

Unit 4: Plotting

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1 Plotting

In this unit, we take a first look at plotting numerical data. Python itself does not have any built-in plotting capabilities, so we will be using `matplotlib` (MPL), the most popular graphics library for Python.

- For details on a particular plotting function, see the [official documentation](#).
- There is an official introductory [tutorial](#) which you can use along-side this unit.

In order to access the functions and objects from `matplotlib`, we first need to import them. The general convention is to use the namespace `plt` for this purpose:

```
[1]: import matplotlib.pyplot as plt
```

Advanced plotting backend for Jupyter notebooks (optional)

When using `matplotlib` in interactive Jupyter notebooks, we can enable a more fancy plotting backend that allows us to dynamically adjust the zoom, etc. This is done by adding the line

```
%matplotlib widget
```

For this to work, the `ipympl` package needs to be installed, see [here](#) for details. Note that this is not supported (and in fact produces a syntax error) in regular `*.py` Python script files.

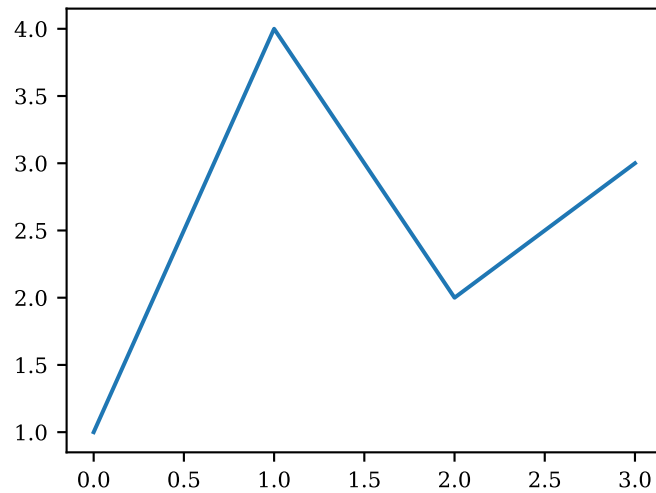
1.1 Line plots

One of the simplest plots we can generate using the `plot()` function is a line defined by a list of y -values.

```
[2]: # import matplotlib library
import matplotlib.pyplot as plt

# Plot list of integers
yvalues = [1, 4, 2, 3]
plt.plot(yvalues)
```

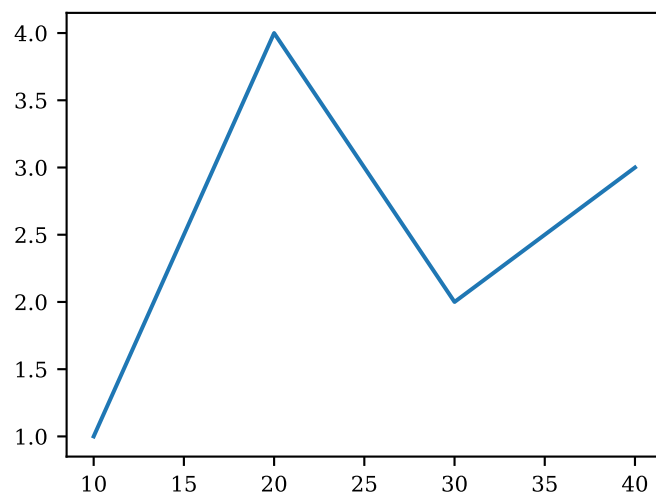
```
[2]: [<matplotlib.lines.Line2D at 0x7f04ffc1aec0>]
```



We didn't even have to specify the corresponding x -values, as MPL automatically assumes them to be $[0, 1, 2, \dots]$. Usually, we want to plot for a given set of x -values like this:

```
[3]: # explicitly specify x-values
xvalues = [10, 20, 30, 40]
plt.plot(xvalues, yvalues)
```

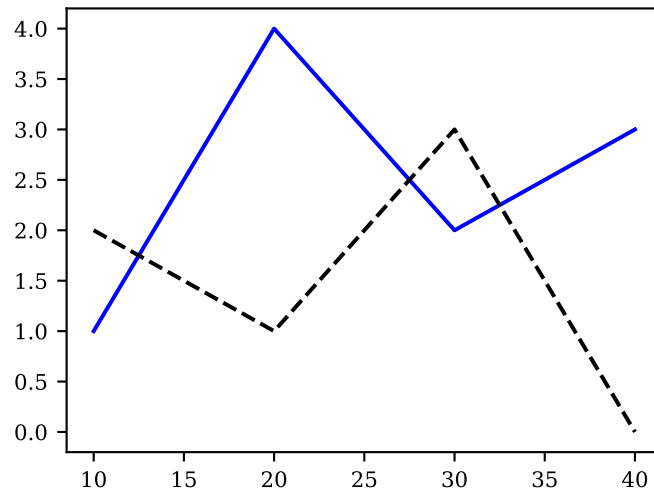
```
[3]: [<matplotlib.lines.Line2D at 0x7f04fce46f20>]
```



Similar to Matlab, we can also specify multiple lines to be plotted in a single graph:

```
[4]: yvalues2 = [2.0, 1.0, 3.0, 0.0]
plt.plot(xvalues, yvalues, 'b-', xvalues, yvalues2, 'k--')
```

```
[4]: [<matplotlib.lines.Line2D at 0x7f04fccde260>,  
      <matplotlib.lines.Line2D at 0x7f04fccdf310>]
```



The characters following each set of y -values are style specifications that are very similar to the ones used in Matlab. More specifically, the letters are short-hand notations for colours (see [here](#) for details):

- b: blue
- g: green
- r: red
- c: cyan
- m: magenta
- y: yellow
- k: black
- w: white

The remaining characters set the line styles. Valid values are

- - solid line
- -- dashed line
- -. dash-dotted line
- : dotted line

Additionally, we can append marker symbols to the style specification. The most frequently used ones are

