COMP110: Principles of Computing

# 7: Data structures

# Learning outcomes

- **Explain** the difference between pass-by-value and pass-by-reference
- **Distinguish** the basic data structures available in Python
- **Determine** the complexity of accessing and manipulating data in these data structures
- **Choose** the correct data structure for a given task

# Worksheet D

- Data structures
- Due in class on **Monday 7th November** (next week)

# Pass by reference

# References

- Our picture of a variable: a labelled box containing a value
- For “plain old data” (e.g. numbers), this is accurate
- For **objects** (i.e. instances of classes), variables actually hold **references** (a.k.a. **pointers**)
- It is possible (indeed common) to have **multiple references** to the same underlying object

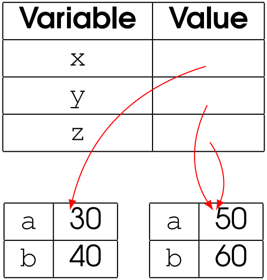
# The wrong picture

```
class Thing:
    def __init__(self,
                 a, b):
        self.a = a
        self.b = b

x = Thing(30, 40)
y = Thing(50, 60)
z = y
```

| Variable | Value | |
|---|---|---|
| x | a | 30 |
| | b | 40 |
| y | a | 50 |
| | b | 60 |
| z | a | 50 |
| | b | 60 |

# The right picture

```
class Thing:
    def __init__(self,
                 a, b):
        self.a = a
        self.b = b

x = Thing(30, 40)
y = Thing(50, 60)
z = y
```



# Values and references

Socrative room code: `FALCOMPED`

```
a = 10
b = a
a = 20
print "a:", a
print "b:", b
```

| Variable | Value |
|---|---|
| a | |
| b | |

# Values and references

Socrative room code: `FALCOMPED`

```
class X:
    def __init__(self, value):
        self.value = value

a = X(10)
b = a
a.value = 20
print "a:", a.value
print "b:", b.value
```

| Variable | Value |
|---|---|
| a | |
| b | |

# Values and references

Socrative room code: `FALCOMPED`

```
class X:
    def __init__(self, value):
        self.value = value

a = X(10)
b = X(10)
a.value = 20
print "a:", a.value
print "b:", b.value
```

| Variable | Value |
| --- | --- |
| a | |
| b | |

# Pass by value

In **function parameters**, “plain old data” is passed by **value**

```
def double(x):
    x *= 2

a = 7
double(a)
print a
```

`double` does not actually do anything, as `x` is just a local copy of whatever is passed in!

# Pass by reference

However, instances are passed by **reference**

```
class Box:
    def __init__(self, v):
        self.value = v

def double(x):
    x.value *= 2

a = Box(7)
double(a)
print a.value
```

`double` now has an effect, as `x` gets a reference to the `Box` instance

# Lists are objects too

```
a = ["Hello"]
b = a
b.append("world")
print a  # ["Hello", "world"]
```

... which means you should be careful when passing lists into functions, because the function might actually change the list!

# Basic containers in Python

# Memory allocation

- Memory is allocated in **blocks**
- The program specifies the size, in bytes, of the block it wants
- The OS allocates a **contiguous** block of that size
- The program owns that block until it frees it
- Forgetting to free a block is called a **memory leak** (not really possible in Python, but a common bug in C++)
- Blocks can be allocated and deallocated at will, but can **never grow or shrink**

# Containers

- Memory management is hard and programmers are lazy
- Containers are an **abstraction**
  - Hide the details of memory allocation, and allow the programmer to write simpler code
- Containers are an **encapsulation**
  - Bundle together the data's representation in memory along with the algorithms for accessing it

# Arrays

- An **array** is a contiguous block of memory in which objects are stored, equally spaced, one after the other
- Each array element has an **index**, starting from zero
- Given the address of the 0th element, it is easy to find the $i$th element:

