

COMP110: Principles of Computing

8: Basic Data Structures

Learning outcomes

- ▶ **Distinguish** basic data structures such as arrays, linked lists and associative maps
- ▶ **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 **3 weeks' time**

Research Journal Peer Review



Basic containers in Python



Memory allocation

Memory allocation

- ▶ Memory is allocated in **blocks**

Memory allocation

- ▶ Memory is allocated in **blocks**
- ▶ The program specifies the size, in bytes, of the block it wants

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

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

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++)

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

Containers

- ▶ Memory management is hard and programmers are lazy

Containers

- ▶ Memory management is hard and programmers are lazy
- ▶ Containers are an **abstraction**

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

- ▶ 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**

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

Arrays

- ▶ An **array** is a contiguous block of memory in which objects are stored, equally spaced, one after the other

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

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:

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

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 $1000 + 4 \times 3 = 1012$

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

Lists

- ▶ An array is a block of memory, so its size is **fixed** once created

Lists

- ▶ An array is a block of memory, so its size is **fixed** once created
- ▶ A **list** is a variable size array

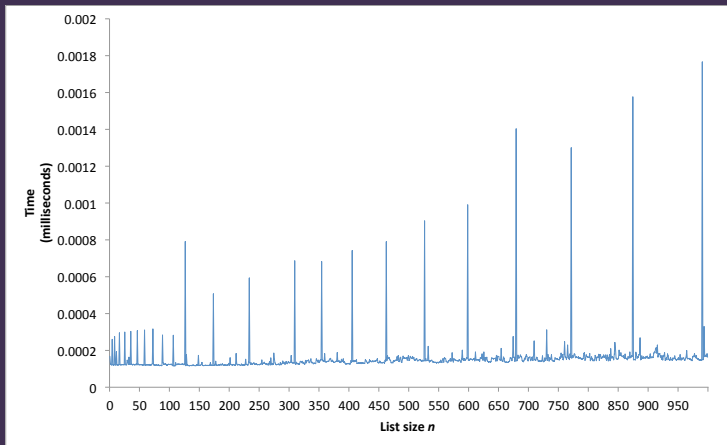
Lists

- ▶ 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

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

Operations on lists

- ▶ **Appending** to a list is **amortised constant time**

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

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**

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

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

- ▶ Tuples are like lists, but are **immutable**

Tuples

- ▶ Tuples are like lists, but are **immutable**
 - ▶ Read-only

Tuples

- ▶ Tuples are like lists, but are **immutable**
 - ▶ Read-only
 - ▶ Once created, can't be changed

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

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, ...

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 `[]`

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

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 `f○○` is a list or tuple of length 4, the following are equivalent:

Unpacking

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

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

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

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:

One weird trick (Java programmers hate it!)

The following are equivalent:

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

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

- ▶ **Strings** are immutable in Python

Strings are immutable

- ▶ **Strings** are immutable in Python
 - ▶ This is not true of all programming languages

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"
```


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!

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

- ▶ Dictionaries are **associative maps**

Dictionaries

- ▶ Dictionaries are **associative maps**
- ▶ A dictionary maps **keys** to **values**

Dictionaries

- ▶ Dictionaries are **associative maps**
- ▶ A dictionary maps **keys** to **values**
 - ▶ Keys must be immutable (numbers, strings, tuples etc)

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)

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**

Using dictionaries

Using dictionaries

Create them using {}:

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

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 dictionaries

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

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

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.items():  
    print key, "is", age, "years old"
```

Dictionaries are unordered

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

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

- ▶ Sets are like dictionaries without the values

Sets

- ▶ Sets are like dictionaries without the values
- ▶ Sets are **unordered** collections of **unique** elements

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:

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: $O(1)$ Insert: $O(n)$	$O(1)$
Delete element	$O(n)$	$O(1)$
Contains element?	$O(n)$	$O(1)$

Pass by reference



References

References

- Our picture of a variable: a labelled box containing a value

References

- ▶ Our picture of a variable: a labelled box containing a value
- ▶ For “plain old data” (e.g. numbers), this is accurate

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**)

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
```

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	
y	
z	

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		
z		

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		

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
```

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
```

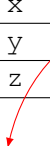
Variable	Value
x	
y	
z	

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
```

Variable	Value
x	
y	
z	



a	30
b	40

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
```

Variable	Value
x	
y	
z	

a	30
b	40

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
```

Variable	Value
x	
y	
z	

a	30
b	40

a	50
b	60

Values and references

Socrative room code: FALCOMPED

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


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
```

Pass by value

Pass by value

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

Pass by value

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

```
def double(x):  
    x *= 2  
  
a = 7  
double(a)  
print a
```

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

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
```

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

Lists are objects too

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

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!