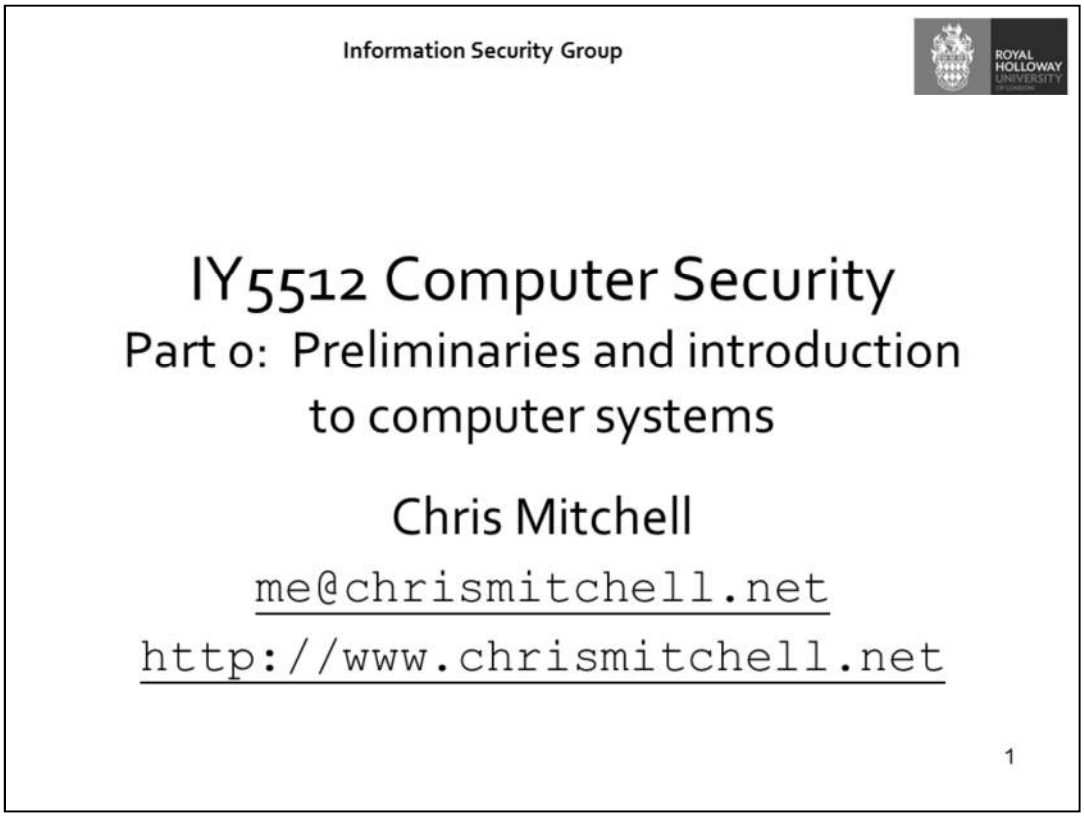
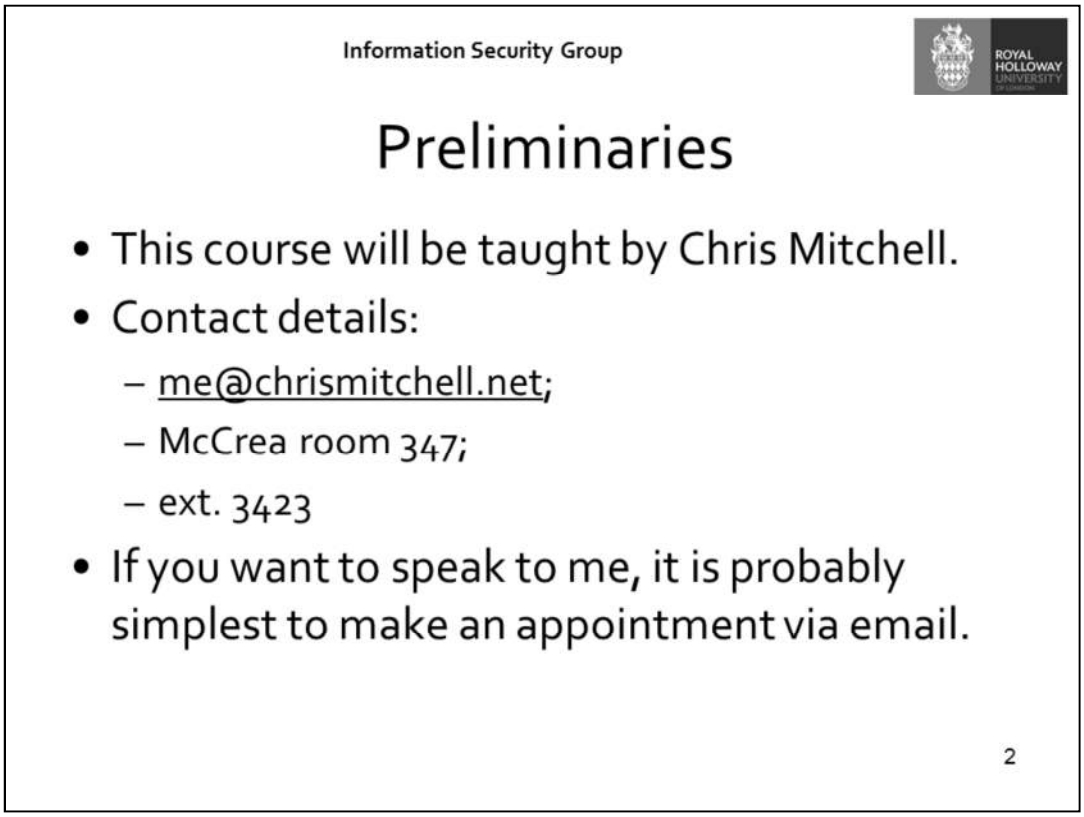


This course covers the topic of *Computer Security*.

This preliminary part of the course serves two main purposes:

• it introduces the content and format of the course material;

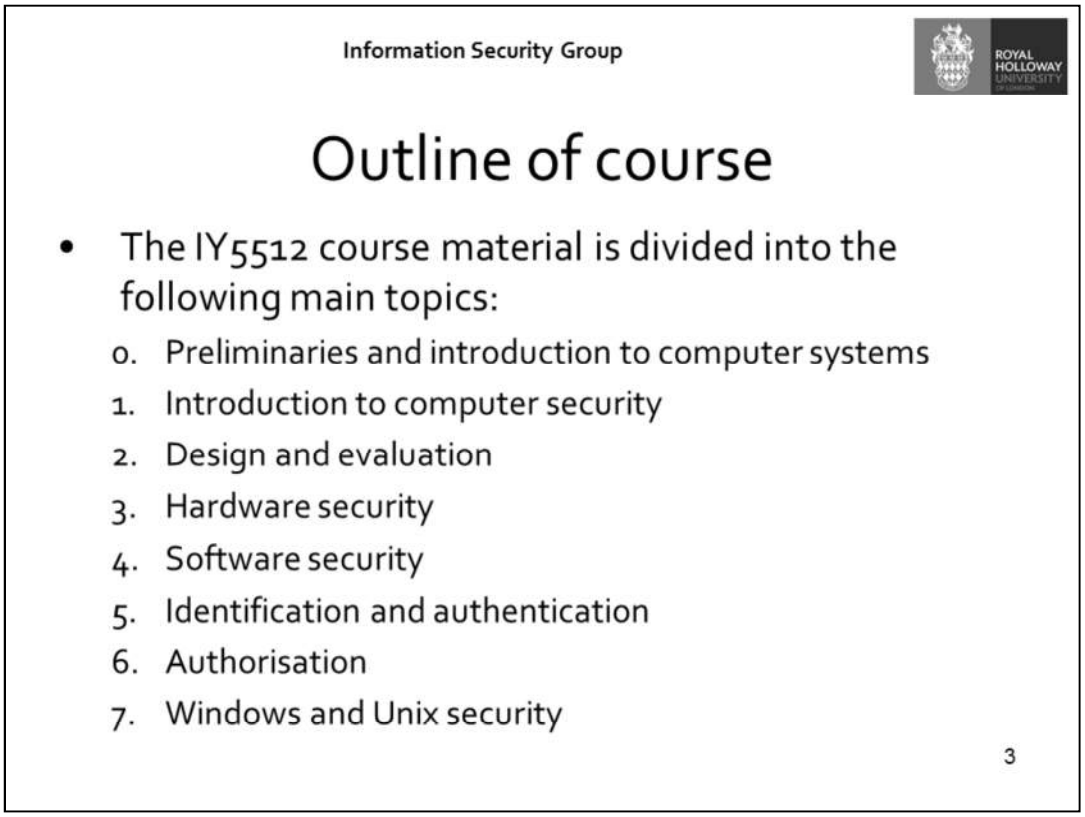
• it provides a brief introduction to computer systems, the main focus of this course.



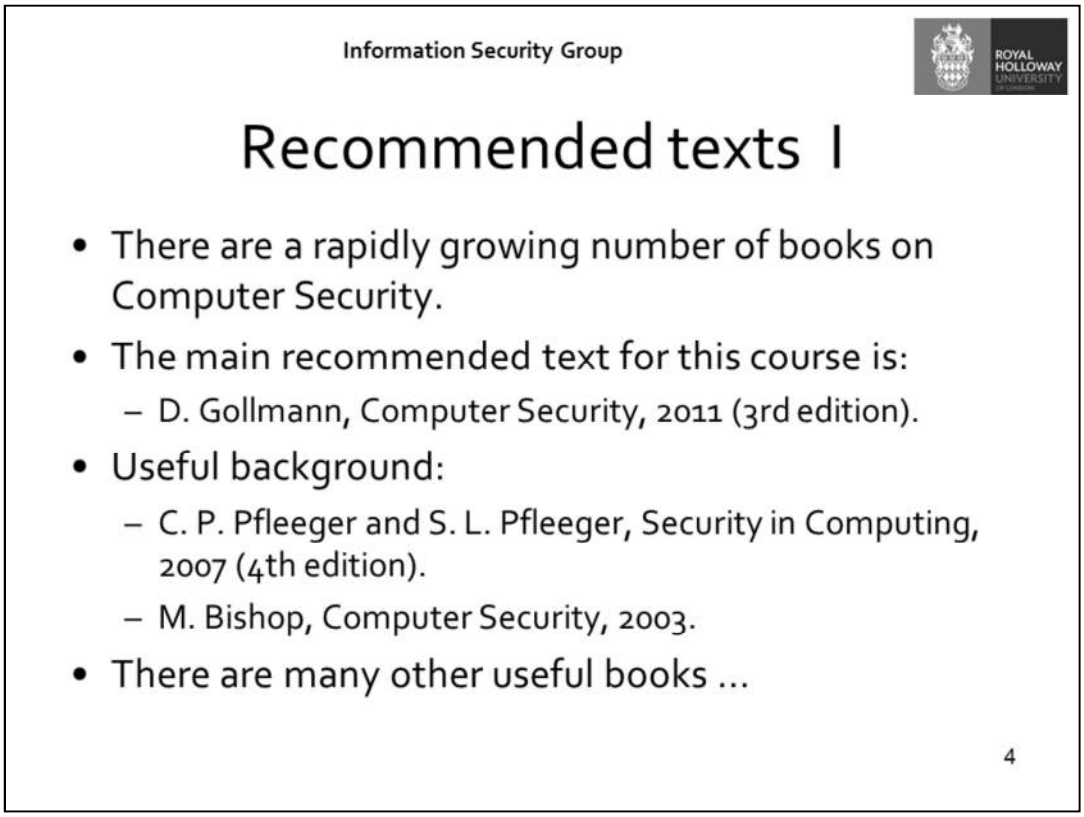
The vast majority of this course will be taught by Chris Mitchell. My contact details are as follows:

me@chrismitchell.net; McCrea room 347; ext. 3423

Whilst I am happy to see you at any time, if you can find me in my office, I am often busy seeing other students and I only work half-time. So it is probably best to make an appointment via email.



The eight main parts of the course are listed above. Each topic has a separate set of overheads and associated notes. In addition, the course involves a number of sets of coursework, which students should complete and hand in for assessment.



The main book recommended for the course is:

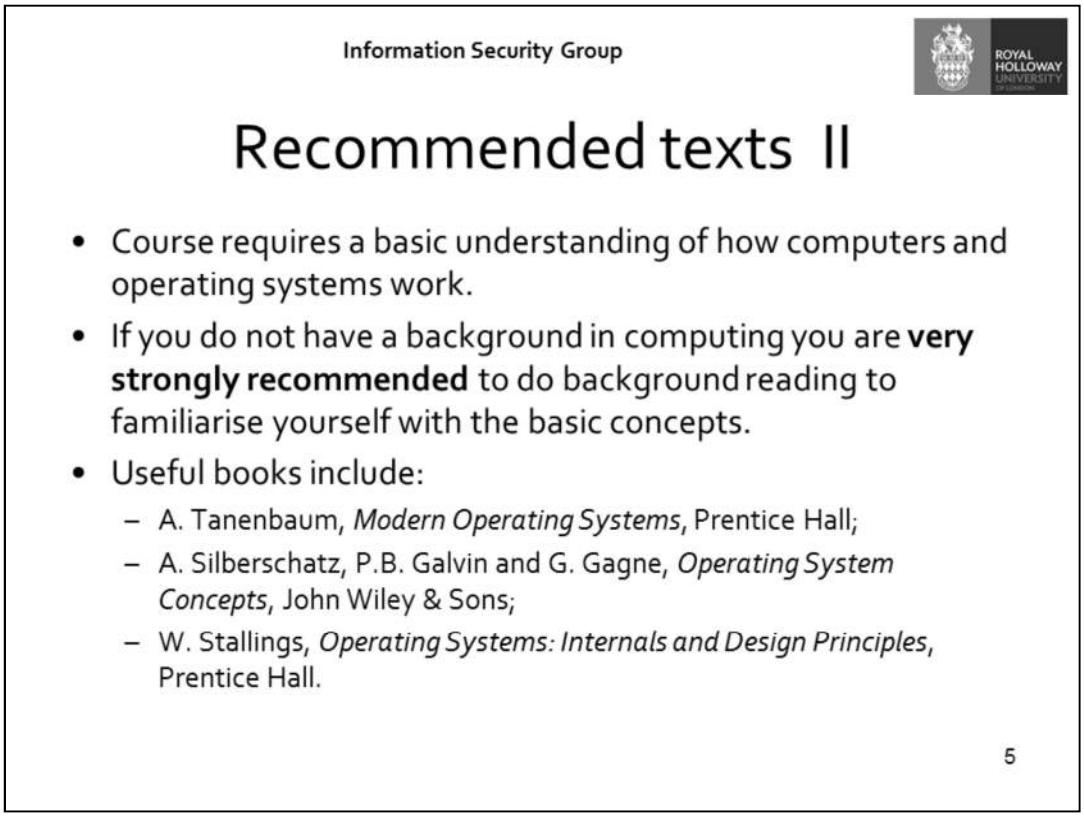
• D. Gollmann, *Computer Security*, John Wiley & Sons, 2011 (3rd edition).

The following are also useful references:

• C. P. Pfleeger and S. L. Pfleeger, *Security in Computing*, Prentice Hall, 2007 (4th edition).

• M. Bishop, *Computer Security*, Addison-Wesley, 2003.

There is an ever-growing number of other books covering similar topics.



