specify some pretty precise plotting of familiar graphs:

sage: from math import sin, cos, pi
sage: P = graphs.PetersenGraph()
sage: d = {'#FF0000': [0, 5], '#FF9900': [1, 6], '#FFFF00': [2, 7],
....:     '#00FF00': [3, 8], '#0000FF': [4, 9]}
sage: pos_dict = {}
sage: for i in range(5):
....:    x = float(cos(pi/2 + ((2*pi)/5)*i))
Here are some more common graphs with typical options:

```
sage: C = graphs.CubeGraph(8)
sage: P = C.graphplot(vertex_labels=False, vertex_size=0, graph_border=True)
sage: P.show()
```

```
sage: G = graphs.HeawoodGraph().copy(sparse=True)
sage: for u, v, l in G.edges(sort=True):
    G.set_edge_label(u, v, f'({u},{v})')
sage: G.graphplot(edge_labels=True).show()
```
Chapter 3. Plots of Other Mathematical Objects
3.1. Graph plotting
The options for plotting also work with directed graphs:

```python
sage: D = DiGraph(
....:     0: [1, 10, 19], 1: [8, 2], 2: [3, 6], 3: [19, 4],
....:     4: [17, 5], 5: [6, 15], 6: [7, 8, 14], 8: [9],
....:     9: [10, 13], 10: [11, 12, 18], 12: [16, 13],
....:     13: [14], 14: [15], 15: [16], 16: [17], 17: [18],
....:     18: [19], 19: []))
sage: for u, v, l in D.edges(sort=True):
....:     D.set_edge_label(u, v, f'{set(l)}')
sage: D.graphplot(edge_labels=True, layout='circular').show()
```

This example shows off the coloring of edges:

```python
sage: from sage.plot.colors import rainbow
sage: C = graphs.CubeGraph(5)
sage: R = rainbow(5)
sage: edge_colors = {}
sage: for i in range(5):
....:     edge_colors[R[i]] = []
sage: for u, v, l in C.edges(sort=True):
....:     for i in range(5):
....:         if u[i] != v[i]:
```

(continues on next page)
....:       edge_colors[R[i]].append((u, v, l))
sage:   C.graphplot(vertex_labels=False, vertex_size=0,
....:       edge_colors=edge_colors).show()

With the partition option, we can separate out same-color groups of vertices:

```
sage: D = graphs.DodecahedralGraph()
sage: Pi = [[6, 5, 15, 14, 7], [16, 13, 8, 2, 4],
....:       [12, 17, 9, 3, 1], [0, 19, 18, 10, 11]]
sage: D.show(partition=Pi)
```

Loops are also plotted correctly:

```
sage: G = graphs.PetersenGraph()
sage: G.allow_loops(True)
sage: G.add_edge(0,0)
sage: G.show()

sage: D = DiGraph({0:[0,1], 1:[2], 2:[3]}, loops=True)
sage: D.show()
sage: D.show(edge_colors={0, 1, 0): [(0, 1, None), (1, 2, None)],
....:       (0, 0, 0): [(2, 3, None)]})
```
3.1. Graph plotting
Chapter 3. Plots of Other Mathematical Objects
More options:

```python
sage: pos = {0: [0.0, 1.5], 1: [-0.8, 0.3], 2: [-0.6, -0.8],
...: 3: [0.6, -0.8], 4: [0.8, 0.3]}
sage: g = Graph({0: [1], 1: [2], 2: [3], 3: [4], 4: [0]})
sage: g.graphplot(pos=pos, layout='spring', iterations=0).plot()
Graphics object consisting of 11 graphics primitives
```

We can plot multiple graphs:

```python
sage: G = Graph()
sage: P = G.graphplot().plot()
sage: P.axes()
False
sage: G = DiGraph()
sage: P = G.graphplot().plot()
sage: P.axes()
False
```

3.1. Graph plotting
sage: T = list(graphs.trees(7))
sage: t = T[3]
sage: t.graphplot(heights={0: [0], 1: [4, 5, 1],
                        2: [2], 3: [3, 6]})
                         ..........
                         ).plot()
Graphics object consisting of 14 graphics primitives

sage: t.set_edge_label(0, 1, -7)
sage: t.set_edge_label(0, 5, 3)
sage: t.set_edge_label(0, 5, 99)
sage: t.set_edge_label(1, 2, 1000)
sage: t.set_edge_label(3, 2, 'spam')
sage: t.set_edge_label(2, 6, 3/2)
sage: t.set_edge_label(0, 4, 66)
sage: t.graphplot(heights={0: [0], 1: [4, 5, 1],
                        2: [2], 3: [3, 6]},
               edge_labels=True)
                         ..........}
                         ).plot()
3.1. Graph plotting
Graphics object consisting of 20 graphics primitives

```python
sage: T = list(graphs.trees(7))
sage: t = T[3]
sage: t.graphplot(layout='tree').show()
```

The tree layout is also useful:

```python
sage: t = DiGraph('JCC????@A??G0??C0??G0??')
sage: t.graphplot(layout='tree', tree_root=0,
......:     tree_orientation="up"
......: ).show()
```

More examples:

```python
sage: D = DiGraph({0:[1,2,3], 2:[1,4], 3:[0]})
sage: D.graphplot().show()
```

```python
sage: D = DiGraph(multiedges=True, sparse=True)
sage: for i in range(5):
......:     D.add_edge((i, i + 1, 'a'))
......:     D.add_edge((i, i - 1, 'b'))
```

(continues on next page)
Chapter 3. Plots of Other Mathematical Objects
3.1. Graph plotting
sage: D.graphplot(edge_labels=True,
.....:     edge_colors=D._color_by_label() 
.....: ).plot()
Graphics object consisting of 34 graphics primitives

sage: g = Graph({}, loops=True, multiedges=True, sparse=True)
sage: g.add_edges([(0, 0, 'a'), (0, 0, 'b'), (0, 1, 'c'),
.....:     (0, 1, 'd'), (0, 1, 'e'), (0, 1, 'f'),
.....:     (0, 1, 'f'), (2, 1, 'g'), (2, 2, 'h')])
sage: g.graphplot(edge_labels=True,
.....:     color_by_label=True,
.....:     edge_style='dashed'
.....: ).plot()
Graphics object consisting of 22 graphics primitives

The edge_style option may be provided in the short format too:
sage: g.graphplot(edge_labels=True,
.....:     color_by_label=True,
.....:     edge_style='--'
.....: ).plot()
Graphics object consisting of 22 graphics primitives
3.1. Graph plotting
**set_edges(***edge_options*)

Set edge plotting parameters for the GraphPlot object.

This function is called by the constructor but can also be called to update the vertex options of an existing GraphPlot object. Note that the changes are cumulative.

EXAMPLES:

```python
sage: g = Graph(loops=True, multiedges=True, sparse=True)
sage: g.add_edges([(0, 0, 'a'), (0, 0, 'b'), (0, 1, 'c'),
                (0, 1, 'd'), (0, 1, 'e'), (0, 1, 'f'),
                (0, 1, 'g'), (2, 2, 'h')])
sage: GP = g.graphplot(vertex_size=100, edge_labels=True,
                    color_by_label=True, edge_style='dashed')
sage: GP.set_edges(edge_style='solid')
sage: GP.plot()
Graphics object consisting of 22 graphics primitives
```

```python
sage: GP.set_edges(edge_color='black')
sage: GP.plot()
Graphics object consisting of 22 graphics primitives
```

```python
sage: d = DiGraph(loops=True, multiedges=True, sparse=True)
```

(continues on next page)
3.1. Graph plotting
sage: d.add_edges([(0, 0, 'a'), (0, 0, 'b'), (0, 1, 'c'), ....: (0, 1, 'd'), (0, 1, 'e'), (0, 1, 'f'), ....: (0, 1, 'f'), (2, 1, 'g'), (2, 2, 'h')])

sage: GP = d.graphplot(vertex_size=100, edge_labels=True, .....: color_by_label=True, edge_style='dashed')

sage: GP.set_edges(edge_style='solid')

sage: GP.plot()

Graphics object consisting of 24 graphics primitives

---

set_pos()

Set the position plotting parameters for this GraphPlot.

EXAMPLES:

This function is called implicitly by the code below:

sage: g = Graph({0: [1, 2], 2: [3], 4: [0, 1]})

sage: g.graphplot(save_pos=True, layout='circular')  # indirect doctest

GraphPlot object for Graph on 5 vertices
3.1. Graph plotting
The following illustrates the format of a position dictionary, but due to numerical noise we do not check the values themselves:

```
sage: g.get_pos()
{0: (0.0, 1.0),
  1: (-0.951..., 0.309...),
  2: (-0.587..., -0.809...),
  3: (0.587..., -0.809...),
  4: (0.951..., 0.309...)}
```

```
sage: T = list(graphs.trees(7))
sage: t = T[3]
sage: t.plot(heights={0: [0], 1: [4, 5, 1], 2: [2], 3: [3, 6]})
Graphics object consisting of 14 graphics primitives
```

```
set_vertices(**vertex_options)
```

Set the vertex plotting parameters for this GraphPlot.

This function is called by the constructor but can also be called to make updates to the vertex options of an existing GraphPlot object. Note that the changes are cumulative.

EXAMPLES:
```python
sage: g = Graph({}, loops=True, multiedges=True, sparse=True)
sage: g.add_edges([(0, 0, 'a'), (0, 0, 'b'), (0, 1, 'c'),
               ....: (0, 1, 'd'), (0, 1, 'e'), (0, 1, 'f'),
               ....: (0, 1, 'f'), (2, 1, 'g'), (2, 2, 'h')])
sage: GP = g.graphplot(vertex_size=100, edge_labels=True,
                    ....: color_by_label=True, edge_style='dashed')
sage: GP.set_vertices(talk=True)
sage: GP.plot()
Graphics object consisting of 22 graphics primitives
sage: GP.set_vertices(vertex_color='green', vertex_shape='^')
sage: GP.plot()
Graphics object consisting of 22 graphics primitives
```

Vertex labels are flexible:

```python
sage: g = graphs.PathGraph(4)
sage: g.plot(vertex_labels=False)
Graphics object consisting of 4 graphics primitives
sage: g.plot(vertex_labels=True)
Graphics object consisting of 8 graphics primitives
```
3.1. Graph plotting
```python
sage: g = graphs.PathGraph(4)
sage: g.plot(vertex_labels=dict(zip(g, ['+', '-', '/', '*']))))
Graphics object consisting of 8 graphics primitives
```

```python
sage: g = graphs.PathGraph(4)
sage: g.plot(vertex_labels=lambda x: str(x % 2))
Graphics object consisting of 8 graphics primitives
```

```python
show(**kwds)
```

Show the (di)graph associated with this GraphPlot object.

INPUT:

This method accepts all parameters of `sage.plot.graphics.Graphics.show()`.

**Note:**

- See the module's documentation for information on default values of this method.
- Any options not used by plot will be passed on to the `show()` method.

**EXAMPLES:**

3.1. Graph plotting
Chapter 3. Plots of Other Mathematical Objects
3.2 Matrix plots

class sage.plot.matrix_plot.MatrixPlot(xy_data_array, xrange, yrange, options)

    Bases: GraphicPrimitive

    Primitive class for the matrix plot graphics type. See matrix_plot? for help actually doing matrix plots.

    INPUT:

    - `xy_data_array` - list of lists giving matrix values corresponding to the grid
    - `xrange` - tuple of 2 floats indicating range for horizontal direction (number of columns in the matrix). If `None`, the defaults are used as indicated in `matrix_plot()`.
    - `yrange` - tuple of 2 floats indicating range for vertical direction (number of rows in the matrix). If `None`, the defaults are used as indicated in `matrix_plot()`.
    - `options` - dict of valid plot options to pass to constructor
2D Graphics, Release 10.0

EXAMPLES:

Note this should normally be used indirectly via \texttt{matrix_plot():}

```python
sage: from sage.plot.matrix_plot import MatrixPlot
sage: M = MatrixPlot([[1,3],[2,4]],(1,2),(2,3),options={'cmap': 'winter'})
```

```
sage: M
MatrixPlot defined by a 2 x 2 data grid
sage: M.yrange
(2, 3)
sage: M.xy_data_array
[[1, 3], [2, 4]]
sage: M.options()
{'cmap': 'winter'}
```

Extra options will get passed on to \texttt{show()}, as long as they are valid:

```python
sage: matrix_plot([[1, 0], [0, 1]], fontsize=10)
Graphics object consisting of 1 graphics primitive
sage: matrix_plot([[1, 0], [0, 1]]).show(fontsize=10)  # These are equivalent
```

\texttt{get\_minmax\_data()}

Returns a dictionary with the bounding box data.

EXAMPLES:

```python
sage: m = matrix_plot(matrix([[1,3,5,1], [2,4,5,6], [1,3,5,7]])[0]
sage: list(sorted(m.get_minmax_data().items()))
[('xmax', 3.5), ('xmin', -0.5), ('ymax', 2.5), ('ymin', -0.5)]
```

\texttt{sage.plot.matrix_plot.matrix_plot(mat, xrange=None, yrange=None, aspect_ratio=1, axes=False, cmap='Greys', colorbar=False, frame=True, marker='', norm=None, flip_y=True, subdivisions=False, ticks_integer=True, vmin=None, vmax=None, subdivision_boundaries=None, subdivision_style=None, colorbar_orientation='vertical', colorbar_format=None, **options)}

A plot of a given matrix or 2D array.

If the matrix is sparse, colors only indicate whether an element is nonzero or zero, so the plot represents the sparsity pattern of the matrix.

If the matrix is dense, each matrix element is given a different color value depending on its relative size compared to the other elements in the matrix.

The default is for the lowest number to be black and the highest number to be white in a greyscale pattern; see the information about normalizing below. To reverse this, use \texttt{cmap='Greys'}.

The tick marks drawn on the frame axes denote the row numbers (vertical ticks) and the column numbers (horizontal ticks) of the matrix.

INPUT:

- \texttt{mat} - a 2D matrix or array
- \texttt{xrange} - (default: None) tuple of the horizontal extent (\texttt{xmin}, \texttt{xmax}) of the bounding box in which to draw the matrix. The image is stretched individually along \texttt{x} and \texttt{y} to fill the box.

If None, the extent is determined by the following conditions. Matrix entries have unit size in data coordinates. Their centers are on integer coordinates, and their center coordinates range from 0 to columns-1 horizontally and from 0 to rows-1 vertically.
If the matrix is sparse, this keyword is ignored.

- **yrange** - (default: None) tuple of the vertical extent (ymin, ymax) of the bounding box in which to draw the matrix. See xrange for details.

The following input must all be passed in as named parameters, if default not used:

- **cmap** - a colormap (default: ‘Greys’), the name of a predefined colormap, a list of colors, or an instance of a matplotlib Colormap.

The list of predefined color maps can be visualized in matplotlib's documentation. You can also type `import matplotlib.cm; matplotlib.cm.datad.keys()` to list their names.

- **colorbar** – boolean (default: False) Show a colorbar or not (dense matrices only).

The following options are used to adjust the style and placement of colorbars. They have no effect if a colorbar is not shown.

  - **colorbar_orientation** – string (default: ‘vertical’), controls placement of the colorbar, can be either ‘vertical’ or ‘horizontal’
  
  - **colorbar_format** – a format string, this is used to format the colorbar labels.
  
  - **colorbar_options** – a dictionary of options for the matplotlib.colorbar API. Documentation for the matplotlib.colorbar module has details.

- **norm** - If None (default), the value range is scaled to the interval [0,1]. If ‘value’, then the actual value is used with no scaling. A matplotlib.colors.Normalize instance may also passed.

- **vmin** - The minimum value (values below this are set to this value)

- **vmax** - The maximum value (values above this are set to this value)

- **flip_y** - (default: True) boolean. If False, the first row of the matrix is on the bottom of the graph. Otherwise, the first row is on the top of the graph.

- **subdivisions** - If True, plot the subdivisions of the matrix as lines.

- **subdivision_boundaries** - a list of lists in the form [row_subdivisions, column_subdivisions], which specifies the row and column subdivisions to use. If not specified, defaults to the matrix subdivisions

- **subdivision_style** - a dictionary of properties passed on to the `line2d()` command for plotting subdivsions. If this is a two-element list or tuple, then it specifies the styles of row and column divisions, respectively.

**EXAMPLES:**

A matrix over \(\mathbb{Z}\) colored with different grey levels:

\[
\text{sage: matrix_plot(matrix([[1,3,5,1],[2,4,5,6],[1,3,5,7]]))}
\]

Graphics object consisting of 1 graphics primitive

Here we make a random matrix over \(\mathbb{R}\) and use `cmap='hsv'` to color the matrix elements different RGB colors:

\[
\text{sage: matrix_plot(random_matrix(RDF, 50), cmap='hsv')}
\]

Graphics object consisting of 1 graphics primitive

By default, entries are scaled to the interval [0,1] before determining colors from the color map. That means the two plots below are the same:

\[
\text{sage: P = matrix_plot(matrix(2,[1,1,3,3]))}
\]

\[
\text{sage: Q = matrix_plot(matrix(2,[2,2,3,3]))}
\]

(continues on next page)
However, we can specify which values scale to 0 or 1 with the vmin and vmax parameters (values outside the range are clipped). The two plots below are now distinguished:

```
sage: P = matrix_plot(matrix(2,[1,1,3,3]), vmin=0, vmax=3, colorbar=True)
sage: Q = matrix_plot(matrix(2,[2,2,3,3]), vmin=0, vmax=3, colorbar=True)
sage: P; Q
```

We can also specify a norm function of ‘value’, which means that there is no scaling performed:

```
sage: matrix_plot(random_matrix(ZZ,10)**.05, norm='value', colorbar=True)
```

Matrix subdivisions can be plotted as well:

```
sage: m=random_matrix(RR,10)
sage: m.subdivide([2,4],[6,8])
sage: matrix_plot(m, subdivisions=True, subdivision_style=dict(color='red', thickness=3))
```

You can also specify your own subdivisions and separate styles for row or column subdivisions:

```
sage: m=random_matrix(RR,10)
sage: matrix_plot(m, subdivisions=True, subdivision_boundaries=[[2,4],[6,8]], subdivision_style=[dict(color='red', thickness=3),dict(linestyle='--', thickness=6)])
```

Generally matrices are plotted with the (0,0) entry in the upper left. However, sometimes if we are plotting an image, we’d like the (0,0) entry to be in the lower left. We can do that with the flip_y argument:

```
sage: matrix_plot(identity_matrix(100), flip_y=False)
```

A custom bounding box in which to draw the matrix can be specified using the xrange and yrange arguments:

```
sage: P = matrix_plot(identity_matrix(10), xrange=(0, pi), yrange=(-pi, 0))
sage: P
sage: P.get_minmax_data()
{'xmax': 3.14159..., 'xmin': 0.0, 'ymax': 0.0, 'ymin': -3.14159...}
```

If the horizontal and vertical dimension of the image are very different, the default aspect_ratio=1 may be unsuitable and can be changed to automatic:

```
sage: matrix_plot(random_matrix(RDF, 2, 2), (-100, 100), (0, 1),
....:     aspect_ratio='automatic')
```
Another random plot, but over $\mathbb{F}_{389}$:

```
sage: m = random_matrix(GF(389), 10)
sage: matrix_plot(m, cmap='Oranges')
Graphics object consisting of 1 graphics primitive
```

It also works if you lift it to the polynomial ring:

```
sage: matrix_plot(m.change_ring(GF(389)['x']), cmap='Oranges')
Graphics object consisting of 1 graphics primitive
```

We have several options for colorbars:

```
sage: matrix_plot(random_matrix(RDF, 50), colorbar=True, colorbar_orientation='horizontal')
Graphics object consisting of 1 graphics primitive
```

```
sage: matrix_plot(random_matrix(RDF, 50), colorbar=True, colorbar_format='%.3f')
Graphics object consisting of 1 graphics primitive
```

The length of a color bar and the length of the adjacent matrix plot dimension may be quite different. This example shows how to adjust the length of the colorbar by passing a dictionary of options to the matplotlib colorbar routines.

```
sage: m = random_matrix(ZZ, 40, 80, x=-10, y=10)
sage: m.plot(colorbar=True, colorbar_orientation='vertical',
       colorbar_options={'shrink':0.50})
Graphics object consisting of 1 graphics primitive
```

Here we plot a random sparse matrix:

```
sage: sparse = matrix(dict([(randint(0, 10), randint(0, 10)), 1) for i in range(100)]))
sage: matrix_plot(sparse)
Graphics object consisting of 1 graphics primitive
```

```
sage: A=random_matrix(ZZ,100000,density=.00001,sparse=True)
sage: matrix_plot(A,marker=',')
Graphics object consisting of 1 graphics primitive
```

As with dense matrices, sparse matrix entries are automatically converted to floating point numbers before plotting. Thus the following works:

```
sage: b=random_matrix(GF(2),200,sparse=True,density=0.01)
sage: matrix_plot(b)
Graphics object consisting of 1 graphics primitive
```

While this returns an error:

```
sage: b=random_matrix(CDF,200,sparse=True,density=0.01)
sage: matrix_plot(b)
Traceback (most recent call last):
...
ValueError: cannot convert entries to floating point numbers
```
To plot the absolute value of a complex matrix, use the `apply_map` method:

```
sage: b=random_matrix(CDF,200,sparse=True,density=0.01)
sage: matrix_plot(b.apply_map(abs))
```

Plotting lists of lists also works:

```
sage: matrix_plot([[1,3,5,1],[2,4,5,6],[1,3,5,7]])
```

As does plotting of NumPy arrays:

```
sage: import numpy
sage: matrix_plot(numpy.random.rand(10, 10))
```

A plot title can be added to the matrix plot:

```
sage: matrix_plot(identity_matrix(50), flip_y=False, title='not identity')
```

The title position is adjusted upwards if the `flip_y` keyword is set to True (this is the default):

```
sage: matrix_plot(identity_matrix(50), title='identity')
```

3.2. Matrix plots
4.1 Arcs of circles and ellipses

class sage.plot.arc.Arc(x, y, r1, r2, angle, s1, s2, options)

Bases: GraphicPrimitive

Primitive class for the Arc graphics type. See arc? for information about actually plotting an arc of a circle or an ellipse.