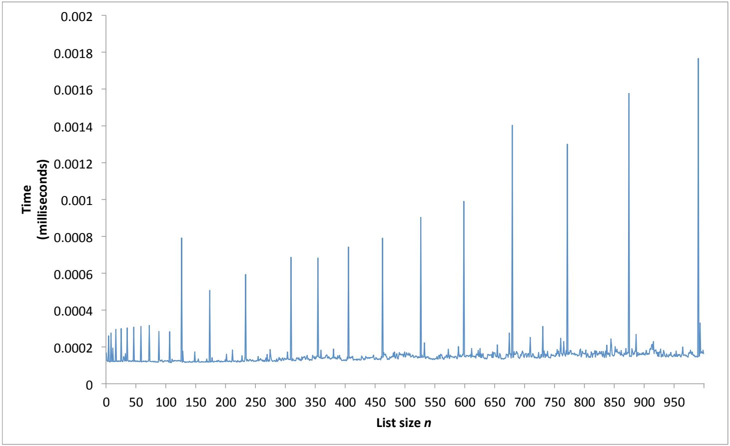
$$\text{address}_i = \text{address}_0 + (i \times \text{elementSize})$$

- E.g. if the array starts at address 1000 and each element is 4 bytes, the 3rd element is at address $1000 + 4 \times 3 = 1012$
- Accessing an array element is **constant time** $O(1)$

# Lists

- An array is a block of memory, so its size is **fixed** once created
- A **list** is a variable size array
- When the list needs to change size, it **creates** a new array, **copies** the contents of the old array, and **deletes** the old array
- Implementation details: `http://www.laurentluce.com/posts/python-list-implementation/`

# Time taken to append an element to a list of size *n*



# Operations on lists

- **Appending** to a list is **amortised constant time**
  - Usually $O(1)$, but can go up to $O(n)$ if the list needs to change size
- **Inserting** anywhere other than the end is **linear time**
  - Can't just insert new bytes into a memory block — need to move all subsequent list elements to make room
- Similarly, **deleting** anything other than the last element is **linear time**

# Tuples

- Tuples are like lists, but are **immutable**
  - Read-only
  - Once created, can't be changed
- Useful for storing sequences of values where adding, inserting, deleting or changing individual values does not make sense
  - E.g. *xy* coordinates, RGB colours, ...
- Create tuples with `()`, just as you create lists with `[]`
  - Exception: a single element tuple is created as `(foo,)` because `(foo)` would be interpreted as a bracketed expression
- Can often omit the parentheses entirely, e.g.

```
my_tuple = 1,2,3
```

# Unpacking

If `foo` is a list or tuple of length 4, the following are equivalent:

```
a, b, c, d = foo
```

```
a = foo[0]
b = foo[1]
c = foo[2]
d = foo[3]
```

- Unpacking requires the number of elements to match exactly — if `foo` has more than 4 elements, the code on the left will give an error

# One weird trick (Java programmers hate it!)

The following are equivalent:

```
a, b = b, a
```

```
temp = a
a = b
b = temp
```

# Strings are immutable

- **Strings** are immutable in Python
  - This is not true of all programming languages
- But wait... we change strings all the time, don't we?

```
my_string = "Hello "
my_string += "world"
```

- This isn't changing the string, it's creating a new one and throwing the old one away!
- Hence building a long string by appending can be slow (appending strings is $O(n)$)

# Dictionaries

- Dictionaries are **associative maps**
- A dictionary maps **keys** to **values**
  - Keys must be immutable (numbers, strings, tuples etc)
  - Values can be anything (including dictionaries or other containers)
- A dictionary is implemented as a **hash table** (see Session 5)

# Using dictionaries

Create them using `{}`:

```
age = {"Alice": 23, "Bob": 36, "Charlie": 27}
```

Access values using `[]`:

```
print age["Alice"]  # prints 23
age["Bob"] = 40     # overwriting an existing item
age["Denise"] = 21  # adding a new item
```

# Iterating over dictionaries

Iterating over a dictionary gives the **keys**:

```
for x in age:
    print x    # prints Alice, Bob, Charlie
```

Use `iteritems` to get **key,value** pairs:

```
for key, value in age.iteritems():
    print key, "is", age, "years old"
```

# Dictionaries are unordered

What does this print?

```
square_root = {}
for i in xrange(30):
    square_root[i*i] = i

for key, value in square_root.iteritems():
    print "The square root of", key, "is", value
```

Dictionaries are **unordered** — never rely on the order of their elements, because the order isn't guaranteed!