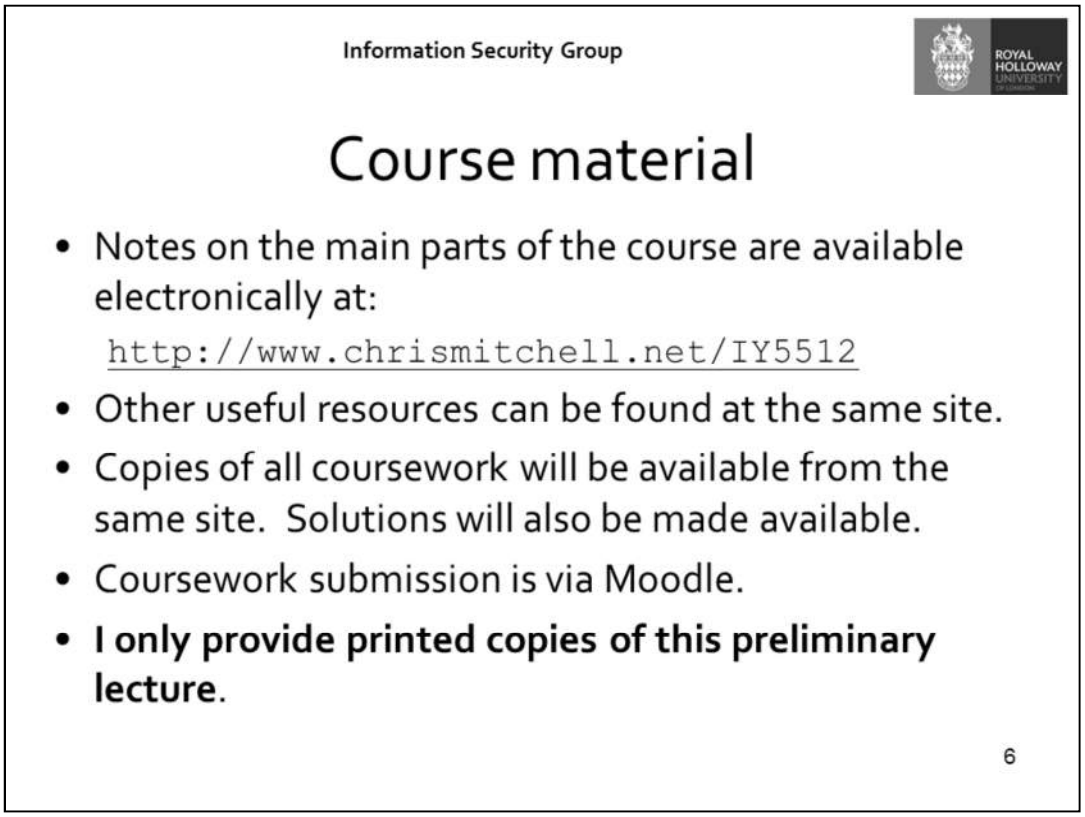
This course requires a basic understanding of how computers and operating systems work.

If you do not have a background in computing you are **very strongly recommended** to do the necessary background reading to familiarise yourself with the basic concepts of computers and operating systems.

There are large number of textbooks covering this material. Useful books include:

- A. Tanenbaum, *Modern Operating Systems*, Prentice Hall;
- A. Silberschatz, P.B. Galvin and G. Gagne, *Operating System Concepts*, John Wiley & Sons;
- W. Stallings, *Operating Systems: Internals and Design Principles*, Prentice Hall.

There is also a wealth of online material.



Notes on the main parts of the course are available electronically on the following web page:

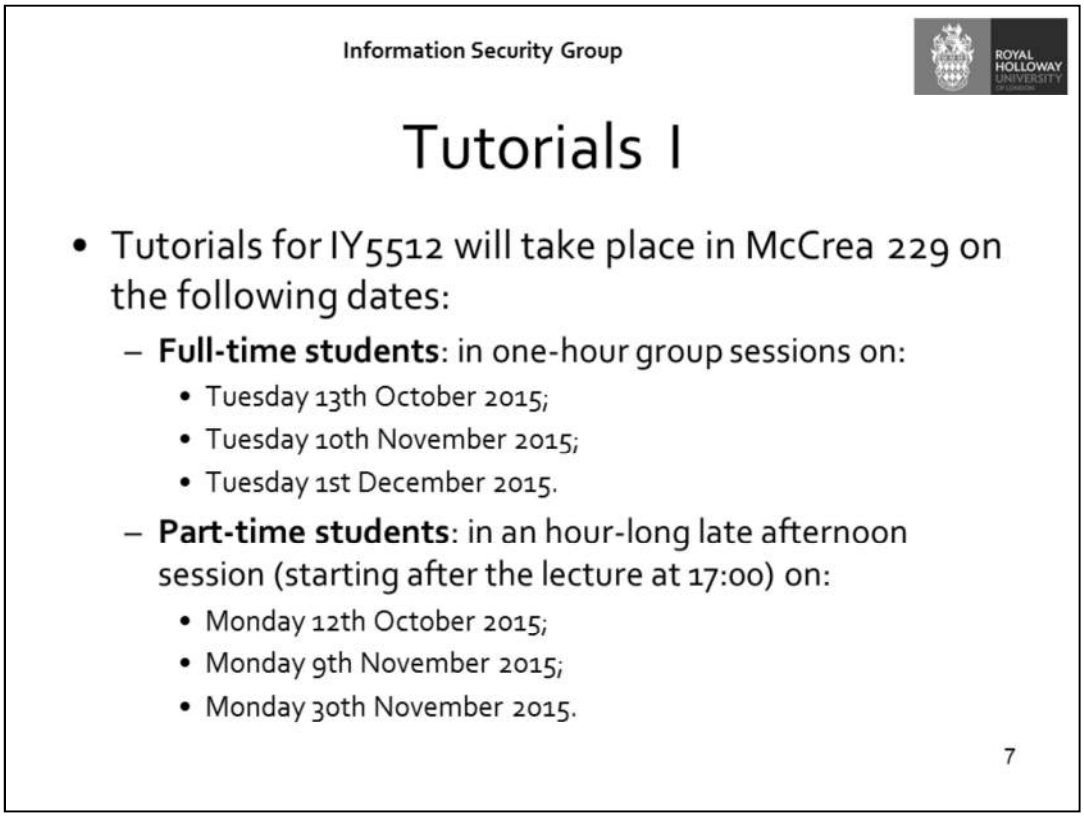
http://www.chrismitchell.net/IY5512

Other useful resources can be found at the same site. All suggestions for additions and corrections to this site will be gratefully received!

Copies of all coursework will be available from the same site. Worked solutions to exercises will be made available in due course (again on the same site).

Please **submit** your coursework for formative feedback via the course Moodle page.

Please note that, whilst I am providing printed copies of this preliminary lecture, you will have to make your own copies of subsequent parts of the course (if you want a hard copy, that is).



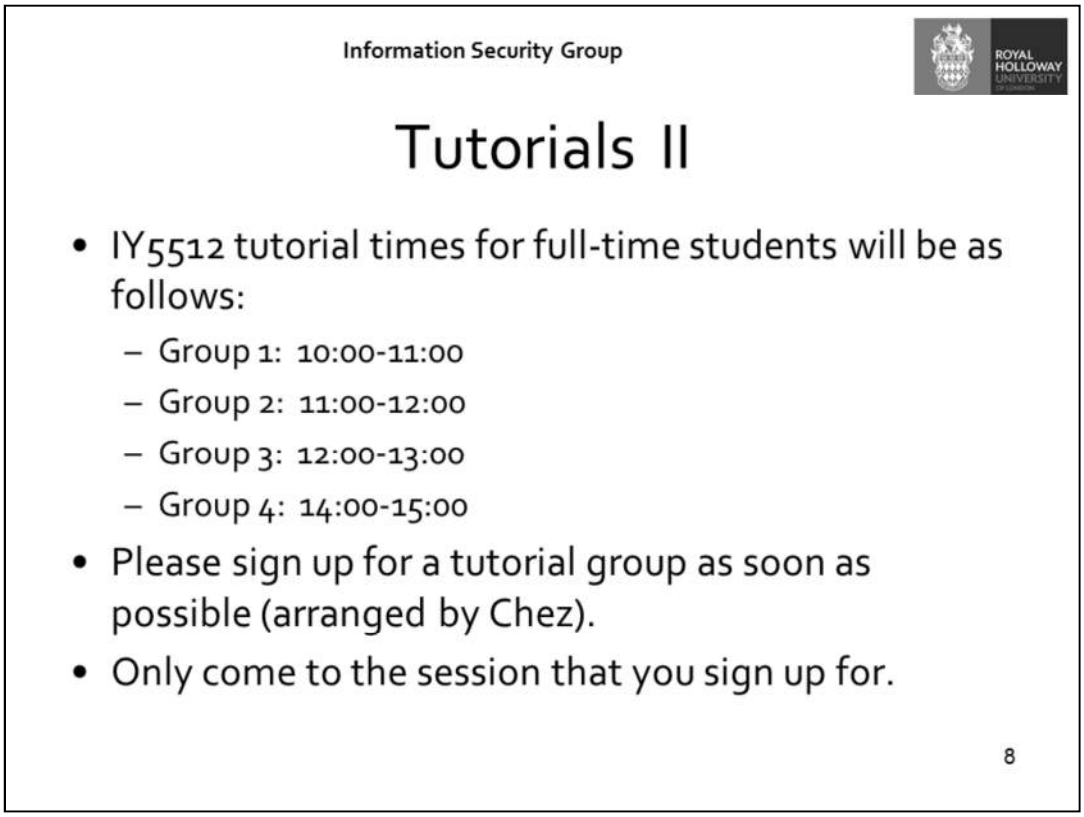
Tutorials for IY5512 will take place in McCrea 229 on the following dates.

Full-time students: in 60-minute group sessions on each of:

- Tuesday 13th October 2015;
- Tuesday 10th November 2015;
- Tuesday 1st December 2015.

Part-time students: in a 60-minute late afternoon session (starting after the lecture at 17:00) on each of:

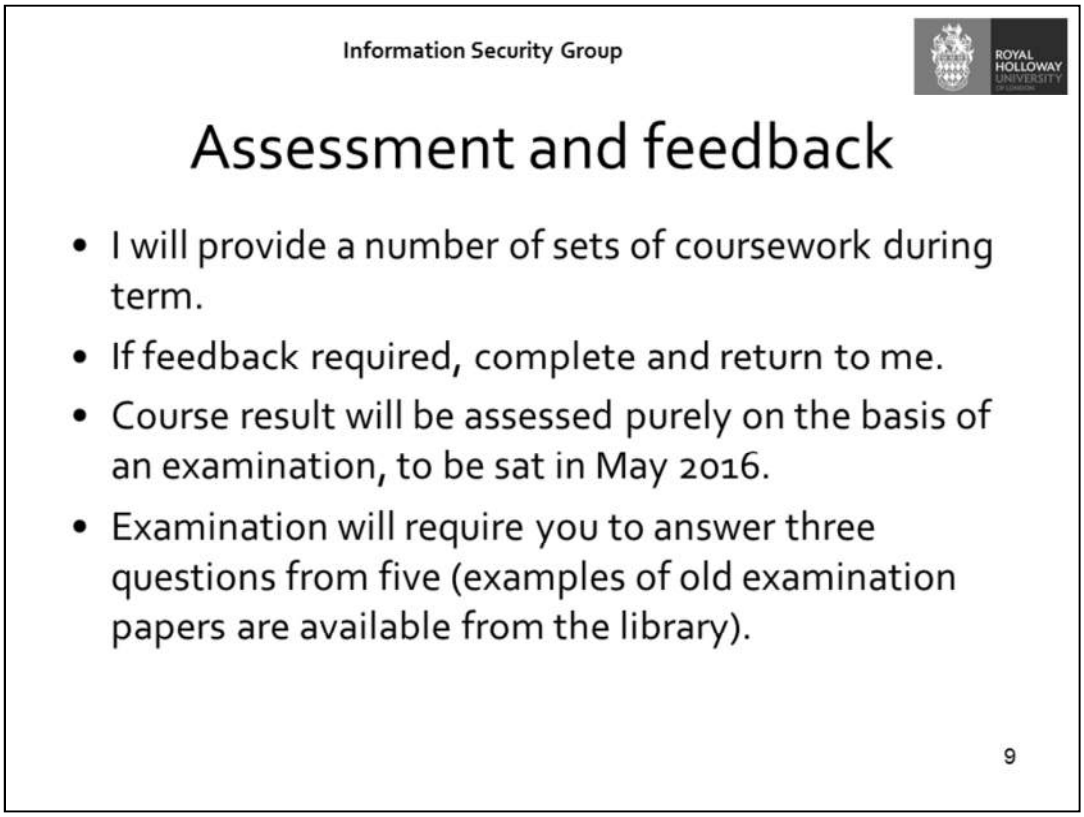
- Monday 12th October 2015;
- Monday 9th November 2015;
- Monday 30th November 2015.



The times of the IY5512 tutorials for full-time students will be as follows:

- Group 1: 10:00-11:00
- Group 2: 11:00-12:00
- Group 3: 12:00-13:00
- Group 4: 14:00-15:00

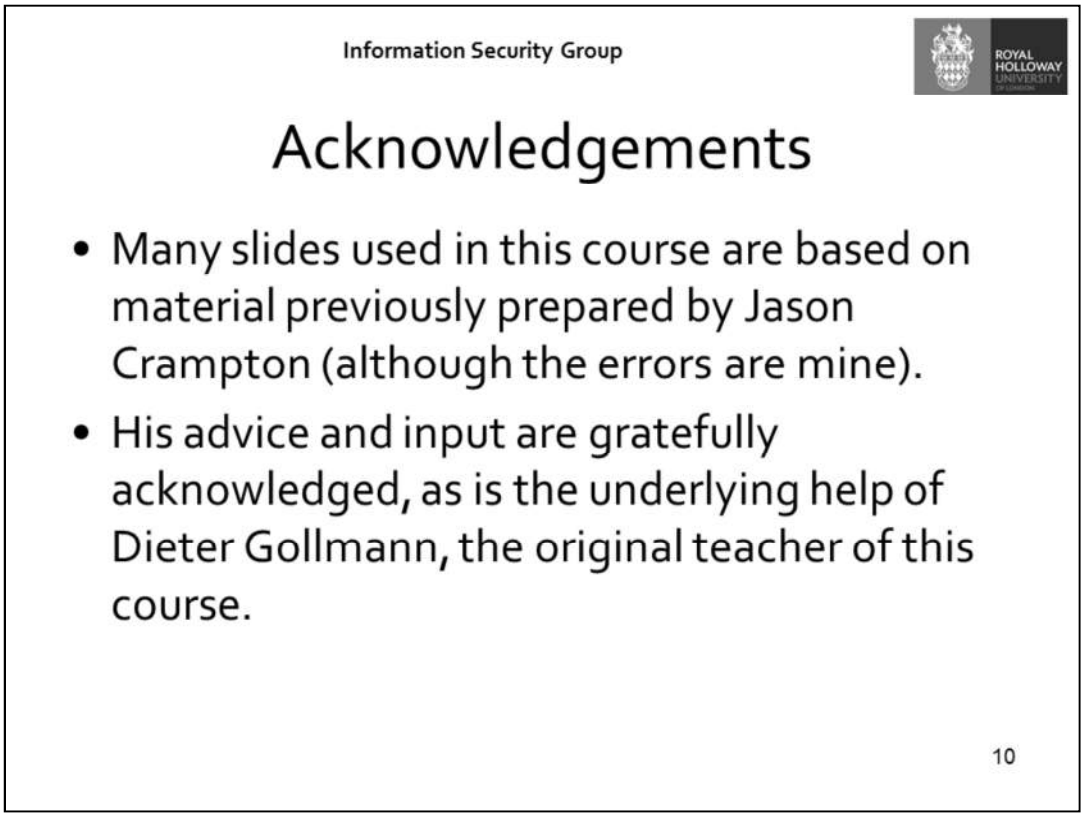
You should sign up for one of these tutorial groups, which apply to all first term courses, at the beginning of term (as arranged by Dr Ciechanowicz) and, apart from in exceptional circumstances, you should only come to the session that you sign up for.



I plan to provide a number of sets of coursework during the term, one for each part of the course. If feedback is required on solutions, then these should be returned to me via Moodle by the deadline marked on the coursework sheet.

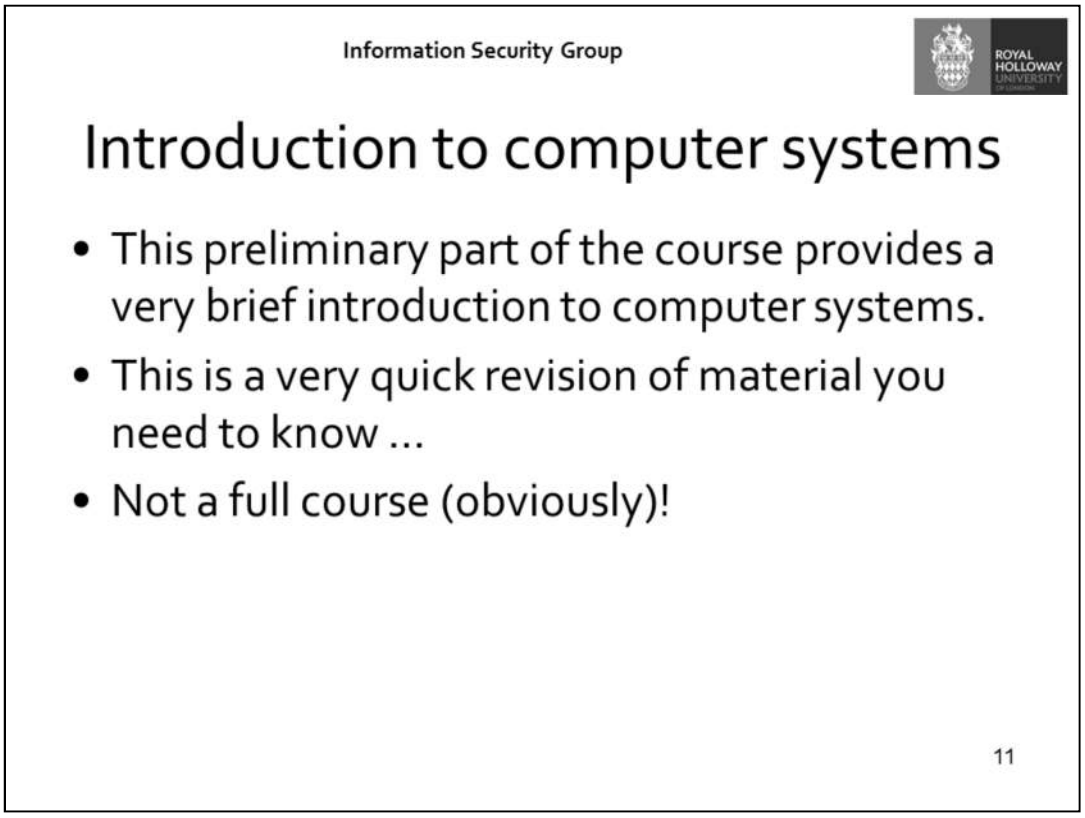
The final mark for this course will be assessed purely on the basis of an examination, to be sat in May 2016. The examination will require you to answer three questions from five (examples of previous years' examination papers are available from the library).