INPUT:

• x, y - coordinates of the center of the arc
• r1, r2 - lengths of the two radii
• angle - angle of the horizontal with width
• sector - sector of angle
• options - dict of valid plot options to pass to constructor

EXAMPLES:

Note that the construction should be done using arc:

sage: from sage.plot.arc import Arc
dsage: print(Arc(0,0,1,1,pi/4,pi/4,pi/2,{}))
Arc with center (0.0,0.0) radii (1.0,1.0) angle 0.78539816339... inside the sector (0.78539816339...,1.5707963267...)

bezier_path()

Return self as a Bezier path.

This is needed to concatenate arcs, in order to create hyperbolic polygons.

EXAMPLES:

sage: from sage.plot.arc import Arc
dsage: op = {'alpha':1,'thickness':1,'rgbcolor':'blue','zorder':0,'linestyle':"--"}
dsage: Arc(2,3,2,2,2,2,0,2,3,op).bezier_path()
Graphics object consisting of 1 graphics primitive

dsage: a = arc((0,0),2,1,0,(pi/5,pi/2+pi/12), linestyle="--", color="red")
dsage: b = a[0].bezier_path()
get_minmax_data()

Return a dictionary with the bounding box data.

The bounding box is computed as minimal as possible.

EXAMPLES:

An example without angle:

```
sage: p = arc((-2, 3), 1, 2)
sage: d = p.get_minmax_data()
sage: d['xmin']
-3.0
sage: d['xmax']
-1.0
sage: d['ymin']
1.0
sage: d['ymax']
5.0
```

The same example with a rotation of angle $\pi/2$:

```
sage: p = arc((-2, 3), 1, 2, pi/2)
sage: d = p.get_minmax_data()
sage: d['xmin']
-4.0
sage: d['xmax']
0.0
sage: d['ymin']
2.0
sage: d['ymax']
4.0
```

plot3d()

`sage.plot.arc.arc` (center, r1, r2=None, angle=0.0, sector=(0.0, 6.283185307179586), alpha=1, thickness=1, linestyle='solid', zorder=5, rgbcolor='blue', aspect_ratio=1.0, **options)

An arc (that is a portion of a circle or an ellipse)

Type `arc.options` to see all options.

INPUT:

- center - 2-tuple of real numbers - position of the center.
- r1, r2 - positive real numbers - radii of the ellipse. If only r1 is set, then the two radii are supposed to be equal and this function returns an arc of circle.
- angle - real number - angle between the horizontal and the axis that corresponds to r1.
- sector - 2-tuple (default: (0,2*pi))- angles sector in which the arc will be drawn.

OPTIONS:

- alpha - float (default: 1) - transparency
• **thickness** - float (default: 1) - thickness of the arc

• **color, rgbcolor** - string or 2-tuple (default: 'blue') - the color of the arc

• **linestyle** - string (default: 'solid') - The style of the line, which is one of 'dashed', 'dotted', 'solid', 'dashdot', or '--', ':', '-', '.', respectively.

**EXAMPLES:**

Plot an arc of circle centered at (0,0) with radius 1 in the sector \((\pi/4, 3\pi/4)\):

```python
sage: arc((0,0), 1, sector=(pi/4,3*pi/4))
Graphics object consisting of 1 graphics primitive
```

Plot an arc of an ellipse between the angles 0 and \(\pi/2\):

```python
sage: arc((2,3), 2, 1, sector=(0,pi/2))
Graphics object consisting of 1 graphics primitive
```

Plot an arc of a rotated ellipse between the angles 0 and \(\pi/2\):

```python
sage: arc((2,3), 2, 1, angle=pi/5, sector=(0,pi/2))
Graphics object consisting of 1 graphics primitive
```

Plot an arc of an ellipse in red with a dashed linestyle:
4.1. Arcs of circles and ellipses
The default aspect ratio for arcs is 1.0:

```python
sage: arc((0,0), 1, sector=(pi/4,3*pi/4)).aspect_ratio()
1.0
```

It is not possible to draw arcs in 3D:

```python
sage: A = arc((0,0,0), 1)
Traceback (most recent call last):
  ...
NotImplementedError
```
4.2 Arrows

```python
class sage.plot.arrow.Arrow(xtail, ytail, xhead, yhead, options)

Bases: GraphicPrimitive

Primitive class that initializes the (line) arrow graphics type

EXAMPLES:

We create an arrow graphics object, then take the 0th entry in it to get the actual Arrow graphics primitive:

```sage```
P = arrow((0,1), (2,3))[0]
sage: type(P)
<class 'sage.plot.arrow.Arrow'>
sage: P
Arrow from (0.0,1.0) to (2.0,3.0)
```

```python```
get_minmax_data()

Returns a bounding box for this arrow.

EXAMPLES:

```sage```
d = arrow((1,1), (5,5)).get_minmax_data()
sage: d['xmin']
1.0
sage: d['xmax']
5.0
```

```python```
plot3d(ztail=0, zhead=0, **kwds)

Takes 2D plot and places it in 3D.

EXAMPLES:

```sage```
A = arrow((0,0),(1,1))[0].plot3d()
sage: A.jmol_repr(A.testing_render_params())[0][0]
'draw line_1 diameter 2 arrow {0.0 0.0 0.0} {1.0 1.0 0.0} '
```

Note that we had to index the arrow to get the Arrow graphics primitive. We can also change the height via the `Graphics.plot3d()` method, but only as a whole:

```sage```
A = arrow((0,0),(1,1)).plot3d(3)
sage: A.jmol_repr(A.testing_render_params())[0][0]
'draw line_1 diameter 2 arrow {0.0 0.0 3.0} {1.0 1.0 3.0} '
```

Optional arguments place both the head and tail outside the xy-plane, but at different heights. This must be done on the graphics primitive obtained by indexing:

```sage```
A=arrow((0,0),(1,1))[0].plot3d(3,4)
sage: A.jmol_repr(A.testing_render_params())[0]
'draw line_1 diameter 2 arrow {0.0 0.0 3.0} {1.0 1.0 4.0} '
```

```python```
class sage.plot.arrow.CurveArrow(path, options)

Bases: GraphicPrimitive

Returns an arrow graphics primitive along the provided path (bezier curve).

EXAMPLES:
```
```python
sage: from sage.plot.arrow import CurveArrow
sage: b = CurveArrow(path=[[0,0],(.5,.5),(1,0)],[(.5,1),(0,0)],
.....: options={})
sage: b
CurveArrow from (0, 0) to (0, 0)
```

```
get_minmax_data()

Returns a dictionary with the bounding box data.

EXAMPLES:
```
```python
sage: from sage.plot.arrow import CurveArrow
sage: b = CurveArrow(path=[[0,0],(.5,.5),(1,0)],[(.5,1),(0,0)],
.....: options={})
sage: d = b.get_minmax_data()
sage: d['xmin']
0.0
sage: d['xmax']
1.0
```

```python
sage.plot.arrow.arrow(tailpoint=None, headpoint=None, **kwds)

Returns either a 2-dimensional or 3-dimensional arrow depending on value of points.

For information regarding additional arguments, see either arrow2d? or arrow3d?.

EXAMPLES:
```
```python
sage: arrow((0,0), (1,1))
Graphics object consisting of 1 graphics primitive
```
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```
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4.2. Arrows
- `arrowsize` - the size of the arrowhead
- `arrowshorten` - the length in points to shorten the arrow (ignored if using path parameter)
- `legend_label` - the label for this item in the legend
- `legend_color` - the color for the legend label
- `zorder` - the layer level to draw the arrow—note that this is ignored in 3D plotting.

EXAMPLES:

A straight, blue arrow:

```
sage: arrow2d((1,1), (3,3))
```
Graphics object consisting of 1 graphics primitive

Make a red arrow:

```
sage: arrow2d((-1,-1), (2,3), color=(1,0,0))
```
Graphics object consisting of 1 graphics primitive

```
sage: arrow2d((-1,-1), (2,3), color='red')
```
Graphics object consisting of 1 graphics primitive

You can change the width of an arrow:
Use a dashed line instead of a solid one for the arrow:

```
sage: arrow2d((1,1), (3,3), linestyle='dashed')
Graphics object consisting of 1 graphics primitive
```

```
sage: arrow2d((1,1), (3,3), linestyle='--')
Graphics object consisting of 1 graphics primitive
```

A pretty circle of arrows:

```
sage: sum([arrow2d((0,0), (cos(x),sin(x)), hue=x/(2*pi)) for x in [0..2*pi,step=0.˓→1]])
Graphics object consisting of 63 graphics primitives
```

If we want to draw the arrow between objects, for example, the boundaries of two lines, we can use the `arrowshorten` option to make the arrow shorter by a certain number of points:

```
sage: L1 = line([(0,0), (1,0)], thickness=10)
sage: L2 = line([(0,1), (1,1)], thickness=10)
sage: A = arrow2d((0.5,0), (0.5,1), arrowshorten=10, rgbcolor=(1,0,0))
sage: L1 + L2 + A
```

(continues on next page)
4.2. Arrows
If BOTH headpoint and tailpoint are None, then an empty plot is returned:

```
sage: arrow2d(headpoint=None, tailpoint=None)
Graphics object consisting of 0 graphics primitives
```

We can also draw an arrow with a legend:

```
sage: arrow((0,0), (0,2), legend_label='up', legend_color='purple')
Graphics object consisting of 1 graphics primitive
```

Extra options will get passed on to `Graphics.show()`, as long as they are valid:

```
sage: arrow2d((-2,2), (7,1), frame=True)
Graphics object consisting of 1 graphics primitive
```

4.2. Arrows
4.2. Arrows
4.3 Bezier paths

class sage.plot.bezier_path.BezierPath(path, options)

Bases: GraphicPrimitive_xydata

Path of Bezier Curves graphics primitive.

The input to this constructor is a list of curves, each a list of points, along which to create the curves, along with a dict of any options passed.

EXAMPLES:

sage: from sage.plot.bezier_path import BezierPath
sage: BezierPath([[0,0], [.5,.5],[1,0]], [(0,0),(.5,1),(0,0)], {'linestyle':'dashed'})
Bezier path from (0.0, 0.0) to (0.0, 0.0)

We use bezier_path() to actually plot Bezier curves:

sage: bezier_path([[0,0],(.5,.5),(1,0)],[(0,0),(.5,1),(0,0)], linestyle="dashed")
Graphics object consisting of 1 graphics primitive
get_minmax_data()

Returns a dictionary with the bounding box data.

EXAMPLES:

```
sage: b = bezier_path([[0,0],(.5,.5),(1,0)],[(.5,1),(0,0)])
sage: d = b.get_minmax_data()
sage: d['xmin']
0.0
sage: d['xmax']
1.0
```

plot3d(z=0, **kwds)

Returns a 3D plot (Jmol) of the Bezier path. Since a BezierPath primitive contains only \( x, y \) coordinates, the path will be drawn in some plane (default is \( z = 0 \)). To create a Bezier path with nonzero (and nonidentical) \( z \) coordinates in the path and control points, use the function bezier3d() instead of bezier_path().

EXAMPLES:

```
sage: b = bezier_path([[0,0],(0,1),(1,0)])
sage: A = b.plot3d()
sage: B = b.plot3d(z=2)
sage: A + B
Graphics3d Object

sage: bezier3d([[0,0,0),(1,0,0),(0,1,0),(0,1,1)])
Graphics3d Object
```

sage.plot.bezier_path.bezier_path(path, alpha=1, fill=False, thickness=1, rgbcolor=(0, 0, 0), zorder=2, linestyle='solid', **options)

Returns a Graphics object of a Bezier path corresponding to the path parameter. The path is a list of curves, and each curve is a list of points. Each point is a tuple \((x,y)\).

The first curve contains the endpoints as the first and last point in the list. All other curves assume a starting point given by the last entry in the preceding list, and take the last point in the list as their opposite endpoint. A curve can have 0, 1 or 2 control points listed between the endpoints. In the input example for path below, the first and second curves have 2 control points, the third has one, and the fourth has no control points:

```
path = [[p1, c1, c2, p2], [c3, c4, p3], [c5, p4], [p5], ...]
```

In the case of no control points, a straight line will be drawn between the two endpoints. If one control point is supplied, then the curve at each of the endpoints will be tangent to the line from that endpoint to the control point. Similarly, in the case of two control points, at each endpoint the curve will be tangent to the line connecting that endpoint with the control point immediately after or immediately preceding it in the list.

So in our example above, the curve between \( p1 \) and \( p2 \) is tangent to the line through \( p1 \) and \( c1 \) at \( p1 \), and tangent to the line through \( p2 \) and \( c2 \) at \( p2 \). Similarly, the curve between \( p2 \) and \( p3 \) is tangent to line(\( p2, c3 \)) at \( p2 \) and tangent to line(\( p3, c4 \)) at \( p3 \). Curve(\( p3, p4 \)) is tangent to line(\( p3, c5 \)) at \( p3 \) and tangent to line(\( p4, c5 \)) at \( p4 \). Curve(\( p4, p5 \)) is a straight line.

INPUT:

- **path** – a list of lists of tuples (see above)
- **alpha** – default: 1
- **fill** – default: False

4.3. Bezier paths
Chapter 4. Basic Shapes
- **thickness** – default: 1
- **linestyle** – default: 'solid', The style of the line, which is one of 'dashed', 'dotted', 'solid', 'dashdot', or '--', ':', '-', '., respectively.
- **rgbcolor** – default: (0,0,0)
- **zorder** – the layer in which to draw

**EXAMPLES:**

```sage
sage: path = [[(0,0),(.5,.1),(.75,3),(1,0)],[(.5,1),(.5,0)],[(.2,.5)]

sage: b = bezier_path(path, linestyle='dashed', rgbcolor='green')

sage: b
Graphics object consisting of 1 graphics primitive
```

To construct a simple curve, create a list containing a single list:

```sage
sage: path = [[(0,0),(.5,1),(1,0)]]

sage: curve = bezier_path(path, linestyle='dashed', rgbcolor='green')

sage: curve
Graphics object consisting of 1 graphics primitive
```

Extra options will get passed on to `show()`, as long as they are valid:
4.4 Circles

class sage.plot.circle.Circle(x, y, r, options)

Bases: GraphicPrimitive

Primitive class for the Circle graphics type. See circle? for information about actually plotting circles.

INPUT:

• x – x-coordinate of center of Circle
• y – y-coordinate of center of Circle
• r – radius of Circle object
• options – dict of valid plot options to pass to constructor

EXAMPLES:

Note this should normally be used indirectly via circle:
sage: from sage.plot.circle import Circle
sage: C = Circle(2,3,5,{'zorder':2})
sage: C
Circle defined by (2.0,3.0) with r=5.0
sage: C.options()['zorder']
2
sage: C.r
5.0

get_minmax_data()

Returns a dictionary with the bounding box data.

EXAMPLES:

sage: p = circle((3, 3), 1)
sage: d = p.get_minmax_data()
sage: d['xmin']
2.0
sage: d['ymin']
2.0

plot3d(z=0, **kwds)

Plots a 2D circle (actually a 50-gon) in 3D, with default height zero.

INPUT:

* z - optional 3D height above \( xy \)-plane.

EXAMPLES:

sage: circle((0,0), 1).plot3d()
Graphics3d Object

This example uses this method implicitly, but does not pass the optional parameter \( z \) to this method:

sage: sum([circle((random(),random()), random()).plot3d(z=random()) for _ in range(20)])
Graphics3d Object

These examples are explicit, and pass \( z \) to this method:

sage: C = circle((2,pi), 2, hue=.8, alpha=.3, fill=True)
sage: c = C[0]
sage: d = c.plot3d(z=2)
sage: d.texture.opacity
0.3

sage: C = circle((2,pi), 2, hue=.8, alpha=.3, linestyle='dotted')
sage: c = C[0]
sage: d = c.plot3d(z=2)
sage: d.jmol_repr(d.testing_render_params())[0][-1]
'color $line_1 translucent 0.7 [204,0,255]'
Return a circle at a point center \( (x, y) \) (or \( (x, y, z) \) and parallel to the \( xy \)-plane) with radius \( r \). Type \texttt{circle}. options to see all options.

**OPTIONS:**

- **alpha** - default: 1
- **fill** - default: False
- **thickness** - default: 1
- **linestyle** - default: 'solid' (2D plotting only) The style of the line, which is one of 'dashed', 'dotted', 'solid', 'dashdot', or '--', ':', '-.', respectively.
- **edgecolor** - default: 'blue' (2D plotting only)
- **facecolor** - default: 'blue' (2D plotting only, useful only if fill=True)
- **rgbcolor** - 2D or 3D plotting. This option overrides edgecolor and facecolor for 2D plotting.
- **legend_label** - the label for this item in the legend
- **legend_color** - the color for the legend label

**EXAMPLES:**

The default color is blue, the default linestyle is solid, but this is easy to change:

```python
sage: c = circle((1,1), 1)
sage: c
Graphics object consisting of 1 graphics primitive
```

```python
sage: c = circle((1,1), 1, rgbcolor=(1,0,0), linestyle='-.')
sage: c
Graphics object consisting of 1 graphics primitive
```

We can also use this command to plot three-dimensional circles parallel to the \( xy \)-plane:

```python
sage: c = circle((1,1,3), 1, rgbcolor=(1,0,0))
sage: c
Graphics3d Object
sage: type(c)
<class 'sage.plot.plot3d.base.TransformGroup'>
```

To correct the aspect ratio of certain graphics, it is necessary to show with a figsize of square dimensions:

```python
sage: c.show(figsize=[5,5], xmin=-1, xmax=3, ymin=-1, ymax=3)
```

Here we make a more complicated plot, with many circles of different colors:

```python
sage: g = Graphics()
sage: step=6; ocur=1/5; paths=16
sage: PI = math.pi   # numerical for speed -- fine for graphics
sage: for r in range(1,paths+1):
    ....:     for x,y in [((r+ocur)*math.cos(n), (r+ocur)*math.sin(n)) for n in range(0, 2*PI+PI/step, PI/step)]:
    ....:         g += circle((x,y), ocur, rgbcolor=hue(r/paths))
    ....:     rnext = (r+1)^2
    ....:     ocur = (rnext-r)-ocur
```

(continues on next page)
4.4. Circles
Note that the `rgbcolor` option overrides the other coloring options. This produces red fill in a blue circle:

```sage
circle((2,3), 1, fill=True, edgecolor='blue', facecolor='red')
```

This produces an all-green filled circle:

```sage
circle((2,3), 1, fill=True, edgecolor='blue', rgbcolor='green')
```

The option `hue` overrides all other options, so be careful with its use. This produces a purplish filled circle:

```sage
circle((2,3), 1, fill=True, edgecolor='blue', rgbcolor='green', hue=.8)
```

And circles with legends:

```sage
circle((4,5), 1, rgbcolor='yellow', fill=True, legend_label='the sun').
show(xmin=0, ymin=0)
```
4.4. Circles
Chapter 4. Basic Shapes
4.4. Circles
Chapter 4. Basic Shapes
Extra options will get passed on to show(), as long as they are valid:

```
sage: circle((0, 0), 2, figsize=[10,10])  # That circle is huge!
Graphics object consisting of 1 graphics primitive
```