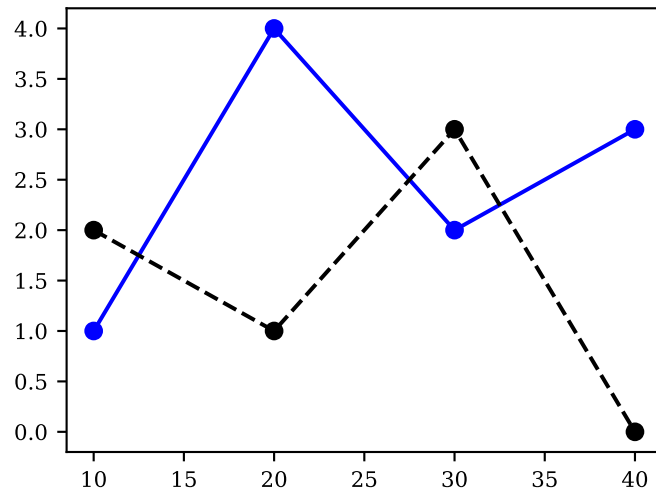
- o: circle
- s: square
- *: star
- x: x
- d: (thin) diamond

The whole list of supported symbols can be found [here](#).

Instead of passing multiple values to be plotted at once, we can also repeatedly call `plot()` to add additional elements to a graph. This is more flexible since we can pass additional arguments which are specific to one particular set of data, such as labels displayed in legends

```
[5]: # Plot two lines by calling plot() twice  
plt.plot(xvalues, yvalues, 'b-o')  
plt.plot(xvalues, yvalues2, 'k--o')
```

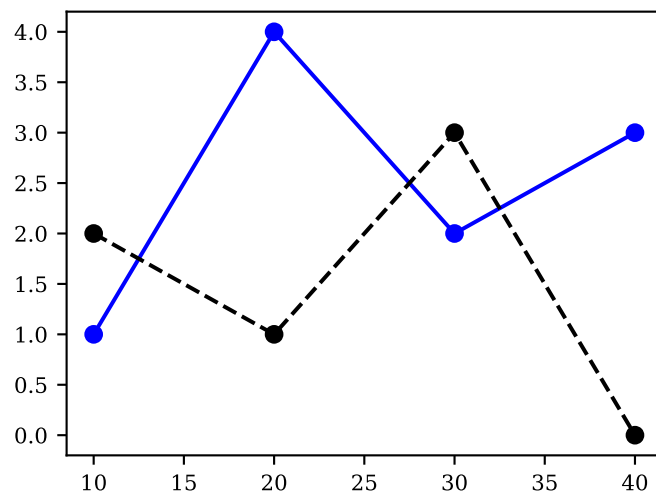
```
[5]: [<matplotlib.lines.Line2D at 0x7f04fcb5c850>]
```



Individual calls to `plot()` also allow us to specify styles more explicitly using keyword arguments:

```
[6]: # pass plot styles as explicit keyword arguments
plt.plot(xvalues, yvalues, color='blue', linestyle='-', marker='o')
plt.plot(xvalues, yvalues2, color='black', linestyle='--', marker='o')
```

```
[6]: [<matplotlib.lines.Line2D at 0x7f04fcbcdf90>]
```



Note that in the example above, we use named colours such as red or blue (see [here](#) for the complete list of named colors). Alternatively, we can use RGB color codes of the form `#ddddd` where `d` are hexadecimal digits.

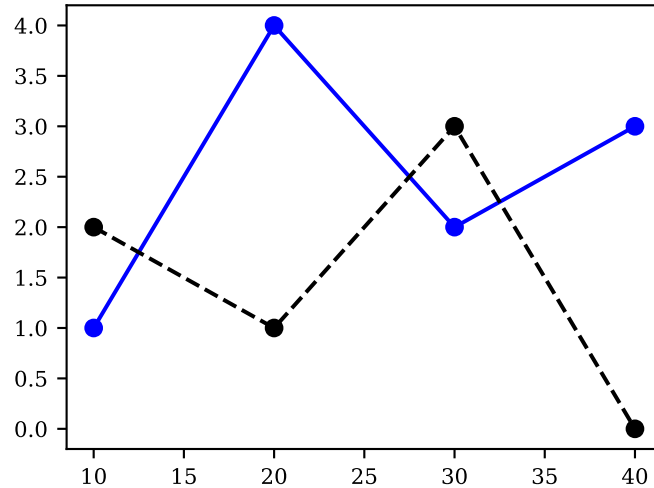
Matplotlib accepts abbreviations for the most common style definitions using the following shortcuts:

- `c` or `color`
- `ls` or `linestyle`
- `lw` or `linewidth`

We can write thus rewrite the above code as follows:

```
[7]: # abbreviate plot style keywords
plt.plot(xvalues, yvalues, c='blue', ls='-', marker='o')
plt.plot(xvalues, yvalues2, c='black', ls='--', marker='o')
```

```
[7]: [<matplotlib.lines.Line2D at 0x7f04fcc533d0>]
```



There is a third way to plot multiple lines in the same plot by passing the y -values as a 2-dimensional array. We explore this alternative in the exercises.

1.2 Scatter plots

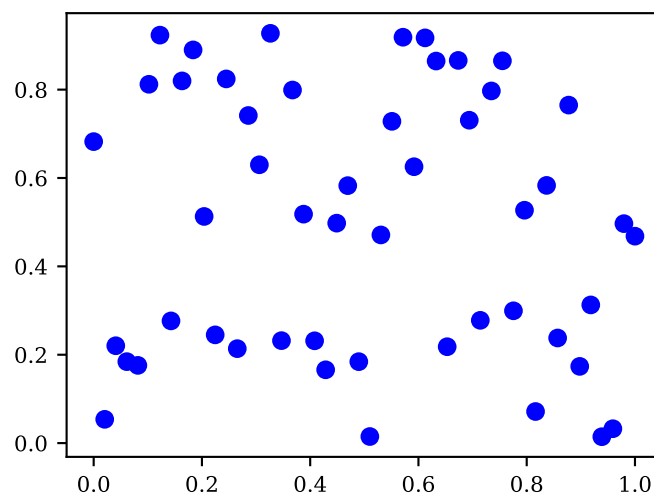
We use the `scatter()` function to create scatter plots in a similar fashion to line plots:

```
[8]: import matplotlib.pyplot as plt
import numpy as np

# Create 50 uniformly-spaced values on unit interval
xvalues = np.linspace(0.0, 1.0, 50)
# Draw random numbers (we learn how to do this in a later unit)
yvalues = np.random.default_rng(123).random(50)

plt.scatter(xvalues, yvalues, color='blue')
```

```
[8]: <matplotlib.collections.PathCollection at 0x7f04fcacb790>
```