Important note: this is the sixth time I have taught this course and set the exam (starting in 2010/11), so do not expect precisely the same style of questions to arise in the examination as were set in the years before 2011.



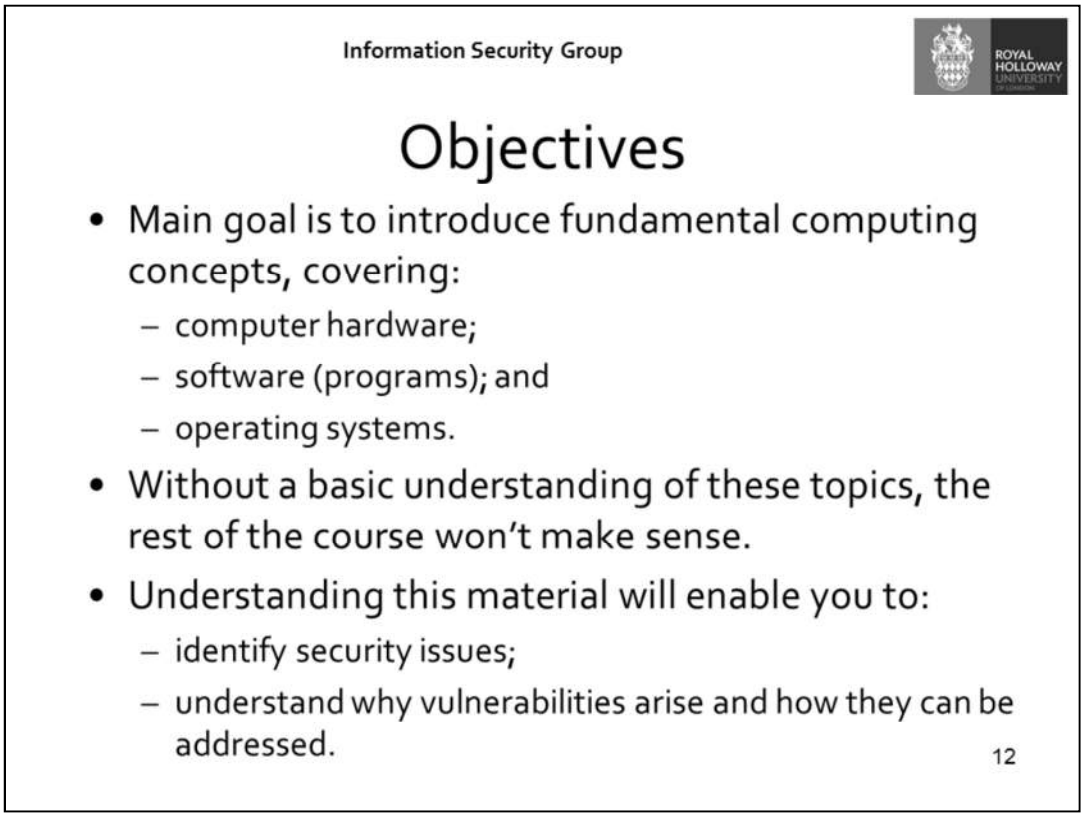
Many of the slides used in this year's version of the course are based on material previously prepared by Jason Crampton (although any errors are due to me).

His advice and input are gratefully acknowledged, as is the underlying help of Dieter Gollmann, the original teacher of this course.



In the remainder of this preliminary part of the course, we provide a very brief introduction to computer systems.

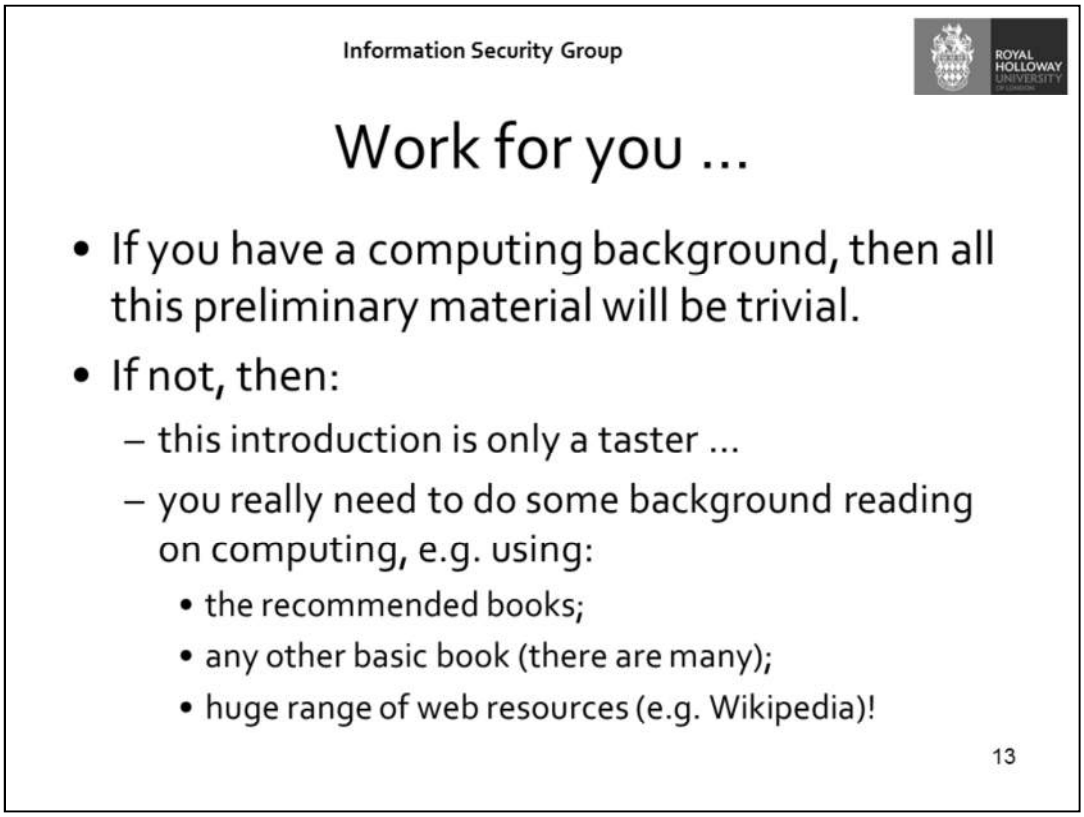
The purpose is to provide you with a very quick reminder of some fundamental topics, understanding of which is necessary to understand the material in this course. This material is NOT intended as a full course – it is just a quick summary intended to highlight areas that you need to understand.



The main goal of this part of the course is to introduce a number of fundamental computing concepts, covering:

- computer hardware;
- computer software (programs); and
- operating systems.

Without a basic understanding of such matters, the rest of the course won't make sense; in particular having a basic understanding of how computers work will enable you to identify security issues, understand why vulnerabilities arise, and see how vulnerabilities can be addressed.

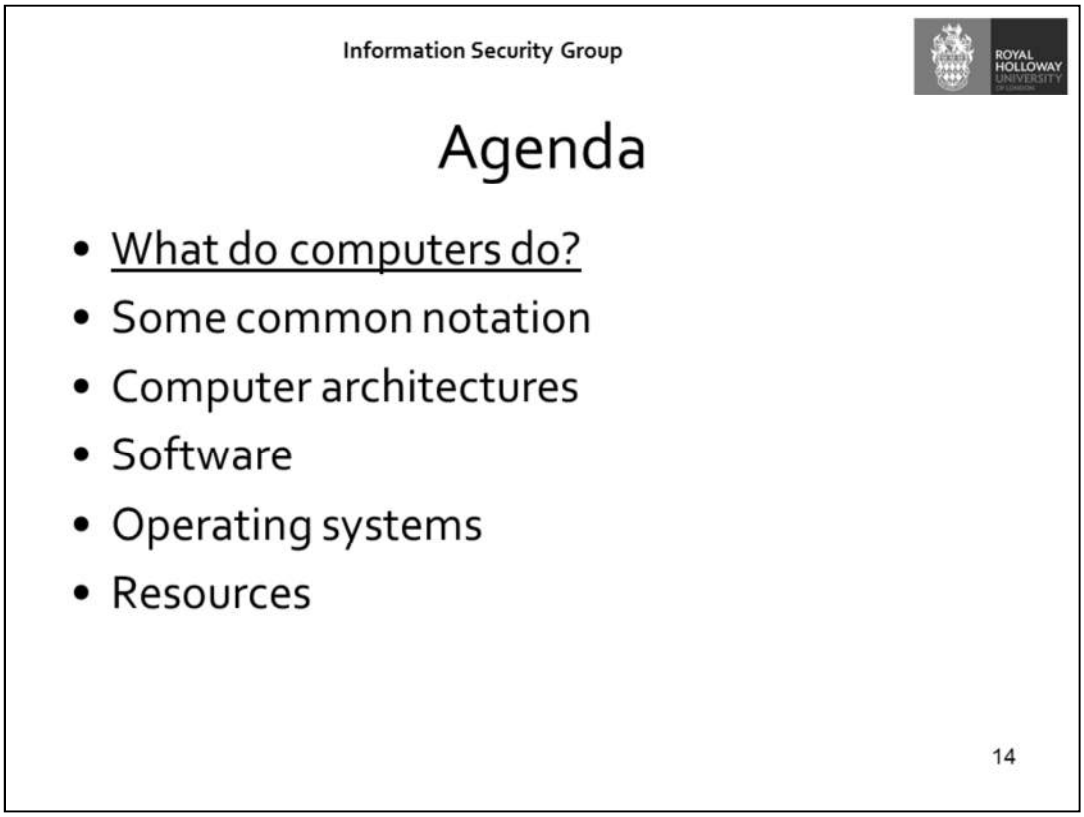


If you have a computing background, then you are likely to find all the material in this part of the course somewhat trivial.

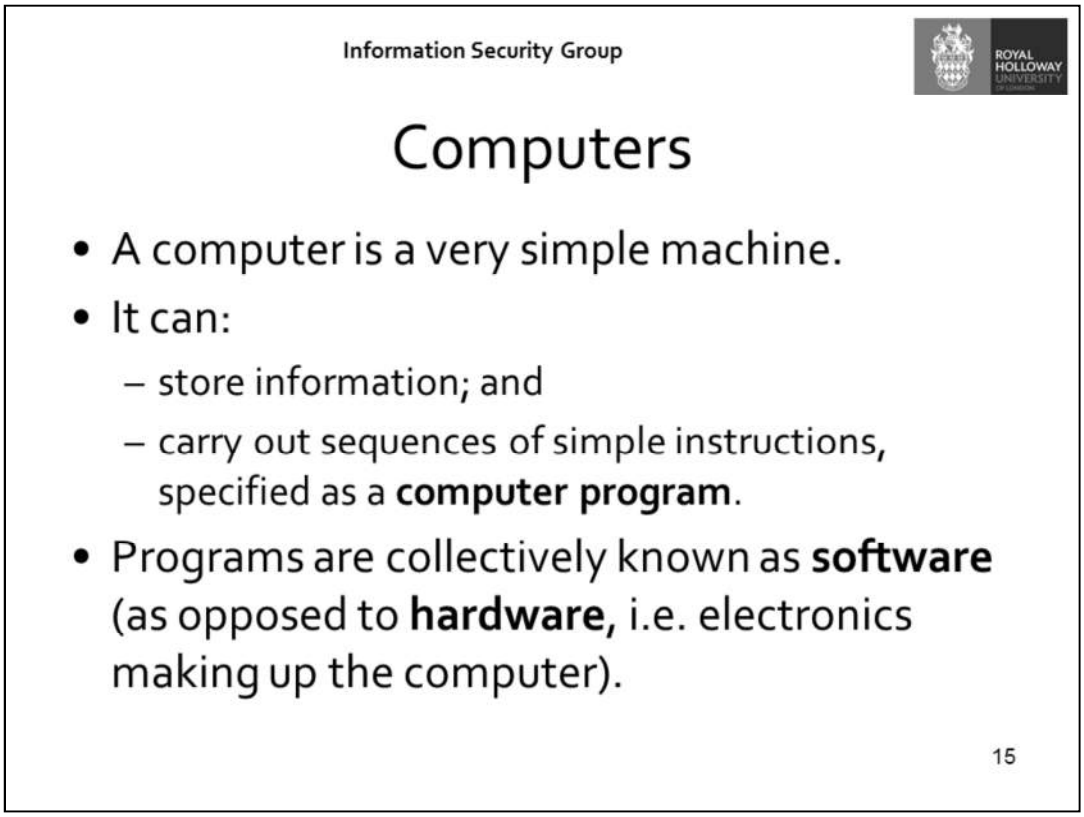
If you don't have a computing background, then this introduction can only give you a taste of this material, and you really need to do some background reading on computing, e.g. by using:

- the recommended books;
- any other basic book (of which there are many);
- some of the huge variety of web resources (including Wikipedia!) …

For example, if you look up 'operating system' under Wikipedia you will get a very nicely written article explaining in greater detail some of the concepts covered in this lecture.



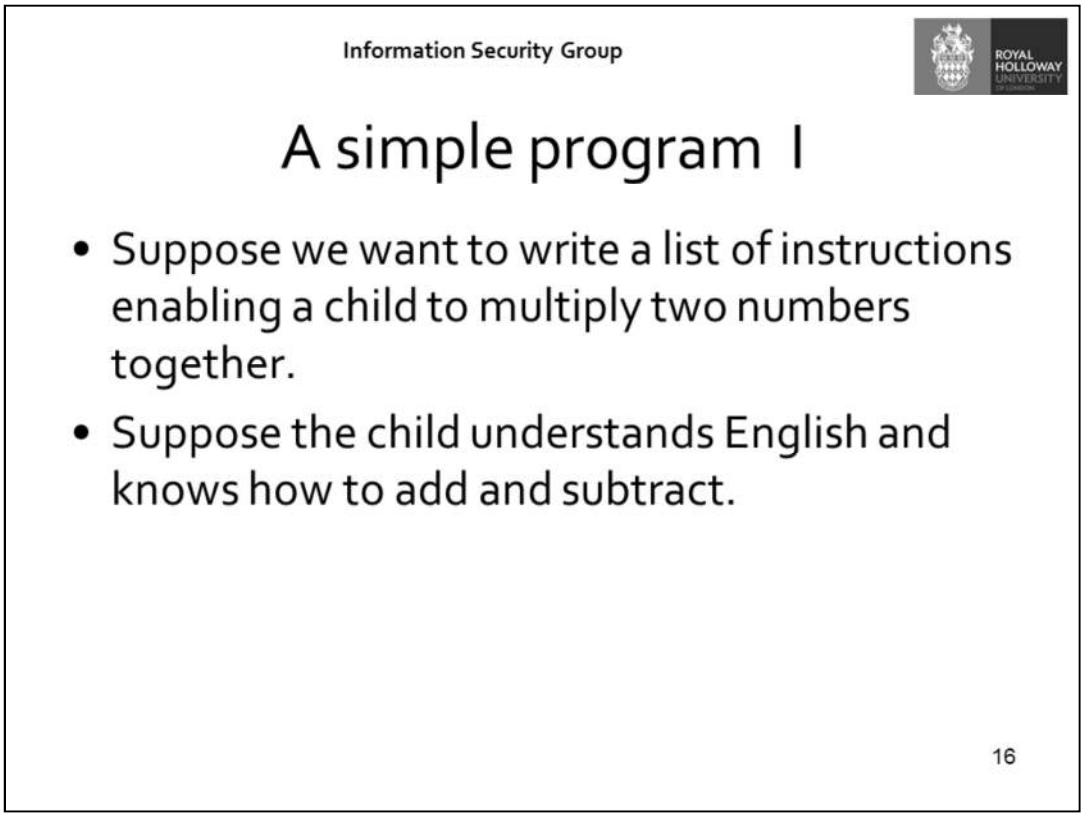
We divide the remainder of this introductory part of the course into the above-listed topics, starting with a general introduction to computers.