```
sage: circle((0, 0), 2).show(figsize=[10,10])  # These are equivalent
```

### 4.5 Disks

**class** `sage.plot.disk.Disk(point, r, angle, options)`

Bases: `GraphicPrimitive`

Primitive class for the Disk graphics type. See `disk?` for information about actually plotting a disk (the Sage term for a sector or wedge of a circle).

**INPUT:**

- `point` - coordinates of center of disk
- `r` - radius of disk
• *angle* - beginning and ending angles of disk (i.e. angle extent of sector/wedge)

• *options* - dict of valid plot options to pass to constructor

**EXAMPLES:**

Note this should normally be used indirectly via disk:

```python
sage: from sage.plot.disk import Disk
sage: D = Disk((1,2), 2, (pi/2,pi), {'zorder':3})
```

```python
d = D.options() ['zorder']
3
d = D.x
1.0
```

**get_minmax_data()**

Returns a dictionary with the bounding box data.

**EXAMPLES:**

```python
sage: D = disk((5,4), 1, (pi/2, pi))
sage: d = D.get_minmax_data()
sage: d[ 'xmin' ]
4.0
sage: d[ 'ymin' ]
3.0
sage: d[ 'xmax' ]
6.0
sage: d[ 'ymax' ]
5.0
```

**plot3d(z=0,**kwds)**

Plots a 2D disk (actually a 52-gon) in 3D, with default height zero.

**INPUT:**

• *z* - optional 3D height above *xy*-plane.

**AUTHORS:**

• Karl-Dieter Crisman (05-09)

**EXAMPLES:**

```python
sage: disk((0,0), 1, (0, pi/2)).plot3d()
```

```python
Graphics3d Object
```

```python
sage: disk((0,0), 1, (0, pi/2)).plot3d(z=2)
```

```python
Graphics3d Object
```

```python
sage: disk((0,0), 1, (pi/2, 0), fill=False).plot3d(3)
```

```python
Graphics3d Object
```

These examples show that the appropriate options are passed:

```python
sage: D = disk((2,3), 1, (pi/4,pi/3), hue=.8, alpha=.3, fill=True)
sage: d = D[0]
```

(continues on next page)
sage: d.plot3d(z=2).texture.opacity 0.3

sage: D = disk((2,3), 1, (pi/4,pi/3), hue=.8, alpha=.3, fill=False)
sage: d = D[0]
sage: d = d.plot3d(z=2)
sage: dd = d.plot3d(z=2)
sage: dd.jmol_repr(dd.testing_render_params())[0][-1]
'color $line_4 translucent 0.7 [204,0,255]'

sage.plot.disk.disk(point, radius, angle, alpha=1, fill=True, rgbcolor=(0, 0, 1), thickness=0,
                  legend_label=None, aspect_ratio=1.0, **options)

A disk (that is, a sector or wedge of a circle) with center at a point = (x, y) (or (x, y, z) and parallel to the
xy-plane) with radius = r spanning (in radians) angle=(rad1, rad2).

Type disk.options to see all options.

EXAMPLES:

Make some dangerous disks:

sage: bl = disk((0.0,0.0), 1, (pi, 3*pi/2), color='yellow')
sage: tr = disk((0.0,0.0), 1, (0, pi/2), color='yellow')
sage: tl = disk((0.0,0.0), 1, (pi/2, pi), color='black')
sage: br = disk((0.0,0.0), 1, (3*pi/2, 2*pi), color='black')
sage: P = tl+tr+bl+br
sage: P.show(xmin=-2,xmax=2,ymin=-2,ymax=2)

The default aspect ratio is 1.0:

sage: disk((0.0,0.0,0.0), 1, (pi, 3*pi/2)).aspect_ratio()
1.0

Another example of a disk:

sage: bl = disk((0.0,0.0,0.0), 1, (pi, 3*pi/2), rgbcolor=(1,1,0))
sage: bl.show(figsize=[5,5])

Note that since thickness defaults to zero, it is best to change that option when using fill=False:

sage: disk((2,3), 1, (pi/4,pi/3), hue=.8, alpha=.3, fill=False)
Graphics object consisting of 1 graphics primitive

The previous two examples also illustrate using hue and rgbcolor as ways of specifying the color of the graphic.

We can also use this command to plot three-dimensional disks parallel to the xy-plane:

sage: d = disk((1,1,3), 1, (pi,3*pi/2), rgbcolor=(1,0,0))
sage: d
Graphics3d Object
sage: type(d)
<... 'sage.plot.plot3d.index_face_set.IndexFaceSet'>

Extra options will get passed on to show(), as long as they are valid:
Chapter 4. Basic Shapes
4.6 Ellipses

class sage.plot.ellipse.Ellipse(x, y, r1, r2, angle, options)

Bases: GraphicPrimitive

Primitive class for the Ellipse graphics type. See ellipse? for information about actually plotting ellipses.

INPUT:
- x, y - coordinates of the center of the ellipse
- r1, r2 - radii of the ellipse
- angle - angle
- options - dictionary of options

EXAMPLES:

Note that this construction should be done using ellipse:

sage: from sage.plot.ellipse import Ellipse
sage: Ellipse(0, 0, 2, 1, pi/4, {})

Ellipse centered at (0.0, 0.0) with radii (2.0, 1.0) and angle 0.78539816339...

get_minmax_data()

Return a dictionary with the bounding box data.

The bounding box is computed to be as minimal as possible.

EXAMPLES:

An example without an angle:

sage: p = ellipse((-2, 3), 1, 2)
sage: d = p.get_minmax_data()
sage: d['xmin']
-3.0
sage: d['xmax']
-1.0
sage: d['ymin']
1.0
sage: d['ymax']
5.0

The same example with a rotation of angle \( \pi/2 \):

sage: p = ellipse((-2, 3), 1, 2, pi/2)
sage: d = p.get_minmax_data()
sage: d['xmin']
(continues on next page)
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```
-4.0
sage: d['xmax']
0.0
sage: d['ymin']
2.0
sage: d['ymax']
4.0
```

plot3d()

Plotting in 3D is not implemented.

```
sage.plot.ellipse.ellipse(center, r1, r2, angle=0, alpha=1, fill=False, thickness=1, edgecolor='blue',
                         facecolor='blue', linestyle='solid', zorder=5, aspect_ratio=1.0,
                         legend_label=None, legend_color=None, **options)
```

Return an ellipse centered at a point center = (x, y) with radii = r1, r2 and angle angle. Type `ellipse.options` to see all options.

**INPUT:**
- center - 2-tuple of real numbers - coordinates of the center
- r1, r2 - positive real numbers - the radii of the ellipse
- angle - real number (default: 0) - the angle between the first axis and the horizontal

**OPTIONS:**
- alpha - default: 1 - transparency
- fill - default: False - whether to fill the ellipse or not
- thickness - default: 1 - thickness of the line
- linestyle - default: 'solid' - The style of the line, which is one of 'dashed', 'dotted', 'solid', 'dashdot', or '---', ':', '-', '--', respectively.
- edgecolor - default: 'black' - color of the contour
- facecolor - default: 'red' - color of the filling
- rgbcolor - 2D or 3D plotting. This option overrides edgecolor and facecolor for 2D plotting.
- legend_label - the label for this item in the legend
- legend_color - the color for the legend label

**EXAMPLES:**
An ellipse centered at (0,0) with major and minor axes of lengths 2 and 1. Note that the default color is blue:

```
sage: ellipse((0,0),2,1)
Graphics object consisting of 1 graphics primitive
```

More complicated examples with tilted axes and drawing options:

```
sage: ellipse((0,0),3,1,pi/6,fill=True,alpha=0.3,linestyle="dashed")
Graphics object consisting of 1 graphics primitive
```

other way to indicate dashed linestyle:
Chapter 4. Basic Shapes
4.6. Ellipses
with colors

```
sage: ellipse((0,0),3,1,pi/6,fill=True,edgecolor='black',facecolor='red',rgbcolor='green')
Graphics object consisting of 1 graphics primitive
```

We see that rgbcolor overrides these other options, as this plot is green:

```
sage: ellipse((0,0),3,1,pi/6,fill=True,edgecolor='black',facecolor='red',rgbcolor='green')
Graphics object consisting of 1 graphics primitive
```

The default aspect ratio for ellipses is 1.0:

```
sage: ellipse((0,0),2,1).aspect_ratio()
1.0
```

One cannot yet plot ellipses in 3D:

```
sage: ellipse((0,0,0),2,1)
Traceback (most recent call last):
```
...\nNotImplementedError: plotting ellipse in 3D is not implemented

We can also give ellipses a legend:

```python
sage: ellipse((0,0),2,1,legend_label="My ellipse", legend_color='green')
```

Graphics object consisting of 1 graphics primitive

---

### 4.7 Line plots

**class** `sage.plot.line.Line(xdata, ydata, options)`

Bases: `GraphicPrimitive_xydata`

Primitive class that initializes the line graphics type.

**EXAMPLES:**

```python
sage: from sage.plot.line import Line
sage: Line([1,2,7], [1,5,-1], {})
```

Line defined by 3 points
**plot3d(z=0, **kwds)**

Plots a 2D line in 3D, with default height zero.

EXAMPLES:

```python
sage: E = EllipticCurve('37a').plot(thickness=5).plot3d()
sage: F = EllipticCurve('37a').plot(thickness=5).plot3d(z=2)
sage: E + F  # long time (5s on sage.math, 2012)
Graphics3d Object
```

**sage.plot.line.line**(points, **kwds)**

Returns either a 2-dimensional or 3-dimensional line depending on value of points.

INPUT:

- **points** - either a single point (as a tuple), a list of points, a single complex number, or a list of complex numbers.

For information regarding additional arguments, see either line2d? or line3d?.

EXAMPLES:

```python
sage: line([(0,0), (1,1)])
Graphics object consisting of 1 graphics primitive
```
4.7. Line plots
sage: line([(0,0,1), (1,1,1)])
Graphics3d Object

Create the line through the given list of points.

INPUT:

- **points** - either a single point (as a tuple), a list of points, a single complex number, or a list of complex numbers.

Type `line2d.options` for a dictionary of the default options for lines. You can change this to change the defaults for all future lines. Use `line2d.reset()` to reset to the default options.

INPUT:

- **alpha** – How transparent the line is
- **thickness** – How thick the line is
- **rgbcolor** – The color as an RGB tuple
- **hue** – The color given as a hue
- **legend_color** – The color of the text in the legend
- **legend_label** – the label for this item in the legend
Any MATPLOTLIB line option may also be passed in. E.g.,

- **linestyle** - (default: "-") The style of the line, which is one of
  - "-" or "solid"
  - "--" or "dashed"
  - ".-" or "dash dot"
  - ":" or "dotted"
  - "None" or " " or "" (nothing)
  The linestyle can also be prefixed with a drawing style (e.g., "steps--")
  - "default" (connect the points with straight lines)
  - "steps" or "steps-pre" (step function; horizontal line is to the left of point)
  - "steps-mid" (step function; points are in the middle of horizontal lines)
  - "steps-post" (step function; horizontal line is to the right of point)

- **marker** - The style of the markers, which is one of
  - "None" or " " or "" (nothing) – default
  - "," (pixel), "." (point)
  - "-" (horizontal line), "|" (vertical line)
  - "o" (circle), "p" (pentagon), "s" (square), "x" (x), "+" (plus), "*" (star)
  - "D" (diamond), "d" (thin diamond)
  - "H" (hexagon), "h" (alternative hexagon)
  - "<" (triangle left), ">" (triangle right), "^" (triangle up), "v" (triangle down)
  - "1" (tri down), "2" (tri up), "3" (tri left), "4" (tri right)
  - 0 (tick left), 1 (tick right), 2 (tick up), 3 (tick down)
  - 4 (caret left), 5 (caret right), 6 (caret up), 7 (caret down)
  - "$\ldots\$" (math TeX string)

- **markersize** – the size of the marker in points

- **markeredgecolor** – the color of the marker edge

- **markerfacecolor** – the color of the marker face

- **markeredgewidth** – the size of the marker edge in points

**EXAMPLES:**

A line with no points or one point:

```sage
declare line([]) #returns an empty plot
Graphics object consisting of 0 graphics primitives
```

```sage
import numpy; line(numpy.array([]))
Graphics object consisting of 0 graphics primitives
```

```sage
line([(1,1)])
Graphics object consisting of 1 graphics primitive
```

A line with numpy arrays:
A line with a legend:

```
sage: line(((0,0),(1,1)], legend_label='line')
```

Graphics object consisting of 1 graphics primitive

Lines with different colors in the legend text:

```
sage: p1 = line([(0,0),(1,1)], legend_label='line')
sage: p2 = line([(1,1),(2,4)], legend_label='squared', legend_color='red')
sage: p1 + p2
```

Graphics object consisting of 2 graphics primitives

Extra options will get passed on to show(), as long as they are valid:

```
sage: line([(0,1), (3,4)], figsize=[10, 2])
```

Graphics object consisting of 1 graphics primitive

```
sage: line([(0,1), (3,4)]).show(figsize=[10, 2]) # These are equivalent
```

We can also use a logarithmic scale if the data will support it:
4.7. Line plots
sage: line([(1,2),(2,4),(3,4),(4,8),(4.5,32)],scale='loglog',base=2)
Graphics object consisting of 1 graphics primitive

Many more examples below!

A blue conchoid of Nicomedes:

sage: L = [[1+5*cos(pi/2+pi*i/100), tan(pi/2+pi*i/100)*(1+5*cos(pi/2+pi*i/100))] for i in range(1,100)]
sage: line(L, rgbcolor=(1/4,1/8,3/4))
Graphics object consisting of 1 graphics primitive

A line with 2 complex points:

sage: i = CC(0,1)
sage: line([1+i, 2+3*i])
Graphics object consisting of 1 graphics primitive

A blue hypotrochoid (3 leaves):

sage: n = 4; h = 3; b = 2
sage: L = [[n*cos(pi*i/100)-h*cos((n/b)*pi*i/100),n*sin(pi*i/100)-h*sin((n/b)*pi*i/100)] for i in range(200)]
(continues on next page)
4.7. Line plots
Chapter 4. Basic Shapes
A blue hypotrochoid (4 leaves):

\[
\text{sage: } n = 6; \ h = 5; \ b = 2 \\
\text{sage: } L = [[n*cos(pi*i/100)+h*cos((n/b)*pi*i/100),n*sin(pi*i/100)-h*sin((n/b)*pi*i/100)] \text{ for } i \text{ in range(200)]] \\
\text{sage: } line(L, rgbcolor=(1/4,1/4,3/4)) \\
\text{Graphics object consisting of 1 graphics primitive}
\]

A red limacon of Pascal:

\[
\text{sage: } L = [[\sin(pi*i/100)+\sin(pi*i/50),-(1+\cos(pi*i/100)+\cos(pi*i/50))] \text{ for } i \text{ in range(-100,101)]} \\
\text{sage: } line(L, rgbcolor=(1,1/4,1/2)) \\
\text{Graphics object consisting of 1 graphics primitive}
\]

A light green trisectrix of Maclaurin:

\[
\text{sage: } L = [[2*(1-4*cos(-pi/2+pi*i/100)^2),10*tan(-pi/2+pi*i/100)*(1-4*cos(-pi/2+pi*i/100))^2)] \text{ for } i \text{ in range(1,100)]}
\]

(continues on next page)
Chapter 4. Basic Shapes
4.7. Line plots
A green lemniscate of Bernoulli:

```python
sage: cosines = [cos(-pi/2+pi*i/100) for i in range(201)]
sage: v = [(1/c, tan(-pi/2+pi*i/100)) for i,c in enumerate(cosines) if c != 0]
sage: L = [(a/(a^2+b^2), b/(a^2+b^2)) for a,b in v]
sage: line(L, rgbcolor=(1/4,3/4,1/8))
Graphics object consisting of 1 graphics primitive
```

A red plot of the Jacobi elliptic function \(sn(x, 2)\), \(-3 < x < 3\):

```python
sage: L = [(i/100.0, real_part(jacobi('sn', i/100.0, 2.0))) for i in ...
.....: range(-300, 300, 30)]
sage: line(L, rgbcolor=(3/4, 1/4, 1/8))
Graphics object consisting of 1 graphics primitive
```

A red plot of \(J_2(x)\), \(0 < x < 10\):

```python
sage: L = [(i/10.0, bessel_J(2,i/10.0)) for i in range(100)]
sage: line(L, rgbcolor=(3/4,1/4,5/8))
Graphics object consisting of 1 graphics primitive
```
4.7. Line plots
Chapter 4. Basic Shapes
4.7. Line plots
A purple plot of the Riemann zeta function $\zeta(1/2 + it), 0 < t < 30$:

```python
sage: i = CDF.gen()
sage: v = [zeta(0.5 + n/10 * i) for n in range(300)]
sage: L = [(z.real(), z.imag()) for z in v]
sage: line(L, rgbcolor=(3/4,1/2,5/8))
```

A purple plot of the Hasse-Weil $L$-function $L(E, 1+it), -1 < t < 10$:

```python
sage: E = EllipticCurve('37a')
sage: vals = E.lseries().values_along_line(1-I, 1+10*I, 100) # critical line
sage: L = [(z[1].real(), z[1].imag()) for z in vals]
sage: line(L, rgbcolor=(3/4,1/2,5/8))
```

A red, blue, and green “cool cat”:

```python
sage: G = plot(-cos(x), -2, 2, thickness=5, rgbcolor=(0.5,1,0.5))
sage: P = polygon([[1,2], [5,6], [5,0]], rgbcolor=(1,0,0))
sage: Q = polygon([(-x,y) for x,y in P[0]], rgbcolor=(0,0,1))
sage: G + P + Q # show the plot
```

Graphics object consisting of 3 graphics primitives
4.7. Line plots
Chapter 4. Basic Shapes
4.8 Points

class sage.plot.point.Point(xdata, ydata, options)

Bases: GraphicPrimitive_xydata

Primitive class for the point graphics type. See point?, point2d? or point3d? for information about actually plotting points.

INPUT:

• xdata – list of x values for points in Point object
• ydata – list of y values for points in Point object
• options – dict of valid plot options to pass to constructor

EXAMPLES:

Note this should normally be used indirectly via point and friends:

```python
sage: from sage.plot.point import Point
sage: P = Point([1,2],[2,3],{’alpha’:0.5})
```

plot3d(z=0, **kwds)

Plots a two-dimensional point in 3-D, with default height zero.

INPUT:

• z - optional 3D height above xy-plane. May be a list if self is a list of points.

EXAMPLES:

One point:

```python
sage: A = point((1, 1))
```

One point with a height:

```python
sage: A = point((1, 1))
```

Multiple points:

```python
sage: P = point(((0, 0), (1, 1)))
```

(continues on next page)
Point set defined by 2 point(s)
sage: q = p.plot3d(size=22)

Multiple points with different heights:

sage: P = point([(0, 0), (1, 1)])
sage: p = P[0]
sage: q = p.plot3d(z=[2, 3])

sage: q.all[0].loc[2]
2.0
sage: q.all[1].loc[2]
3.0

Note that keywords passed must be valid point3d options:

sage: A = point(((1, 1), size=22))
sage: a = A[0]; a
Point set defined by 1 point(s)
sage: b = a.plot3d()
sage: b.size
22
sage: b = a.plot3d(pointsize=23)  # only 2D valid option
sage.plot.point.point(points, **kwds)

Return either a 2-dimensional or 3-dimensional point or sum of points.

INPUT:

• points - either a single point (as a tuple), a list of points, a single complex number, or a list of complex numbers.

For information regarding additional arguments, see either point2d? or point3d?.

See also:

`sage.plot.point.point2d()`, `sage.plot.plot3d.shapes2.point3d()`

EXAMPLES:

```
sage: point((1, 2))
Graphics object consisting of 1 graphics primitive
```
sage: point((1, 2, 3))
Graphics3d Object

Extra options will get passed on to show(), as long as they are valid:

sage: point([(cos(theta), sin(theta)) for theta in srange(0, 2*pi, pi/8)], frame=True)
Graphics object consisting of 1 graphics primitive

sage: point([(cos(theta), sin(theta)) for theta in srange(0, 2*pi, pi/8)]).show(frame=True) # These are equivalent

sage.plot.point point2d(points, alpha=1, aspect_ratio='automatic', faceted=False, legend_color=None, legend_label=None, marker='o', markeredgecolor=None, rgbcolor=(0, 0, 1), size=10, **options)

A point of size size defined by point = (x, y).