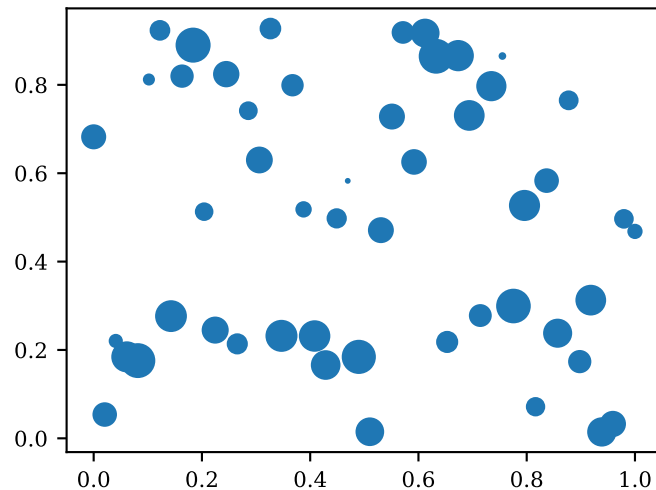


We could in principle create scatter plots using `plot()` by turning off the connecting lines. However, `scatter()` allows us to specify the color and marker size as collections, so we can vary these for every point. `plot()`, on the other hand, imposes the same style on all points plotted in that particular function call.

```
[9]: # Draw random marker sizes
size = np.random.default_rng(456).random(len(yvalues)) * 150.0

# plot with point-specific marker sizes
plt.scatter(xvalues, yvalues, s=size)
```

```
[9]: <matplotlib.collections.PathCollection at 0x7f04fcb3bb50>
```



1.3 Plotting categorical data

Instead of numerical values on the x -axis, we can also plot categorical variables using the function `bar()`.

For example, assume we have three categories and each has an associated numerical value:

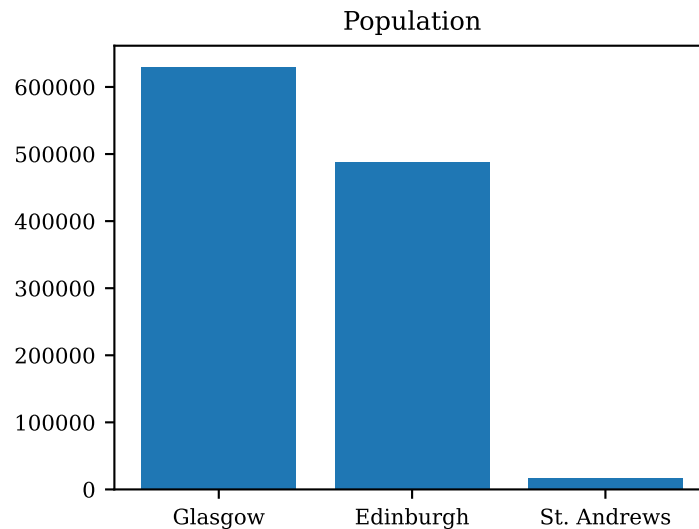
```
[10]: import matplotlib.pyplot as plt

# Define category labels
cities = ['Glasgow', 'Edinburgh', 'St. Andrews']
population = [630000, 488000, 16800]

# Create bar chart
plt.bar(cities, population)

# Add overall title
plt.title('Population')
```

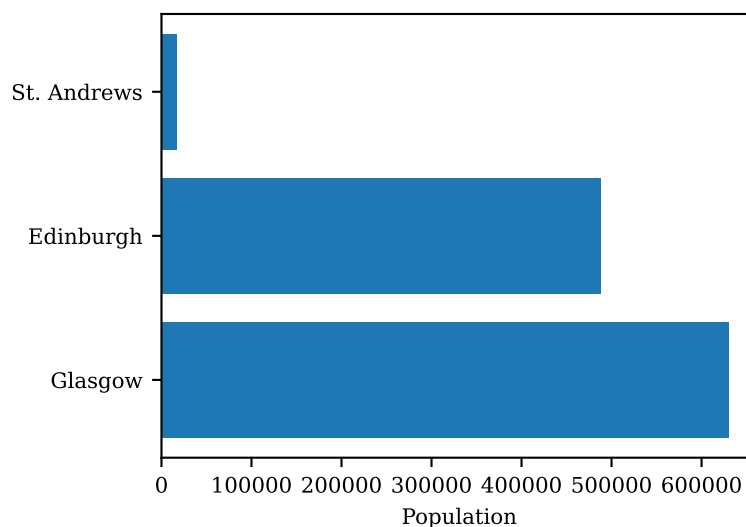
```
[10]: Text(0.5, 1.0, 'Population')
```



We use `barh()` to create *horizontal* bars:

```
[11]: plt.barh(cities, population)
      plt.xlabel('Population')
```

```
[11]: Text(0.5, 0, 'Population')
```



1.4 Adding labels and annotations

Matplotlib has numerous functions to add labels and annotations:

- Use `title()` and `suptitle()` to add titles to your graphs. The latter adds a title for the whole figure, which might span multiple plots (axes).
- We can add axis labels by calling `xlabel()` and `ylabel()`.
- To add a legend, call `legend()`, which in its most simple form takes a list of labels which are in the same order as the plotted data.
- Use `text()` to add additional text at arbitrary locations.
- Use `annotate()` to display text next to some data point; it's easier to position correctly than `text()` and you can add arrows!

```
[12]: import matplotlib.pyplot as plt

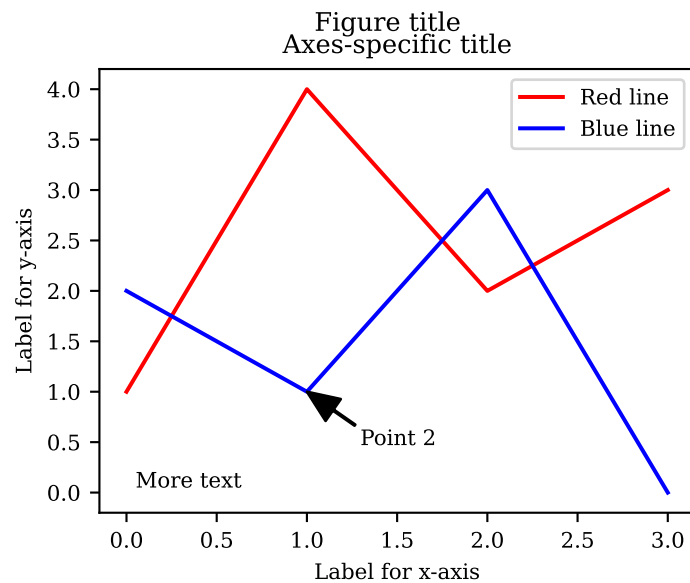
xvalues = [0, 1, 2, 3]
yvalues = [1, 4, 2, 3]
yvalues2 = [2.0, 1.0, 3.0, 0.0]

plt.plot(xvalues, yvalues, 'r', xvalues, yvalues2, 'b')
plt.suptitle('Figure title')
plt.title('Axes-specific title')
plt.xlabel('Label for x-axis')
plt.ylabel('Label for y-axis')
plt.legend(['Red line', 'Blue line'])

# Adds text at data coordinates (0.05, 0.05)
plt.text(0.05, 0.05, 'More text')

# Annotate second point
plt.annotate('Point 2',
            (xvalues[1], yvalues2[1]), (20, -20),
            textcoords='offset points',
            arrowprops={'facecolor': 'black', 'width': 0.5, 'headwidth': 10.0})
)
```

```
[12]: Text(20, -20, 'Point 2')
```



1.5 Plot limits, ticks and tick labels

We adjust the plot limits, ticks and tick labels as follows:

- Plotting limits are set using the `xlim()` and `ylim()` functions. Each accepts a tuple (min,max) to set the desired range.
- Ticks and tick labels can be set by calling `xticks()` or `yticks()`.

```
[13]: import matplotlib.pyplot as plt
import numpy as np

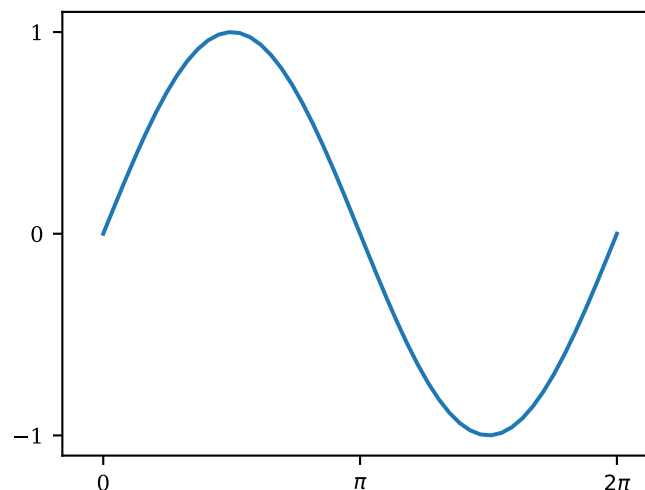
xvalues = np.linspace(0.0, 2*np.pi, 50)
plt.plot(xvalues, np.sin(xvalues))
```



```
# Set major ticks for x and y axes, and xtick labels.
# We can use LaTeX code in labels!
plt.xticks([0.0, np.pi, 2*np.pi], ['0', r'$\pi$', r'$2\pi$'])
plt.yticks([-1.0, 0.0, 1.0])

# Adjust plot limits in x and y direction
plt.xlim((-0.5, 2*np.pi + 0.5))
plt.ylim((-1.1, 1.1))
```

[13]: (-1.1, 1.1)



1.6 Adding straight lines

Quite often, we want to add horizontal or vertical lines to highlight a particular value. We can do this using the functions

- `axhline()` to add a *horizontal* line at a given y -value.
- `axvline()` to add a *vertical* line at a given x -value.
- `axline()` to add a line defined by two points or by a single point and a slope.

Examples:

Consider the sine function from above. We can add a horizontal line at 0 and two vertical lines at the points where the function attains its minimum and maximum as follows:

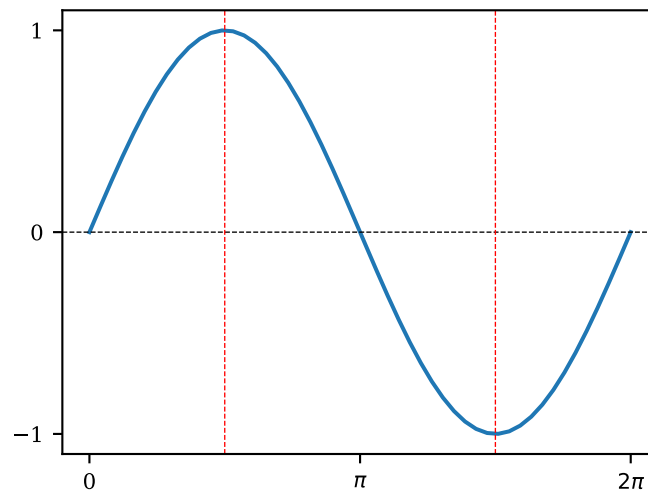
```
[14]: import matplotlib.pyplot as plt
import numpy as np

# Plot sine function (same as above)
xvalues = np.linspace(0.0, 2*np.pi, 50)
plt.plot(xvalues, np.sin(xvalues))
plt.xticks([0.0, np.pi, 2*np.pi], ['0', r'$\pi$', r'$2\pi$'])
plt.yticks([-1, 0, 1])

# Add black dashed horizontal line at y-value 0
plt.axhline(0.0, lw=0.5, ls='--', c='black')

# Add red dashed vertical lines at maximum / minimum points
plt.axvline(0.5*np.pi, lw=0.5, ls='--', c='red')
plt.axvline(1.5*np.pi, lw=0.5, ls='--', c='red')
```

