An introduction to Python Programming for Research

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Chapter 1

Introduction

1.1 Why teach Python?

- In this first session, we will introduce Python.
- This course is about programming for data analysis and visualisation in research.
- It’s not mainly about Python.
- But we have to use some language.

1.1.1 Why Python?

- Python is quick to program in
- Python is popular in research, and has lots of libraries for science
- Python interfaces well with faster languages
- Python is free, so you’ll never have a problem getting hold of it, wherever you go.

1.1.2 Why write programs for research?

- Not just labour saving
- Scripted research can be tested and reproduced

1.1.3 Sensible Input - Reasonable Output

Programs are a rigorous way of describing data analysis for other researchers, as well as for computers. Computational research suffers from people assuming each other’s data manipulation is correct. By sharing codes, which are much more easy for a non-author to understand than spreadsheets, we can avoid the “SIRO” problem. The old saw “Garbage in Garbage out” is not the real problem for science:

- Sensible input
- Reasonable output

1.2 Many kinds of Python

1.2.1 The IPython Notebook

The easiest way to get started using Python, and one of the best for research data work, is the IPython Notebook.

In the notebook, you can easily mix code with discussion and commentary, and mix code with the results of that code; including graphs and other data visualisations.
We’re going to be mainly working in the IPython notebook in this course. To get hold of a copy of the notebook, follow the setup instructions shown on the course website, or use the installation in UCL teaching cluster rooms.

IPython notebooks consist of discussion cells, referred to as “markdown cells”, and “code cells”, which contain Python. This document has been created using IPython notebook, and this very cell is a Markdown Cell.

In [2]: print("This cell is a code cell")

This cell is a code cell

Code cell inputs are numbered, and show the output below.
Markdown cells contain text which uses a simple format to achieve pretty layout, for example, to obtain: bold, italic
• Bullet
We write:

**bold**, *italic*

* Bullet

> Quote

See the Markdown documentation at This Hyperlink

### 1.2.2 Typing code in the notebook

When working with the notebook, you can either be in a cell, typing its contents, or outside cells, moving around the notebook.

- When in a cell, press escape to leave it. When moving around outside cells, press return to enter.
- Outside a cell:
  - Use arrow keys to move around.
  - Press `b` to add a new cell below the cursor.
  - Press `m` to turn a cell from code mode to markdown mode.
  - Press `shift+enter` to calculate the code in the block.
- Press `h` to see a list of useful keys in the notebook.
- Inside a cell:
  - Press `tab` to suggest completions of variables. (Try it!)

*Supplementary material:* Learn more about the notebook [here](#). Try these [videos](#)

### 1.2.3 Python at the command line

Data science experts tend to use a “command line environment” to work. You’ll be able to learn this at our “Software Carpentry” workshops, which cover other skills for computationally based research.

```bash
In [3]: %bash
   #: Above line tells Python to execute this cell as *shell code*
   #: not Python, as if we were in a command line
   #: This is called a 'cell magic'

   python -c "print(2*4)"
```

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### 1.2.4 Python scripts

Once you get good at programming, you’ll want to be able to write your own full programs in Python, which work just like any other program on your computer. We’ll not cover this in this course, you can learn more about this in MPHYG001. Here are some examples:

```python
In [4]: %writefile eight.py
   #: writefile

print(2*4)
```

Writing eight.py
We can make the script directly executable (on Linux or Mac) by inserting a [hash-bang](https://en.wikipedia.org/wiki/Shebang_(Unix))

In [6]: `%%writefile eight.py`  

```bash  
#! /usr/bin/env python  
print(2*7)  
```

Overwriting eight.py

In [7]: `%%bash`  

```bash  
chmod u+x eight.py  
```

In [8]: `%%bash`  

```bash  
./eight.py  
```

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1.2.5 Python Libraries

We can write our own python libraries, called modules which we can import into the notebook and invoke:

In [9]: `%%writefile draw_eight.py`  

```python  
# Above line tells the notebook to treat the rest of this  
# cell as content for a file on disk.  
  
import numpy as np  
import math  
import matplotlib.pyplot as plt  
  
def make_figure():  
    theta=np.arange(0,4*math.pi,0.1)  
    eight=plt.figure()  
    axes=eight.add_axes([0,0,1,1])  
    axes.plot(0.5*np.sin(theta),np.cos(theta/2))  
    return eight  
  
Writing draw_eight.py

In a real example, we could edit the file on disk using a program such as Notepad++ for windows or Atom for Mac.

In [10]: `import draw_eight` # Load the library file we just wrote to disk

In [11]: image=draw_eight.make_figure()
There is a huge variety of available packages to do pretty much anything. For instance, try import antigravity

In [1]: %matplotlib inline
Chapter 2

An example Python data analysis notebook

2.1 Why write software to manage your data and plots?

We can use programs for our entire research pipeline. Not just big scientific simulation codes, but also the small scripts which we use to tidy up data and produce plots. This should be code, so that the whole research pipeline is recorded for reproducibility. Data manipulation in spreadsheets is much harder to share or check.

2.2 A tour of capabilities

We’re going to start with a look at some of the awesome things that you can do with programming, for motivation for when it gets difficult. However, you will not understand all the detail of the code in this section, and nor should you. (If you do, maybe one of our more advanced courses is more appropriate for you!)

2.3 Supplementary materials

You can see another similar demonstration on the software carpentry site at http://swcarpentry.github.io/python-novice-inflammation/01-numpy.html We’ll try to give links to other sources of Python training along the way. Part of our “flipped classroom” approach is that we assume you know how to use the internet! If you find something confusing out there, please bring it along to the next session. In this course, we’ll always try to draw your attention to other sources of information about what we’re learning. Paying attention to as many of these as you need to, is just as important as these core notes.

2.4 The example program: a “graph of green land”.

2.4.1 Importing Libraries

Research programming is all about using libraries: tools other people have provided programs that do many cool things. By combining them we can feel really powerful but doing minimum work ourselves. The python syntax to import someone else’s library is “import”.

In [2]: import geopy # A python library for investigating geographic information. # https://pypi.python.org/pypi/geopy
Now, if you try to follow along on this example in an IPython notebook, you’ll probably find that you just got an error message.
You’ll need to wait until we’ve covered installation of additional python libraries later in the course, then come back to this and try again. For now, just follow along and try get the feel for how programming for data-focused research works.