INPUT:
• **points** – either a single point (as a tuple), a list of points, a single complex number, or a list of complex numbers
• **alpha** – how transparent the point is
• **faceted** – if True, color the edge of the point (only for 2D plots)
• **hue** – the color given as a hue
• **legend_color** – the color of the legend text
• **legend_label** – the label for this item in the legend
• **marker** – the marker symbol for 2D plots only (see documentation of **plot()** for details)
• **markeredgecolor** – the color of the marker edge (only for 2D plots)
• **rgbcolor** – the color as an RGB tuple
• **size** – how big the point is (i.e., area in points^2=(1/72 inch)^2)
• **zorder** – the layer level in which to draw

**EXAMPLES:**

A purple point from a single tuple of coordinates:

```sage
sage: point((0.5, 0.5), rgbcolor=hue(0.75))
Graphics object consisting of 1 graphics primitive
```

![Graph](attachment:image.png)
Points with customized markers and edge colors:

```python
sage: r = [(random(), random()) for _ in range(10)]
sage: point(r, marker='d', markeredgecolor='red', size=20)
```

Graphics object consisting of 1 graphics primitive

Passing an empty list returns an empty plot:

```python
sage: point([])
```

Graphics object consisting of 0 graphics primitives

```python
sage: import numpy; point(numpy.array([]))
```

Graphics object consisting of 0 graphics primitives

If you need a 2D point to live in 3-space later, this is possible:

```python
sage: A = point((1, 1))
sage: a = A[0]; a
Point set defined by 1 point(s)
sage: b = a.plot3d(z=3)
```

This is also true with multiple points:

```python
sage: P = point([(0, 0), (1, 1)])
sage: p = P[0]
```
Chapter 4. Basic Shapes
Here are some random larger red points, given as a list of tuples:

```
sage: point(((0.5, 0.5), (1, 2), (0.5, 0.9), (-1, -1)), rgbcolor=hue(1), size=30)
```

Graphics object consisting of 1 graphics primitive

And an example with a legend:

```
sage: point((0, 0), rgbcolor='black', pointsize=40, legend_label='origin')
```

Graphics object consisting of 1 graphics primitive

The legend can be colored:

```
sage: P = points(((0, 0), (1, 0)), pointsize=40, legend_label='origin', legend_color='red')
sage: P + plot(x^2, (x, 0, 1), legend_label='plot', legend_color='green')
```

Graphics object consisting of 2 graphics primitives

Extra options will get passed on to show(), as long as they are valid:

```
sage: point(((cos(theta), sin(theta)) for theta in srange(0, 2*pi, pi/8)), frame=True)
```
4.8. Points
Graphics object consisting of 1 graphics primitive

\texttt{sage: point([[\cos(\theta), \sin(\theta)] \text{ for } \theta \text{ in } \text{srange}(0, 2\pi, \pi/8)]).} \\
\quad \textbackslash{}\rightarrow \text{show(frame=\text{True})} \ # \text{These are equivalent}

For plotting data, we can use a logarithmic scale, as long as we are sure not to include any nonpositive points in the logarithmic direction:

\texttt{sage: point([(1, 2), (2, 4), (3, 4), (4, 8), (4.5, 32)], scale='\text{semilogy}', base=2)}

Graphics object consisting of 1 graphics primitive

Since Sage Version 4.4 (\texttt{github issue \#8599}), the size of a 2d point can be given by the argument \texttt{size} instead of \texttt{pointsize}. The argument \texttt{pointsize} is still supported:

\texttt{sage: point((3, 4), size=100)}

Graphics object consisting of 1 graphics primitive

\texttt{sage: point((3, 4), pointsize=100)}

Graphics object consisting of 1 graphics primitive

We can plot a single complex number:
We can also plot a list of complex numbers:

```
sage: point([I, 1 + I, 2 + 2*I], pointsize=100)
```

Graphics object consisting of 1 graphics primitive

```
sage.plot.point.points(points, **kwds)
```

Return either a 2-dimensional or 3-dimensional point or sum of points.

INPUT:

- **points** - either a single point (as a tuple), a list of points, a single complex number, or a list of complex numbers.

For information regarding additional arguments, see either point2d? or point3d?.

See also:

```
sage.plot.point.point2d(), sage.plot.plot3d.shapes2.point3d()
```

EXAMPLES:
Chapter 4. Basic Shapes
4.8. Points

[Diagram showing a graph with two points at (1, 1) and (2, 2)]
sage: point((1, 2))
Graphics object consisting of 1 graphics primitive

Extra options will get passed on to show(), as long as they are valid:

sage: point([(cos(theta), sin(theta)) for theta in srange(0, 2*pi, pi/8)], frame=True)
Graphics object consisting of 1 graphics primitive
sage: point([(cos(theta), sin(theta)) for theta in srange(0, 2*pi, pi/8)]).show(frame=True) # These are equivalent
4.9 Polygons

```python
class sage.plot.polygon.Polygon(xdata, ydata, options):
    Bases: GraphicPrimitive_xydata
    Primitive class for the Polygon graphics type. For information on actual
    plotting, please see polygon(), polygon2d(), or polygon3d().

    INPUT:
    • xdata – list of x-coordinates of points defining Polygon
    • ydata – list of y-coordinates of points defining Polygon
    • options – dict of valid plot options to pass to constructor

    EXAMPLES:
    Note this should normally be used indirectly via polygon():

    sage: from sage.plot.polygon import Polygon
    sage: P = Polygon([1,2,3],[2,3,2],{'alpha':.5})
    sage: P
    Polygon defined by 3 points
    sage: P.options()['alpha']
    0.500000000000000
    sage: P.ydata
    [2, 3, 2]
```

```python
plot3d(z=0, **kwds)
    Plots a 2D polygon in 3D, with default height zero.
    INPUT:
    • z - optional 3D height above xy-plane, or a list of heights
      corresponding to the list of 2D polygon points.

    EXAMPLES:
    A pentagon:

    sage: polygon([(cos(t), sin(t)) for t in srange(0, 2*pi, 2*pi/5)]).plot3d()
    Graphics3d Object

    Showing behavior of the optional parameter z:

    sage: P = polygon(((0,0), (1,2), (0,1), (-1,2)))
    sage: p = P[0]; p
    Polygon defined by 4 points
    sage: q = p.plot3d()
    sage: q.obj_repr(q.testing_render_params())[2]
    ['v 0 0 0', 'v 1 2 0', 'v 0 1 0', 'v -1 2 0']
    sage: r = p.plot3d(z=3)
    sage: r.obj_repr(r.testing_render_params())[2]
    ['v 0 0 3', 'v 1 2 3', 'v 0 1 3', 'v -1 2 3']
    sage: s = p.plot3d(z=[0,1,2,3])
    sage: s.obj_repr(s.testing_render_params())[2]
    ['v 0 0 0', 'v 1 2 1', 'v 0 1 2', 'v -1 2 3']
```
sage.plot.polygon.polygon(points, **options)

Return either a 2-dimensional or 3-dimensional polygon depending on value of points.

For information regarding additional arguments, see either polygon2d() or polygon3d(). Options may be found and set using the dictionaries polygon2d.options and polygon3d.options.

EXAMPLES:

```
sage: polygon([(0,0), (1,1), (0,1)])
Graphics object consisting of 1 graphics primitive
```

```
sage: polygon([(0,0,1), (1,1,1), (2,0,1)])
Graphics3d Object
```

Extra options will get passed on to show(), as long as they are valid:

```
sage: polygon([(0,0), (1,1), (0,1)], axes=False)
Graphics object consisting of 1 graphics primitive
```

```
sage: polygon([(0,0), (1,1), (0,1)]).show(axes=False) # These are equivalent
```

sage.plot.polygon.polygon2d(points, alpha=1, rgbcolor=(0, 0, 1), edgecolor=None, thickness=None, legend_label=None, legend_color=None, aspect_ratio=1.0, fill=True, **options)

Return a 2-dimensional polygon defined by points.
Type `polygon2d.options` for a dictionary of the default options for polygons. You can change this to change the defaults for all future polygons. Use `polygon2d.reset()` to reset to the default options.

**EXAMPLES:**

We create a purple-ish polygon:

```
sage: polygon2d([[1,2], [5,6], [5,0]], rgbcolor=(1,0,1))
```

By default, polygons are filled in, but we can make them without a fill as well:

```
sage: polygon2d([[1,2], [5,6], [5,0]], fill=False)
```

In either case, the thickness of the border can be controlled:

```
sage: polygon2d([[1,2], [5,6], [5,0]], fill=False, thickness=4, color='orange')
```

For filled polygons, one can use different colors for the border and the interior as follows:

```
sage: L = [[0,0]]+[[i/100, 1.1+cos(i/20)] for i in range(100)]+[[[1,0]]
sage: polygon2d(L, color="limegreen", edgecolor="black", axes=False)
```
Chapter 4. Basic Shapes
Some modern art – a random polygon, with legend:

```sage
v = [(randrange(-5,5), randrange(-5,5)) for _ in range(10)]
sage: polygon2d(v, legend_label='some form')
Graphics object consisting of 1 graphics primitive
```

An aperiodic monotile, [Smi2023]:

```sage
s = sqrt(3)
sage: polygon2d([[0, 0], [0, s], [1, s], [3/2, 3/2*s], [3, s], [3, 0], [4, 0], ....: [9/2, -1/2*s], [3, -s], [3/2, -1/2*s], [1, -s], [-1, -s], ....: [-3/2, -1/2*s]], axes=False)
```

A purple hexagon:

```sage
L = [[cos(pi*i/3),sin(pi*i/3)] for i in range(6)]
sage: polygon2d(L, rgbcolor=(1,0,1))
```

A green deltoid:

```sage
L = [[-1+cos(pi*i/100)*(1+cos(pi*i/100)),2*sin(pi*i/100)*(1-cos(pi*i/100))] for i in range(200)]
```

(continues on next page)
4.9. Polygons
A blue hypotrochoid:

\[ \text{sage: } L = \left[ [6 \cdot \cos\left(\frac{\pi \cdot i}{100}\right) + 5 \cdot \cos\left(\frac{6}{2} \cdot \frac{\pi \cdot i}{100}\right), 6 \cdot \sin\left(\frac{\pi \cdot i}{100}\right) - 5 \cdot \sin\left(\frac{6}{2} \cdot \frac{\pi \cdot i}{100}\right)] \text{ for } i \in \text{range}(200) \right] \]

\[ \text{sage: } \text{polygon2d}(L, \text{rgbcolor}=(1/8, 1/4, 1/2)) \]

Graphics object consisting of 1 graphics primitive

A purple epicycloid:

\[ \text{sage: } m = 9; b = 1 \]

\[ \text{sage: } L = \left[ [m \cdot \cos\left(\frac{\pi \cdot i}{100}\right) + b \cdot \cos\left(\frac{m}{b} \cdot \frac{\pi \cdot i}{100}\right), m \cdot \sin\left(\frac{\pi \cdot i}{100}\right) - b \cdot \sin\left(\frac{m}{b} \cdot \frac{\pi \cdot i}{100}\right)] \text{ for } i \in \text{range}(200) \right] \]

(continues on next page)
A brown astroid:

\[
\begin{align*}
\text{sage: } & L = \left[\cos\left(\frac{\pi i}{100}\right)^3, \sin\left(\frac{\pi i}{100}\right)^3 \right] \text{ for } i \text{ in range(200)} \\
\text{sage: } & \text{polygon2d}(L, \text{rgbcolor}=(3/4, 1/4, 1/4)) \\
\end{align*}
\]

Graphics object consisting of 1 graphics primitive

And, my favorite, a greenish blob:

\[
\begin{align*}
\text{sage: } & L = \left[\cos\left(\frac{\pi i}{100}\right)(1+\cos\left(\frac{\pi i}{50}\right)), \sin\left(\frac{\pi i}{100}\right)(1+\sin\left(\frac{\pi i}{50}\right)) \right] \text{ for } i \text{ in range(200)} \\
\text{sage: } & \text{polygon2d}(L, \text{rgbcolor}=(1/8, 3/4, 1/2)) \\
\end{align*}
\]

Graphics object consisting of 1 graphics primitive

This one is for my wife:

\[
\begin{align*}
\text{sage: } & L = \left[\sin\left(\frac{\pi i}{100}\right)+\sin\left(\frac{\pi i}{50}\right), -(1+\cos\left(\frac{\pi i}{100}\right)+\cos\left(\frac{\pi i}{50}\right)) \right] \text{ for } i \text{ in range(-100, 100)} \\
\text{sage: } & \text{polygon2d}(L, \text{rgbcolor}=(1, 1/4, 1/2)) \\
\end{align*}
\]

Graphics object consisting of 1 graphics primitive

4.9. Polygons
Chapter 4. Basic Shapes
4.9. Polygons
One can do the same one with a colored legend label:

```python
sage: polygon2d(L, color='red', legend_label='For you!', legend_color='red')
```

Graphics object consisting of 1 graphics primitive

Polygons have a default aspect ratio of 1.0:

```python
sage: polygon2d([[1,2], [5,6], [5,0]]).aspect_ratio()
```

1.0

AUTHORS:

- David Joyner (2006-04-14): the long list of examples above.

## 4.10 Arcs in hyperbolic geometry

AUTHORS:

- Hartmut Monien (2011 - 08)

Three models of the hyperbolic plane are implemented: Upper Half Plane, Poincaré Disk, and Klein Disk, each with its different domain and metric tensor.
Upper half plane (UHP)

In this model, hyperbolic points are described by two coordinates, which we will represent by a complex number in the domain

\[ H = \{ z \in \mathbb{C} \mid \Im(z) > 0 \} \]

with the corresponding metric tensor

\[ ds^2 = \frac{dzd\bar{z}}{3(z)^2}. \]

Poincaré disk (PD)

In this model, hyperbolic points are described by two coordinates, which we will represent by a complex number within the unit circle, having therefore the following domain

\[ D = \{ z \in \mathbb{C} \mid |z| < 1 \} \]

with the corresponding metric tensor

\[ ds^2 = 4\frac{dzd\bar{z}}{(1 - |z|^2)^2}. \]

Klein disk (KM)

In this model, the domain is again complex numbers within the unit circle as in the Poincaré disk model, but the corresponding metric tensor is different:

\[ ds^2 = \frac{dzd\bar{z}}{1 - |z|^2} + \frac{(z \cdot dz)^2}{(1 - |z|^2)^2}. \]

See also:
sage.geometry.hyperbolic_space.hyperbolic_geodesic

REFERENCES:

For additional models of the hyperbolic plane and its relationship see [CFKP1997]. For a more detailed explanation on hyperbolic arcs see [Sta1993].

class sage.plot.hyperbolic_arc.HyperbolicArc(A, B, model, options)

Bases: HyperbolicArcCore

Primitive class for hyperbolic arc type.

See hyperbolic_arc? for information about plotting a hyperbolic arc in the complex plane.

INPUT:

- A, B – end points of the hyperbolic arc
- model – the hyperbolic model used, which is one of the following:
  - 'UHP' - upper half plane
  - 'PD' - Poincaré disk
  - 'KM' - Klein disk
class sage.plot.hyperbolic_arc.HyperbolicArcCore(path, options)
Bases: BezierPath

Base class for Hyperbolic arcs and hyperbolic polygons in the hyperbolic plane.
The Upper Half Model, Poincaré Disk Model, and Klein Disk model are supported.
sage.plot.hyperbolic_arc.hyperbolic_arc(a, b, model='UHP', alpha=1, fill=False, thickness=1, rgbcolor='blue', zorder=2, linestyle='solid', **options)

Plot an arc from a to b in hyperbolic plane.

INPUT:
• a, b - complex numbers connected by a hyperbolic arc
• model – (default: 'UHP') hyperbolic model used, which is one of the following:
  – 'UHP' - upper half plane
  – 'PD' - Poincaré disk
  – 'KM' - Klein disk
  – 'HM' - hyperboloid model

OPTIONS:
• alpha – default: 1
• thickness – default: 1
• rgbcolor – default: 'blue'
• linestyle – (default: 'solid') the style of the line, which is one of 'dashed', 'dotted', 'solid', 'dashdot', or '--', ':', '-', ':', '--', respectively

EXAMPLES:
Show a hyperbolic arc from 0 to 1:

```
sage: hyperbolic_arc(0, 1)
Graphics object consisting of 1 graphics primitive
```

Show a hyperbolic arc from 1/2 to i with a red thick line:

```
sage: hyperbolic_arc(0.5, I, color='red', thickness=2)
Graphics object consisting of 1 graphics primitive
```

Show a hyperbolic arc from 1 + i to 1 + 2i with dashed line:

```
sage: hyperbolic_arc(1+I, 1+2*I, linestyle='dashed', color='green')
Graphics object consisting of 1 graphics primitive
```

```
sage: hyperbolic_arc(-1+I, 1+2*I, linestyle='--', color='orange')
Graphics object consisting of 1 graphics primitive
```

Show a hyperbolic arc from a 1 + i to infinity:

```
sage: hyperbolic_arc(1 + I, infinity, color='brown')
Graphics object consisting of 1 graphics primitive
```

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4.10. Arcs in hyperbolic geometry
We can also plot hyperbolic arcs in other models.

We show a hyperbolic arc from $i$ to $-1$ in red, another hyperbolic arc from $e^{i\pi/3}$ to $0.6 \cdot e^{i3\pi/4}$ with dashed style in green, and finally a hyperbolic arc from $-0.5 + 0.5i$ to $0.5 - 0.5i$ together with the disk frontier in the Poincaré disk model:

```python
sage: z1 = CC(0,1)
sage: z2 = CC(-1,0)
sage: z3 = CC((cos(pi/3),sin(pi/3)))
sage: z4 = CC((0.6*cos(3*pi/4),0.6*sin(3*pi/4)))
sage: z5 = CC(-0.5,0.5)
sage: z6 = CC(0.5,-0.5)
sage: a1 = hyperbolic_arc(z1, z2, model="PD", color="red")
sage: a2 = hyperbolic_arc(z3, z4, model="PD", color="green")
sage: a3 = hyperbolic_arc(z5, z6, model="PD", linestyle="--")
sage: a1 + a2 + a3
Graphics object consisting of 6 graphics primitives
```

We show the arcs defined by the same endpoints in the Klein disk model (note that these are not the image of those arcs when changing between the models):

```python
sage: a1 = hyperbolic_arc(z1, z2, model="KM", color="red")
sage: a2 = hyperbolic_arc(z3, z4, model="KM", color="green")
sage: a3 = hyperbolic_arc(z5, z6, model="KM", linestyle="--")
```

(continues on next page)
Show a hyperbolic arc from \((1, 2, \sqrt{6})\) to \((-2, -3, \sqrt{14})\) in the hyperboloid model:

```
sage: a = (1,2,sqrt(6))
sage: b = (-2,-3,sqrt(14))
sage: hyperbolic_arc(a, b, model="HM")
Graphics3d Object
```

4.11 Polygons and triangles in hyperbolic geometry

AUTHORS:

- Hartmut Monien (2011-08)
- Vincent Delecroix (2014-11)

class sage.plot.hyperbolic_polygon.HyperbolicPolygon(pts, model, options)

    Bases: HyperbolicArcCore

    Primitive class for hyperbolic polygon type.
See hyperbolic_polygon? for information about plotting a hyperbolic polygon in the complex plane.

INPUT:
- **pts** – coordinates of the polygon (as complex numbers)
- **options** – dict of valid plot options to pass to constructor

EXAMPLES:
Note that constructions should use `hyperbolic_polygon()` or `hyperbolic_triangle()`:

```python
sage: from sage.plot.hyperbolic_polygon import HyperbolicPolygon
sage: print(HyperbolicPolygon([0, 1/2, I], "UHP", {}))
Hyperbolic polygon (0.000000000000000, 0.500000000000000, 1.00000000000000*I)
```

Return a hyperbolic polygon in the hyperbolic plane with vertices **pts**.
Type `?hyperbolic_polygon` to see all options.