A computer is, conceptually at least, a very simple machine that can store information, and carry out sequences of simple instructions, specified in the form of a **computer program**.

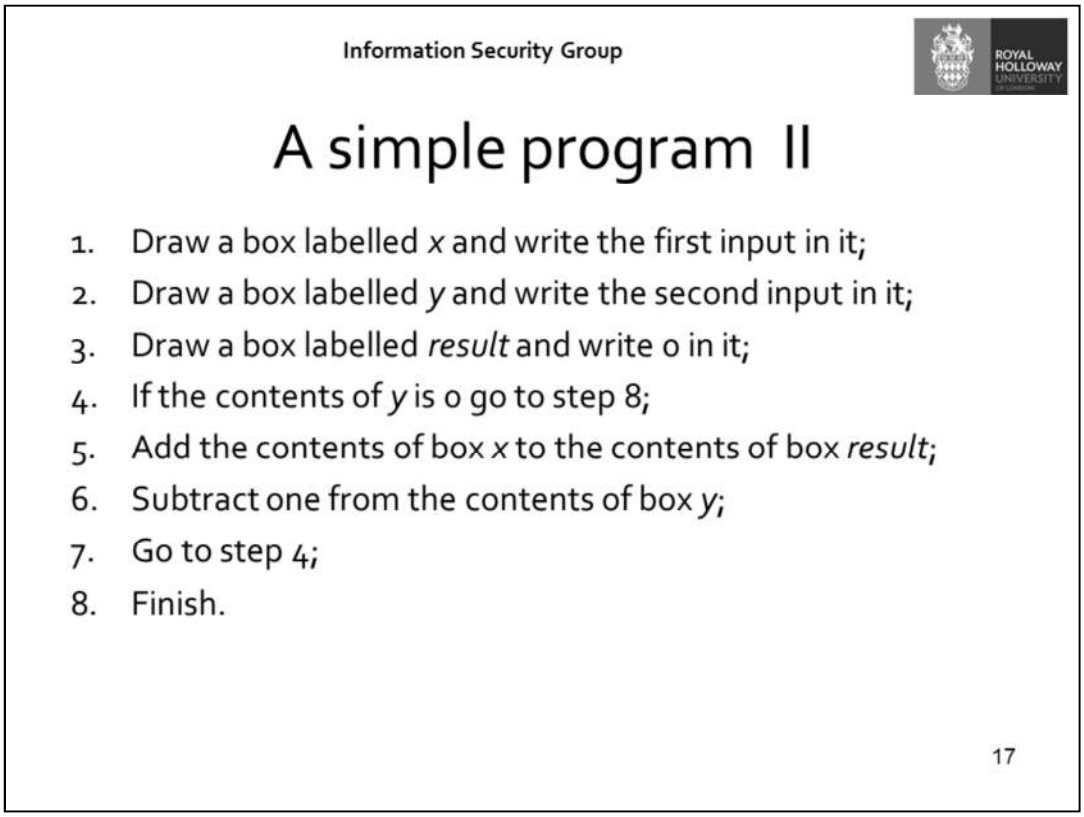
These programs operate on stored data and **inputs** (e.g. provided by a user) to give **outputs**.

Programs are collectively known as **software** (as opposed to the **hardware**, i.e. the physical electronics making up the computer).



As an example, suppose that we want to write a list of instructions that will enable an intelligent child to multiply two numbers together.

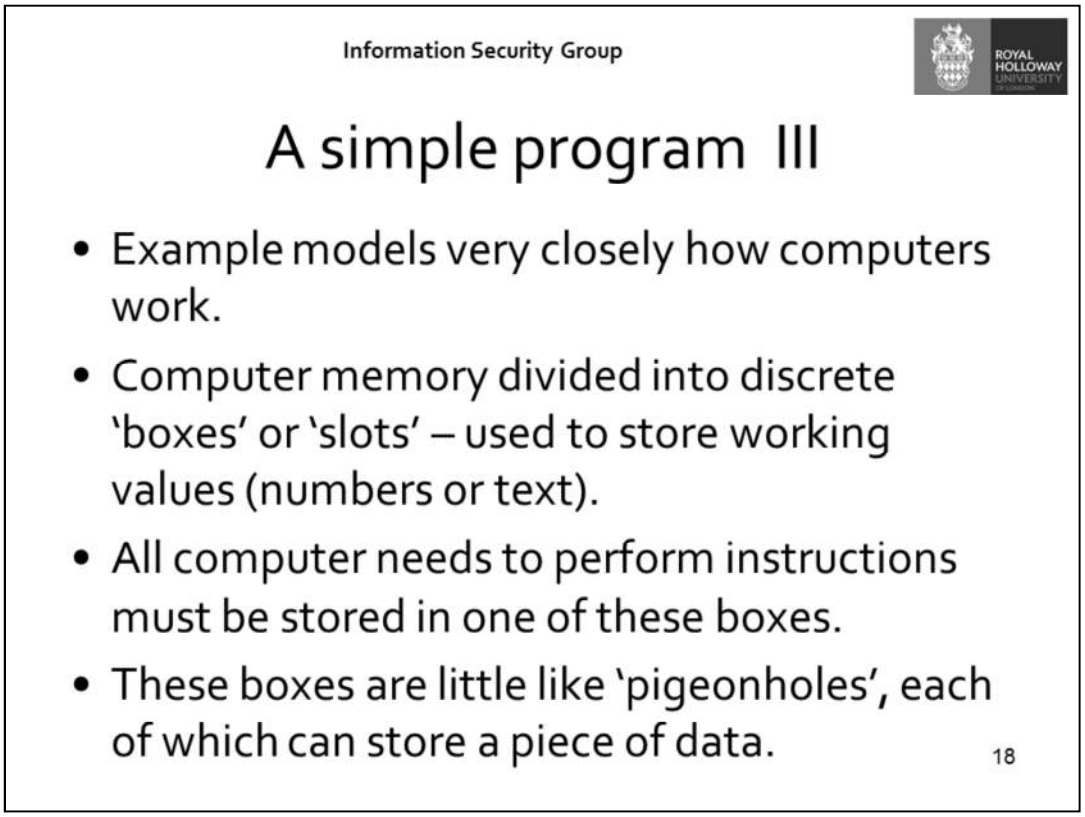
We suppose that the child understands English and already knows how to add and subtract.



One possible sequence of instructions is as follows:

1. Draw a box labelled *x* and write the first input in it;
2. Draw a box labelled *y* and write the second input in it;
3. Draw a box labelled *result* and write 0 in it;
4. If the contents of *y* is 0 go to step 8;
5. Add the contents of box *x* to the contents of box *result*;
6. Subtract one from the contents of box *y*;
7. Go to step 4;
8. Finish.

Note that this is just one example of a list of instructions to achieve the desired objective. It is possible to write an unlimited number of different programs that achieve the same result.



Note that this example models very closely how computers work. In particular, computer memory is divided into discrete containers (called **memory locations**), which can be thought of as 'boxes', 'slots', or 'cells'. These memory locations can be used to store individual working values, such as whole numbers, floating point numbers, or characters (letters, digits, etc.) from a piece of text, e.g. for a word processor.

Everything the computer needs to perform a sequence of instructions must be stored in one of these memory locations. As an analogy, think about how individual cells in a spreadsheet work, or imagine them as pigeonholes within which data can be stored.

Information Security Group

Running the simple program

- Suppose we want to multiply 6 and 3:
  1. Draw a box labelled *x* and write the first input in it;
  2. Draw a box labelled *y* and write the second input in it;
  3. Draw a box labelled *result* and write 0 in it;
  4. If the contents of *y* is 0 go to step 8;
  5. Add the contents of box *x* to the contents of box *result*;
  6. Subtract one from the contents of box *y*;
  7. Go to step 4;
  8. Finish.

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We now illustrate the operation of our 'program' using some simple inputs. Try using the program with some other (small) inputs and see whether it works.

Information Security Group

Running the simple program

- Suppose we want to multiply 6 and 3:
  1. Draw a box labelled *x* and write the first input in it;
  2. Draw a box labelled *y* and write the second input in it;
  3. Draw a box labelled *result* and write 0 in it;
  4. If the contents of *y* is 0 go to step 8;
  5. Add the contents of box *x* to the contents of box *result*;
  6. Subtract one from the contents of box *y*;
  7. Go to step 4;
  8. Finish.

x | 6 |

20

As we run through operation of the program, the results of the operations performed are shown on the left of the slides. The current step is shown in red.

Information Security Group

Running the simple program

- Suppose we want to multiply 6 and 3:
  1. Draw a box labelled *x* and write the first input in it;
  2. Draw a box labelled *y* and write the second input in it;
  3. Draw a box labelled *result* and write 0 in it;
  4. If the contents of *y* is 0 go to step 8;
  5. Add the contents of box *x* to the contents of box *result*;
  6. Subtract one from the contents of box *y*;
  7. Go to step 4;
  8. Finish.

x	6
y	3

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Information Security Group

Running the simple program

- Suppose we want to multiply 6 and 3:
  1. Draw a box labelled *x* and write the first input in it;
  2. Draw a box labelled *y* and write the second input in it;
  3. Draw a box labelled *result* and write 0 in it;
  4. If the contents of *y* is 0 go to step 8;
  5. Add the contents of box *x* to the contents of box *result*;
  6. Subtract one from the contents of box *y*;
  7. Go to step 4;
  8. Finish.

x	6
y	3
result	0

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Information Security Group

Running the simple program

- Suppose we want to multiply 6 and 3:
  1. Draw a box labelled *x* and write the first input in it;
  2. Draw a box labelled *y* and write the second input in it;
  3. Draw a box labelled *result* and write 0 in it;
  4. If the contents of *y* is 0 go to step 8;
  5. Add the contents of box *x* to the contents of box *result*;
  6. Subtract one from the contents of box *y*;
  7. Go to step 4;
  8. Finish.

x	6
y	3
result	0

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Note that this is a **decision** step. The ability of a computer to execute different sequences of instructions depending on computations it makes (or inputs it receives) enables computers to do very sophisticated tasks using a simple set of instructions.

Information Security Group

Running the simple program

- Suppose we want to multiply 6 and 3:
  1. Draw a box labelled *x* and write the first input in it;
  2. Draw a box labelled *y* and write the second input in it;
  3. Draw a box labelled *result* and write 0 in it;
  4. If the contents of *y* is 0 go to step 8;
  5. Add the contents of box *x* to the contents of box *result*;
  6. Subtract one from the contents of box *y*;
  7. Go to step 4;
  8. Finish.

x	6
y	3
result	6

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Information Security Group

Running the simple program

- Suppose we want to multiply 6 and 3:
  1. Draw a box labelled *x* and write the first input in it;
  2. Draw a box labelled *y* and write the second input in it;
  3. Draw a box labelled *result* and write 0 in it;
  4. If the contents of *y* is 0 go to step 8;
  5. Add the contents of box *x* to the contents of box *result*;
  6. Subtract one from the contents of box *y*;
  7. Go to step 4;
  8. Finish.

x	6
y	2
result	6

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Information Security Group

Running the simple program

- Suppose we want to multiply 6 and 3:
  1. Draw a box labelled *x* and write the first input in it;
  2. Draw a box labelled *y* and write the second input in it;
  3. Draw a box labelled *result* and write 0 in it;
  4. If the contents of *y* is 0 go to step 8;
  5. Add the contents of box *x* to the contents of box *result*;
  6. Subtract one from the contents of box *y*;
  7. Go to step 4;
  8. Finish.

x	6
y	2
result	6

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Information Security Group

Running the simple program

- Suppose we want to multiply 6 and 3:
  1. Draw a box labelled *x* and write the first input in it;
  2. Draw a box labelled *y* and write the second input in it;
  3. Draw a box labelled *result* and write 0 in it;
  4. If the contents of *y* is 0 go to step 8;
  5. Add the contents of box *x* to the contents of box *result*;
  6. Subtract one from the contents of box *y*;
  7. Go to step 4;
  8. Finish.

x	6
y	2
result	6

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Information Security Group

Running the simple program

- Suppose we want to multiply 6 and 3:
  1. Draw a box labelled *x* and write the first input in it;
  2. Draw a box labelled *y* and write the second input in it;
  3. Draw a box labelled *result* and write 0 in it;
  4. If the contents of *y* is 0 go to step 8;
  5. Add the contents of box *x* to the contents of box *result*;
  6. Subtract one from the contents of box *y*;
  7. Go to step 4;
  8. Finish.

x	6
y	2
result	12

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Information Security Group

Running the simple program

- Suppose we want to multiply 6 and 3:
  1. Draw a box labelled *x* and write the first input in it;
  2. Draw a box labelled *y* and write the second input in it;
  3. Draw a box labelled *result* and write 0 in it;
  4. If the contents of *y* is 0 go to step 8;
  5. Add the contents of box *x* to the contents of box *result*;
  6. Subtract one from the contents of box *y*;
  7. Go to step 4;
  8. Finish.

x	6
y	1
result	12

29

Information Security Group

Running the simple program

- Suppose we want to multiply 6 and 3:
  1. Draw a box labelled *x* and write the first input in it;
  2. Draw a box labelled *y* and write the second input in it;
  3. Draw a box labelled *result* and write 0 in it;
  4. If the contents of *y* is 0 go to step 8;
  5. Add the contents of box *x* to the contents of box *result*;
  6. Subtract one from the contents of box *y*;
  7. Go to step 4;
  8. Finish.

x	6
y	1
result	12

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Information Security Group

Running the simple program

- Suppose we want to multiply 6 and 3:
  1. Draw a box labelled *x* and write the first input in it;
  2. Draw a box labelled *y* and write the second input in it;
  3. Draw a box labelled *result* and write 0 in it;
  4. If the contents of *y* is 0 go to step 8;
  5. Add the contents of box *x* to the contents of box *result*;
  6. Subtract one from the contents of box *y*;
  7. Go to step 4;
  8. Finish.

x	6
y	1
result	12

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Information Security Group

Running the simple program

- Suppose we want to multiply 6 and 3:
  1. Draw a box labelled *x* and write the first input in it;
  2. Draw a box labelled *y* and write the second input in it;
  3. Draw a box labelled *result* and write 0 in it;
  4. If the contents of *y* is 0 go to step 8;
  5. Add the contents of box *x* to the contents of box *result*;
  6. Subtract one from the contents of box *y*;
  7. Go to step 4;
  8. Finish.

x	6
y	1
result	18

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Information Security Group

Running the simple program

- Suppose we want to multiply 6 and 3:
  1. Draw a box labelled *x* and write the first input in it;
  2. Draw a box labelled *y* and write the second input in it;
  3. Draw a box labelled *result* and write 0 in it;
  4. If the contents of *y* is 0 go to step 8;
  5. Add the contents of box *x* to the contents of box *result*;
  6. Subtract one from the contents of box *y*;
  7. Go to step 4;
  8. Finish.

x	6
y	0
result	18

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Information Security Group

Running the simple program

- Suppose we want to multiply 6 and 3:
  1. Draw a box labelled *x* and write the first input in it;
  2. Draw a box labelled *y* and write the second input in it;
  3. Draw a box labelled *result* and write 0 in it;
  4. If the contents of *y* is 0 go to step 8;
  5. Add the contents of box *x* to the contents of box *result*;
  6. Subtract one from the contents of box *y*;
  7. Go to step 4;
  8. Finish.