[14]: <matplotlib.lines.Line2D at 0x7f04fc82e5c0>



1.7 Object-oriented interface

So far, we have only used the so-called pyplot interface which involves calling *global* plotting functions from `matplotlib.pyplot`. This interface is intended to be similar to Matlab, but is also somewhat limited and less clean.

We can instead use the object-oriented interface (called this way because we call methods of the [Figure](#) and [Axes](#) objects). While there is not much point in using the object-oriented interface in a Jupyter notebook when we want to create a single graph, it should be the preferred method when writing re-usable code in Python files.

To use the object-oriented interface, we need to get figure and axes objects. The easiest way to accomplish this is using the `subplots()` function, like this:

```
fig, ax = plt.subplots()
```

As an example, we recreate the graph from the section on labels and annotations using the object-oriented interface:

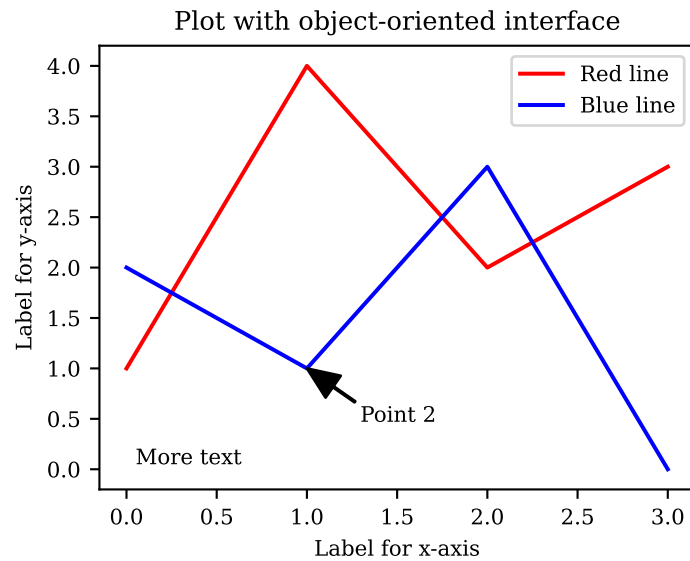
```
[15]: import matplotlib.pyplot as plt

xvalues = [0, 1, 2, 3]
yvalues = [1, 4, 2, 3]
yvalues2 = [2.0, 1.0, 3.0, 0.0]

fig, ax = plt.subplots()
ax.plot(xvalues, yvalues, color='red', label='Red line')
ax.plot(xvalues, yvalues2, color='blue', label='Blue line')
ax.set_xlabel('Label for x-axis')
ax.set_ylabel('Label for y-axis')
ax.legend()
ax.set_title('Plot with object-oriented interface')
ax.text(0.05, 0.05, 'More text')

# Annotate second point
ax.annotate('Point 2',
            (xvalues[1], yvalues2[1]), (20, -20),
            textcoords='offset points',
            arrowprops={'facecolor': 'black', 'width': 0.5, 'headwidth': 10.0})
```

```
[15]: Text(20, -20, 'Point 2')
```



The code is quite similar, except that attributes are set using the `set_xxx()` methods of the `ax` object. For example, instead of calling `xlim()`, we use `ax.set_xlim()`.

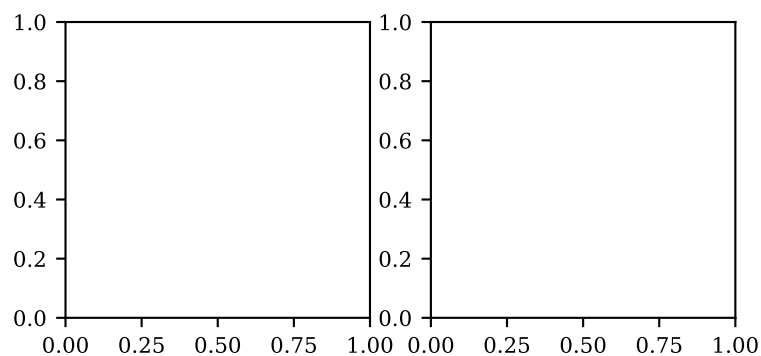
1.8 Working with multiple plots (axes)

The object-oriented interface becomes particularly useful if we want to create multiple axes (or figures). This can also be achieved using with the pyplot programming model but is somewhat more obscure.

For example, to create a row with two plots, we use:

```
[16]: import matplotlib.pyplot as plt

# Create one figure with 2 axes objects, arranged as two columns in a single row
fig, ax = plt.subplots(1, 2, figsize=(4.5, 2.0))
```

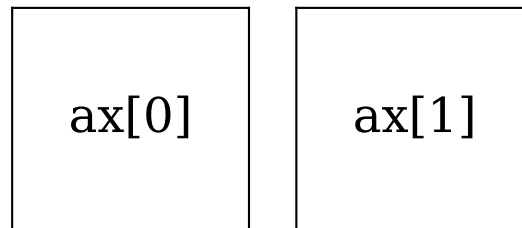


With multiple axes objects in a single figure (as in the above example), the `ax` returned by `subplots()` is a NumPy array. Its elements map to the individual panels within the figure in a natural way.