INPUT:
- **pts** – a list or tuple of complex numbers

OPTIONS:
- **model** – default: UHP Model used for hyperbolic plane
- **alpha** – default: 1
- **fill** – default: False
- **thickness** – default: 1
- **rgbcolor** – default: 'blue'
- **linestyle** – (default: 'solid') the style of the line, which is one of 'dashed', 'dotted', 'solid', 'dashdot', or '--', ':', '-', '-', respectively

EXAMPLES:
Show a hyperbolic polygon with coordinates $-1, 3i, 2 + 2i, 1 + i$:

```python
sage: hyperbolic_polygon([-1,3*I,2+2*I,1+I])
Graphics object consisting of 1 graphics primitive
```

With more options:

```python
sage: hyperbolic_polygon([-1,3*I,2+2*I,1+I], fill=True, color='red')
Graphics object consisting of 1 graphics primitive
```

With a vertex at $\infty$:

```python
sage: hyperbolic_polygon([-1,0,1,Infinity], color='green')
Graphics object consisting of 1 graphics primitive
```

Poincare disc model is supported via the parameter **model**. Show a hyperbolic polygon in the Poincare disc model with coordinates $1, i, -1, -i$:
4.11. Polygons and triangles in hyperbolic geometry
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4.11. Polygons and triangles in hyperbolic geometry
Klein model is also supported via the parameter `model`. Show a hyperbolic polygon in the Klein model with coordinates $1, e^{i \pi / 3}, e^{i 2 \pi / 3}, -1, e^{i 4 \pi / 3}, e^{i 5 \pi / 3}$:

```python
sage: p1 = 1
sage: p2 = (cos(pi/3), sin(pi/3))
sage: p3 = (cos(2*pi/3), sin(2*pi/3))
sage: p4 = -1
sage: p5 = (cos(4*pi/3), sin(4*pi/3))
sage: p6 = (cos(5*pi/3), sin(5*pi/3))
sage: hyperbolic_polygon([p1,p2,p3,p4,p5,p6], model="KM", fill=True, color='purple')
```

Hyperboloid model is supported partially, via the parameter `model`. Show a hyperbolic polygon in the hyperboloid model with coordinates $(3, 3, \sqrt{19})$, $(3, -3, \sqrt{19})$, $(-3, -3, \sqrt{19})$, $(-3, 3, \sqrt{19})$:
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Filling a `hyperbolic_polygon` in hyperboloid model is possible although jaggy. We show a filled hyperbolic polygon in the hyperboloid model with coordinates 
\((1, 1, \sqrt{3}), (0, 2, \sqrt{5}), (2, 0, \sqrt{5})\). (The doctest is done at lower resolution than the picture below to give a faster result.)

```
sage: pts = [(1,1,sqrt(3)), (0,2,sqrt(5)), (2,0,sqrt(5))]
sage: hyperbolic_polygon(pts, model="HM", resolution=50, 
....:       color='yellow', fill=True)
```

`sage.plot.hyperbolic_polygon.hyperbolic_triangle(a, b, c, model='UHP', **options)`

Return a hyperbolic triangle in the hyperbolic plane with vertices \((a, b, c)\).

Type `?hyperbolic_polygon` to see all options.

**INPUT:**

- a, b, c – complex numbers in the upper half complex plane

**OPTIONS:**

- alpha – default: 1
• fill – default: False
• thickness – default: 1
• rgbcolor – default: 'blue'
• linestyle – (default: 'solid') the style of the line, which is one of 'dashed', 'dotted', 'solid', 'dashdot', or '--', ':', '-', '--', respectively.

EXAMPLES:
Show a hyperbolic triangle with coordinates $0, 1/2 + i\sqrt{3}/2$ and $-1/2 + i\sqrt{3}/2$:

```
sage: hyperbolic_triangle(0, -1/2+I*sqrt(3)/2, 1/2+I*sqrt(3)/2)
Graphics object consisting of 1 graphics primitive
```

A hyperbolic triangle with coordinates $0, 1$ and $2 + i$ and a dashed line:

```
sage: hyperbolic_triangle(0, 1, 2+i, fill=true, rgbcolor='red', linestyle='--')
Graphics object consisting of 1 graphics primitive
```

A hyperbolic triangle with a vertex at $\infty$:

```
sage: hyperbolic_triangle(-5,Infinity,5)
Graphics object consisting of 1 graphics primitive
```

It can also plot a hyperbolic triangle in the Poincaré disk model:
4.11. Polygons and triangles in hyperbolic geometry
4.12 Regular polygons in the upper half model for hyperbolic plane

AUTHORS:
- Javier Honrubia (2016-01)

class sage.plot.hyperbolic_regular_polygon.HyperbolicRegularPolygon(sides, i_angle, center, options)

Bases: HyperbolicPolygon

Primitive class for regular hyperbolic polygon type.

See hyperbolic_regular_polygon? for information about plotting a hyperbolic regular polygon in the upper complex halfplane.
4.12. Regular polygons in the upper half model for hyperbolic plane
INPUT:

- sides – number of sides of the polygon
- i_angle – interior angle of the polygon
- center – center point as a complex number of the polygon

EXAMPLES:

Note that constructions should use `hyperbolic_regular_polygon()`:

```
sage: from sage.plot.hyperbolic_regular_polygon import HyperbolicRegularPolygon
sage: print(HyperbolicRegularPolygon(5, pi/2, I, {}))
Hyperbolic regular polygon (sides=5, i_angle=1/2*pi, center=1.00000000000000*I)
```

The code verifies there exists a compact hyperbolic regular polygon with the given data, checking

\[ A(P) = \pi(s - 2) - s \cdot \alpha > 0, \]

where \( s \) is sides and \( \alpha \) is i_angle. This raises an error if the `i_angle` is less than the minimum to generate a compact polygon:

```
sage: from sage.plot.hyperbolic_regular_polygon import HyperbolicRegularPolygon
sage: P = HyperbolicRegularPolygon(4, pi/2, I, {})
Traceback (most recent call last):
  ... ValueError: there exists no hyperbolic regular compact polygon, for sides=4 the interior angle must be less than 1/2*pi
```

It is an error to give a center outside the upper half plane in this model:

```
sage: from sage.plot.hyperbolic_regular_polygon import HyperbolicRegularPolygon
sage: P = HyperbolicRegularPolygon(4, pi/4, 1-I, {})
Traceback (most recent call last):
  ... ValueError: center: 1.00000000000000 - 1.00000000000000*I is not a valid point in the upper half plane model of the hyperbolic plane
```

Return a hyperbolic regular polygon in the upper half model of Hyperbolic plane given the number of sides, interior angle and possibly a center.

Type `?hyperbolic_regular_polygon` to see all options.

INPUT:

- sides – number of sides of the polygon
- i_angle – interior angle of the polygon
- center – (default: `i`) hyperbolic center point (complex number) of the polygon

OPTIONS:

- alpha – default: 1
• fill – default: False
• thickness – default: 1
• rgbcolor – default: 'blue'
• linestyle – (default: 'solid') the style of the line, which can be one of the following:
  – 'dashed' or '--'
  – 'dotted' or ':'
  – 'solid' or '-'
  – 'dashdot' or '-.'

EXAMPLES:

Show a hyperbolic regular polygon with 6 sides and square angles:

```sage
g = hyperbolic_regular_polygon(6, pi/2)
sage: g.plot()
Graphics object consisting of 1 graphics primitive
```

With more options:
The code verifies if there exists a hyperbolic regular polygon with the given data, checking

\[ A(P) = \pi(s - 2) - s \cdot \alpha > 0, \]

where \( s \) is sides and \( \alpha \) is \( \text{i\_angle} \). This raises an error if the \( \text{i\_angle} \) is less than the minimum to generate a compact polygon:

sage: hyperbolic_regular_polygon(4, pi/2)
Traceback (most recent call last):
  ...
ValueError: there exists no hyperbolic regular compact polygon, for sides=4 the interior angle must be less than 1/2*pi

It is an error to give a center outside the upper half plane in this model:

sage: from sage.plot.hyperbolic_regular_polygon import hyperbolic_regular_polygon
sage: hyperbolic_regular_polygon(4, pi/4, 1-I)
Traceback (most recent call last):
  ...
ValueError: center: 1.00000000000000 - 1.00000000000000*I is not a valid point in the upper half plane model of the hyperbolic plane
5.1 Graphics objects

This file contains the definition of the class `Graphics`. Usually, you don’t call the constructor of this class directly (although you can do it), you would use `plot()` instead.

AUTHORS:

- Jeroen Demeyer (2012-04-19): split off this file from plot.py (github issue #12857)
- Punarbasu Purkayastha (2012-05-20): Add logarithmic scale (github issue #4529)
- Emily Chen (2013-01-05): Add documentation for `show()` figsize parameter (github issue #5956)
- Eric Gourgoulhon (2015-03-19): Add parameter axes_labels_size (github issue #18004)

```python
class sage.plot.graphics.Graphics
    Bases: WithEqualityById, SageObject

    TheGraphicsobjectisanemptylistofgraphicsobjects. Itisuseful tousethisobjectwhenuinitializingaforloop
where differentgraphicsobjectwillbeaddedtotheemptyobject.

EXAMPLES:
```

```
sage: G = Graphics(); print(G)
Graphics object consisting of 0 graphics primitives
sage: c = circle((1,1), 1)
sage: G+=c; print(G)
Graphics object consisting of 1 graphics primitive
```

Here we make a graphic of embedded isosceles triangles, coloring each one with a different color as we go:

```
sage: h=10; c=0.4; p=0.5
sage: G = Graphics()
```

```
sage: for x in srange(1,h+1):
    ....:     l = [[0,x*sqrt(3)],[x/2,-x*sqrt(3)/2],[x/2,-x*sqrt(3)/2],[0,x*sqrt(3)]]
    ....:     G+=line(l,color=hue(c + p*(x/h)))
```

```
sage: G.show(figsize=[5,5])
```

We can change the scale of the axes in the graphics before displaying.: 

```
sage: G = plot(exp, 1, 10)  # long time
sage: G.show(scale='semilogy')  # long time
```
_rich_repr_(display_manager, **kwds)

Rich Output Magic Method

See sage.repl.rich_output for details.

EXAMPLES:

```python
sage: from sage.repl.rich_output import get_display_manager
sage: dm = get_display_manager()
```

```python
sage: g = Graphics()
```

```python
sage: g._rich_repr_(dm)
```

OutputImagePng container

LEGEND_OPTIONS = {'back_color': 'white', 'borderaxespad': None, 'borderpad': 0.6,
'thickness': 'medium', 'font_style': 'normal', 'font_variant': 'normal',
'font_weight': 'medium', 'handlelength': 0.05, 'handletextpad': 0.5,
'labelspacing': 0.02, 'loc': 'best', 'markerscale': 0.6, 'numpoints': 2,
'shadow': True, 'title': None}

SHOW_OPTIONS = {'aspect_ratio': None, 'axes': None, 'axes_labels': None,
'axes_labels_size': None, 'base': None, 'dpi': 100,
'fig_tight': True, 'figsize': None, 'flip_x': False, 'flip_y': False,
'fontsize': None, 'frame': False, 'gridlines': None, 'griddlinesstyle': None,
'hgridlinesstyle': None, 'legend_options': {}, 'scale': None, 'show_legend': None,
'tick_formatter': None, 'ticks': None, 'ticks_integer': False, 'title': None,
'title_pos': None, 'transparent': False, 'typeset': 'default',
'vgriddlinesstyle': None, 'xmax': None, 'xmin': None, 'ymax': None, 'ymin': None}

add_primitive(primitive)

Adds a primitive to this graphics object.

EXAMPLES:

We give a very explicit example:

```python
sage: G = Graphics()
```

```python
sage: from sage.plot.line import Line
```

```python
sage: from sage.plot.arrow import Arrow
```

```python
sage: L = Line([3,4,2,7,-2],[1,2,e,4,5.],{'alpha':1,'thickness':2,'rgbcolor':(0,
˓→1,1),'legend_label':''})
```

```python
sage: A = Arrow(2,-5,.1,.2,{'width':3,'head':0,'rgbcolor':(1,0,0),'linestyle':
˓→'dashed','zorder':8,'legend_label':''})
```

```python
sage: G.add_primitive(L)
```

```python
sage: G.add_primitive(A)
```

```python
sage: G
```

Graphics object consisting of 2 graphics primitives

aspect_ratio()

Get the current aspect ratio, which is the ratio of height to width of a unit square, or ‘automatic’.

OUTPUT: a positive float (height/width of a unit square), or ‘automatic’ (expand to fill the figure).

EXAMPLES:

The default aspect ratio for a new blank Graphics object is ‘automatic’:
The aspect ratio can be explicitly set different than the object’s default:

```
sage: P = circle((1,1), 1)
sage: P.aspect_ratio()
1.0
sage: P.set_aspect_ratio(2)
sage: P.aspect_ratio()
2.0
sage: P.set_aspect_ratio('automatic')
sage: P.aspect_ratio()
'automatic'
```

**axes**(show=None)

Set whether or not the \(x\) and \(y\) axes are shown by default.

**INPUT:**

- *show* - bool

If called with no input, return the current axes setting.

**EXAMPLES:**

```
sage: L = line([[(1,2), (3,-4), (2, 5), (1,2)]])
```

By default the axes are displayed.

```
sage: L.axes()
True
```

But we turn them off, and verify that they are off.

```
sage: L.axes(False)
sage: L.axes()
False
```

Displaying \(L\) now shows a triangle but no axes.

```
sage: L
Graphics object consisting of 1 graphics primitive
```

**axes_color**(c=None)

Set the axes color.

If called with no input, return the current axes_color setting.

**INPUT:**

- *c* - an RGB color 3-tuple, where each tuple entry is a float between 0 and 1

**EXAMPLES:** We create a line, which has like everything a default axes color of black.

```
```
We change the axes color to red and verify the change.

```
sage: L.axes_color((1,0,0))
(1.0, 0.0, 0.0)
```

When we display the plot, we’ll see a blue triangle and bright red axes.

```
sage: L
Graphics object consisting of 1 graphics primitive
```

### axes_label_color

Set the color of the axes labels.

The axes labels are placed at the edge of the x and y axes, and are not on by default (use the `axes_labels` command to set them; see the example below). This function just changes their color.

**INPUT:**

- `c` - an RGB 3-tuple of numbers between 0 and 1

If called with no input, return the current `axes_label_color` setting.

**EXAMPLES:** We create a plot, which by default has axes label color black.

```
sage: p = plot(sin, (-1,1))
sage: p.axes_label_color()
(0, 0, 0)
```

We change the labels to be red, and confirm this:

```
sage: p.axes_label_color((1,0,0))
sage: p.axes_label_color()
(1.0, 0.0, 0.0)
```

We set labels, since otherwise we won’t see anything.

```
sage: p.axes_labels(['$x$ axis', '$y$ axis'])
```

In the plot below, notice that the labels are red:

```
sage: p
Graphics object consisting of 1 graphics primitive
```

### axes_labels

Set the axes labels.

**INPUT:**

- `l` - (default: None) a list of two strings or None

**OUTPUT:** a 2-tuple of strings

If `l` is None, returns the current `axes_labels`, which is itself by default None. The default labels are both empty.
EXAMPLES: We create a plot and put x and y axes labels on it.

```python
sage: p = plot(sin(x), (x, 0, 10))
sage: p.axes_labels(['x', 'y'])
('x', 'y')
```

Now when you plot p, you see x and y axes labels:

```python
sage: p
Graphics object consisting of 1 graphics primitive
```

Notice that some may prefer axes labels which are not typeset:

```python
sage: plot(sin(x), (x, 0, 10), axes_labels=['x', 'y'])
Graphics object consisting of 1 graphics primitive
```

`axes_labels_size(s=None)`
Set the relative size of axes labels w.r.t. the axes tick marks.

**INPUT:**

- `s` - float, relative size of axes labels w.r.t. to the tick marks, the size of the tick marks being set by `fontsize()`.

If called with no input, return the current relative size.

**EXAMPLES:**

```python
sage: p = plot(sin(x^2), (x, -3, 3), axes_labels=['x', 'y'])
sage: p.axes_labels_size()  # default value
1.6
sage: p.axes_labels_size(2.5)
sage: p.axes_labels_size()  # 2.5
```

Now the axes labels are large w.r.t. the tick marks:

```python
sage: p
Graphics object consisting of 1 graphics primitive
```

`axes_range(xmin=None, xmax=None, ymin=None, ymax=None)`
Set the ranges of the x and y axes.

**INPUT:**

- `xmin`, `xmax`, `ymin`, `ymax` - floats

**EXAMPLES:**

```python
sage: L = line([(1,2), (3,-4), (2, 5), (1,2)])
sage: L.set_axes_range(-1, 20, 0, 2)
sage: d = L.get_axes_range()
sage: d['xmin'], d['xmax'], d['ymin'], d['ymax']
(-1.0, 20.0, 0.0, 2.0)
```
**axes_width(w=None)**

Set the axes width. Use this to draw a plot with really fat or really thin axes.

**INPUT:**

- **w** - a float

If called with no input, return the current `axes_width` setting.

**EXAMPLES:** We create a plot, see the default axes width (with funny Python float rounding), then reset the width to 10 (very fat).

```sage
p = plot(cos, (-3,3))
p.axes_width()
0.8
p.axes_width(10)
p.axes_width()
10.0
```

Finally we plot the result, which is a graph with very fat axes.

```sage
p
```

**description()**

Print a textual description to stdout.

This method is mostly used for doctests.

**EXAMPLES:**

```sage
print(polytopes.hypercube(2).plot().description())
Polygon defined by 4 points: [(-1.0, -1.0), (1.0, -1.0), (1.0, 1.0), (-1.0, -1.0)]
Line defined by 2 points: [(-1.0, 1.0), (-1.0, -1.0)]
Line defined by 2 points: [(1.0, -1.0), (-1.0, -1.0)]
Line defined by 2 points: [(1.0, -1.0), (1.0, 1.0)]
Line defined by 2 points: [(1.0, 1.0), (-1.0, 1.0)]
Point set defined by 4 point(s): [(1.0, -1.0), (1.0, 1.0), (-1.0, 1.0), (-1.0, -1.0)]
```

**flip(flip_x=False, flip_y=False)**

Get the flip options and optionally mirror this graphics object.

**INPUT:**

- **flip_x** – boolean (default: False); if True, replace the current flip x option by its opposite
- **flip_y** – boolean (default: False); if True, replace the current flip y option by its opposite

**OUTPUT:** a tuple containing the new flip options

**EXAMPLES:**

When called without arguments, this just returns the current flip options:

```sage
L = line([(1, 0), (2, 3)])
L.flip()
(False, False)
```
Otherwise, the specified options are changed and the new options are returned:

```python
sage: L.flip(flip_y=True)
(False, True)
sage: L.flip(True, True)
(True, False)
```

**fontsize**(*s=None*)

Set the font size of axes labels and tick marks.

Note that the relative size of the axes labels font w.r.t. the tick marks font can be adjusted via `axes_labels_size()`.

**INPUT:**

- *s* - integer, a font size in points.

If called with no input, return the current fontsize.

**EXAMPLES:**

```python
sage: L = line([(1,2), (3,-4), (2, 5), (1,2)])
sage: L.fontsize()
10
sage: L.fontsize(20)
sage: L.fontsize()
20
```

All the numbers on the axes will be very large in this plot:

```python
sage: L
Graphics object consisting of 1 graphics primitive
```

**get_axes_range()**

Returns a dictionary of the range of the axes for this graphics object. This is fall back to the ranges in `get_minmax_data()` for any value which the user has not explicitly set.

**Warning:** Changing the dictionary returned by this function does not change the axes range for this object. To do that, use the `set_axes_range()` method.

**EXAMPLES:**

```python
sage: L = line([(1,2), (3,-4), (2, 5), (1,2)])
sage: list(sorted(L.get_axes_range().items()))
[('xmax', 3.0), ('xmin', 1.0), ('ymax', 5.0), ('ymin', -4.0)]
sage: L.set_axes_range(xmin=-1)
sage: list(sorted(L.get_axes_range().items()))
[('xmax', 3.0), ('xmin', -1.0), ('ymax', 5.0), ('ymin', -4.0)]
```

**get_minmax_data()**

Return the x and y coordinate minimum and maximum

**Warning:** The returned dictionary is mutable, but changing it does not change the xmin/xmax/ymin/ymax data. The minmax data is a function of the primitives which make up this
Graphics object. To change the range of the axes, call methods \texttt{xmin()}, \texttt{xmax()}, \texttt{ymin()}, \texttt{ymax()}, or \texttt{set_axes_range()}.

**OUTPUT:**

A dictionary whose keys give the xmin, xmax, ymin, and ymax data for this graphic.

**EXAMPLES:**

```
sage: g = line([(-1,1), (3,2)])
sage: list(sorted(g.get_minmax_data().items()))
[(‘xmax’, 3.0), (‘xmin’, -1.0), (‘ymax’, 2.0), (‘ymin’, 1.0)]
```

Note that changing ymax doesn’t change the output of get_minmax_data:

```
sage: g.ymax(10)
sage: list(sorted(g.get_minmax_data().items()))
[(‘xmax’, 3.0), (‘xmin’, -1.0), (‘ymax’, 2.0), (‘ymin’, 1.0)]
```

The width/height ratio (in output units, after factoring in the chosen aspect ratio) of the plot is limited to \(10^{-15} \ldots 10^{15}\), otherwise floating point errors cause problems in matplotlib:

```
sage: l = line([[1e-19,-1], (-1e-19,1)], aspect_ratio=1.0)
sage: l.get_minmax_data()
sage: l = line([[0,0], (1,1)], aspect_ratio=1e19)
sage: l.get_minmax_data()
{‘xmax’: 5000.50000000000, ‘xmin’: -4999.50000000000, ‘ymax’: 1.0, ‘ymin’: 0.0}
```

**inset**(*graphics*, *pos=None, fontsize=None*)

Add a graphics object as an inset.