x	6
y	0
result	18

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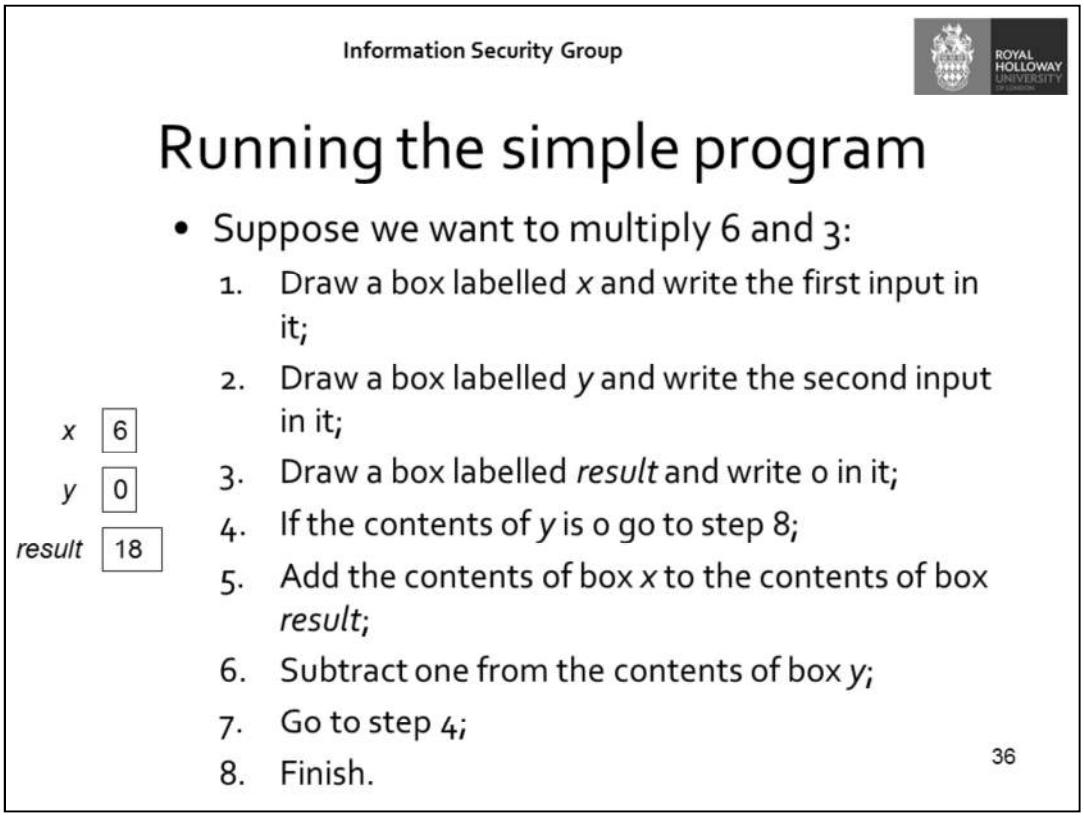
Information Security Group

Running the simple program

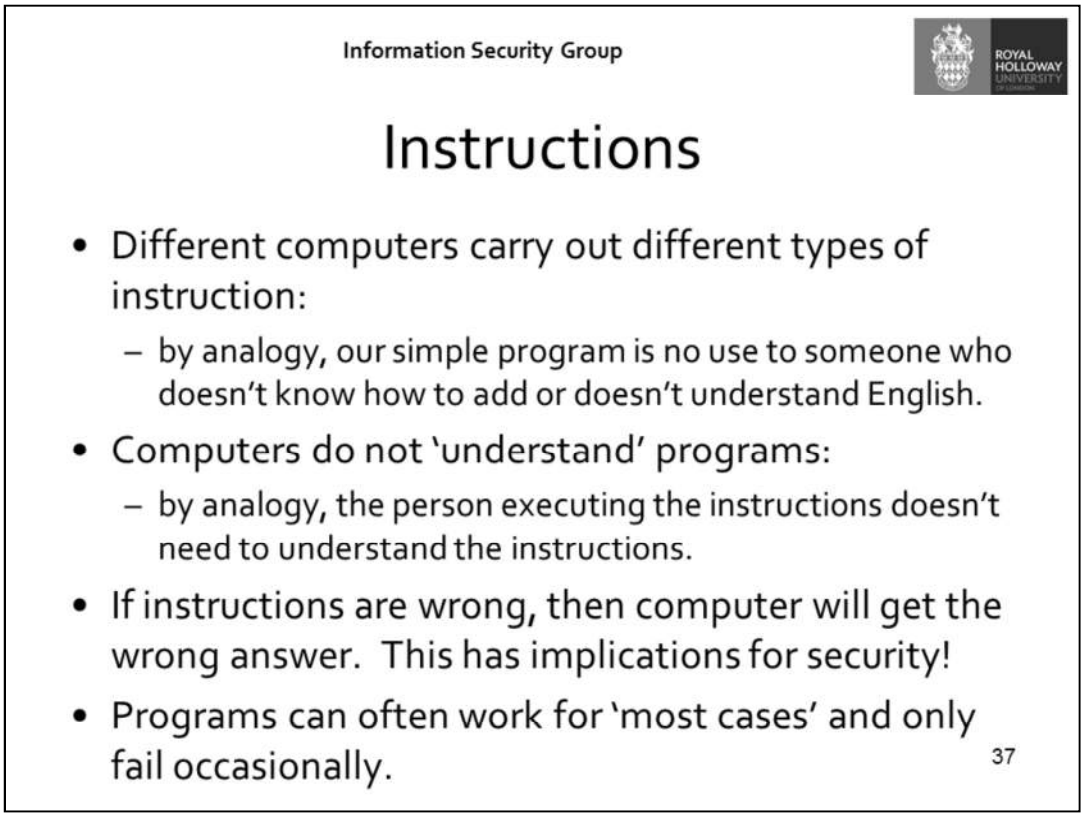
- Suppose we want to multiply 6 and 3:
  1. Draw a box labelled *x* and write the first input in it;
  2. Draw a box labelled *y* and write the second input in it;
  3. Draw a box labelled *result* and write 0 in it;
  4. If the contents of *y* is 0 go to step 8;
  5. Add the contents of box *x* to the contents of box *result*;
  6. Subtract one from the contents of box *y*;
  7. Go to step 4;
  8. Finish.

x	6
y	0
result	18

35



The program terminates on step 8, and the desired result is contained in box *result*.



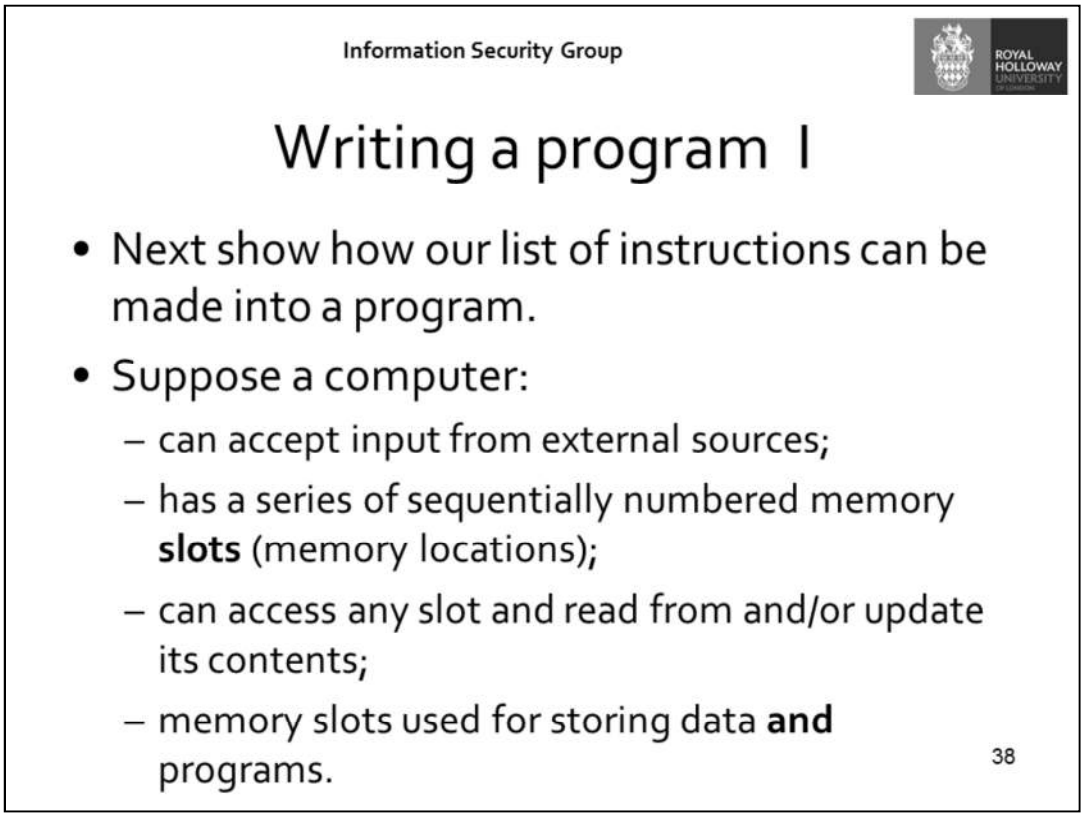
Different types of computer carry out different types of instruction; by analogy, our simple program is of no use to someone who doesn't know how to add or who doesn't understand English.

Computers do not 'understand' programs in the way that we might understand why a set of instructions is designed the way that it is. By analogy, it is not necessary for the person executing the instructions to understand the rationale for the instructions. There are many everyday analogies for this:

• as children we may have been taught simple techniques for multiplying numbers of more than one digit together – these typically consist of sets of rules which give the right answer, but as children we had no idea *why* they worked;

• knitting patterns consists of complex sequences of instructions which, if followed correctly, result in a garment of the right size and shape – however, the knitter does not need to know why the instructions are put together the way they are.

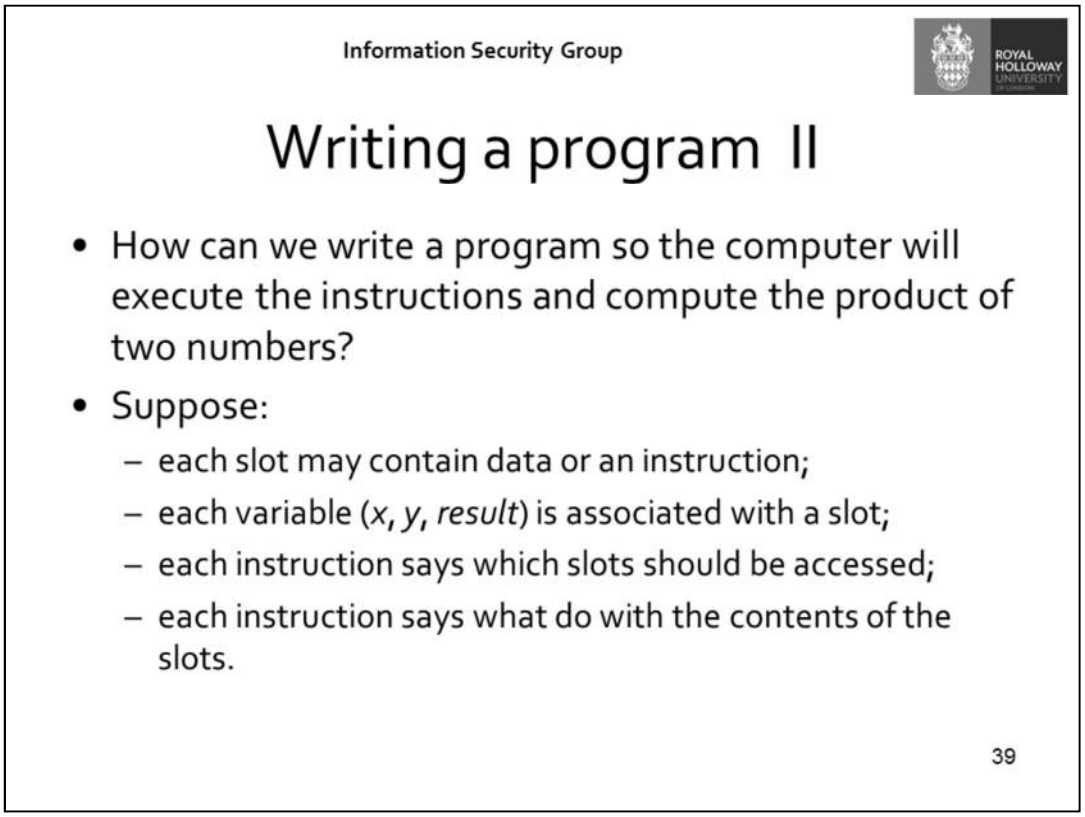
If the sequence of instructions is wrong (e.g. by poor design or as a result of a typing error) the computer will compute the wrong answer. This has major implications for security! Note especially that programs can often work for 'most cases' and only fail occasionally, meaning that software is often deployed that is faulty, but where the faults are very hard to find from testing.



We next see how a computer program is written, using our simple list of instructions for multiplication as an example.

We suppose that a computer:

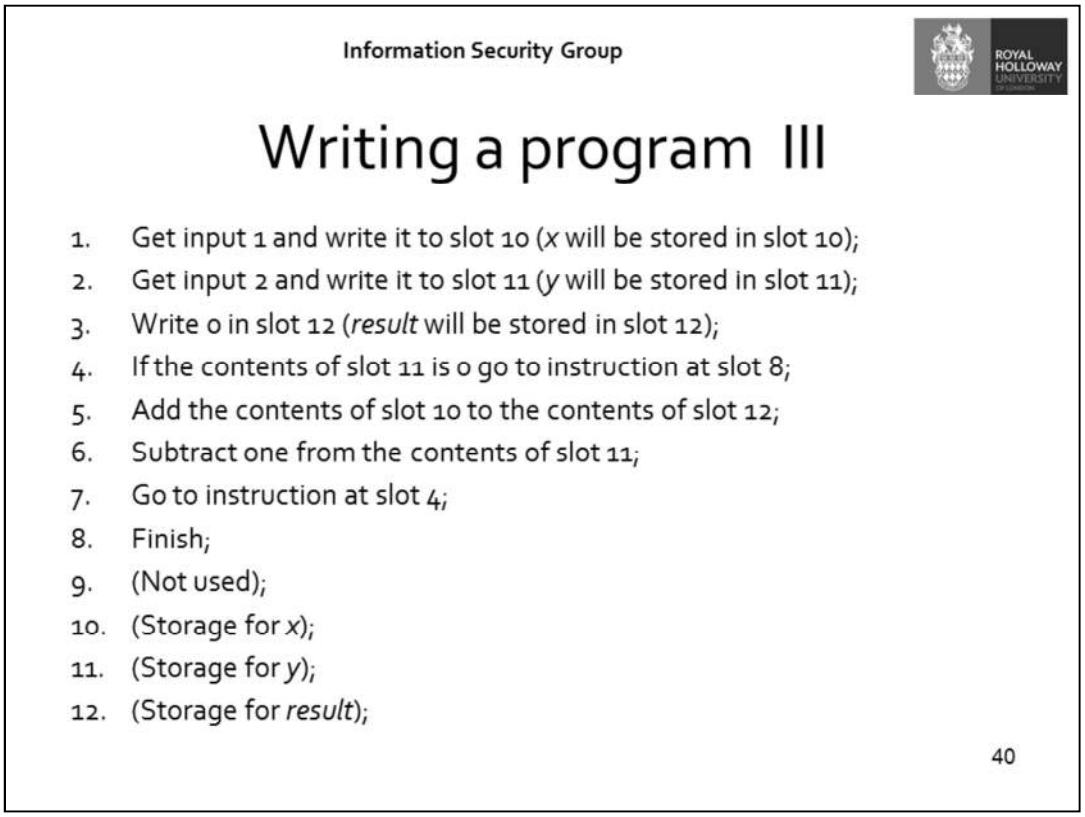
- can accept input from external sources;
- has a series of sequentially numbered memory **slots** (memory locations);
- can access any slot and can then read from, and/or update, the contents of this slot;
- the computer memory is used both for storing data and for storing the program (i.e. the sequence of instructions the computer must follow).



How can we write a program so that the computer will execute the instructions and compute the product of two numbers?

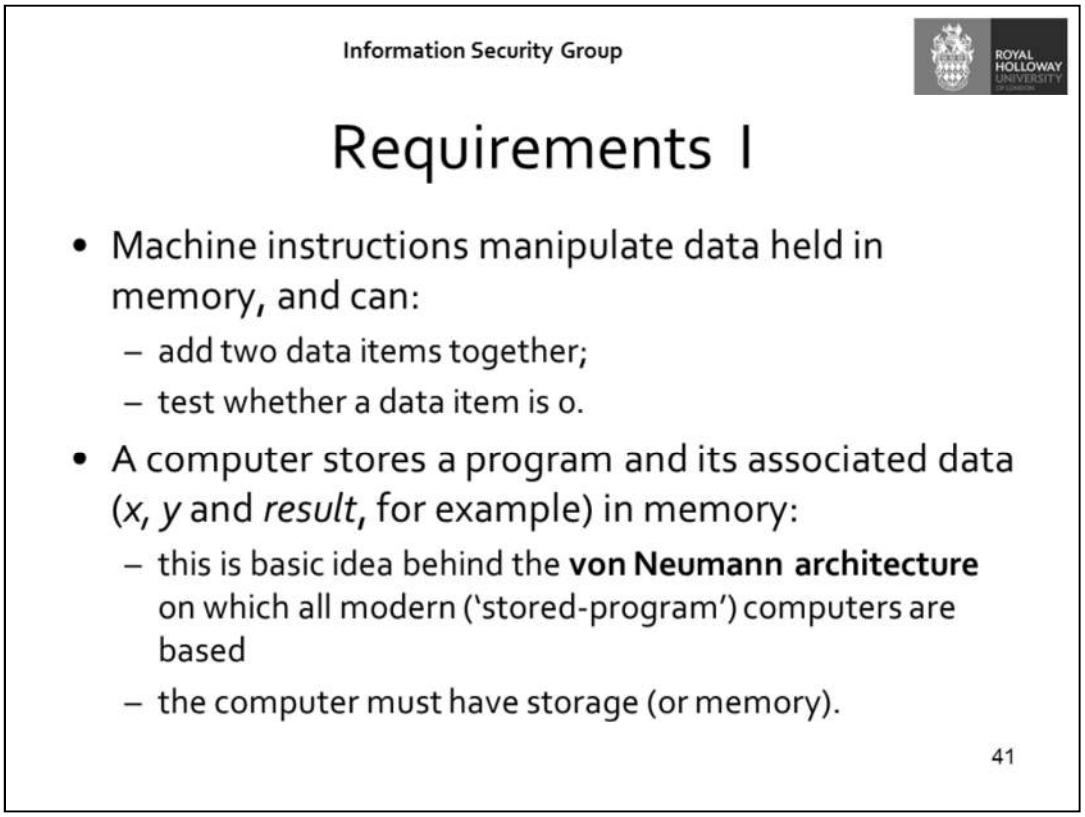
We make the following underlying assumptions (which model how real world computers operate):

- each slot may contain data or an instruction;
- each variable (*x*, *y* and *result* in our simple example) is associated with a slot;
- each instruction says which slots should be accessed;
- each instruction says what do with the contents of the slots.