We can visualise this mapping for the case of a single row and two columns as follows:

```
[17]: fig, ax = plt.subplots(1, 2, figsize=(3.5,1.5))
      for i, axes in enumerate(ax):
          # Turn off ticks of both axes
          axes.set_xticks(())
          axes.set_yticks(())
          # Label axes object
          text = f'ax[{i}]'
```

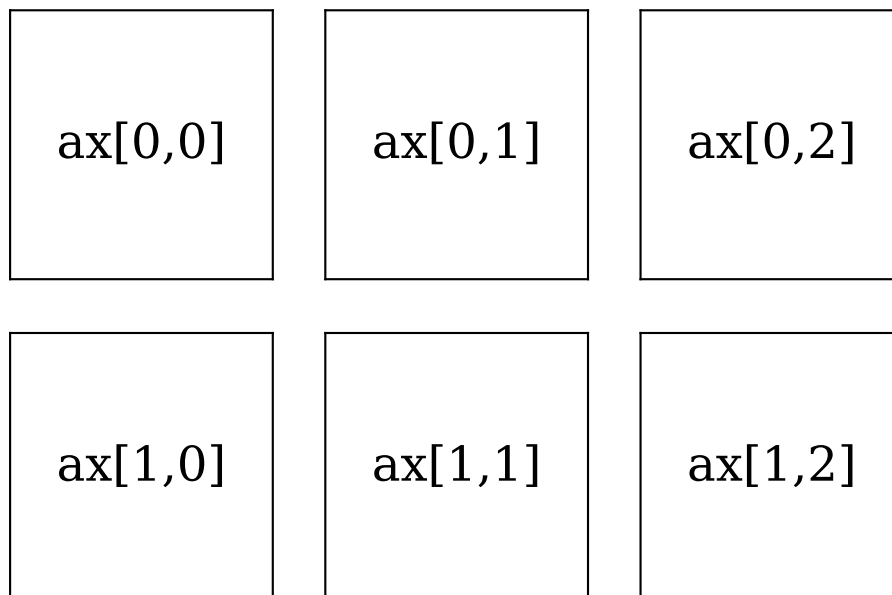
```
axes.text(0.5, 0.5, text, transform=axes.transAxes, va='center',
         ha='center', fontsize=18)
```



Don't worry about the details of how this graph is generated, the only take-away here is how axes objects are mapped to the panels in the figure.

If we request panels in two dimensions, the `ax` object will be a 2-dimensional array, and the mapping of axes objects to panels will look like this instead:

```
[18]: # Request figure with 2 rows, 3 columns
fig, ax = plt.subplots(2, 3, figsize=(6,4))
for i, axrow in enumerate(ax):
    for j, axes in enumerate(axrow):
        # Turn off ticks of both axes
        axes.set_xticks(())
        axes.set_yticks(())
        # Label axes object
        text = f'ax[{i},{j}]'
        axes.text(0.5, 0.5, text, transform=axes.transAxes, va='center',
                 ha='center', fontsize=18)
```



Returning to our initial example, we can use the elements of `ax` to plot into individual panels:

```
[19]: import matplotlib.pyplot as plt
import numpy as np

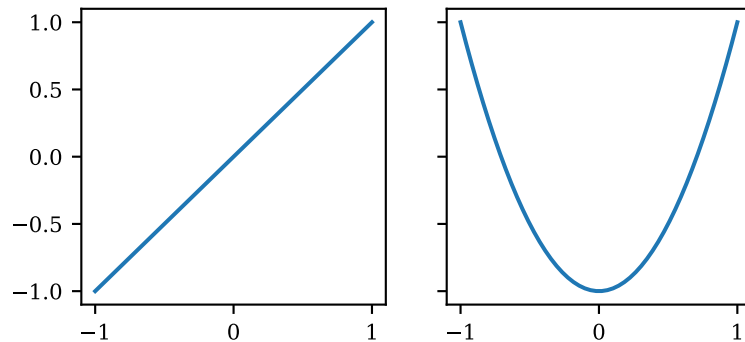
fig, ax = plt.subplots(1, 2, sharex=True, sharey=True, figsize=(4.5, 2.0))
xvalues = np.linspace(-1.0, 1.0, 50)

# Plot into first column
```

```
ax[0].plot(xvalues, xvalues)

# Plot into second column
ax[1].plot(xvalues, 2*xvalues**2.0 - 1)
```

[19]: [

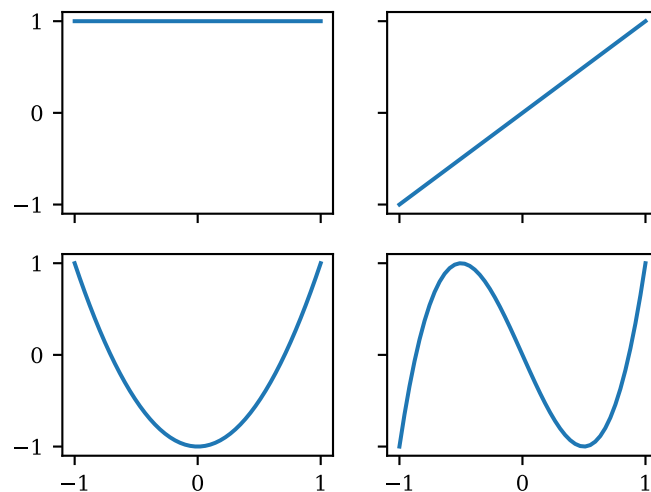


The next example illustrates how to create a figure with four panels:

```
[20]: # create figure with 2 rows, 2 columns
fig, ax = plt.subplots(2, 2, sharex=True, sharey=True)

xvalues = np.linspace(-1.0, 1.0, 50)

# Plot the first four Chebyshev polynomials on the interval [-1,1]
for i in range(2):
    for j in range(2):
        yvalues = np.cos((j + i*2) * np.arccos(xvalues))
        ax[i,j].plot(xvalues, yvalues)
```



Note the use of `sharex=True` and `sharey=True`. This tells matplotlib that all axes share the same plot limits, so the tick labels can be omitted in the figure's interior to preserve space.

With multiple axes per figure, we can also see the difference between the labels generated by `set_title()` and `suptitle()`.