```
In [3]: geocoder=geopy.geocoders.GoogleV3(domain="maps.google.co.uk")
   geocoder.geocode('Cambridge', exactly_one=False)

Out[3]: [Location(Cambridge, UK, (52.205337, 0.121817, 0.0))]
```

### 2.4.2 Comments

Code after a # symbol doesn’t get run.

```
In [4]: print("This runs")#
   print "This doesn’t"
   # print This doesn’t either
```

This runs

### 2.4.3 Functions

We can wrap code up in a function, so that we can repeatedly get just the information we want.

```
In [5]: def geolocate(place):
   return geocoder.geocode(place, exactly_one = False)[0][1]
```

Defining functions which put together code to make a more complex task seem simple from the outside is the most important thing in programming. The output of the function is stated by “return”; the input comes in in brackets after the function name:

```
In [6]: geolocate('London')
```

```
Out[6]: (51.5073509, -0.1277583)
```

### 2.4.4 Variables

We can store a result in a variable:

```
In [7]: london_location = geolocate("London")
   print(london_location)
```

```
(51.5073509, -0.1277583)
```

### 2.4.5 More complex functions

The google maps API allows us to fetch a map of a place, given a latitude and longitude. The URLs look like: http://maps.googleapis.com/maps/api/staticmap?size=400x400&center=51.51,-0.1275&zoom=12 We’ll probably end up working out these URLs quite a bit. So we’ll make ourselves another function to build up a URL given our parameters.
In [8]: import requests
def request_map_at(lat, long, satellite=True, zoom=10, size=(400, 400), sensor=False):
    base = "http://maps.googleapis.com/maps/api/staticmap?"

    params = {
        "sensor": str(sensor).lower(),
        "zoom": zoom,
        "size": "x".join(map(str, size)),
        "center": "x".join(map(str, (lat, long))),
        "style": "feature:all|element:labels|visibility:off"
    }
    if satellite:
        params["maptype"] = "satellite"

    return requests.get(base, params=params)

In [9]: map_response = request_map_at(51.5072, -0.1275)

2.4.6 Checking our work

In [10]: map_response
Out [10]: <Response [200]>

Let's see what URL we ended up with:

In [11]: url = map_response.url
    print(url[0:50])
    print(url[50:100])
    print(url[100:])

http://maps.googleapis.com/maps/api/staticmap?size=400x400&maptype=satellite&sensor=false&style=feature:all|element:labels|visibility:off&zoom=10&center=51.5072%2C-0.1275

We can write automated tests so that if we change our code later, we can check the results are still valid.

In [12]: assert "http://maps.googleapis.com/maps/api/staticmap?" in url
   assert "center=51.5072%2C-0.1275" in url
   assert "zoom=10" in url
   assert "size=400x400" in url
   assert "sensor=false" in url

Our previous function comes back with an Object representing the web request. In object oriented programming, we use the . operator to get access to a particular property of the object, in this case, the actual image at that URL is in the content property. It's a big file, so I'll just get the first few chars:

In [13]: map_response.content[0:20]
Out [13]: b'\x89PNG\r\n\x1a\n\x00\x00\x00\rIHDR\x00\x00\x00\x01\x90'

2.4.7 Displaying results
I'll need to do this a lot, so I'll wrap up our previous function in another function, to save on typing.
In [14]: def map_at(*args, **kwargs):
    return request_map_at(*args, **kwargs).content

I can use a library that comes with IPython notebook to display the image. Being able to work with variables which contain images, or documents, or any other weird kind of data, just as easily as we can with numbers or letters, is one of the really powerful things about modern programming languages like Python.

In [15]: map_png = map_at(*london_location)

In [16]: print("The type of our map result is actually a: ", type(map_png))

The type of our map result is actually a: <class 'bytes'>

In [17]: import IPython
   IPython.core.display.Image(map_png)

Out[17]:
2.4.8 Manipulating Numbers

Now we get to our research project: we want to find out how urbanised the world is, based on satellite imagery, along a line between two cities. We expect the satellite image to be greener in the countryside.

We’ll use lots more libraries to count how much green there is in an image.

In [18]: from io import BytesIO # An object to convert between files and unicode strings
       import numpy as np # A library to deal with matrices
       from matplotlib import image as img # A library to deal with images

Let’s define what we count as green:

In [19]: def is_green(pixels):
    
        threshold=1.1
        greener_than_red = pixels[:,1] > threshold* pixels[:,0]
        greener_than_blue = pixels[:,1] > threshold* pixels[:,2]
        green = np.logical_and(greener_than_red, greener_than_blue)
        return green

This code has assumed we have our pixel data for the image as a $400 \times 400 \times 3$ 3-d matrix, with each of the three layers being red, green, and blue pixels.

We find out which pixels are green by comparing, element-by-element, the middle (green, number 1) layer to the top (red, zero) and bottom (blue, 2)

Now we just need to parse in our data, which is a PNG image, and turn it into our matrix format:

In [20]: def count_green_in_png(data):
       
           pixels = img.imread(BytesIO(data)) # Get our PNG image as a numpy array
           return np.sum(is_green(pixels))

In [21]: print(count_green_in_png(map_at(*london_location)))

108030

We’ll also need a function to get an evenly spaced set of places between two endpoints:

In [22]: def location_sequence(start, end, steps):
       
           lats = np.linspace(start[0], end[0], steps) # "Linearly spaced" data
           longs = np.linspace(start[1], end[1], steps)
           return np.vstack((lats, longs)).T

In [23]: location_sequence(geolocate("London"), geolocate("Cambridge"), 5)

Out[23]: array([[ 1.5073509e+01, -1.27758300e-01],
               [ 1.681847e+01, -6.53644750e-02],
               [ 1.856339e+01, -2.97065000e-03],
               [ 2.0308405e+01,  5.94231750e-02],
               [ 2.2053370e+01,  1.21817000e-01]])

2.4.9 Creating Images

We should display the green content to check our work:

In [24]: def show_green_in_png(data):
       
           pixels=img.imread(BytesIO(data)) # Get our PNG image as rows of pixels
           green = is_green(pixels)
out = green[:,:,np.newaxis]*np.array([0,1,0])[np.newaxis,np.newaxis,:,]  

buffer = BytesIO()  
result = img.imsave(buffer, out, format='png')  
return buffer.getvalue()  

In [25]: IPython.core.display.Image(
    map_at(*london_location)  
)  

Out[25]:

In [26]: IPython.core.display.Image(
    show_green_in_png(
        map_at(
            *london_location)))
2.4.10 Looping

We can loop over each element in our list of coordinates, and get a map for that place:

```
In [27]: for location in location_sequence:
    geolocate("London"),
    geolocate("Birmingham"),
    IPython.core.display.display( IPython.core.display.Image(
        map_at(*location))
```
So now we can count the green from London to Birmingham!

In [28]: [count_green_in_png(map_at(*location))

    for location in location_sequence(geolocate("London"),
                                        geolocate("Birmingham"),
                                        10)]

Out[28]: [108030,
          124815,
          155611,
          158217,
          187903,
          159104,
          159053,
          156974,
          154885,
          148267]
2.4.11 Plotting graphs

Let’s plot a graph.

`In [29]: import matplotlib.pyplot as plt`

`In [30]: plt.plot([count_green_in_png(map_at(*location))
                  for location in location_sequence(geolocate("London"),
                                                  geolocate("Birmingham"),
                                                  10)])`

`Out[30]: [<matplotlib.lines.Line2D at 0x2b7862b3f0f0>]`

From a research perspective, of course, this code needs a lot of work. But I hope the power of using programming is clear.

2.4.12 Composing Program Elements

We built little pieces of useful code, to:

- Find latitude and longitude of a place
- Get a map at a given latitude and longitude
- Decide whether a (red,green,blue) triple is mainly green
- Decide whether each pixel is mainly green
- Plot a new image showing the green places
- Find evenly spaced points between two places

By putting these together, we can make a function which can plot this graph automatically for any two places:
And that’s it! We’ve covered, very very quickly, the majority of the python language, and much of the theory of software engineering.

Now we’ll go back, carefully, through all the concepts we touched on, and learn how to use them properly ourselves.
Chapter 3

Variables

3.1 Variable Assignment

When we generate a result, the answer is displayed, but not kept anywhere.

In [1]: 2*3
Out[1]: 6

If we want to get back to that result, we have to store it. We put it in a box, with a name on the box. This is a variable.

In [2]: six = 2*3
In [3]: print(six)
6

If we look for a variable that hasn’t ever been defined, we get an error.

In [4]: print(seven)

---------------------------------------------------------------------
NameError                        Traceback (most recent call last)
<ipython-input-4-37b67c799511> in <module>()
----> 1 print(seven)

NameError: name 'seven' is not defined

That’s not the same as an empty box, well labeled:

In [5]: nothing = None
In [6]: print(nothing)
None
(None is the special python value for a no-value variable.)

Supplementary Materials: There’s more on variables at http://swcarpentry.github.io/python-novice-inflammation/01-numpy.html

Anywhere we could put a raw number, we can put a variable label, and that works fine:

```
In [7]: print(5*six)
30

In [8]: scary = six*six*six
In [9]: print(scary)
216
```

### 3.2 Reassignment and multiple labels

But here’s the real scary thing: it seems like we can put something else in that box:

```
In [10]: scary = 25
In [11]: print(scary)
25
```

Note that the data that was there before has been lost. No labels refer to it any more - so it has been "Garbage Collected"! We might imagine something pulled out of the box, and thrown on the floor, to make way for the next occupant.

In fact, though, it is the label that has moved. We can see this because we have more than one label referring to the same box:

```
In [12]: name = "James"
In [13]: nom = name
In [14]: print(nom)
James

In [15]: print(name)
James
```

And we can move just one of those labels:

```
In [16]: nom = "Hetherington"
In [17]: print(name)
James

In [18]: print(nom)
```

21
So we can now develop a better understanding of our labels and boxes: each box is a piece of space (an address) in computer memory. Each label (variable) is a reference to such a place.

When the number of labels on a box (“variables referencing an address”) gets down to zero, then the data in the box cannot be found any more.

After a while, the language’s “Garbage collector” will wander by, notice a box with no labels, and throw the data away, making that box available for more data.

Old fashioned languages like C and Fortran don’t have Garbage collectors. So a memory address with no references to it still takes up memory, and the computer can more easily run out.

So when I write:

```
In [19]: name = "Jim"
```

The following things happen:

1. A new text object is created, and an address in memory is found for it.
2. The variable “name” is moved to refer to that address.
3. The old address, containing “James”, now has no labels.
4. The garbage collector frees the memory at the old address.

Supplementary materials: There’s an online Python tutor which is great for visualising memory and references. Try the [scenario we just looked at](http://www.pythontutor.com/visualize.html#code=name+%3D+%22James%22%0Anom+%3D+name%0Aprint(nom%29%0Aprint(name%29%0Aname%3D+%22Jim%22%0Aprint(nom%29%0Aprint(name%29&mode=display&origin=opt-frontend.js&cumulative=false&heapPrimitives=true&textReferences=false&py=3&rawInputLstJSON=%5B%5D&curInstr=10)

Labels are contained in groups called “frames”: our frame contains two labels, ‘nom’ and ‘name’.

### 3.3 Objects and types

An object, like `name`, has a type. In the online Python tutor example, we see that the objects have type “str”. `str` means a text object: Programmers call these ‘strings’.

```
In [20]: type(name)
```

```
Out[20]: str
```

Depending on its type, an object can have different properties: data fields inside the object.

Consider a Python complex number for example:

```
In [21]: z=3+1j
In [22]: type(z)
```

```
Out[22]: complex
```

```
In [23]: z.real
```

```
Out[23]: 3.0
```

```
In [24]: z.imag
```

```
Out[24]: 1.0
```

```
In [25]: x = "Banana"
```

```
In [26]: type(x)
```

22
3.4 Reading error messages.

It’s important, when learning to program, to develop an ability to read an error message and find, from amongst all the confusing noise, the bit of the error message which tells you what to change!

We don’t yet know what is meant by AttributeError, or “Traceback”.

```
In [29]: second_complex_number=5-6j
    print("Gets to here")
    print(second_complex_number.wrong)
    print("Didn't get to here")

Gets to here

-------------------------------------------------------------------------
AttributeError Traceback (most recent call last)
<ipython-input-29-3eaebc91b05c> in <module>()
     1 second_complex_number=5-6j
```
But in the above, we can see that the error happens on the third line of our code cell. We can also see that the error message: > 'complex' object has no attribute 'wrong' …tells us something important. Even if we don’t understand the rest, this is useful for debugging!

### 3.5 Variables and the notebook kernel

When I type code in the notebook, the objects live in memory between cells.

```python
In [30]: number = 0
In [31]: print(number)
0

If I change a variable:

In [32]: number = number + 1
In [33]: print(number)
1
```

It keeps its new value for the next cell. But cells are not always evaluated in order.

If I now go back to Input 22, reading `number = number + 1`, and run it again, with shift-enter. Number will change from 2 to 3, then from 3 to 4. Try it!

So it’s important to remember that if you move your cursor around in the notebook, it doesn’t always run top to bottom.

**Supplementary material:**

Chapter 4

Using Functions

4.1 Calling functions

We often want to do thing to our objects that are more complicated than just assigning them to variables.

In [1]: `len("pneumonoultramicroscopicsilicovolcanoconiosis")`
Out [1]: 45

In [2]: `len([3,5,15])`
Out [2]: 3

Here we have “called a function”. The function `len` takes one input, and has one output. The output is the length of whatever the input was.

Programmers also call function inputs “parameters” or, confusingly, “arguments”. Here’s another example:

In [3]: `sorted("Python")`
Out [3]: ['P', 'h', 'n', 'o', 't', 'y']

Which gives us back a list of the letters in Python, sorted alphabetically.

The input goes in brackets after the function name, and the output emerges wherever the function is used.

So we can put a function call anywhere we could put a “literal” object or a variable.

In [4]: `name = 'Jim'`

In [5]: `len(name)*8`
Out [5]: 24

In [6]: `x = len('Mike')`
   y = len('Bob')
   z = x+y

In [7]: `print(z)`
4.2 Using methods

Objects come associated with a bunch of functions designed for working on objects of that type. We access these with a dot, just as we do for data attributes:

```
In [8]: "shout".upper()
Out[8]: 'SHOUT'
```

These are called methods. If you try to use a method defined for a different type, you get an error:

```
In [9]: x = 5
   x.upper()

-------------------------------------------------------------------------
AttributeError            Traceback (most recent call last)
  <ipython-input-9-5d563274bba7> in <module>()
     1 x = 5
----> 2 x.upper()

AttributeError: 'int' object has no attribute 'upper'
```

If you try to use a method that doesn’t exist, you get an error:

```
In [10]: x = 5
   x.wrong

-------------------------------------------------------------------------
AttributeError            Traceback (most recent call last)
  <ipython-input-10-131d304742ae> in <module>()
     1 x = 5
----> 2 x.wrong

AttributeError: 'int' object has no attribute 'wrong'
```

Methods and properties are both kinds of attribute, so both are accessed with the dot operator. Objects can have both properties and methods:

```
In [11]: z = 1+5j

In [12]: z.real
Out[12]: 1.0

In [13]: z.conjugate()
Out[13]: (1-5j)
```
4.3 Functions are just a type of object!

Now for something that will take a while to understand: don’t worry if you don’t get this yet, we’ll look again at this in much more depth later in the course.

If we forget the (), we realise that a method is just a property which is a function!