The above program formalises the example program we looked at previously.

- Memory locations (slots) 1–8 contain the text or code section of the program.
- Memory location 9 is not being used.
- Memory locations 10–12 contain the data section of the program, i.e. where working data (variables) are located.

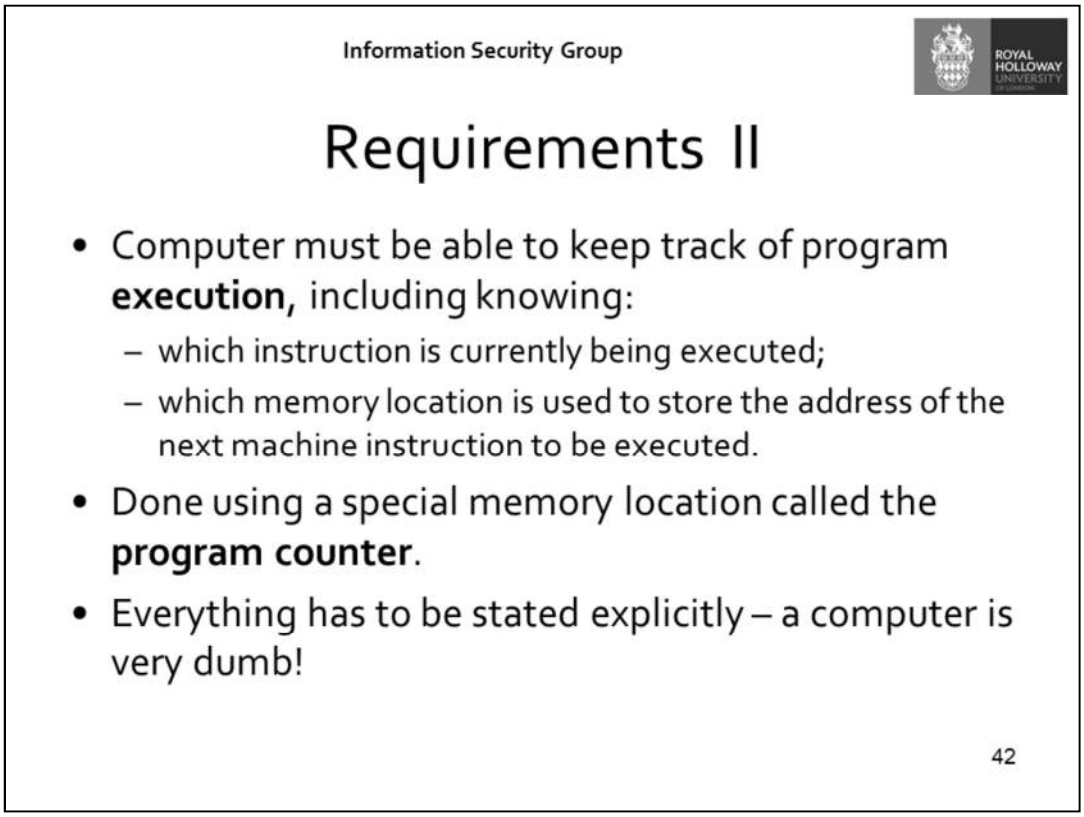


Machine instructions manipulate data held in memory, and can, for example:

- add two data items together;
- test whether a data item is 0.

A computer stores a program and its associated data (*x, y* and *result*, for example) in memory. This is the basic idea behind the **von Neumann architecture** on which all modern ('stored-program') computers are based. The computer must have storage (or memory) which can be used to store the data and the program.

Note that, because the data and the program are stored in the same type of memory, a malfunctioning program might accidentally over-write part of the program instead of modifying the data. This is exactly the sort of problem we encounter in real life, and such an error can cause major security issues.



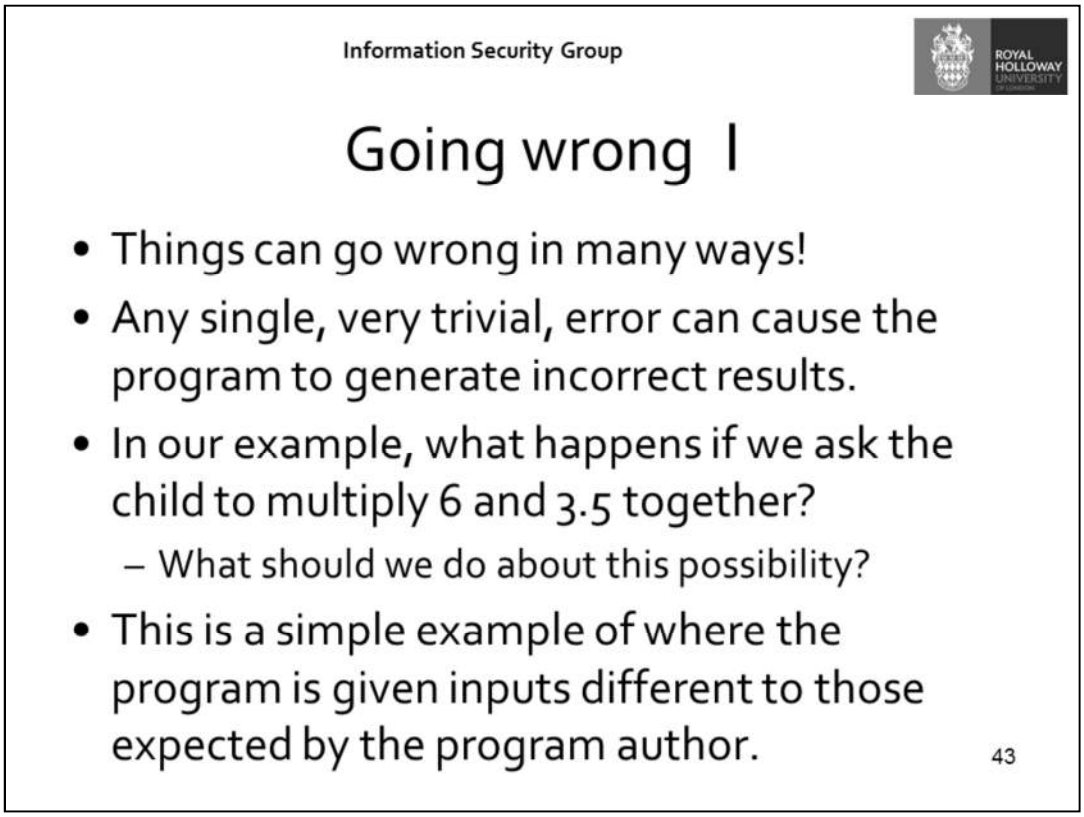
A computer must be able to keep track of the **execution** of a program. In particular at any time it must know:

• which instruction is currently being executed;

• which memory location is used to store the address of the next machine instruction to be executed.

This is achieved using a special memory location called the **program counter**. The contents of the program counter indicate the location of the next instruction to be executed (every memory location has a unique numerical address).

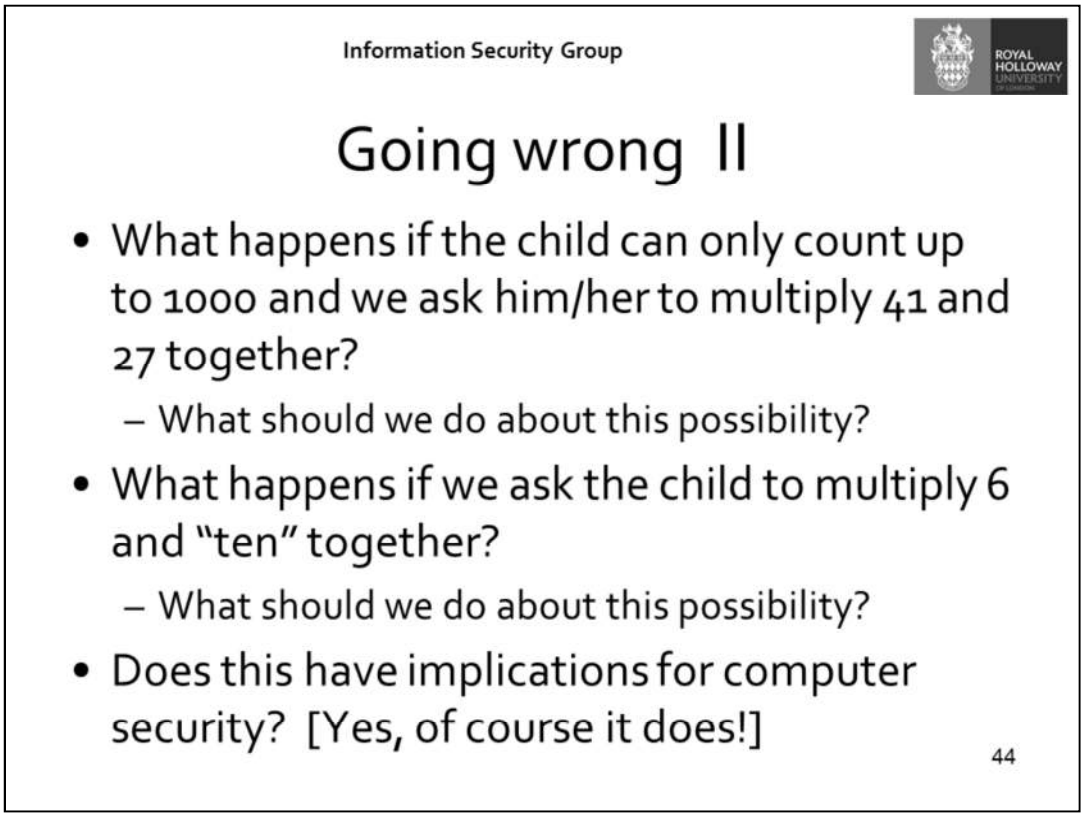
Everything has to be explicitly stated – a computer has no intelligence; it is simply a machine following instructions.



Things can go wrong in many ways! Any single, very trivial, error can cause the program to generate incorrect results.

In our example, what happens if we ask the child to multiply 6 and 3.5 together? What should we do about this possibility?

This is an example of unexpected input to a program – i.e. the program is designed to cope with inputs equal to whole numbers, and may fail in unexpected ways if given something other than a whole number.

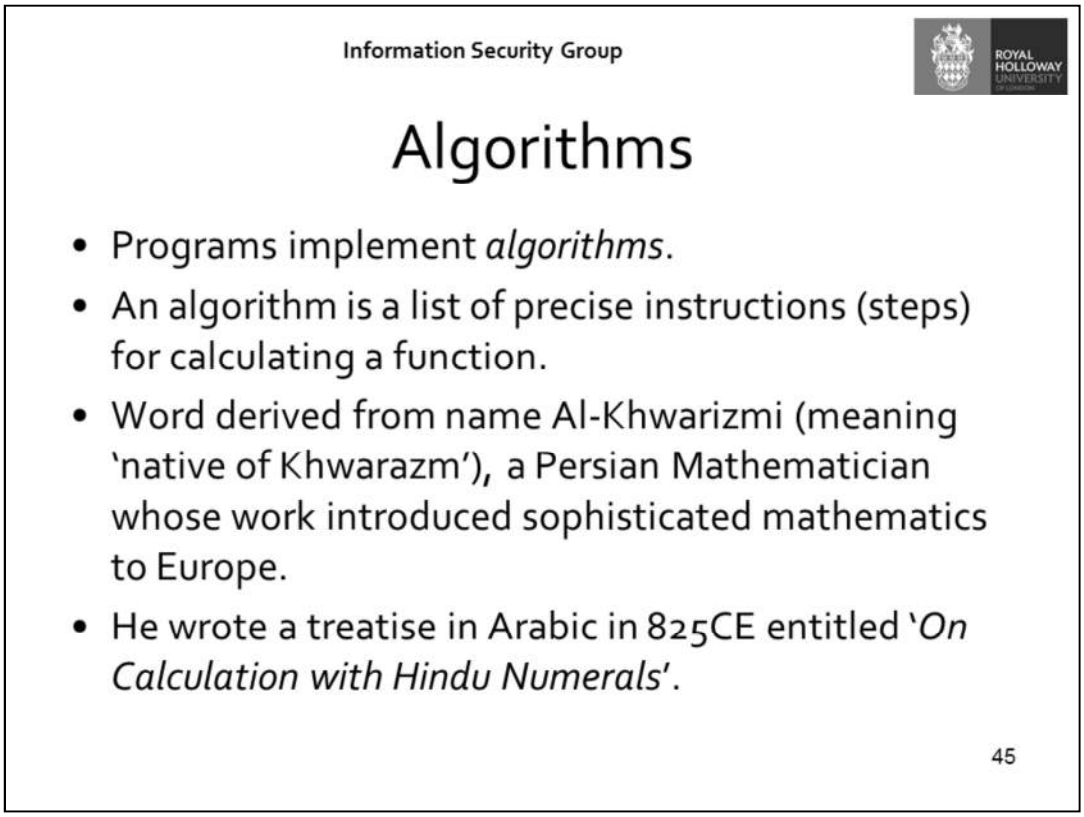


What happens if the child can only count up to 1000 and we ask him/her to multiply 41 and 27 together? What should we do about this possibility?

What happens if we ask the child to multiply 6 and “ten” together? What should we do about this possibility?

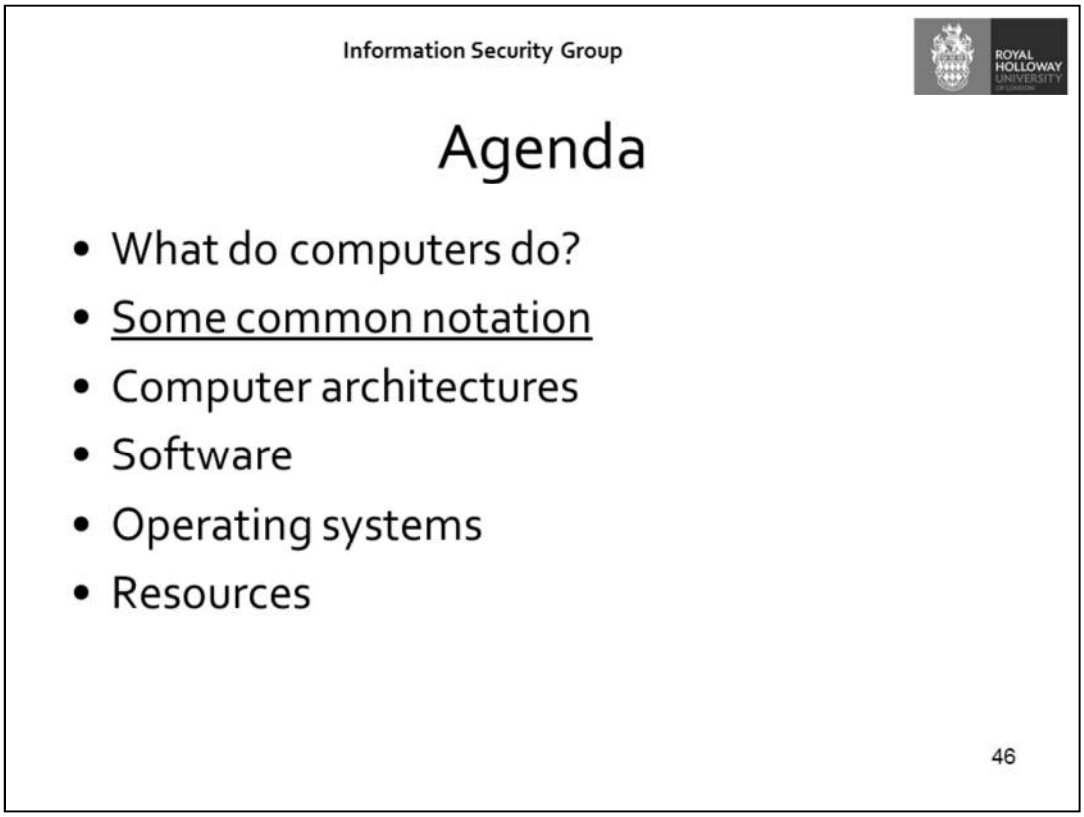
Does this have implications for computer security? [Yes, of course it does!]