# Sets

- Sets are like dictionaries without the values
- Sets are **unordered** collections of **unique** elements
- Certain operations on sets scale better on average than the equivalent operations on lists:

| **Operation** | **List** | **Set** |
|---|---|---|
| Add element | Append: $O(1)$<br>Insert: $O(n)$ | $O(1)$ |
| Delete element | $O(n)$ | $O(1)$ |
| Contains element? | $O(n)$ | $O(1)$ |

# 2-dimensional arrays

# 2-dimensional arrays

Common problem: we want to represent a **2-dimensional array** of values (i.e. a grid)

$$
\begin{array}{cccc}
v_{0,0} & v_{1,0} & \cdots & v_{w-1,0} \\
v_{0,1} & v_{1,1} & \cdots & v_{w-1,1} \\
\vdots & \vdots & \ddots & \vdots \\
v_{0,h-1} & v_{1,h-1} & \cdots & v_{w-1,h-1}
\end{array}
$$

# Approach 1: flat list

- For a $w \times h$ array, create a list of size $wh$
- The element in column $x$ row $y$ is accessed by `list[y * w + x]`
- E.g. $w = 5, h = 4$:

| | | | | |
|---|---|---|---|---|
| 0 | 1 | 2 | 3 | 4 |
| 5 | 6 | 7 | 8 | 9 |
| 10 | 11 | 12 | 13 | 14 |
| 15 | 16 | 17 | 18 | 19 |

# Approach 2: list of lists

- For a $w \times h$ array, create a list of size $w$, where each element is a list of size $h$
  - Each element of the "outer" list represents a column of the array
- The element in column $x$ row $y$ is accessed by `list[x][y]`, i.e. the $y$th element of the $x$th column

# Approach 3: dictionary

- Represent the array as a dictionary whose keys are `(x,y)` tuples
- The element in column *x* row *y* is accessed by `list[x, y]`

# Approach 4: NumPy array

- Requires NumPy or SciPy, and can only store numeric types
- However, highly optimised for intensive calculations (e.g. “tinkering” with image pixel colours...?)

# Which is best?

- Flat list is reasonably efficient but not very readable
- List of lists is a reasonable trade-off between efficiency and readability
- Dictionary allows for “sparse” arrays (e.g. some cells can be missing)
- NumPy array is less versatile but faster in some use cases

There is no single “best” approach — it depends how you use it

# More data structures

# Stacks and queues

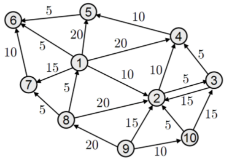
- A **stack** is a **last-in first-out (LIFO)** data structure
- Items can be **pushed** to the **top** of the stack
- Items can be **popped** from the **top** of the stack

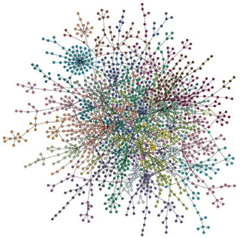
- A **queue** is a **first-in first-out (LIFO)** data structure
- Items can be **enqueued** to the **back** of the queue
- Items can be **dequeued** from the **front** of the queue

# Stacks and queues in Python

- Stacks can be implemented efficiently as lists
- Queues can be implemented as lists, but not efficiently
- `deque` (from the `collections` module) implements an efficient **double-ended queue**
- Inserting and removing elements from the start and end of a `deque` is $O(1)$

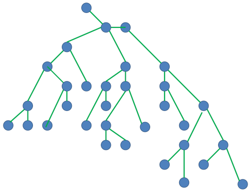
# Graphs

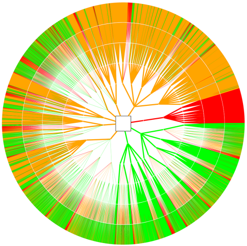


- A **graph** is defined by:
  - A collection of **nodes** or **vertices** (points)
  - A collection of **edges** or **arcs** (undirected lines or directed arrows between points)
- Often used to model **networks** (e.g. social networks, transport networks, game levels, finite state automata, ...)

# Trees





- A **tree** is a special type of directed graph where:
  - One node (the **root**) has no incoming edges
  - All other nodes have exactly 1 incoming edge
- Edges go from **parent** to **child**
  - All nodes except the root have exactly one parent
  - Nodes can have 0, 1 or many children
- Used to model **hierarchies** (e.g. file systems, object inheritance, scene graphs, state-action trees, ...)

*“Smart data structures and dumb code works a lot better than the other way around.”*

— Eric S. Raymond