```python
In [14]: z.conjugate
Out[14]: <function complex.conjugate>
In [15]: type(z.conjugate)
Out[15]: builtin_function_or_method
In [16]: somefunc = z.conjugate
In [17]: somefunc()  
Out[17]: (1-5j)
```

Functions are just a kind of variable:

```python
In [18]: magic = sorted
In [19]: type(magic)
Out[19]: builtin_function_or_method
In [20]: magic(["Technology", "Advanced"])
Out[20]: ['Advanced', 'Technology']
In [21]: def double(data):
   return data*2
In [22]: double(5)
Out[22]: 10
In [23]: double
Out[23]: <function __main__.double>
In [24]: testtwo = double
In [25]: testtwo(3)
Out[25]: 16
In [26]: testtwo(5,6,7)
```

```
---------------------------------------------------------------------------
TypeError                               Traceback (most recent call last)
<ipython-input-26-2816b5f0c79e> in <module>()
      1 testtwo(5,6,7)
----> 3 testtwo(5,6,7)

TypeError: double() takes 1 positional argument but 3 were given
```

```python
In [27]: def testten(input):
   return 5*double(input)
In [28]: testten(4)
Out[28]: 40
```
4.4 Getting help on functions and methods

The ‘help’ function, when applied to a function, gives help on it!

In [29]: help(sorted)

Help on built-in function sorted in module builtins:

sorted(iterable, key=None, reverse=False)
    Return a new list containing all items from the iterable in ascending order.

    A custom key function can be supplied to customise the sort order, and the
    reverse flag can be set to request the result in descending order.

In [30]: help(z.conjugate)

Help on built-in function conjugate:

conjugate(...) method of builtins.complex instance
    complex.conjugate() -> complex

    Return the complex conjugate of its argument. (3-4j).conjugate() == 3+4j.

The ‘dir’ function, when applied to an object, lists all its attributes (properties and methods):

In [31]: dir("Hexxo")

Out[31]: ['__add__',
                '__class__',
                '__contains__',
                '__delattr__',
                '__dir__',
                '__doc__',
                '__eq__',
                '__format__',
                '__ge__',
                '__getattribute__',
                '__getitem__',
                '__getnewargs__',
                '__gt__",
                '__hash__',
                '__init__',
                '__iter__',
                '__le__',
                '__len__',
                '__lt__',
                '__mod__',
                '__mul__',
                '__ne__',
                '__new__',
                '__reduce__',
                '__reduce_ex__',
                ...]
Most of these are confusing methods beginning and ending with __ part of the internals of python.
Again, just as with error messages, we have to learn to read past the bits that are confusing, to the bit we want:

```
In [32]: "Hexro".replace("x", "1")
Out[32]: 'Hello'
```

### 4.5 Operators

Now that we know that functions are a way of taking a number of inputs and producing an output, we should look again at what happens when we write:

```
In [33]: x = 2 + 3
In [34]: print(x)
5
```

This is just a pretty way of calling an “add” function. Things would be more symmetrical if add were actually written

```
x = +(2, 3)
```

Where `+` is just the name of the name of the adding function.

In python, these functions do exist, but they’re actually methods of the first input: they’re the mysterious `__` functions we saw earlier (Two underscores.)

```
In [35]: x.__add__(7)
Out[35]: 12
```

We call these symbols, `+`, `-` etc, “operators”.

The meaning of an operator varies for different types:

```
In [36]: [2, 3, 4] + [5, 6]
Out[36]: [2, 3, 4, 5, 6]
```

Sometimes we get an error when a type doesn’t have an operator:

```
In [37]: 7 - 2
Out[37]: 5
In [38]: [2, 3, 4] - [5, 6]
```

```
---------------------------------------------------------------------------
TypeError                               Traceback (most recent call last)
<ipython-input-38-4627195e7799> in <module>()
----> 1 [2, 3, 4] - [5, 6]

TypeError: unsupported operand type(s) for -: 'list' and 'list'
```
The word “operand” means “thing that an operator operates on”!
Or when two types can’t work together with an operator:

```
In [39]: [2, 3, 4] + 5
```

```
---------------------------------------------------------------------------
TypeError                               Traceback (most recent call last)
<ipython-input-39-84117f41979f> in <module>()
----> 1 [2, 3, 4] + 5

TypeError: can only concatenate list (not "int") to list
```

Just as in Mathematics, operators have a built-in precedence, with brackets used to force an order of operations:

```
In [40]: print(2 + 3 * 4)
```

```
14
```

```
In [41]: print((2 + 3) * 4)
```

```
20
```

*Supplementary material:* http://www.mathcs.emory.edu/~valerie/courses/fall10/155/resources/op_precedence.html
Chapter 5

Types

We have seen that Python objects have a ‘type’:

In [1]: type(5)
Out [1]: int

5.1 Floats and integers

Python has two core numeric types, int for integer, and float for real number.

In [2]: one=1
ten=10
one_float=1.0
ten_float=10.
In [3]: tenth=one_float/ten_float
In [4]: tenth
Out [4]: 0.1
In [5]: one//ten
Out [5]: 0
In [6]: 2+3
Out [6]: 5
In [7]: "Hello "+"World"
Out [7]: 'Hello World'

With integers, we can be clear about what we want: divide an integer by an integer and return another integer, or divide an integer by an integer and return a floating point. Most other languages do not afford that kind of distinction! It can lead to hard-to-find bugs.

In [8]: print(one//ten, one/ten)
0 0.1
The divided by operator / means divide by for real numbers. Whereas // means divide by integers for integers, and divide by floats for floats.

```
In [10]: 10//3
Out[10]: 3
In [11]: 10/3
Out[11]: 3.3333333333333335
In [12]: 10//3.0
Out[12]: 3.0
In [13]: str(5)
Out[13]: '5'
In [14]: 10/float(3)
Out[14]: 3.3333333333333335
```

I lied when I said that the float type was a real number. It’s actually a computer representation of a real number called a “floating point number”. Representing $\sqrt{2}$ or $\frac{1}{3}$ perfectly would be impossible in a computer, so we use a finite amount of memory to do it.

Supplementary material:
- https://docs.python.org/2/tutorial/floatingpoint.html
- http://floating-point-gui.de/formats/fp/
- Advanced: http://docs.oracle.com/cd/E19957-01/806-3568/ncg_goldberg.html

## 5.2 Strings

Python has a built in string type, supporting many useful methods.