This is another example of unexpected inputs to a program. This is a major cause of real world security problems – where the designer of a program doesn’t think about what would happen if the program is given inputs other than those the designer expects it to be given, and doesn’t include measures in the program to deal with such cases.

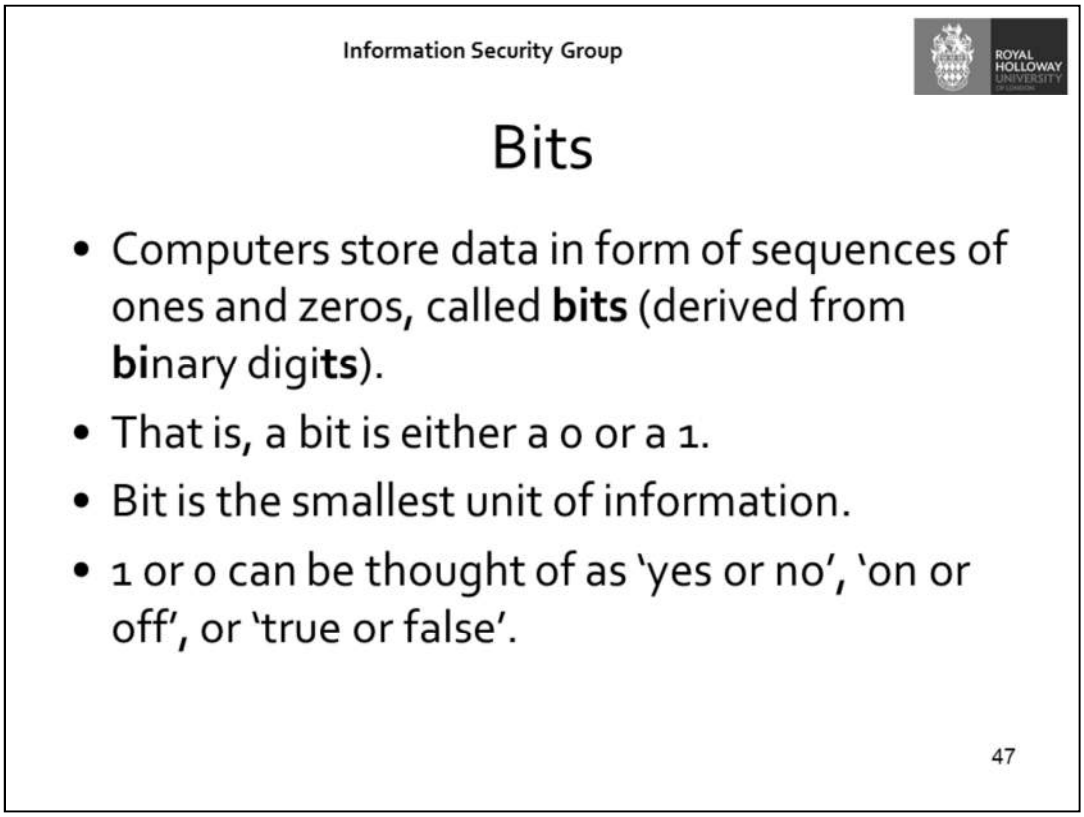


Programs implement *algorithms*, where an algorithm is a list of precise instructions (steps) for calculating a function.

The term 'algorithm' is derived from the name Al-Khwarizmi (meaning 'native of Khwarazm'), a Persian Mathematician whose work introduced sophisticated mathematics to Europe. He wrote a treatise in Arabic in 825CE entitled '*On Calculation with Hindu Numerals*'.

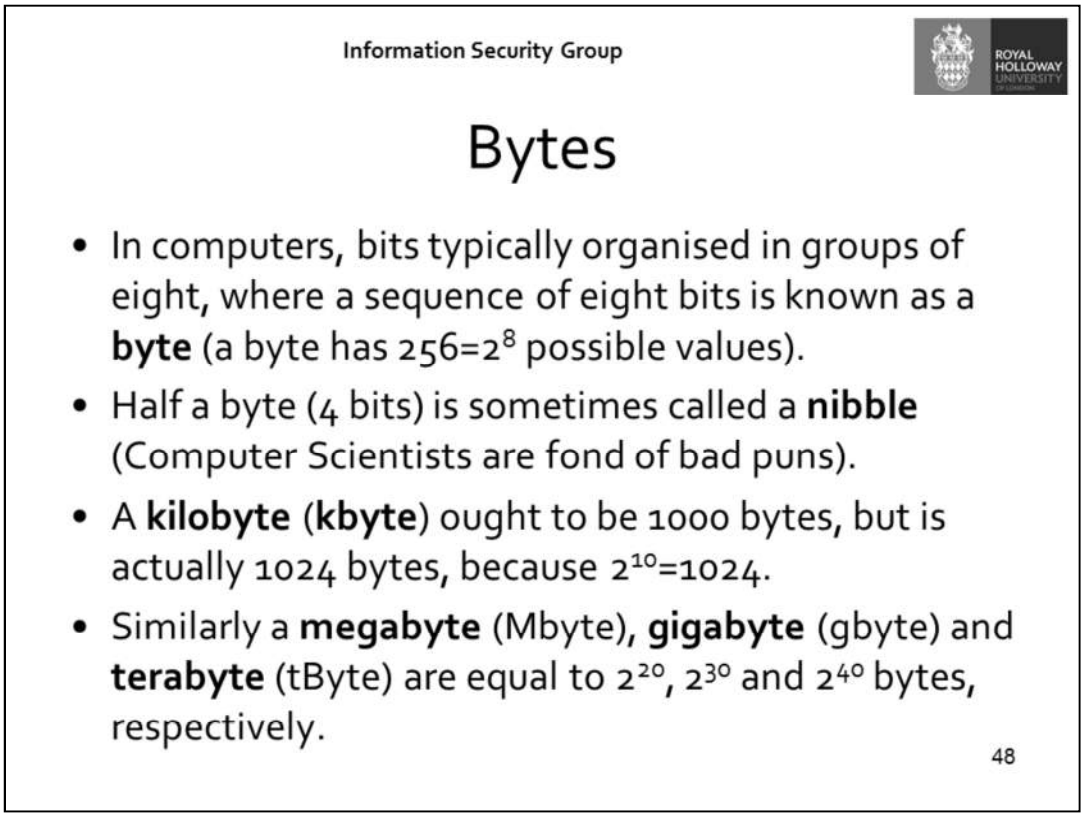


We next introduce some common mathematical notation used when describing computers and their operation. If this is all unfamiliar to you, then please spend some time reading around and familiarising yourself with these ideas.



Computers store and process data in the form of sequences of ones and zeros, where each one or zero is called a **bit** (the term is derived from **bi**nary digi**t**). That is, a bit is either a 0 (zero) or a 1 (one). A bit is the smallest unit of information.

The 1 or 0 can be thought of as 'yes or no', 'on or off', or 'true or false', depending on the context.

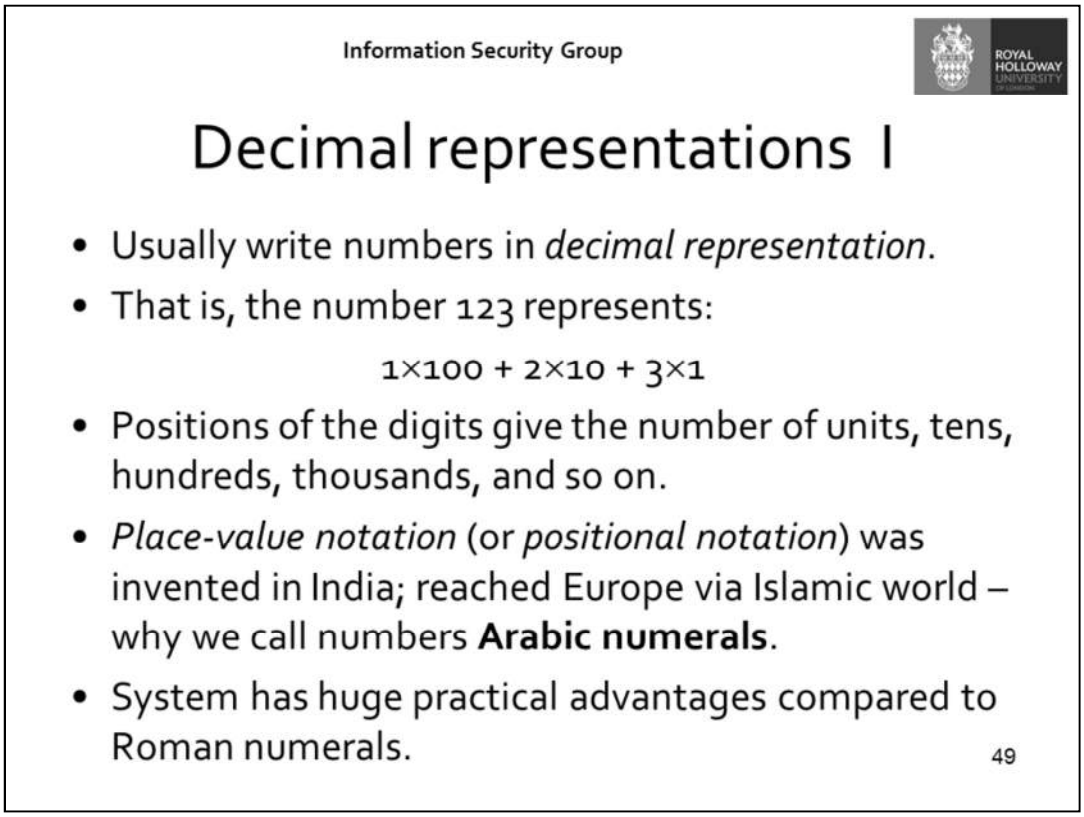


In computers, bits are typically organised in groups of eight, where a sequence of eight bits is usually known as a **byte** (a byte has $256=2^8$ possible values). Sometimes a byte is referred to as an **octet**.

Half a byte (4 bits) is sometimes called a **nibble** (many Computer Scientists are fond of bad puns).

A **kilobyte** (**kbyte**) ought to be 1000 bytes, but is actually 1024 bytes, because $2^{10}=1024$.

Similarly a **megabyte** (Mbyte), **gigabyte** (gbyte) and **terabyte** (tByte) are equal to 2^{20}, 2^{30} and 2^{40} bytes, respectively.



We normally write numbers using something known as a *decimal representation*.

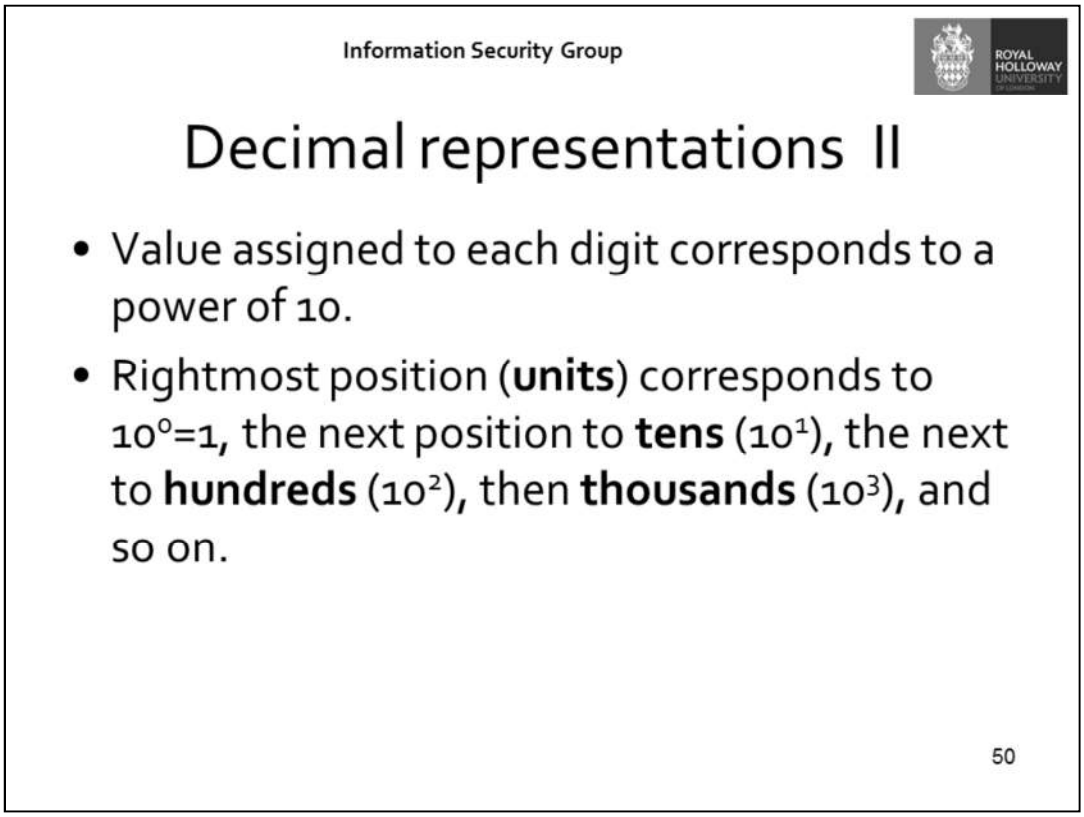
That is, the number 123 represents:

$1\times100 + 2\times10 + 3\times1$

The positions of the digits indicate the number of units, tens, hundreds, thousands, and so on.

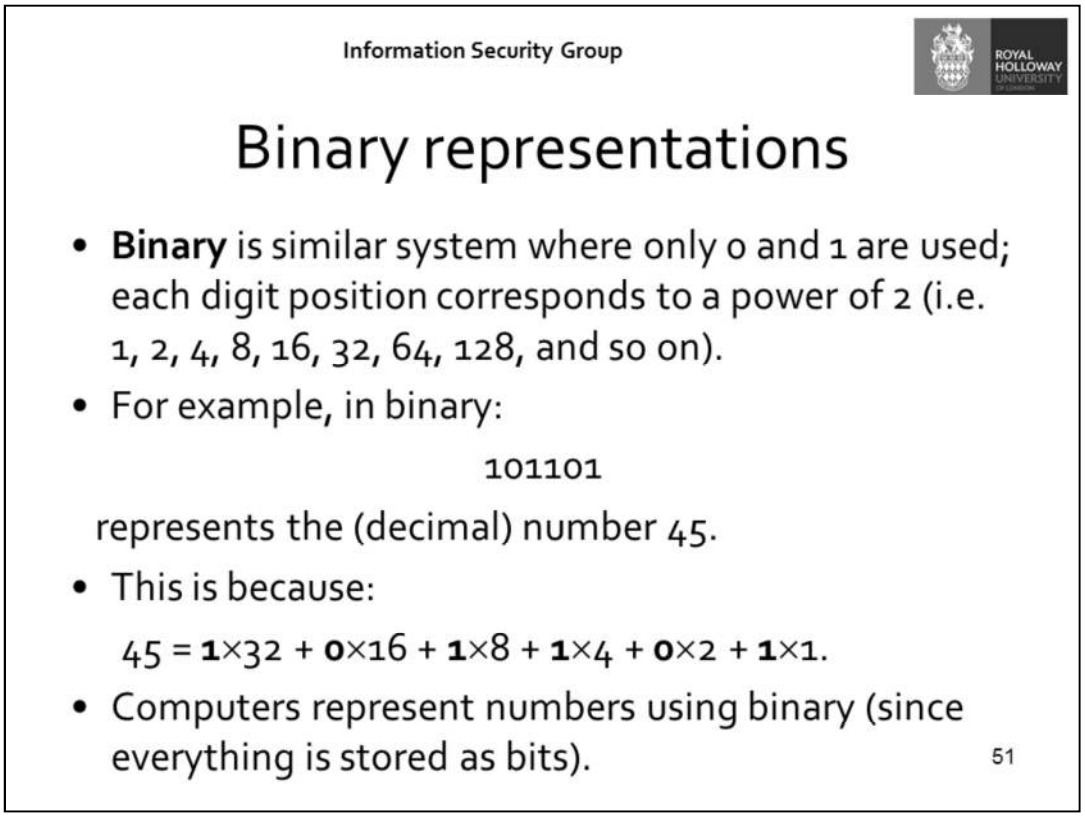
This idea of *place-value notation* (or *positional notation*) was invented in India around 1500 years ago, and reached Europe via the Islamic world, which is why we refer to our numerals as Arabic numerals.