**INPUT:**

- **graphics** – the graphics object (instance of \texttt{Graphics}) to be added as an inset to the current graphics
- **pos** – (default: \texttt{None}) 4-tuple \texttt{(left, bottom, width, height)} specifying the location and size of the inset on the final figure, all quantities being in fractions of the figure width and height; if \texttt{None}, the value \texttt{(0.7, 0.7, 0.2, 0.2)} is used
- **fontsize** – (default: \texttt{None}) integer, font size (in points) for the inset; if \texttt{None}, the value of 6 points is used, unless \texttt{fontsize} has been explicitly set in the construction of \texttt{graphics} (in this case, it is not overwritten here)

**OUTPUT:**

- instance of \texttt{MultiGraphics}

**EXAMPLES:**

```
sage: f(x) = x^2*sin(1/x)
sage: g1 = plot(f(x), (x, -2, 2), axes_labels=['$x$', '$y$'])
sage: g2 = plot(f(x), (x, -0.3, 0.3), axes_labels=['$x$', '$y$'], 
             frame=True)
```
Using non-default values for the position/size and the font size:

sage: g1.inset(g2, pos=(0.15, 0.7, 0.25, 0.25), fontsize=8)
Multigraphics with 2 elements

We can add another inset by invoking `inset` on the last output:

sage: g1g2 = _
sage: g3 = plot(f(x), (x, -0.05, 0.05), axes_labels=['$x$', '$y$'],
.....: frame=True)
sage: g1g2.inset(g3, pos=(0.65, 0.12, 0.25, 0.25))
Multigraphics with 3 elements

**legend**(show=\texttt{None})

Set whether or not the legend is shown by default.

**INPUT:**

- show - (default: None) a boolean

If called with no input, return the current legend setting.
Chapter 5. Infrastructure and Low-Level Functions
EXAMPLES:

By default no legend is displayed:

```python
sage: P = plot(sin)
sage: P.legend()
False
```

But if we put a label then the legend is shown:

```python
sage: P = plot(sin, legend_label='sin')
sage: P.legend()
True
```

We can turn it on or off:

```python
sage: P.legend(False)
sage: P.legend()
False
sage: P.legend(True)
sage: P # show with the legend
Graphics object consisting of 1 graphics primitive
```

Construct or modify a Matplotlib figure by drawing `self` on it.

INPUT (partial description, involving only Matplotlib objects; see `show()` for the other arguments):

- `figure` – (default: `None`) Matplotlib figure (class `matplotlib.figure.Figure`) on which `self` is to be displayed; if `None`, the figure will be created from the parameter `figsize`
- `figsize` – (default: `None`) width or [width, height] in inches of the Matplotlib figure in case `figure` is `None`; if `figsize` is `None`, Matplotlib’s default (6.4 x 4.8 inches) is used
- `sub` – (default: `None`) subpart of the figure, as an instance of Matplotlib “axes” (class `matplotlib.axes.Axes`) on which `self` is to be drawn; if `None`, the subpart will be created so as to cover the whole figure

OUTPUT:

- a `matplotlib.figure.Figure` object; if the argument `figure` is provided, this is the same object as `figure`.

EXAMPLES:

```python
sage: c = circle((1,1),1)
sage: print(c.matplotlib())
Figure(640x480)
```

To obtain the first Matplotlib `Axes` object inside of the figure, you can do something like the following.
```python
sage: p = plot(sin(x), (x, -2*pi, 2*pi))
sage: figure = p.matplotlib()
sage: axes = figure.axes[0]
```

**plot()**

Draw a 2D plot of this graphics object, which just returns this object since this is already a 2D graphics object.

**EXAMPLES:**

```python
sage: S = circle((0,0), 2)
sage: S.plot() is S
True
```

It does not accept any argument (github issue #19539):

```python
sage: S.plot(1)
Traceback (most recent call last):
...
TypeError: plot() takes 1 positional argument but 2 were given
```

**plot3d(z=0, **kwds)**

Returns an embedding of this 2D plot into the xy-plane of 3D space, as a 3D plot object. An optional parameter z can be given to specify the z-coordinate.

**EXAMPLES:**

```python
sage: sum([plot(z*sin(x), 0, 10).plot3d(z) for z in range(6)]) # long time
Graphics3d Object
```

**save(filename, legend_back_color='white', legend_borderpad=0.6, legend_borderaxespad=None,
legend_columnspacing=None, legend_fancybox=False, legend_font_family='sans-serif',
legend_font_size='medium', legend_font_style='normal', legend_font_variant='normal',
legend_font_weight='medium', legend_handlerlen=0.05, legend_handlerpad=0.5,
legend_labelspacing=0.02, legend_loc='best', legend_markerscale=0.6, legend_ncol=1,
legend_numpoints=2, legend_shadow=True, legend_title=None, **kwds)**

Save the graphics to an image file.

**INPUT:**

- **filename** – string. The filename and the image format given by the extension, which can be one of the following:
  - .eps
  - .pdf
  - .pgf
  - .png
  - .ps
- .sobj (for a Sage object you can load later),
- .svg,
- empty extension will be treated as .sobj.

All other keyword arguments will be passed to the plotter.

OUTPUT:

• none.

EXAMPLES:

```sage
c = circle((1,1), 1, color='red')
sage: from tempfile import NamedTemporaryFile
sage: with NamedTemporaryFile(suffix='.png') as f:
....:     c.save(f.name, xmin=-1, xmax=3, ymin=-1, ymax=3)
```

To make a figure bigger or smaller, use figsize:

```sage
c.save(f.name, figsize=5, xmin=-1, xmax=3, ymin=-1, ymax=3)
```

By default, the figure grows to include all of the graphics and text, so the final image may not be exactly the figure size you specified. If you want a figure to be exactly a certain size, specify the keyword fig_tight=False:

```sage
c.save(f.name, figsize=[8,4], fig_tight=False,
....:     xmin=-1, xmax=3, ymin=-1, ymax=3)
```

You can also pass extra options to the plot command instead of this method, e.g.

```sage
plot(x^2 - 5, (x, 0, 5), ymin=0).save(tmp_filename(ext='.png'))
```

will save the same plot as the one shown by this command:

```sage
plot(x^2 - 5, (x, 0, 5), ymin=0)
```

Graphics object consisting of 1 graphics primitive

(This test verifies that github issue #8632 is fixed.)

**save_image**

```sage
def save_image(filename=None, *args, **kwds)
Save an image representation of self.
```

The image type is determined by the extension of the filename. For example, this could be .png, .jpg, .gif, .pdf, .svg. Currently this is implemented by calling the **save()** method of self, passing along all arguments and keywords.

**Note:** Not all image types are necessarily implemented for all graphics types. See **save()** for more details.

EXAMPLES:

```sage
import tempfile
c = circle((1,1), 1, color='red')
sage: with tempfile.NamedTemporaryFile(suffix='.png') as f:
....:     c.save_image(f.name, xmin=-1, xmax=3,
....:                   ymin=-1, ymax=3)
```
set_aspect_ratio(ratio)
Set the aspect ratio, which is the ratio of height and width of a unit square (i.e., height/width of a unit square), or ‘automatic’ (expand to fill the figure).

INPUT:

* ratio - a positive real number or ‘automatic’

EXAMPLES: We create a plot of the upper half of a circle, but it doesn’t look round because the aspect ratio is off:

```
sage: P = plot(sqrt(1-x^2),(x,-1,1)); P
Graphics object consisting of 1 graphics primitive
```

So we set the aspect ratio and now it is round:

```
sage: P.set_aspect_ratio(1)
sage: P.aspect_ratio()
1.0
sage: P
Graphics object consisting of 1 graphics primitive
```

Note that the aspect ratio is inherited upon addition (which takes the max of aspect ratios of objects whose aspect ratio has been set):

```
sage: P + plot(sqrt(4-x^2),(x,-2,2))
Graphics object consisting of 2 graphics primitives
```

In the following example, both plots produce a circle that looks twice as tall as wide:

```
sage: Q = circle((0,0), 0.5); Q.set_aspect_ratio(2)
sage: (P + Q).aspect_ratio(); P+Q
2.0
Graphics object consisting of 2 graphics primitives
```

set_axes_range(xmin=None, xmax=None, ymin=None, ymax=None)
Set the ranges of the x and y axes.

INPUT:

* xmin, xmax, ymin, ymax - floats

EXAMPLES:

```
sage: L = line([(1,2), (3,-4), (2, 5), (1,2)]
sage: L.set_axes_range(-1, 20, 0, 2)
sage: d = L.get_axes_range()
sage: d['xmin'], d['xmax'], d['ymin'], d['ymax']
(-1.0, 20.0, 0.0, 2.0)
```

set_flip(flip_x=None, flip_y=None)
Set the flip options for this graphics object.

INPUT:
• `flip_x` – boolean (default: `None`); if not `None`, set the `flip_x` option to this value

• `flip_y` – boolean (default: `None`); if not `None`, set the `flip_y` option to this value

EXAMPLES:

```python
sage: L = line([(1, 0), (2, 3)])
sage: L.set_flip(flip_y=True)
sage: L.flip()
(False, True)
sage: L.set_flip(True, False)
sage: L.flip()
(True, False)
```

`set_legend_options(**kwds)`

Set various legend options.

INPUT:

• `title` - (default: `None`) string, the legend title

• `ncol` - (default: 1) positive integer, the number of columns

• `columnspacing` - (default: `None`) the spacing between columns

• `borderaxespad` - (default: `None`) float, length between the axes and the legend

• `back_color` - (default: ‘white’) This parameter can be a string denoting a color or an RGB tuple. The string can be a color name as in (‘red’, ‘green’, ‘yellow’, ...) or a floating point number like ‘0.8’ which gets expanded to (0.8, 0.8, 0.8). The tuple form is just a floating point RGB tuple with all values ranging from 0 to 1.

• `handlelength` - (default: 0.05) float, the length of the legend handles

• `handletextpad` - (default: 0.5) float, the pad between the legend handle and text

• `labelspacing` - (default: 0.02) float, vertical space between legend entries

• `loc` - (default: ‘best’) May be a string, an integer or a tuple. String or integer inputs must be one of the following:

  - 0, ‘best’
  - 1, ‘upper right’
  - 2, ‘upper left’
  - 3, ‘lower left’
  - 4, ‘lower right’
  - 5, ‘right’
  - 6, ‘center left’
  - 7, ‘center right’
  - 8, ‘lower center’
  - 9, ‘upper center’
  - 10, ‘center’

  Tuple arguments represent an absolute (x, y) position on the plot in axes coordinates (meaning from 0 to 1 in each direction).
2D Graphics, Release 10.0

- `markerscale` - (default: 0.6) float, how much to scale the markers in the legend.
- `numpoints` - (default: 2) integer, the number of points in the legend for line
- `borderpad` - (default: 0.6) float, the fractional whitespace inside the legend border (between 0 and 1)
- `font_family` - (default: `sans-serif`) string, one of `serif`, `sans-serif`, `cursive`, `fantasy`, `monospace`
- `font_style` - (default: `normal`) string, one of `normal`, `italic`, `oblique`
- `font_variant` - (default: `normal`) string, one of `normal`, `small-caps`
- `font_weight` - (default: `medium`) string, one of `black`, `extra bold`, `bold`, `semibold`, `medium`, `normal`, `light`
- `font_size` - (default: `medium`) string, one of `xx-small`, `x-small`, `small`, `medium`, `large`, `x-large`, `xx-large` or an absolute font size (e.g. 12)
- `shadow` - (default: True) boolean - draw a shadow behind the legend
- `fancybox` - (default: False) a boolean. If True, draws a frame with a round fancybox.

These are all keyword arguments.

**OUTPUT:** a dictionary of all current legend options

**EXAMPLES:**

By default, no options are set:

```
sage: p = plot(tan, legend_label='tan')
sage: p.set_legend_options()
{}  
```

We build a legend without a shadow:

```
sage: p.set_legend_options(shadow=False)
sage: p.set_legend_options()['shadow']
False  
```

To set the legend position to the center of the plot, all these methods are roughly equivalent:

```
sage: p.set_legend_options(loc='center'); p
Graphics object consisting of 1 graphics primitive

sage: p.set_legend_options(loc=10); p
Graphics object consisting of 1 graphics primitive

sage: p.set_legend_options(loc=(0.5,0.5)); p  # aligns the bottom of the box to the center
Graphics object consisting of 1 graphics primitive
```

```
show(legend_back_color='white', legend_borderpad=0.6, legend.borderaxespad=None, legend_columnsspacing=None, legend_fancybox=False, legend_font_family='sans-serif', legend_font_size='medium', legend_font_style='normal', legend_font_variant='normal', legend_font_weight='medium', legend.handlelength=0.05, legend.handletextpad=0.5, legend_labelspacing=0.02, legend_loc='best', legend_markerscale=0.6, legend_ncol=1, legend_numpoints=2, legend_shadow=True, legend_title=None, **kwds)
```

Show this graphics image immediately.

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This method attempts to display the graphics immediately, without waiting for the currently running code (if any) to return to the command line. Be careful, calling it from within a loop will potentially launch a large number of external viewer programs.

OPTIONAL INPUT:

- **dpi** - (default: 100) dots per inch
- **figsize** - (default: [6.4, 4.8]) [width, height] inches. The maximum value of each of the width and the height can be 327 inches, at the default dpi of 100 dpi, which is just shy of the maximum allowed value of 32768 dots (pixels).
- **fig_tight** - (default: True) whether to clip the drawing tightly around drawn objects. If True, then the resulting image will usually not have dimensions corresponding to **figsize**. If False, the resulting image will have dimensions corresponding to **figsize**.
- **aspect_ratio** - the perceived height divided by the perceived width. For example, if the aspect ratio is set to 1, circles will look round and a unit square will appear to have sides of equal length, and if the aspect ratio is set 2, vertical units will be twice as long as horizontal units, so a unit square will be twice as high as it is wide. If set to 'automatic', the aspect ratio is determined by **figsize** and the picture fills the figure.
- **axes** - (default: True)
- **axes_labels** - (default: None) list (or tuple) of two strings; the first is used as the label for the horizontal axis, and the second for the vertical axis.
- **axes_labels_size** - (default: current setting – 1.6) scale factor relating the size of the axes labels with respect to the size of the tick marks.
- **fontsize** - (default: current setting – 10) positive integer; used for axes labels; if you make this very large, you may have to increase figsize to see all labels.
- **frame** - (default: False) draw a frame around the image
- **gridlines** - (default: None) can be any of the following:
  - None, False: do not add grid lines.
  - True, “automatic”, “major”: add grid lines at major ticks of the axes.
  - “minor”: add grid at major and minor ticks.
  - [xlist,ylist]: a tuple or list containing two elements, where xlist (or ylist) can be any of the following.
    * None, False: don’t add horizontal (or vertical) lines.
    * True, “automatic”, “major”: add horizontal (or vertical) grid lines at the major ticks of the axes.
    * “minor”: add horizontal (or vertical) grid lines at major and minor ticks of axes.
    * an iterable yielding numbers n or pairs (n,opts), where n is the coordinate of the line and opt is a dictionary of MATPLOTLIB options for rendering the line.
- **gridlinesstyle**, **hgridlinesstyle**, **vgridlinesstyle** - (default: None) a dictionary of MATPLOTLIB options for the rendering of the grid lines, the horizontal grid lines or the vertical grid lines, respectively.
- **transparent** - (default: False) If True, make the background transparent.
- **axes_pad** - (default: 0.02 on "linear" scale, 1 on "log" scale).
- In the "linear" scale, it determines the percentage of the axis range that is added to each end of each axis. This helps avoid problems like clipping lines because of line-width, etc. To get axes that are exactly the specified limits, set `axes_pad` to zero.

- On the "log" scale, it determines the exponent of the fraction of the minimum (resp. maximum) that is subtracted from the minimum (resp. added to the maximum) value of the axis. For instance if the minimum is $m$ and the base of the axis is $b$ then the new minimum after padding the axis will be $m - m/b^{\text{axes}_\text{pad}}$.

**ticks_integer** - (default: False) guarantee that the ticks are integers (the `ticks` option, if specified, will override this)

**ticks** - A matplotlib locator for the major ticks, or a number. There are several options. For more information about locators, type `from matplotlib import ticker` and then `ticker?`.

  - If this is a locator object, then it is the locator for the horizontal axis. A value of None means use the default locator.
  
  - If it is a list of two locators, then the first is for the horizontal axis and one for the vertical axis. A value of None means use the default locator (so a value of [None, my_locator] uses my_locator for the vertical axis and the default for the horizontal axis).

  - If in either case above one of the entries is a number $m$ (something which can be coerced to a float), it will be replaced by a MultipleLocator which places major ticks at integer multiples of $m$. See examples.

  - If in either case above one of the entries is a list of numbers, it will be replaced by a FixedLocator which places ticks at the locations specified. This includes the case of of the empty list, which will give no ticks. See examples.

**tick_formatter** - A matplotlib formatter for the major ticks. There are several options. For more information about formatters, type `from matplotlib import ticker` and then `ticker?`.

  If the value of this keyword is a single item, then this will give the formatting for the horizontal axis only (except for the "latex" option). If it is a list or tuple, the first is for the horizontal axis, the second for the vertical axis. The options are below:

  - If one of the entries is a formatter object, then it used. A value of None means to use the default locator (so using `tick_formatter=[None, my_formatter]` uses my_formatter for the vertical axis and the default for the horizontal axis).

  - If one of the entries is a symbolic constant such as $\pi$, $e$, or $\sqrt{2}$, ticks will be formatted nicely at rational multiples of this constant.

  **Warning:** This should only be used with the `ticks` option using nice rational multiples of that constant!

  - If one of the entries is the string "latex", then the formatting will be nice typesetting of the ticks. This is intended to be used when the tick locator for at least one of the axes is a list including some symbolic elements. This uses matplotlib’s internal LaTeX rendering engine. If you want to use an external LaTeX compiler, then set the keyword option `typeset`. See examples.

**title** - (default: None) The title for the plot

**title_pos** - (default: None) The position of the title for the plot. It must be a tuple or a list of two real numbers ($x_{\text{pos}}$, $y_{\text{pos}}$) which indicate the relative position of the title within the plot. The plot itself can be considered to occupy, in relative terms, the region within a unit square $[0, 1] \times [0, 1]$. The title text is centered around the horizontal factor $x_{\text{pos}}$ of the plot. The baseline of the title text is present at the vertical factor $y_{\text{pos}}$ of the plot.
Hence, title_pos=(0.5, 0.5) will center the title in the plot, whereas title_pos=(0.5, 1.1) will center the title along the horizontal direction, but will place the title a fraction 0.1 times above the plot.

- If the first entry is a list of strings (or numbers), then the formatting for the horizontal axis will be typeset with the strings present in the list. Each entry of the list of strings must be provided with a corresponding number in the first entry of ticks to indicate its position on the axis. To typeset the strings with "latex" enclose them within "$" symbols. To have similar custom formatting of the labels along the vertical axis, the second entry must be a list of strings and the second entry of ticks must also be a list of numbers which give the positions of the labels. See the examples below.

• show_legend - (default: None) If True, show the legend
• legend_* - all the options valid for set_legend_options() prefixed with legend_
• base - (default: 10) the base of the logarithm if a logarithmic scale is set. This must be greater than 1. The base can be also given as a list or tuple (basex, basey). basex sets the base of the logarithm along the horizontal axis and basey sets the base along the vertical axis.
• scale – (default: "linear") string. The scale of the axes. Possible values are
  - "linear" – linear scaling of both the axes
  - "loglog" – sets both the horizontal and vertical axes to logarithmic scale
  - "semilogx" – sets only the horizontal axis to logarithmic scale.
  - "semilogy" – sets only the vertical axis to logarithmic scale.
The scale can be also be given as single argument that is a list or tuple (scale, base) or (scale, basex, basey).

Note:
- If the scale is "linear", then irrespective of what base is set to, it will default to 10 and will remain unused.

• xmin – starting x value in the rendered figure.
• xmax – ending x value in the rendered figure.
• ymin – starting y value in the rendered figure.
• ymax – ending y value in the rendered figure.
• flip_x – (default: False) boolean. If True, flip the horizontal axis.
• flip_y – (default: False) boolean. If True, flip the vertical axis.
• typeset – (default: "default") string. The type of font rendering that should be used for the text. The possible values are
  - "default" – Uses matplotlib's internal text rendering engine called Mathtext (see https://matplotlib.org/users/mathtext.html). If you have modified the default matplotlib settings, for instance via a matplotlibrc file, then this option will not change any of those settings.
  - "latex" – LaTeX is used for rendering the fonts. This requires LaTeX, dvipng and Ghostscript to be installed.
– "type1" – Type 1 fonts are used by matplotlib in the text in the figure. This requires LaTeX, dvipng and Ghostscript to be installed.