```
In [18]: given = "James"
   family = "Hetherington"
   full = given + " " + family

So + for strings means “join them together” - concatenate.
```
In [19]: print(full.upper())

JAMES HETHERINGTON

In [20]: 2*4
Out[20]: 8

As for `float` and `int`, the name of a type can be used as a function to convert between types:

In [21]: ten
Out[21]: 10
In [22]: one
Out[22]: 1
In [23]: type(ten)
Out[23]: int
In [24]: print(ten+one)
11

In [25]: print(float(str(ten) + str(one)))
101.0

We can remove extraneous material from the start and end of a string:

In [26]: 5
Out[26]: 5
In [27]: " Hello ".strip()
Out[27]: 'Hello'

5.3 Lists

Python’s basic container type is the list

We can define our own list with square brackets:

In [28]: [1, 3, 7]
Out[28]: [1, 3, 7]
In [29]: type([1, 3, 7])
Out[29]: list

Lists do not have to contain just one type:

In [30]: various_things = [1, 2, "banana", 3.4, [1,2] ]
We access an **element** of a list with an `int` in square brackets:

In [31]: one = 1
two = 2
three = 3

In [32]: my_new_list = [one, two, three]
In [33]: middle_value_in_list = my_new_list[1]
In [34]: middle_value_in_list
Out[34]: 2
In [35]: [1, 2, 3][1]
Out[35]: 2
In [36]: various_things[2]
Out[36]: 'banana'
In [37]: index = 2
   various_things[index]
Out[37]: 'banana'

Note that list indices start from zero.
We can quickly make a list with numbers counted up:

In [38]: count_to_five = list(range(5))
   print(count_to_five)
[0, 1, 2, 3, 4]

We can use a string to join together a list of strings:

In [39]: name = ['James', 'Philip', 'John', 'Hetherington']
   print(" -> ".join(name))
James -> Philip -> John -> Hetherington

And we can split up a string into a list:

In [40]: "Ernst Stavro Blofeld".split("o")
Out[40]: ['Ernst Stavr', ' B', 'feld']

We can an item to a list:

In [41]: name.append("Jr")
   print(name)
['James', 'Philip', 'John', 'Hetherington', 'Jr']

Or we can add more than one:

In [42]: name.extend(['the', "third"])
   print(name)
['James', 'Philip', 'John', 'Hetherington', 'Jr', 'the', 'third']
5.4 Sequences

Many other things can be treated like lists. Python calls things that can be treated like lists sequences. A string is one such sequence type

```
In [43]: print(count_to_five[1])
   print("James"[2])

1
m
```

```
In [44]: print(count_to_five[1:3])
   print("Hello World"[4:8])

[1, 2]
o Wo
```

```
In [45]: print(len(various_things))
   print(len("Python"))

5
6
```

```
In [46]: len([[1, 2], 4])

Out[46]: 2
```

```
In [47]: print("John" in name)
   print(9 in count_to_five)

True
False
```

5.5 Unpacking

Multiple values can be unpacked when assigning from sequences, like dealing out decks of cards.

```
In [48]: mylist = ['Goodbye', 'Cruel']
   a, b = mylist
   print(a)

Goodbye
```

```
In [49]: a = mylist[0]
   b = mylist[1]
```
Chapter 6

Containers

6.1 Checking for containment.

The list we saw is a container type: its purpose is to hold other objects. We can ask python whether or not a container contains a particular item:

In [1]: 'Dog' in ['Cat', 'Dog', 'Horse']
Out[1]: True

In [2]: 'Bird' in ['Cat', 'Dog', 'Horse']
Out[2]: False

In [3]: 2 in range(5)
Out[3]: True

In [4]: 99 in range(5)
Out[4]: False

6.2 Mutability

An array can be modified:

In [5]: name = "James Philip John Hetherington".split(" ")
   ...: print(name)
[['James', 'Philip', 'John', 'Hetherington']

In [6]: name[0] = "Dr"
   ...: name[1:3] = ["Griffiths-"
   ...: print(" ".join(name))
Dr Griffiths- Hetherington PhD
6.3 Tuples

A tuple is an immutable sequence:

In [7]: my_tuple = ('Hello', 'World')

In [8]: my_tuple

Out[8]: ('Hello', 'World')

In [9]: my_tuple[0] = 'Goodbye'

---------------------------------------------------------------------------

TypeError                                Traceback (most recent call last)
<ipython-input-9-98e64e9effd8> in <module>()
----> 1 my_tuple[0] = 'Goodbye'

TypeError: 'tuple' object does not support item assignment

str is immutable too:

In [10]: fish = "Hake"
   fish[0] = 'R'

---------------------------------------------------------------------------

TypeError                                Traceback (most recent call last)
<ipython-input-10-fe8069275347> in <module>()
    1 fish = "Hake"
----> 2 fish[0] = 'R'

TypeError: 'str' object does not support item assignment

But note that container reassignment is moving a label, **not** changing an element:

In [11]: fish = "Rake"  ## OK!

Supplementary material: Try the [online memory visualiser](https://example.com) for this one.

6.4 Memory and containers

The way memory works with containers can be important:

In [12]: x = list(range(3))
   print(x)

[0, 1, 2]
Supplementary material: This one works well at the [memory visualiser](http://www.python tutor.com/visualize.html?code=%%5B%%0A0, 1, 2%%0A%%0AIn [14]: z = x[0:3]%%0Ay[1] = "Gotcha!"%%0Aprint(x)%%0Aprint(y)%%0Aprint(z)%%0A[0, 'Gotcha!', 2]%%0A[0, 'Gotcha!', 2]%%0A[0, 1, 'Really?']

The explanation: While $y$ is a second label on the *same object*, $z$ is a separate object with the same data. Nested objects make it even more complicated:

In [18]: x = [['a', 'b'], 'c']
   y = x
   z = x[0:2]

   x[0][1] = 'd'
   z[1] = 'e'

In [20]: y
Try the [visualiser](http://www.pythontutor.com/visualize.html#code=x%3D%5B%5B'a','b'%5D,'c'%5D0Ay%3Dx%0Afrontend.js&cumulative=false&heapPrimitives=true&textReferences=false&py=2&rawInputLstJSON=%5B%5D&curInstr=0) again.

### 6.5 Identity vs Equality

Having the same data is different from being the same actual object in memory:

```
In [22]: print([1, 2] == [1, 2])
   print([1, 2] is [1, 2])

True
False
```

The `==` operator checks, element by element, that two containers have the same data. The `is` operator checks that they are actually the same object.

```
In [23]: [0, 1, 2] == range(3)
Out[23]: False
In [24]: [0, 1, 2] is range(3)
Out[24]: False
```

But, and this point is really subtle, for immutables, the python language might save memory by reusing a single instantiated copy. This will always be safe.

```
In [25]: print("Hello" == "Hello")
   print("Hello" is "Hello")

True
True
```
Chapter 7

Dictionaries

7.1 The Python Dictionary

Python supports a container type called a dictionary. This is also known as an “associative array”, “map” or “hash” in other languages. In a list, we use a number to look up an element:

```
In [1]: names="Martin Luther King".split(" ")
names[1]
Out[1]: 'Luther'
```

In a dictionary, we look up an element using another object of our choice:

```
In [2]: me = { "name": "James", "age": 39, "Jobs": ["Programmer", "Teacher"] }
In [3]: print(me)
{'Jobs': ['Programmer', 'Teacher'], 'name': 'James', 'age': 39}
```

```
In [4]: print(me['Jobs'])
['Programmer', 'Teacher']
```

```
In [5]: print(type(me))
<class 'dict'>
```

7.2 Keys and Values

The things we can use to look up with are called keys:

```
In [6]: me.keys()
Out[6]: dict_keys(['Jobs', 'name', 'age'])
```

The things we can look up are called values:

```
In [7]: me.values()
```
Out[7]: dict_values([['Programmer', 'Teacher'], 'James', 39])

When we test for containment on a dict we test on the keys:

In [8]: 'Jobs' in me
Out[8]: True

In [9]: 'James' in me
Out[9]: False

In [10]: 'James' in me.values()
Out[10]: True

7.3 Immutable Keys Only

The way in which dictionaries work is one of the coolest things in computer science: the “hash table”. This is way beyond the scope of this course, but it has a consequence:

You can only use immutable things as keys.

In [11]: good_match = {"Lamb", "Mint": True, "Bacon", "Chocolate": False}

but:

In [12]: illegal = {[1,2]: 3}

Supplementary material: You can start to learn about the ‘hash table’ here. This material is very advanced, but, I think, really interesting!

7.4 No guarantee of order

Another consequence of the way dictionaries work is that there’s no guaranteed order among the elements:

In [13]: my_dict = {'0': 0, '1':1, '2': 2, '3': 3, '4': 4}
print(my_dict)
print(my_dict.values())

{'4': 4, '0': 0, '1': 1, '2': 2, '3': 3}
dict_values([4, 0, 1, 2, 3])

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7.5 Sets

A set is a list which cannot contain the same element twice.

In [14]: name = "James Hetherington"
    unique_letters = set(name)

In [15]: unique_letters

Out[15]: {' ', 'H', 'J', 'a', 'e', 'g', 'h', 'i', 'm', 'n', 'o', 'r', 's', 't'}

In [16]: print("".join(unique_letters))

It has no particular order, but is really useful for checking or storing unique values.

In [18]: alist = [1, 2, 3]
    is_unique = len(set(alist)) == len(alist)
    print(is_unique)

True

7.6 Safe Lookup

In [19]: x = {'a':1, 'b':2}

In [20]: x['a']

Out[20]: 1

In [21]: x['fish']

---------------------------------------------------------------------------
KeyError                                 Traceback (most recent call last)
<ipython-input-21-81af752ce649> in <module>()
----> 1 x['fish']

KeyError: 'fish'

In [22]: x.get('a')

Out[22]: 1

In [23]: x.get('fish')

In [24]: x.get('fish', 'tuna') == 'tuna'

Out[24]: True
Chapter 8

Data structures

8.1 Nested Lists and Dictionaries

In research programming, one of our most common tasks is building an appropriate structure to model our complicated data. Later in the course, we’ll see how we can define our own types, with their own attributes, properties, and methods. But probably the most common approach is to use nested structures of lists, dictionaries, and sets to model our data. For example, an address might be modelled as a dictionary with appropriately named fields:

```
In [1]: UCL={
    'City': 'London',
    'Street': 'Gower Street',
    'Postcode': 'WC1E 6BT'}
```

```
In [2]: James={
    'City': 'London',
    'Street': 'Waterson Street',
    'Postcode': 'E2 8HH'
}
```

A collection of people’s addresses is then a list of dictionaries:

```
In [3]: addresses=[UCL, James]
```

```
In [4]: addresses
Out[4]: [{'City': 'London', 'Postcode': 'WC1E 6BT', 'Street': 'Gower Street'},
         {'City': 'London', 'Postcode': 'E2 8HH', 'Street': 'Waterson Street'}]
```

A more complicated data structure, for example for a census database, might have a list of residents or employees at each address:

```
In [5]: UCL['people']=['Clare', 'James', 'Owain']
```

```
In [6]: James['people']=['Sue', 'James']
```

```
In [7]: addresses
Out[7]: [{'City': 'London',
         'Postcode': 'WC1E 6BT',
         'Street': 'Gower Street',
         'people': ['Clare', 'James', 'Owain']},
         {'City': 'London',
         'Postcode': 'E2 8HH',
         'Street': 'Waterson Street',
         'people': ['Sue', 'James']}
```
Which is then a list of dictionaries, with keys which are strings or lists. We can go further, e.g.:

```
In [8]: UC['Residential']=False
```

And we can write code against our structures:

```
In [9]: leaders = [place['people'][0] for place in addresses]
   print(leaders)
['Clare', 'Sue']
```

This was an example of a ‘list comprehension’, which have used to get data of this structure, and which we’ll see more of in a moment...

### 8.2 Exercise: a Maze Model.

Work with a partner to design a data structure to represent a maze using dictionaries and lists.

- Each place in the maze has a name, which is a string.
- Each place in the maze has zero or more people currently standing at it, by name.
- Each place in the maze has a maximum capacity of people that can fit in it.
- From each place in the maze, you can go from that place to a few other places, using a direction like ‘up’, ‘north’, or ‘sideways’

Create an example instance, in a notebook, of a simple structure for your maze:

- The front room can hold 2 people. James is currently there. You can go outside to the garden, or upstairs to the bedroom, or north to the kitchen.
- From the kitchen, you can go south to the front room. It fits 1 person.
- From the garden you can go inside to living room. It fits 3 people. Sue is currently there.
- From the bedroom, you can go downstairs. You can also jump out of the window to the garden. It fits 2 people.

Make sure that your model:

- Allows empty rooms
- Allows you to jump out of the upstairs window, but not to fly back up.
- Allows rooms which people can’t fit in.

```
In [10]: cities = [{'name': "London", "capacity": 8, "residents": ["Me","Sue"],
                   'name': "Edinburgh", "capacity": 1, "residents": ["Dave"]},
                   {'name': "Cardiff", "capacity": 1, "residents": []}]

In [11]: len(cities[2]['residents'])
Out[11]: 0
In [12]:
```
8.2.1 Solution: my Maze Model

Here’s one possible solution to the Maze model. Yours will probably be different, and might be just as good. That’s the artistry of software engineering: some solutions will be faster, others use less memory, while others will be easier for other people to understand. Optimising and balancing these factors is fun!

```python
In [1]: house = {
    'living' : {
        'exits' : {
            'north' : 'kitchen',
            'outside': 'garden',
            'upstairs': 'bedroom'
        },
        'people' : ['James'],
        'capacity' : 2
    },
    'kitchen' : {
        'exits' : {
            'south' : 'living'
        },
        'people' : [],
        'capacity' : 1
    },
    'garden' : {
        'exits' : {
            'inside' : 'living'
        },
        'people' : ['Sue'],
        'capacity' : 3
    },
    'bedroom' : {
        'exits' : {
            'downstairs' : 'living',
            'jump' : 'garden'
        },
        'people' : [],
        'capacity' : 1
    }
}
```

Some important points:

- The whole solution is a complete nested structure.
- I used indenting to make the structure easier to read.
- Python allows code to continue over multiple lines, so long as sets of brackets are not finished.
- There is an Empty person list in empty rooms, so the type structure is robust to potential movements of people.
- We are nesting dictionaries and lists, with string and integer data.

```python
In [2]: people_so_far = 0

    for room_name in house:
        people_so_far = people_so_far + len(house[room_name][\'people\'])

print people_so_far
```
File "<ipython-input-2-a3d2f066e414>", line 6
print people_so_far
^ SyntaxError: Missing parentheses in call to 'print'

In [3]:
Chapter 9
Control and Flow

9.1 Turing completeness

Now that we understand how we can use objects to store and model our data, we only need to be able to control the flow of our program in order to have a program that can, in principle, do anything!

Specifically we need to be able to:

• Control whether a program statement should be executed or not, based on a variable. “Conditionality”
• Jump back to an earlier point in the program, and run some statements again. “Branching”

Once we have these, we can write computer programs to process information in arbitrary ways: we are Turing Complete!

9.2 Conditionality

Conditionality is achieved through Python’s if statement:

```
In [1]: x = -3
    if x < 0:
        print(x, " is negative")
        print("This is controlled")
        print("Always run this")

-3 is negative
This is controlled
Always run this
```

The first time through, the print statement never happened.

The controlled statements are indented. Once we remove the indent, the statements will once again happen regardless.

9.3 Else and Elif

Python’s if statement has optional elif (else-if) and else clauses:

```
In [2]: x = -3
    if x < 0:
        print("x is negative")
```

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else:
    print("x is positive")

x is negative

In [3]: x = 5
    if x < 0:
        print("x is negative")
    elif x == 0:
        print("x is zero")
    else:
        print("x is positive")

x is positive

Try editing the value of x here, and note that other sections are found.

In [4]: choice = 'dlgkdglkgk jhdjkg'
    if choice == 'high':
        print(1)
    elif choice == 'medium':
        print(2)
    else:
        print(3)

3

9.4 Comparison

True and False are used to represent boolean (true or false) values.

In [5]: 1 > 2

Out[5]: False

Comparison on strings is alphabetical.

In [6]: "UCL" > "King's"

Out[6]: True

There’s no automatic conversion of the string True to true:

In [7]: True == "True"

Out[7]: False

Be careful not to compare values of different types. At best, the language won’t allow it and an issue an error, at worst it will allow it and do some behind-the-scene conversion that may be surprising.

In [8]: '1' < 2