To illustrate, we re-use the previous example with two panels in a single row:

```
[21]: fig, ax = plt.subplots(1, 2, figsize=(4.5,2.0))
for i, axes in enumerate(ax):
    axes.set_xticks(())
```

```

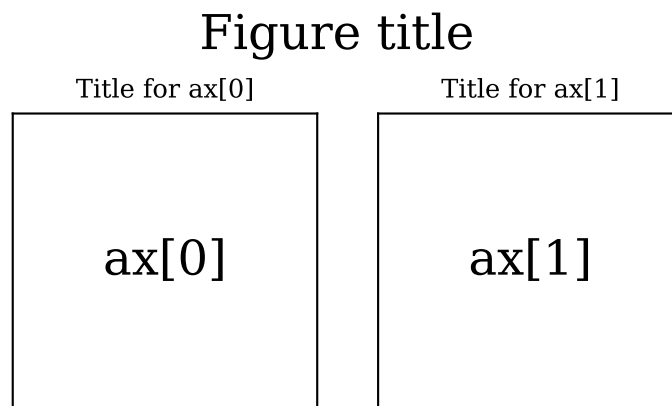
axes.set_yticks(())
text = f'ax[{i}]'
axes.text(0.5, 0.5, text, transform=axes.transAxes, va='center',
         ha='center', fontsize=18)

# Add axes-specific title
axes.set_title(f'Title for ax[{i}]')

# set overall figure title:
# this is an attribute of the Figure object!
fig.suptitle('Figure title', fontsize=18, va='bottom', y=1.02)

```

[21]: Text(0.5, 1.02, 'Figure title')



1.9 Optional exercises

1.9.1 Exercise 1: Trigonometric functions

Plot the functions $\sin(x)$ and $\cos(x)$ on the interval $[-\pi, \pi]$, each in a separate graph. Include a legend for each plot, and add pretty tick labels at $[-\pi, 0, \pi]$ which use the \LaTeX symbol for π . Add an overall title “Trigonometric functions”.

Hint: NumPy defines the functions `np.sin()` and `np.cos()` as well as the value `np.pi`.

1.9.2 Exercise 2: Logarithmic scaling

In economics and finance, we often plot using the \log_{10} scale if the plotted data are of very different orders of magnitude.

Create a figure with two sub-plots, each plotting the function $f(x) = 10^x$ on a uniformly-spaced interval $[-5, 5]$ with 100 points. Use the (default) linear scale in the first plot, but apply the \log_{10} scale in the second.

Hint: You can set the axis scale to log by calling `yscale('log')`, or `set_yscale('log')` when using the object-oriented interface.

1.9.3 Exercise 3: Multiple lines in single plot

In this exercise, we explore yet another alternative to plot multiple lines in a single graph.

The `plot()` function accepts y -values specified as a matrix in which each column corresponds to a different line. The number of rows must correspond to the length of the vector of x -values, which are assumed to be identical for all columns of y -values.

1. Consider the following family of polynomials in x parametrised by a :

$$p(x; a) = a(x - 0.5)^2$$

Assume there are 5 such polynomials with a 's given by the values

```
a = np.linspace(0.4, 4.0, 5)
```

- Create a common set of x -values using an equidistant grid of 50 points on the interval $[0, 1]$.
 - Construct the matrix of y -values with shape $(50, 5)$ and plot all polynomials with a single call to `plot()`.
 - Add a legend that maps a value of a to the corresponding line in the plot.
2. Plot each polynomial separately using a loop. Use the i -th elements of the following arrays as plot styles for the i -th polynomial:

```
colors = ['red', 'blue', 'black', 'green', 'purple']  
linewidths = [1.0, 1.5, 2.0, 1.5, 1.0]  
linestyles = ['-', '--', '-.', ':', '-']
```

Add a legend that maps a value of a to the corresponding line in the plot.

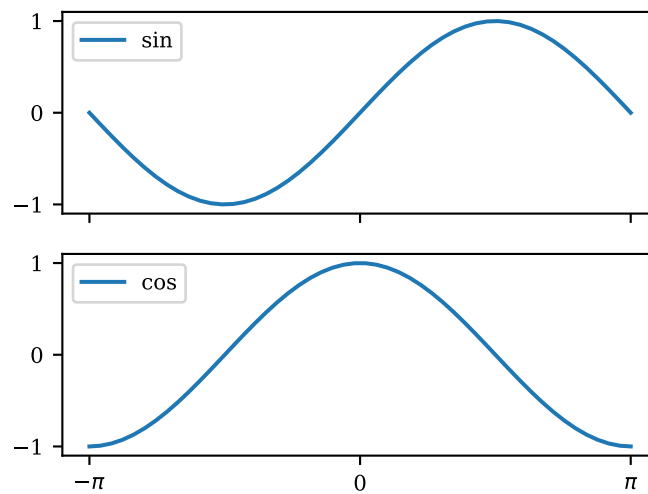
1.10 Solutions

1.10.1 Solution for exercise 1

```
[22]: import matplotlib.pyplot as plt  
import numpy as np  
  
xvalues = np.linspace(-np.pi, np.pi, 50)  
# Create figure with two rows, one column  
fig, ax = plt.subplots(2, 1, sharey=True, sharex=True)  
  
xticks = [-np.pi, 0.0, np.pi]  
# Tick labels use LaTeX notation for pi, which is \pi and has to be  
# surrounded by $$.  
xticklabels = [r'$-\pi$', '0', r'$\pi$']  
yticks = [-1.0, 0.0, 1.0]  
  
# Create sin() plot using first axes object  
ax[0].plot(xvalues, np.sin(xvalues), label='sin')  
ax[0].set_xticks(xticks)  
ax[0].set_xticklabels(xticklabels)  
ax[0].set_yticks(yticks)  
ax[0].legend(loc='upper left')  
  
# Create cos() plot using second axes object  
ax[1].plot(xvalues, np.cos(xvalues), label='cos')  
ax[1].set_xticks(xticks)  
ax[1].set_xticklabels(xticklabels)  
ax[1].set_yticks(yticks)  
ax[1].legend(loc='upper left')  
  
# Add overall figure title (this is not axes-specific)  
fig.suptitle('Trigonometric functions')
```

```
[22]: Text(0.5, 0.98, 'Trigonometric functions')
```