OUTPUT:

This method does not return anything. Use `save()` if you want to save the figure as an image.

EXAMPLES:

```python
sage: c = circle((1,1), 1, color='red')
sage: c.show(xmin=-1, xmax=3, ymin=-1, ymax=3)
```

You can make the picture larger by changing `figsize` with width, height each having a maximum value of 327 inches at default dpi:

```python
sage: p = ellipse((0,0),4,1)
sage: p.show(figsize=[327,10],dpi=100)
sage: p.show(figsize=[328,10],dpi=80)
```

You can turn off the drawing of the axes:

```python
sage: show(plot(sin,-4,4), axes=False)
```

You can also label the axes. Putting something in dollar signs formats it as a mathematical expression:

```python
sage: show(plot(sin,-4,4), axes_labels=('x','y'))
```

You can add a title to a plot:

```python
sage: show(plot(sin,-4,4), title=r'A plot of $\sin(x)$')
```

You can also provide the position for the title to the plot. In the plot below the title is placed on the bottom left of the figure:

```python
sage: plot(sin, -4, 4, title='Plot sin(x)', title_pos=(0.05,-0.05))
```

If you want all the text to be rendered by using an external LaTeX installation then set the `typeset` option to "latex". This requires that LaTeX, dvipng and Ghostscript be installed:

```python
sage: plot(x, typeset='latex') # optional - latex
```

If you want all the text in your plot to use Type 1 fonts, then set the `typeset` option to "type1". This requires that LaTeX, dvipng and Ghostscript be installed:

```python
sage: plot(x, typeset='type1') # optional - latex
```

You can turn on the drawing of a frame around the plots:

```python
sage: show(plot(sin,-4,4), frame=True)
```

You can make the background transparent:

```python
sage: plot(sin(x), (x, -4, 4), transparent=True)
```
Prior to github issue #19485, legends by default had a shadowless gray background. This behavior can be recovered by passing in certain `legend_options`:

```python
sage: p = plot(sin(x), legend_label=r'$\sin(x)$')
sage: p.show(legend_options={'back_color': (0.9,0.9,0.9), 'shadow': False})
```

We can change the scale of the axes in the graphics before displaying:

```python
sage: G = plot(exp, 1, 10)
sage: G.show(scale='semilogy')
```

We can change the base of the logarithm too. The following changes the vertical axis to be on log scale, and with base 2. Note that the base argument will ignore any changes to the axis which is in linear scale.:

```python
sage: G.show(scale='semilogy', base=2) # long time # y axis as powers of 2
sage: G.show(scale='semilogy', base=(3,2)) # base ignored for x-axis
```

The scale can be also given as a 2-tuple or a 3-tuple:

```python
sage: G.show(scale=('loglog', 2.1)) # long time # both x and y axes in base 2.1
sage: G.show(scale=('loglog', 2, 3)) # long time # x in base 2, y in base 3
```

The base need not be an integer, though it does have to be made a float.:

```python
sage: G.show(scale='semilogx', base=float(e)) # base is e
```

Logarithmic scale can be used for various kinds of plots. Here are some examples:

```python
sage: G = list_plot([10**i for i in range(10)]) # long time
sage: G.show(scale='semilogy') # long time

sage: G = parametric_plot((x, x**2), (x, 1, 10))
sage: G.show(scale='loglog')

sage: disk((5,5), 4, (0, 3*pi/2)).show(scale='loglog',base=2)

sage: x, y = var('x, y')
sage: G = plot_vector_field((2^x,y^2),(x,1,10),(y,1,100))
sage: G.show(scale='semilogx',base=2)
```

Flip the horizontal or vertical axis.

```python
sage: G = plot(x^3, -2, 3)
sage: G.show(flip_x=True)
sage: G.show(flip_y=True)
```

Add grid lines at the major ticks of the axes.

```python
sage: c = circle((0,0), 1)
sage: c.show(gridlines=True)
```
Add grid lines at the major and minor ticks of the axes.

```sage
sage: u,v = var('u v')
sage: f = exp(-(u^2+v^2))
sage: p = plot_vector_field(f.gradient(), (u,-2,2), (v,-2,2))
sage: p.show(gridlines="minor")
```

Add only horizontal or vertical grid lines.

```sage
sage: p = plot(sin,-10,20)
sage: p.show(gridlines=[None, "automatic"])
sage: p.show(gridlines=["minor", False])
```

Add grid lines at specific positions (using lists/tuples).

```sage
sage: x, y = var('x, y')
sage: p = implicit_plot((y^2-x^2)*(x-1)*(2*x-3)-4*(x^2+y^2-2*x)^2, 
\[\ldots\]
(x,-2,2), (y,-2,2), plot_points=1000)
sage: p.show(gridlines=[[1,0],[-1,0,1]])
```

Add grid lines at specific positions (using iterators).

```sage
sage: def maple_leaf(t):
\[\ldots\]
return (100/(100+(t-pi/2)^8))*(2-sin(7*t)-cos(30*t)/2)
sage: p = polar_plot(maple_leaf, -pi/4, 3*pi/2, color="red",plot_points=1000) # long time
sage: p.show(gridlines=([-3,-2.75,..,3], range(-1,5,2))) # long time
```

Add grid lines at specific positions (using functions).

```sage
sage: y = x^5 + 4*x^4 - 10*x^3 - 40*x^2 + 9*x + 36
sage: p = plot(y, -4.1, 1.1)
sage: xlines = lambda a,b: [z for z,m in y.roots()]
sage: p.show(gridlines=[xlines, [0]], frame=True, axes=False)
```

Change the style of all the grid lines.

```sage
sage: b = bar_chart([-3,5,-6,11], color='red')
sage: b.show(gridlines=[[-1,-0.5,..,4],True],
\[\ldots\]
gridlinesstyle=dict(color="blue", linestyle=":"))
```

Change the style of the horizontal or vertical grid lines separately.

```sage
sage: p = polar_plot(2 + 2*cos(x), 0, 2*pi, color=hue(0.3))
sage: p.show(gridlines=True,
\[\ldots\]
hgridlinesstyle=dict(color="orange", linewidth=1.0),
\[\ldots\]
vgridlinesstyle=dict(color="blue", linestyle":"))
```

Change the style of each grid line individually.
Grid lines can be added to contour plots.

```python
sage: f = sin(x^2 + y^2)*cos(x)*sin(y)
sage: c = contour_plot(f, (x, -4, 4), (y, -4, 4), plot_points=100)
sage: c.show(gridlines=True, gridlinesstyle={'linestyle':':', 'linewidth':1, 'color':'red'})
```

Grid lines can be added to matrix plots.

```python
sage: M = MatrixSpace(QQ,10).random_element()
sage: matrix_plot(M).show(gridlines=True)
```

By default, Sage increases the horizontal and vertical axes limits by a certain percentage in all directions. This is controlled by the `axes_pad` parameter. Increasing the range of the axes helps avoid problems with lines and dots being clipped because the linewidth extends beyond the axes. To get axes limits that are exactly what is specified, set `axes_pad` to zero. Compare the following two examples:

```python
sage: plot(sin(x), (x, -pi, pi),thickness=2)+point((pi, -1), pointsize=15)
Graphics object consisting of 2 graphics primitives
sage: plot(sin(x), (x, -pi, pi),thickness=2,axes_pad=0)+point((pi, -1),
WebHost='color':'red')
Graphics object consisting of 2 graphics primitives
```

The behavior of the `axes_pad` parameter is different if the axis is in the "log" scale. If $b$ is the base of the axis, the minimum value of the axis, is decreased by the factor $1/b^{\text{axes_pad}}$ of the minimum and the maximum value of the axis is increased by the same factor of the maximum value. Compare the axes in the following two plots to see the difference.

```python
sage: plot_loglog(x, (1.1*10**-2, 9990))
Graphics object consisting of 1 graphics primitive
sage: plot_loglog(x, (1.1*10**-2, 9990), axes_pad=0)
Graphics object consisting of 1 graphics primitive
```

Via matplotlib, Sage allows setting of custom ticks. See above for more details.

Here the labels are not so useful:
Now put ticks at multiples of 2:

```
sage: plot(sin(pi*x), (x, -8, 8), ticks=2)
```

Graphics object consisting of 1 graphics primitive

Or just choose where you want the ticks:

```
sage: plot(sin(pi*x), (x, -8, 8), ticks=[[-7,-3,0,3,7],[-1/2,0,1/2]])
```

Graphics object consisting of 1 graphics primitive

Or no ticks at all:

```
sage: plot(sin(pi*x), (x, -8, 8), ticks=[[[]],[]])
```

Graphics object consisting of 1 graphics primitive

This can be very helpful in showing certain features of plots.

```
sage: plot(1.5/(1+e^(-x)), (x, -10, 10), ticks=[[None, 1.5/4]]) # It's right at f(x)=0.75!
```

Graphics object consisting of 1 graphics primitive

But be careful to leave enough room for at least two major ticks, so that the user can tell what the scale is:

```
sage: plot(x^2,(x,1,8),ticks=6).show()
```

Traceback (most recent call last):
  ... Value Error: Expand the range of the independent variable to allow two multiples of your tick locator (option `ticks`).

We can also do custom formatting if you need it. See above for full details:

```
sage: plot(2*x+1,(x,0,5),ticks=pi/6,tick_formatter=pi)
```

# not tested (broken with matplotlib 3.6)

Graphics object consisting of 1 graphics primitive

This is particularly useful when setting custom ticks in multiples of $\pi$.

```
sage: plot(sin(x),(x,0,2*pi),ticks=pi/3,tick_formatter=pi)
```

Graphics object consisting of 1 graphics primitive

But keep in mind that you will get exactly the formatting you asked for if you specify both formatters. The first syntax is recommended for best style in that case.
Custom tick labels can be provided by providing the keyword `tick_formatter` with the list of labels, and simultaneously providing the keyword `ticks` with the positions of the labels.

```python
sage: plot(x, (x,0,3), ticks=[[1,2.5], [0.5,1,2]], tick_formatter=[["$x_1$","$x_2$"], ["$y_1$","$y_2$","$y_3$"]])
```

The following sets the custom tick labels only along the horizontal axis.

```python
sage: plot(x**2, (x,0,2), ticks=[[1,2], None], tick_formatter=[["$x_1$","$x_2$"], None])
```

If the number of tick labels do not match the number of positions of tick labels, then it results in an error:

```python
sage: plot(x**2, (x,0,2), ticks=[[2], None], tick_formatter=[["$x_1$","$x_2$"], None]).show()
Traceback (most recent call last):
...
ValueError: If the first component of the list `tick_formatter` is a list then the first component of `ticks` must also be a list of equal length.
```

When using logarithmic scale along the axis, make sure to have enough room for two ticks so that the user can tell what the scale is. This can be effected by increasing the range of the independent variable, or by changing the base, or by providing enough tick locations by using the `ticks` parameter.

By default, Sage will expand the variable range so that at least two ticks are included along the logarithmic axis. However, if you specify ticks manually, this safety measure can be defeated:

```python
sage: list_plot_loglog([(1,2),(2,3)], plotjoined=True, ticks=[[1],[1]])
doctest:...: UserWarning: The x-axis contains fewer than 2 ticks; the logarithmic scale of the plot may not be apparent to the reader.
doctest:...: UserWarning: The y-axis contains fewer than 2 ticks; the logarithmic scale of the plot may not be apparent to the reader.
Graphics object consisting of 1 graphics primitive
```

This one works, since the horizontal axis is automatically expanded to contain two ticks and the vertical axis is provided with two ticks:

```python
sage: list_plot_loglog([(1,2),(2,3)], plotjoined=True, ticks=[None,[1,10]])
```

Another example in the log scale where both the axes are automatically expanded to show two major ticks:

```python
sage: list_plot_loglog([(2,0.5), (3, 4)], plotjoined=True)
```

When using `title_pos`, it must be ensured that a list or a tuple of length two is used. Otherwise, a warning is raised:
2D Graphics, Release 10.0

sage: plot(x, -4, 4, title='Plot x', title_pos=0.05)

Graphics object consisting of 1 graphics primitive

doctest:...: ...RichReprWarning: Exception in _rich_repr_ while displaying...
object: 'title_pos' must be a list or tuple of two real numbers.

tick_label_color(c=None)

Set the color of the axes tick labels.

INPUT:

- c - an RGB 3-tuple of numbers between 0 and 1

If called with no input, return the current tick_label_color setting.

EXAMPLES:

sage: p = plot(cos, (-3,3))
sage: p.tick_label_color()
(0, 0, 0)
sage: p.tick_label_color((1,0,0))
sage: p.tick_label_color()
(1.0, 0.0, 0.0)
sage: p

Graphics object consisting of 1 graphics primitive

xmax(xmax=None)

EXAMPLES:

sage: g = line([(-1,1), (3,2)])
sage: g.xmax()
3.0
sage: g.xmax(10)
sage: g.xmax()
10.0

xmin(xmin=None)

EXAMPLES:

sage: g = line([(-1,1), (3,2)])
sage: g.xmin()
-1.0
sage: g.xmin(-3)
sage: g.xmin()
-3.0

ymax(ymax=None)

EXAMPLES:

sage: g = line([(-1,1), (3,2)])
sage: g.ymax()
2.0
sage: g.ymax(10)
sage: g.ymax()
10.0

5.1. Graphics objects
ymin\( (ymin=None) \)

EXAMPLES:

```
sage: g = line([(-1,1), (3,2)])
sage: g.ymin()
1.0
sage: g.ymin(-3)
sage: g.ymin()
-3.0
```

sage.plot.graphics.GraphicsArray(*args, **kwargs)

This is deprecated (see github issue #28675). Use sage.plot.multigraphics.GraphicsArray instead.

sage.plot.graphics.is_Graphics(x)

Return True if x is a Graphics object.

EXAMPLES:

```
sage: from sage.plot.graphics import is_Graphics
sage: is_Graphics(1)
False
sage: is_Graphics(disk((0.0, 0.0), 1, (0, pi/2)))
True
```

5.2 Graphics arrays and insets

This module defines the classes MultiGraphics and GraphicsArray. The class MultiGraphics is the base class for 2-dimensional graphical objects that are composed of various Graphics objects, arranged in a given canvas. The subclass GraphicsArray is for Graphics objects arranged in a regular array.

AUTHORS:

- Eric Gourgoulhon (2019-05-24): initial version, refactoring the class GraphicsArray that was defined in the module graphics.

class sage.plot.multigraphics.GraphicsArray(array)

Bases: MultiGraphics

This class implements 2-dimensional graphical objects that constitute an array of Graphics drawn on a single canvas.

The user interface is through the function graphics_array().

INPUT:

- array – either a list of lists of Graphics elements (generic case) or a single list of Graphics elements (case of a single-row array)

EXAMPLES:

An array made of four graphics objects:

```
sage: g1 = plot(sin(x^2), (x, 0, 6), axes_labels=['$x$', '$y$'],
.....:     ..    axes=False, frame=True, gridlines='minor')
sage: y = var('y')
sage: g2 = streamline_plot((sin(x), cos(y)), (x,-3,3), (y,-3,3),
```
5.2. Graphics arrays and insets

If one constructs the graphics array from a single list of graphics objects, one obtains a single-row array:

```
sage: G = graphics_array([g1, g2, g3, g4])
sage: G
Graphics Array of size 1 x 4
```

We note that the overall aspect ratio of the figure is 4/3 (the default), which makes g1 elongated, while the aspect ratio of g2, which has been specified with the parameter aspect_ratio=1 is preserved. To get a better aspect ratio for the whole figure, one can use the option figsize in the method `show()`:

```
sage: G.show(figsize=[8, 3])
```
We can access individual elements of the graphics array with the square-bracket operator:

```
sage: G = graphics_array([[g1, g2], [g3, g4]])  # back to the 2x2 array
sage: print(G)
Graphics Array of size 2 x 2
sage: G[0] is g1
True
sage: G[1] is g2
True
sage: G[2] is g3
True
sage: G[3] is g4
True
```

Note that with respect to the square-bracket operator, G is considered as a flattened list of graphics objects, not as an array. For instance, G[0, 1] throws an error:

```
sage: G[0, 1]
Traceback (most recent call last):
...  
TypeError: list indices must be integers or slices, not tuple
```

G[::] returns the full (flattened) list of graphics objects composing G:

```
sage: G[:]
[Graphics object consisting of 1 graphics primitive,  
 Graphics object consisting of 1 graphics primitive,  
 Graphics object consisting of 51 graphics primitives,  
 Graphics object consisting of 2 graphics primitives]
```

The total number of Graphics objects composing the array is returned by the function \texttt{len}:

```
sage: len(G)
4
```

The square-bracket operator can be used to replace elements in the array:

```
sage: G[0] = g4
sage: G
Graphics Array of size 2 x 2
```

\texttt{append}(g)

Append a graphics to the array.

Currently not implemented.

\texttt{ncols}()

Number of columns of the graphics array.

EXAMPLES:

```
sage: R = rainbow(6)
sage: L = [plot(x^n, (x,0,1), color=R[n]) for n in range(6)]
sage: G = graphics_array(L, 2, 3)
sage: G.ncols()
```

(continues on next page)
sage: graphics_array(L).ncols()

6

\textbf{nrows()}

Number of rows of the graphics array.

**EXAMPLES:**

```
sage: R = rainbow(6)
sage: L = [plot(x^n, (x,0,1), color=R[n]) for n in range(6)]
sage: G = graphics_array(L, 2, 3)
sage: G.nrows()
2
sage: graphics_array(L).nrows()
1
```

\textbf{position(index)}

Return the position and relative size of an element of \texttt{self} on the canvas.

**INPUT:**

\begin{itemize}
\item index – integer specifying which element of \texttt{self}
\end{itemize}

**OUTPUT:**

\begin{itemize}
\item a 4-tuple (left, bottom, width, height) giving the location and relative size of the element on the canvas, all quantities being expressed in fractions of the canvas width and height
\end{itemize}

**EXAMPLES:**

```
sage: g1 = plot(sin(x), (x, -pi, pi))
sage: g2 = circle((0,1), 1.)
sage: G = graphics_array([g1, g2])
sage: G.position(0)  # tol 5.0e-3
(0.025045451349937315, 0.03415488992713045, 0.4489880779745068, 0.9345951100728696)
sage: G.position(1)  # tol 5.0e-3
(0.5170637412999687, 0.20212705964722733, 0.4489880779745068, 0.5986507706326758)
```

**class** \texttt{sage.plot.multigraphics.MultiGraphics(graphics_list)}

**Bases:** \texttt{WithEqualityById, SageObject}

Base class for objects composed of \texttt{Graphics} objects.

Both the display and the output to a file of \texttt{MultiGraphics} objects are governed by the method \texttt{save()}, which is called by the rich output display manager, via \texttt{graphics_from_save()}.

The user interface is through the functions \texttt{multi_graphics()} (generic multi-graphics) and \texttt{graphics_array()} (subclass \texttt{GraphicsArray}).

**INPUT:**
• **graphics_list** – a list of graphics along with their positions on the common canvas; each element of graphics_list is either
  - a pair (graphics, position), where graphics is a Graphics object and position is the 4-tuple (left, bottom, width, height) specifying the location and size of the graphics on the canvas, all quantities being in fractions of the canvas width and height
  - or a single Graphics object; its position is then assumed to occupy the whole canvas, except for some padding; this corresponds to the default position (left, bottom, width, height) = (0.125, 0.11, 0.775, 0.77)

**EXAMPLES:**

A multi-graphics made from two graphics objects:

```sage
sage: g1 = plot(sin(x^3), (x, -pi, pi))
sage: g2 = circle((0,0), 1, color='red')
sage: G = multi_graphics([g1, (g2, (0.2, 0.55, 0.3, 0.3))])
sage: G
Multigraphics with 2 elements
```

Since no position was given for g1, it occupies the whole canvas. Moreover, we note that g2 has been drawn over g1 with a white background. To have a transparent background instead, one has to construct g2 with the keyword transparent set to True:
We can add a new graphics object to G via the method \texttt{append()}:

\begin{verbatim}
sage: g3 = complex_plot(zeta, (-20, 10), (-20, 20),
                      ....:     axes_labels=['$x$', '$y$'], frame=True)
sage: G.append(g3, pos=(0.63, 0.12, 0.3, 0.3))
sage: G
Multigraphics with 3 elements
\end{verbatim}

We can access the individual elements composing G with the square-bracket operator:

\begin{verbatim}
sage: print(G[0])
Graphics object consisting of 1 graphics primitive
sage: G[0] is g1
True
sage: G[1] is g2
True
sage: G[2] is g3
True
\end{verbatim}
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G[: ] returns the full list of graphics objects composing G:

```python
sage: G[: ]
[Graphics object consisting of 1 graphics primitive,
 Graphics object consisting of 1 graphics primitive,
 Graphics object consisting of 1 graphics primitive]
sage: len(G)
3
```

**append**(*graphics, pos=None*)

Append a graphics object to self.

**INPUT:**

• *graphics* – the graphics object (instance of Graphics) to be added to self

• *pos* – (default: None) 4-tuple (left, bottom, width, height) specifying the location and size of graphics on the canvas, all quantities being in fractions of the canvas width and height; if None, graphics is assumed to occupy the whole canvas, except for some padding; this corresponds to the default position (left, bottom, width, height) = (0.125, 0.11, 0.775, 0.77)

**EXAMPLES:**

Let us consider a multigraphics with 2 elements:

```python
sage: g1 = plot(chebyshev_T(4, x), (x, -1, 1), title='n=4',
....: color='red')
sage: g2 = plot(chebyshev_T(8, x), (x, -1, 1), title='n=8',
....: color='red')
sage: G = multi_graphics([(g1, (0.125, 0.2, 0.4, 0.4)),
....: (g2, (0.55, 0.4, 0.4, 0.4))])
sage: G
Multigraphics with 2 elements
```

We append a third plot to it:

```python
sage: g3 = plot(chebyshev_T(16, x), (x, -1, 1), title='n=16',
....: color='brown')
sage: G.append(g3, pos=(0.55, 0.11, 0.4, 0.15))
sage: G
Multigraphics with 3 elements
```

We may use append to add a title:

```python
sage: title = text("Chebyshev polynomials", (0, 0), fontsize=16,
....: axes=False)
sage: G.append(title, pos=(0.18, 0.8, 0.7, 0.1))
sage: G
Multigraphics with 4 elements
```

**See also:**

**inset**

**inset**(*graphics, pos=None, fontsize=None*)

Add a graphics object as an inset.

**INPUT:**

• *graphics* – the graphics object (instance of Graphics) to be added as an inset
5.2. Graphics arrays and insets
Chebyshev polynomials

$n=4$

$n=8$

$n=16$
• pos – (default: None) 4-tuple (left, bottom, width, height) specifying the location and relative size of the inset on the canvas, all quantities being expressed in fractions of the canvas width and height; if None, the value (0.7, 0.7, 0.2, 0.2) is used

• fontsize – (default: None) integer, font size (in points) for the inset; if None, the value of 6 points is used, unless fontsize has been explicitly set in the construction of graphics (in this case, it is not overwritten here)

OUTPUT:
• instance of MultiGraphics

EXAMPLES:
Let us consider a graphics array of 2 elements:

```
sage: G = graphics_array([plot(sin, (0, 2*pi)),
                        ....: plot(cos, (0, 2*pi))])
sage: G
Graphics Array of size 1 x 2
```

and add some inset at the default position:

```
sage: c = circle((0,0), 1, color='red', thickness=2, frame=True)
sage: G.inset(c)
```

Multigraphics with 3 elements
We may customize the position and font size of the inset:

```
sage: G.inset(c, pos=(0.3, 0.7, 0.2, 0.2), fontsize=8)
```

```
Multigraphics with 3 elements
```

---

**matplotlib**

```python
matplotlib(figure=None, figsize=None, **kwds)
```

Construct or modify a Matplotlib figure by drawing `self` on it.

**INPUT:**

- `figure` – (default: `None`) Matplotlib figure (class `matplotlib.figure.Figure`) on which `self` is to be displayed; if `None`, the figure will be created from the parameter `figsize`
- `figsize` – (default: `None`) width or [width, height] in inches of the Matplotlib figure in case `figure` is `None`; if `figsize` is `None`, Matplotlib’s default (6.4 x 4.8 inches) is used
- `kwds` – options passed to the `matplotlib()` method of each graphics object constituting `self`

**OUTPUT:**

- a `matplotlib.figure.Figure` object; if the argument `figure` is provided, this is the same object as `figure`.

**EXAMPLES:**

Let us consider a `GraphicsArray` object with 3 elements:

---

5.2. Graphics arrays and insets
sage: G = graphics_array([plot(sin(x^k), (x, 0, 3))
......: for k in range(1, 4)])

If \texttt{matplotlib()} is invoked without any argument, a Matplotlib figure is created and contains the 3 graphics element of the array as 3 Matplotlib \texttt{Axes}:

```python
sage: fig = G.matplotlib()
sage: fig
<Figure size 640x480 with 3 Axes>
sage: type(fig)
<class 'matplotlib.figure.Figure'>
```

Specifying the figure size (in inches):

```python
sage: G.matplotlib(figsize=(8., 5.))
<Figure size 800x500 with 3 Axes>
```

If a single number is provided for \texttt{figsize}, it is considered to be the width; the height is then computed according to Matplotlib’s default aspect ratio (4/3):

```python
sage: G.matplotlib(figsize=8.)
<Figure size 800x600 with 3 Axes>
```

An example of use with a preexisting created figure, created by \texttt{pyplot}:

```python
sage: import matplotlib.pyplot as plt
sage: fig1 = plt.figure(1)
sage: fig1
<Figure size 640x480 with 0 Axes>
sage: fig_out = G.matplotlib(figure=fig1)
sage: fig_out
<Figure size 640x480 with 3 Axes>
```

Note that the output figure is the same object as the input one:

```python
sage: fig_out is fig1
True
```

It has however been modified by \texttt{G.matplotlib(figure=fig1)}, which has added 3 new \texttt{Axes} to it.

Another example, with a figure created from scratch, via Matplotlib’s \texttt{Figure}:

```python
sage: from matplotlib.figure import Figure
sage: fig2 = Figure()
sage: fig2
<Figure size 640x480 with 0 Axes>
sage: G.matplotlib(figure=fig2)
<Figure size 640x480 with 3 Axes>
sage: fig2
<Figure size 640x480 with 3 Axes>
```

\texttt{plot()}

Return \texttt{self} since \texttt{self} is already a graphics object.

EXAMPLES:
```sage
g1 = plot(cos, 0, 1)
g2 = circle((0,0), 1)
G = multi_graphics([g1, g2])
G.plot() is G
True
```

**position(index)**

Return the position and relative size of an element of `self` on the canvas.

**INPUT:**

- `index` – integer specifying which element of `self`

**OUTPUT:**

- a 4-tuple `(left, bottom, width, height)` giving the location and relative size of the element on the canvas, all quantities being expressed in fractions of the canvas width and height

**EXAMPLES:**

```sage
g1 = plot(sin(x^2), (x, 0, 4))
g2 = circle((0,0), 1, rgbcolor='red', fill=True, axes=False)
G = multi_graphics([g1, (g2, (0.15, 0.2, 0.1, 0.15))])
G.position(0) # tol 1.0e-13
(0.125, 0.11, 0.775, 0.77)
G.position(1) # tol 1.0e-13
(0.15, 0.2, 0.1, 0.15)
```

**save(filename, figsize=None, **kwds)**

Save `self` to a file, in various formats.

**INPUT:**

- `filename` – (string) the file name; the image format is given by the extension, which can be one of the following:
  - .eps,
  - .pdf,
  - .png,
  - .ps,
  - .sobj (for a Sage object you can load later),
  - .svg,
- `figsize` – (default: None) width or [width, height] in inches of the Matplotlib figure; if none is provided, Matplotlib’s default (6.4 x 4.8 inches) is used
- `**kwds` – keyword arguments, like `dpi=...`, passed to the plotter, see `show()`

**EXAMPLES:**

```sage:F = tmp_filename(ext='.png')
L = [plot(sin(k*x), (x,-pi,pi)) for k in [1..3]]
G = graphics_array(L)
G.save(F, dpi=500, axes=False)
```
\textbf{save\_image}(\texttt{filename=None, *args, **kwds})

Save an image representation of \texttt{self}. The image type is determined by the extension of the filename. For example, this could be \texttt{.png}, \texttt{.jpg}, \texttt{.gif}, \texttt{.pdf}, \texttt{.svg}. Currently this is implemented by calling the \texttt{save()} method of \texttt{self}, passing along all arguments and keywords.

\textbf{Note:} Not all image types are necessarily implemented for all graphics types. See \texttt{save()} for more details.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: plots = [[plot(m*cos(x + n*pi/4), (x, 0, 2*pi))
.....: for n in range(3)] for m in range(1,3)]
sage: G = graphics_array(plots)
sage: G.save_image(tmp_filename(ext='png'))
\end{verbatim}

\textbf{show}(**\texttt{kwds})

Show \texttt{self} immediately.

This method attempts to display the graphics immediately, without waiting for the currently running code (if any) to return to the command line. Be careful, calling it from within a loop will potentially launch a large number of external viewer programs.

\textbf{OPTIONAL INPUT:}

- \texttt{dpi} – dots per inch
- \texttt{figsize} – width or [width, height] of the figure, in inches; the default is 6.4 x 4.8 inches
- \texttt{axes} – boolean; if \texttt{True}, all individual graphics are endowed with axes; if \texttt{False}, all axes are removed (this overrides the \texttt{axes} option set in each graphics)
- \texttt{frame} – boolean; if \texttt{True}, all individual graphics are drawn with a frame around them; if \texttt{False}, all frames are removed (this overrides the \texttt{frame} option set in each graphics)
- \texttt{fontsize} – positive integer, the size of fonts for the axes labels (this overrides the \texttt{fontsize} option set in each graphics)

\textbf{OUTPUT:}

This method does not return anything. Use \texttt{save()} if you want to save the figure as an image.

\textbf{EXAMPLES:}

This draws a graphics array with four trig plots and no axes in any of the plots and a figure width of 4 inches:

\begin{verbatim}
sage: G = graphics_array([[plot(sin), plot(cos)],
.....: [plot(tan), plot(sec)]])
sage: G.show(axes=False, figsize=4)
\end{verbatim}

Same thing with a frame around each individual graphics:

\begin{verbatim}
sage: G.show(axes=False, frame=True, figsize=4)
\end{verbatim}

Actually, many options are possible; for instance, we may set \texttt{fontsize} and \texttt{gridlines}:

\begin{verbatim}
sage: G.show(axes=False, frame=True, figsize=4, fontsize=8,
.....: gridlines='major')
\end{verbatim}
5.2. Graphics arrays and insets
5.3 Plotting primitives

```python
class sage.plot.primitive.GraphicPrimitive(options):
    Bases: WithEqualityById, SageObject

    Base class for graphics primitives, e.g., things that knows how to draw themselves in 2D.

    EXAMPLES:
    We create an object that derives from GraphicPrimitive:

    sage: P = line((-1,-2), (3,5))
    sage: P[0]
    Line defined by 2 points
    sage: type(P[0])
    <class 'sage.plot.line.Line'>

    options()
    Return the dictionary of options for this graphics primitive.
    By default this function verifies that the options are all valid; if any aren’t, then a verbose message is printed
    with level 0.

    EXAMPLES:
    sage: from sage.plot.primitive import GraphicPrimitive
    sage: GraphicPrimitive({}).options()
    {}

    plot3d(**kwds)
    Plots 3D version of 2D graphics object. Not implemented for base class.

    EXAMPLES:
    sage: from sage.plot.primitive import GraphicPrimitive
    sage: G=GraphicPrimitive({})
```

(continues on next page)
sage: G.plot3d()
Traceback (most recent call last):
... 
NotImplementedError: 3D plotting not implemented for Graphics primitive

**set_options**(new_options)

Change the options to *new_options*.

**EXAMPLES:**

sage: from sage.plot.circle import Circle
sage: c = Circle(0,0,1,{})
sage: c.set_options({'thickness': 0.6})
sage: c.options()
{'thickness': 0.6...}

**set_zorder**(zorder)

Set the layer in which to draw the object.

**EXAMPLES:**

sage: P = line([(-2,-3), (3,4)], thickness=4)
sage: p=P[0]
sage: p.set_zorder(2)
sage: p.options()['zorder']
2
sage: Q = line([(-2,-4), (3,5)], thickness=4,zorder=1,hue=.5)
sage: P=Q # blue line on top
Graphics object consisting of 2 graphics primitives
sage: q=Q[0]
sage: q.set_zorder(3)
sage: P+Q # teal line on top
Graphics object consisting of 2 graphics primitives
sage: q.options()['zorder']
3

**class** sage.plot.primitive.GraphicPrimitive_xydata(*options*)

Bases: GraphicPrimitive

**get_minmax_data**()

Returns a dictionary with the bounding box data.

**EXAMPLES:**

sage: d = polygon([[1,2], [5,6], [5,0]], rgbcolor=(1,0,1))[0].get_minmax_data()
sage: d['ymin']
0.0
sage: d['xmin']
1.0

sage: d = point((3, 3), rgbcolor=hue(0.75))[0].get_minmax_data()
sage: d['xmin']
3.0

(continues on next page)
```python
sage: d['ymin']
3.0

sage: l = line(([100, 100], (120, 120)))[0]
sage: d = l.get_minmax_data()
sage: d['xmin']
100.0
sage: d['xmax']
120.0
```

## 5.4 Plotting utilities

### class sage.plot.misc.FastCallablePlotWrapper(ff, imag_tol)

Bases: FastCallableFloatWrapper

A fast-callable wrapper for plotting that returns nan instead of raising an error whenever the imaginary tolerance is exceeded.

A detailed rationale for this can be found in the superclass documentation.

**EXAMPLES:**

The float incarnation of “not a number” is returned instead of an error being thrown if the answer is complex:

```python
sage: from sage.plot.misc import FastCallablePlotWrapper
sage: f = sqrt(x)
sage: ff = fast_callable(f, vars=[x], domain=CDF)
sage: fff = FastCallablePlotWrapper(ff, imag_tol=1e-8)
sage: fff(1)
1.0
sage: fff(-1)
nan
```

### sage.plot.misc.get_matplotlib_linestyle(linestyle, return_type)

Function which translates between matplotlib linestyle in short notation (i.e. '-', '--', ':', '-.') and long notation (i.e. ‘solid’, ‘dashed’, ‘dotted’, ‘dashdot’).

If linestyle is none of these allowed options, the function raises a ValueError.

**INPUT:**

- **linestyle** - The style of the line, which is one of
  - "-" or "solid"
  - "--" or "dashed"
  - "-." or "dash dot"
  - ":" or "dotted"
  - "None" or " " or "" (nothing)

The linestyle can also be prefixed with a drawing style (e.g., "steps--")
  - "default" (connect the points with straight lines)
2D Graphics, Release 10.0

- "steps" or "steps-pre" (step function; horizontal line is to the left of point)
- "steps-mid" (step function; points are in the middle of horizontal lines)
- "steps-post" (step function; horizontal line is to the right of point)

If linestyle is None (of type NoneType), then we return it back unmodified.

• return_type - The type of linestyle that should be output. This argument takes only two values - "long" or "short".

EXAMPLES:

Here is an example how to call this function:

```python
sage: from sage.plot.misc import get_matplotlib_linestyle
sage: get_matplotlib_linestyle(':', return_type='short')
'\cdot'
sage: get_matplotlib_linestyle(':', return_type='long')
'dotted'
```

`sage.plot.misc.setup_for_eval_on_grid(funcs, ranges, plot_points=None, return_vars=False, imaginary_tolerance=1e-08)`

Calculate the necessary parameters to construct a list of points, and make the functions fast_callable.

INPUT:

• funcs – a function, or a list, tuple, or vector of functions
• ranges – a list of ranges. A range can be a 2-tuple of numbers specifying the minimum and maximum, or a 3-tuple giving the variable explicitly.
• plot_points – a tuple of integers specifying the number of plot points for each range. If a single number is specified, it will be the value for all ranges. This defaults to 2.
• return_vars – (default False) If True, return the variables, in order.
• imaginary_tolerance – (default: 1e-8); if an imaginary number arises (due, for example, to numerical issues), this tolerance specifies how large it has to be in magnitude before we raise an error. In other words, imaginary parts smaller than this are ignored in your plot points.

OUTPUT:

• fast_funcs - if only one function passed, then a fast callable function. If funcs is a list or tuple, then a tuple of fast callable functions is returned.
• range_specs - a list of range_specs: for each range, a tuple is returned of the form (range_min, range_max, range_step) such that srange(range_min, range_max, range_step, include_endpoint=True) gives the correct points for evaluation.

EXAMPLES:

```python
sage: x,y,z=var('x,y,z')
sage: f(x,y)=x+y-z
sage: g(x,y)=x+y
sage: h(y)=-y
sage: sage.plot.misc.setup_for_eval_on_grid(f, [(0, 2),(1,3),(-4,1)], plot_points=5)
(<sage...>, [(0.0, 2.0, 0.5), (1.0, 3.0, 0.5), (-4.0, 1.0, 1.25)])
sage: sage.plot.misc.setup_for_eval_on_grid([g,h], [(0, 2),(-1,1)], plot_points=5)
((<sage...>, <sage...>), [(0.0, 2.0, 0.5), (-1.0, 1.0, 0.5)])
```

(continues on next page)
sage: sage.plot.misc.setup_for_eval_on_grid([sin, cos], [(-1, 1)], plot_points=9)
((<sage...>, <sage...>), [(-1.0, 1.0, 0.25)])
sage: sage.plot.misc.setup_for_eval_on_grid([lambda x: x**2, cos], [(-1, 1)], plot_
    --points=9)
((<function <lambda> ...>, <sage...>), [(-1.0, 1.0, 0.25)])
sage: sage.plot.misc.setup_for_eval_on_grid(x+y, [(x,-1,1),(y,-2,2)])
((<sage...>,), [(-1.0, 1.0, 2.0), (-2.0, 2.0, 4.0)])
sage: sage.plot.misc.setup_for_eval_on_grid(x+y, [(x,-1,1),(y,-1,1)], plot_
    --points=[4,9])
((<sage...>,), [(-1.0, 1.0, 0.6666666666666666), (-1.0, 1.0, 0.25)])
sage: sage.plot.misc.setup_for_eval_on_grid(x+y, [(x,-1,1),(y,-1,1)], plot_
    --points=[4,9,10])
Traceback (most recent call last):
... ValueError: plot_points must be either an integer or a list of integers, one for
    each range
sage: sage.plot.misc.setup_for_eval_on_grid(x+y, [(1,-1),(y,-1,1)], plot_points=[4,
    9,10])
Traceback (most recent call last):
... ValueError: Some variable ranges specify variables while others do not

Beware typos: a comma which should be a period, for instance:

sage: sage.plot.misc.setup_for_eval_on_grid(x+y, [(x, 1, 2), (y, 0,1, 0.2)], plot_
    --points=[4,9,10])
Traceback (most recent call last):
... ValueError: At least one variable range has more than 3 entries: each should either
    have 2 or 3 entries, with one of the forms (xmin, xmax) or (x, xmin, xmax)

sage: sage.plot.misc.setup_for_eval_on_grid(x+y, [(y,1,-1),(x,-1,1)], plot_points=5)
(<sage...>, [(-1.0, 1.0, 0.5), (-1.0, 1.0, 0.5)])
sage: sage.plot.misc.setup_for_eval_on_grid(x+y, [(x,1,-1),(x,-1,1)], plot_points=5)
Traceback (most recent call last):
... ValueError: range variables should be distinct, but there are duplicates
sage: sage.plot.misc.setup_for_eval_on_grid(x+y, [(x,1,1),(y,-1,1)])
Traceback (most recent call last):
... ValueError: plot start point and end point must be different

sage.plot.misc.unify_arguments(funcs)

Return a tuple of variables of the functions, as well as the number of “free” variables (i.e., variables that defined
in a callable function).

INPUT:
• **funcs** – a list of functions; these can be symbolic expressions, polynomials, etc

**OUTPUT:** functions, expected arguments

• A tuple of variables in the functions

• A tuple of variables that were “free” in the functions

**EXAMPLES:**

```python
sage: x,y,z=var('x,y,z')
sage: f(x,y)=x+y-z
sage: g(x,y)=x+y
sage: h(y)=-y
sage: sage.plot.misc.unify_arguments((f,g,h))
((x, y, z), (z,))
sage: sage.plot.misc.unify_arguments((g,h))
((x, y), ())
sage: sage.plot.misc.unify_arguments((f,z))
((x, y, z), (z,))
sage: sage.plot.misc.unify_arguments((h,z))
((y, z), (z,))
sage: sage.plot.misc.unify_arguments((x+y,x-y))
((x, y), (x, y))
```
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