Trigonometric functions



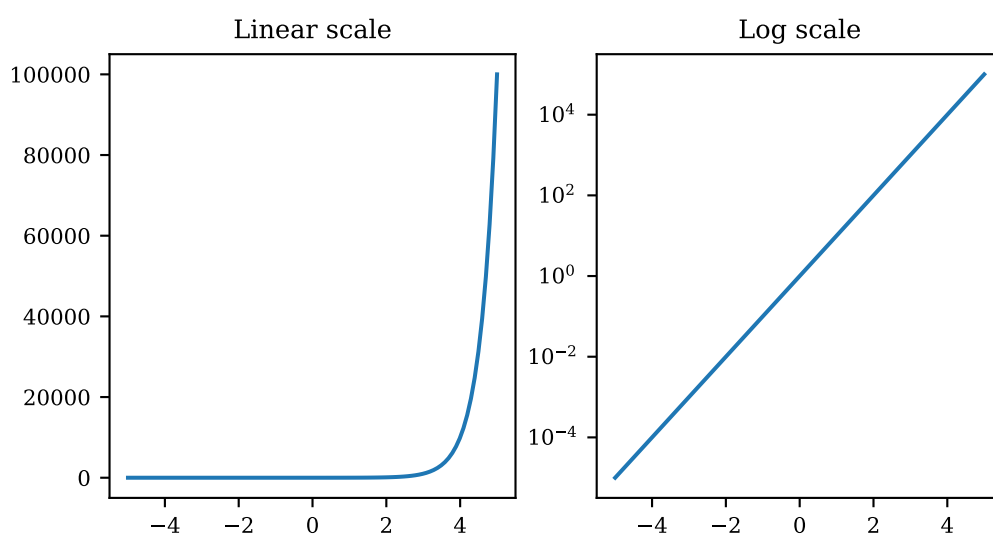
1.10.2 Solution for exercise 2

```
[23]: import matplotlib.pyplot as plt
import numpy as np

xvalues = np.linspace(-5.0, 5.0, 100)
fig, ax = plt.subplots(1, 2, sharex=True, figsize=(6,3))
ax[0].plot(xvalues, 10.0**xvalues)
ax[0].set_title('Linear scale')

ax[1].plot(xvalues, 10.0**xvalues)
# Set y-axis to log scale (assumes base-10 log)
ax[1].set_yscale('log')
ax[1].set_title('Log scale')
```

[23]: Text(0.5, 1.0, 'Log scale')



1.10.3 Solution for exercise 3

First we plot all polynomials in a single call to `plot()`. For this to work, we need to pass the y -values as a matrix where each column corresponds to a different line.

```
[24]: import numpy as np
import matplotlib.pyplot as plt

# Create common x-values
xvalues = np.linspace(0.0, 1.0, 50)

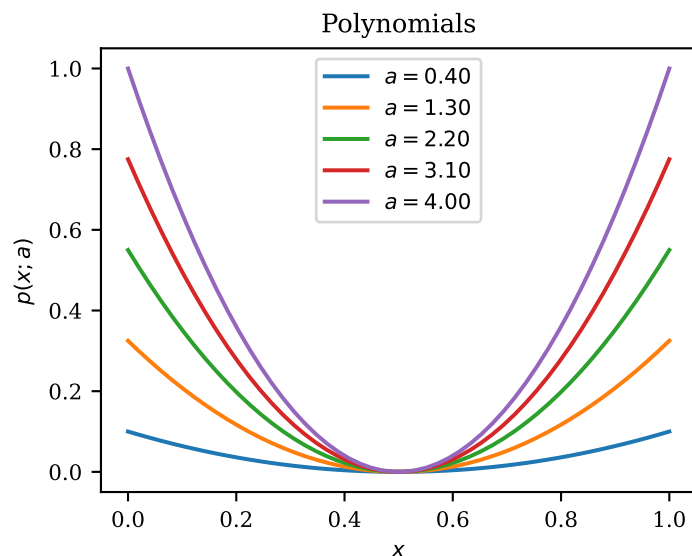
# Create parameters
a = np.linspace(0.4, 4.0, 5)

# Evaluate polynomials on common x-values:
# each column corresponds to a different parametrisation
poly = np.zeros((len(xvalues), len(a)))
# Iterate over parameters and create each set of corresponding y-values
for i, ai in enumerate(a):
    poly[:,i] = ai * (xvalues - 0.5)**2.0

plt.plot(xvalues, poly)
plt.xlabel('$x$')
plt.ylabel(r'$p(x;a)$')
plt.title('Polynomials')

# Create legend:
# we need to pass labels in same order as the corresponding columns
labels = [r'$a={:.2f}$'.format(ai) for ai in a]
plt.legend(labels)
```

```
[24]: <matplotlib.legend.Legend at 0x7f04fc1dff40>
```



We now call `plot()` for each polynomial separately. This allows us to specify detailed style settings for each line.

```
[25]: fig, ax = plt.subplots(1,1)

# Different styles for each parametrisation
colors = ['red', 'blue', 'black', 'green', 'purple']
linewidths = [1.0, 1.5, 2.0, 1.5, 1.0]
```

```

linestyles = ['-', '--', '-.', ':', '-']

n = poly.shape[1]
for i in range(n):
    label = r'$a={:.2f}$'.format(a[i])
    ax.plot(xvalues, poly[:,i], c=colors[i], lw=linewidths[i],
            ls=linestyles[i], label=label)

# calling legend without arguments will use the
# text provided as label argument to each plot()
ax.legend()
ax.set_xlabel('$x$')
ax.set_ylabel(r'$p(x;a)$')
ax.set_title('Polynomials')

```

[25]: Text(0.5, 1.0, 'Polynomials')