This system has huge practical advantages for computation by comparison with Roman numerals, the system which was in use in Europe prior to the arrival of the positional notation.



The value assigned to each digit in a decimal representation corresponds to a power of 10.

That is, the rightmost position (the **units**) corresponds to $10^0=1$, the next position to **tens** (10^1), the next to **hundreds** (10^2), then **thousands** (10^3), and so on.



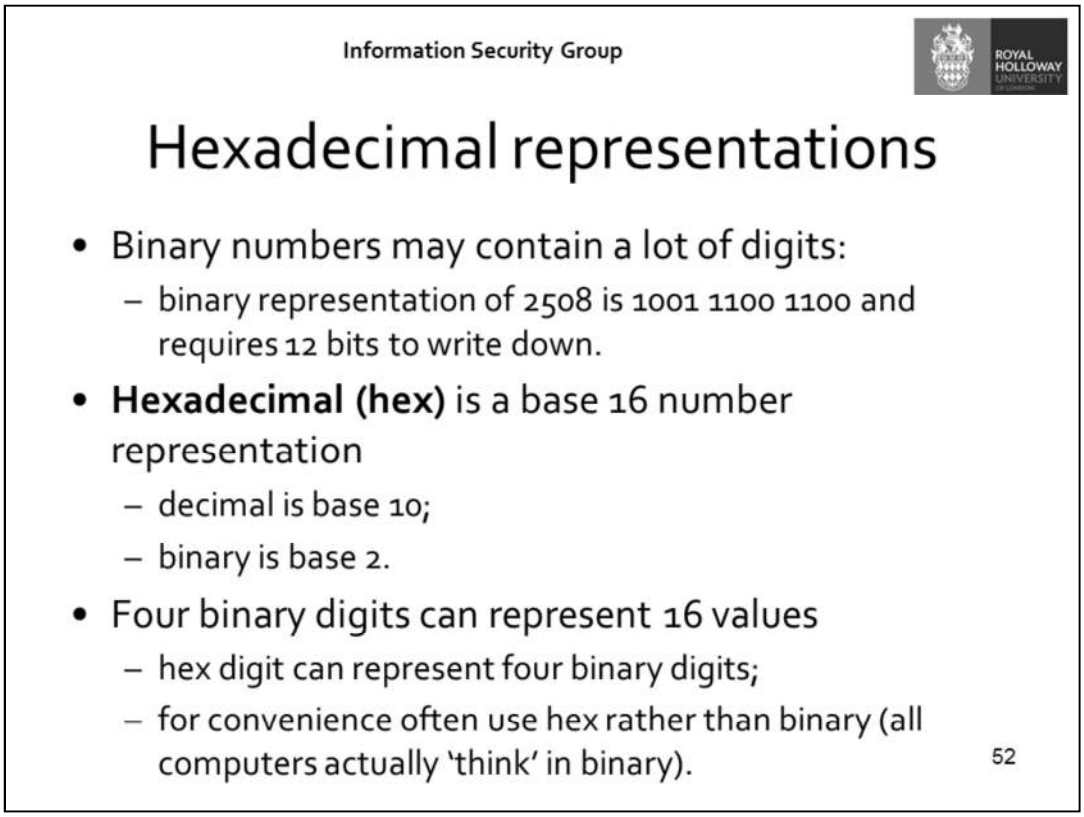
We can devise a similar system (called **binary**) where only the digits 0 and 1 are used, and where each digit position corresponds to a power of 2 (i.e. 1, 2, 4, 8, 16, 32, 64, 128, and so on).

For example, in binary 101101 represents the (decimal) number 45.

This is because:

45 = **1**×32 + **0**×16 + **1**×8 + **1**×4 + **0**×2 + **1**×1.

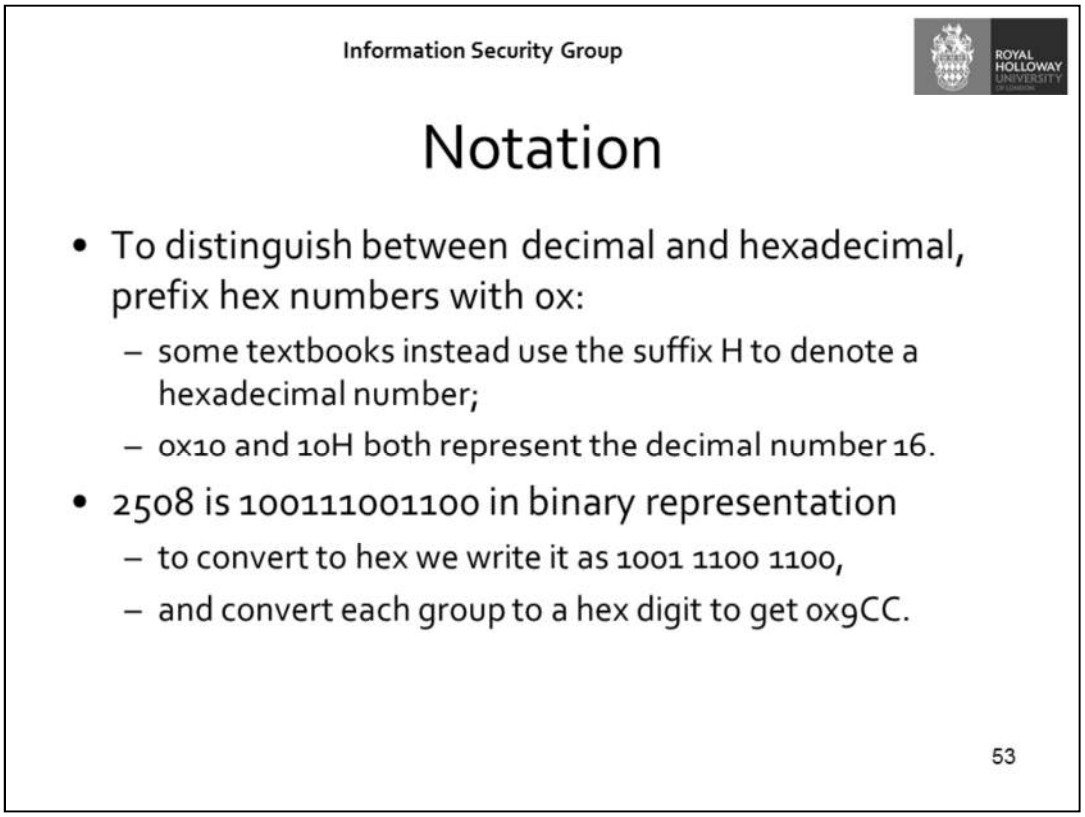
Computers represent numbers using binary, since everything inside the computer is stored as a sequence of bits.



Binary representations of numbers may contain a lot of digits, and hence writing numbers in binary is rather laborious. For example, the binary representation of 2508 is 1001 1100 1100, i.e. requires 12 bits to write down.

Hexadecimal (hex) is a base 16 number representation. By contrast decimal is base 10 and binary is base 2.

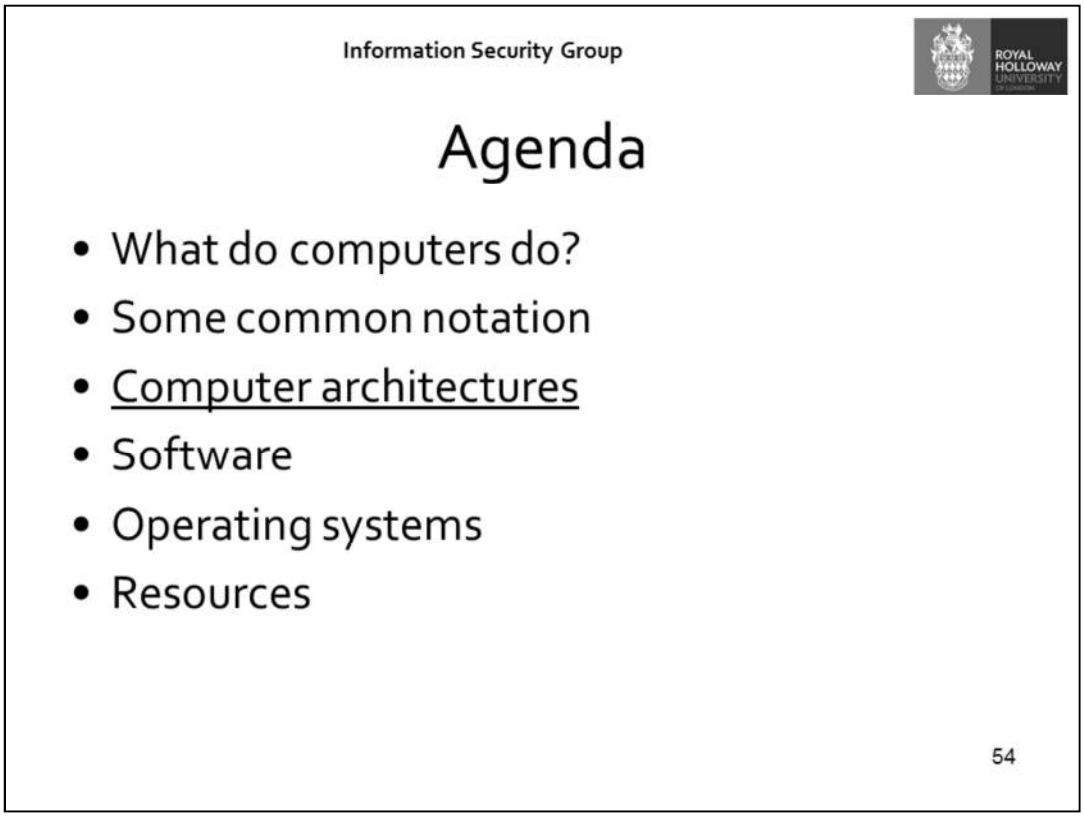
Four binary digits can represent 16 values and a hex digit can represent four binary digits. For convenience we often use hex rather than binary to write numbers as stored in a computer (remembering, of course, that all computers actually operate in binary).



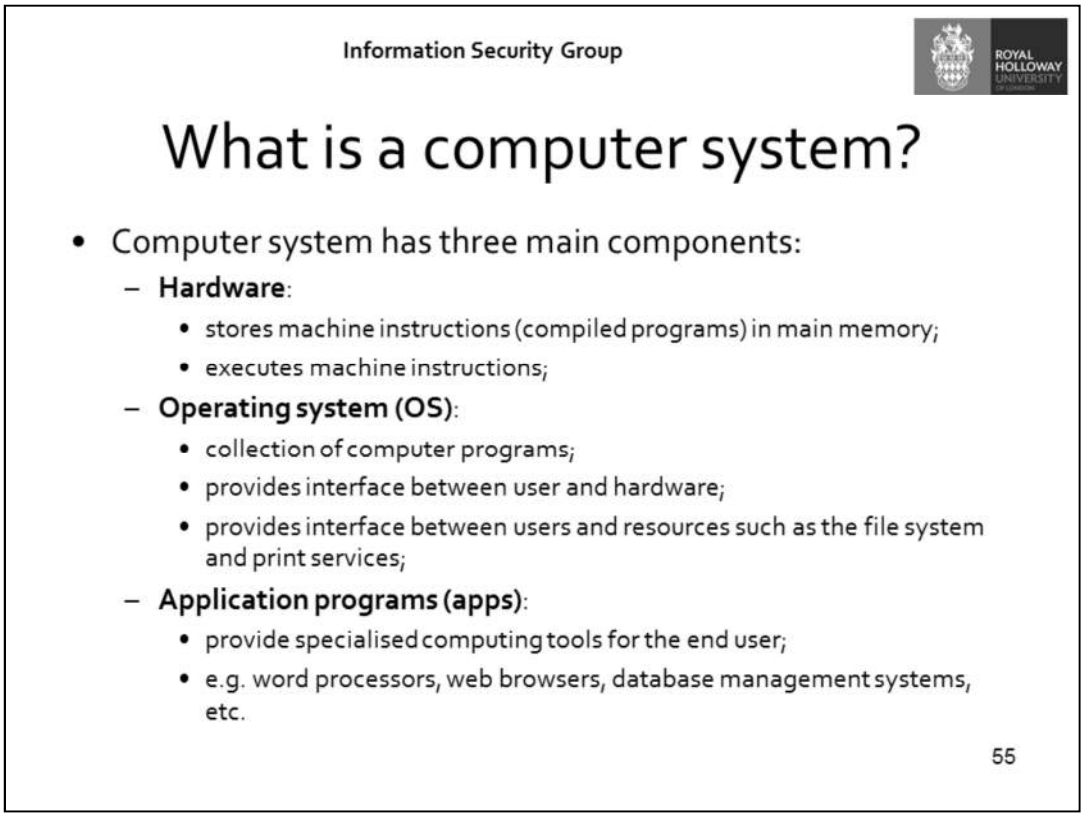
In order to distinguish between decimal and hexadecimal, it is common to prefix a hexadecimal number with the string 0x:

- alternatively, some textbooks use the suffix H to denote a hexadecimal number;
- for example, 0x10 and 10H both represent the decimal number 16.

We know (from a previous slide) that 2508 is 100111001100 in binary representation. To convert to hex we write it as 1001 1100 1100, and then convert each group of four bits to a hex digit to get the hex representation 0x9CC.

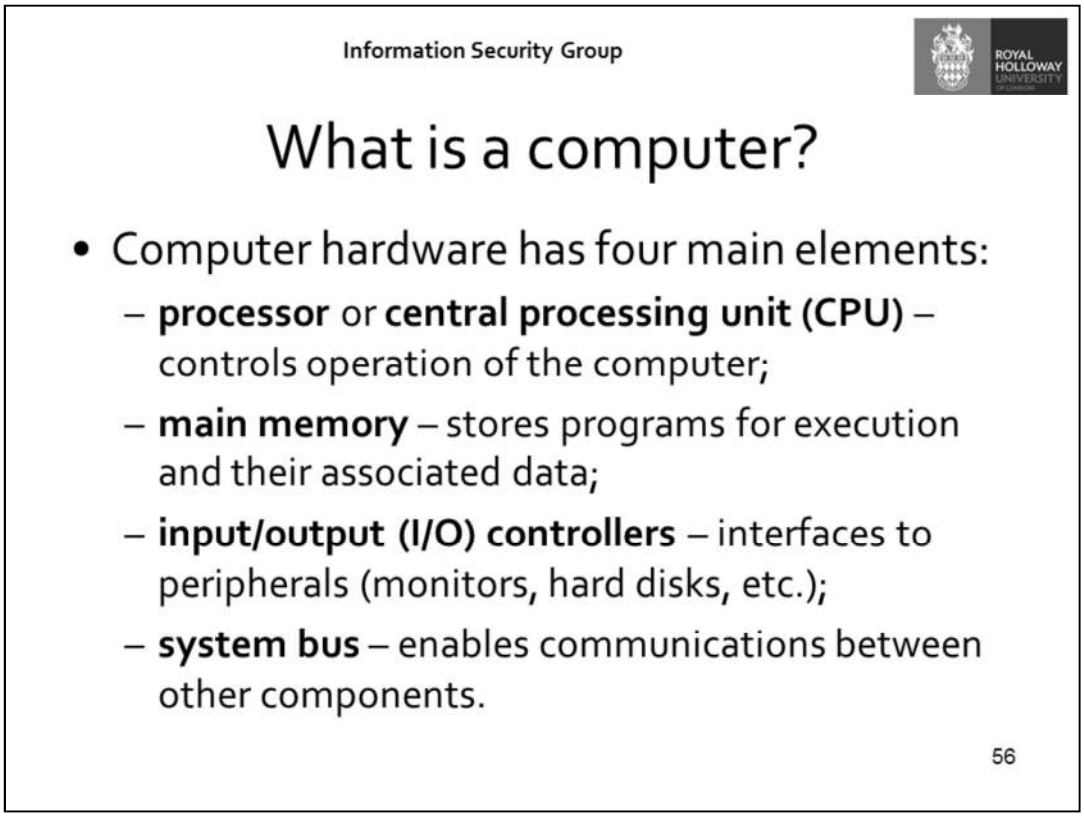


So far we have focussed on what computer systems can do. We next consider how they are put together.



A computer system has three main components, as follows.

- The **Hardware**:
  - stores machine instructions (compiled programs) in main memory; and
  - executes machine instructions.
- The **Operating system** (the **OS**) is a collection of computer programs that:
  - provides an interface between a user and the hardware; and
  - provides an interface between the users and the system resources, such as the file system and print services.
- The **Application programs** (or **apps**):
  - provide specialised computing tools for the end user;
  - include word processors, web browsers, database management systems, games, etc.



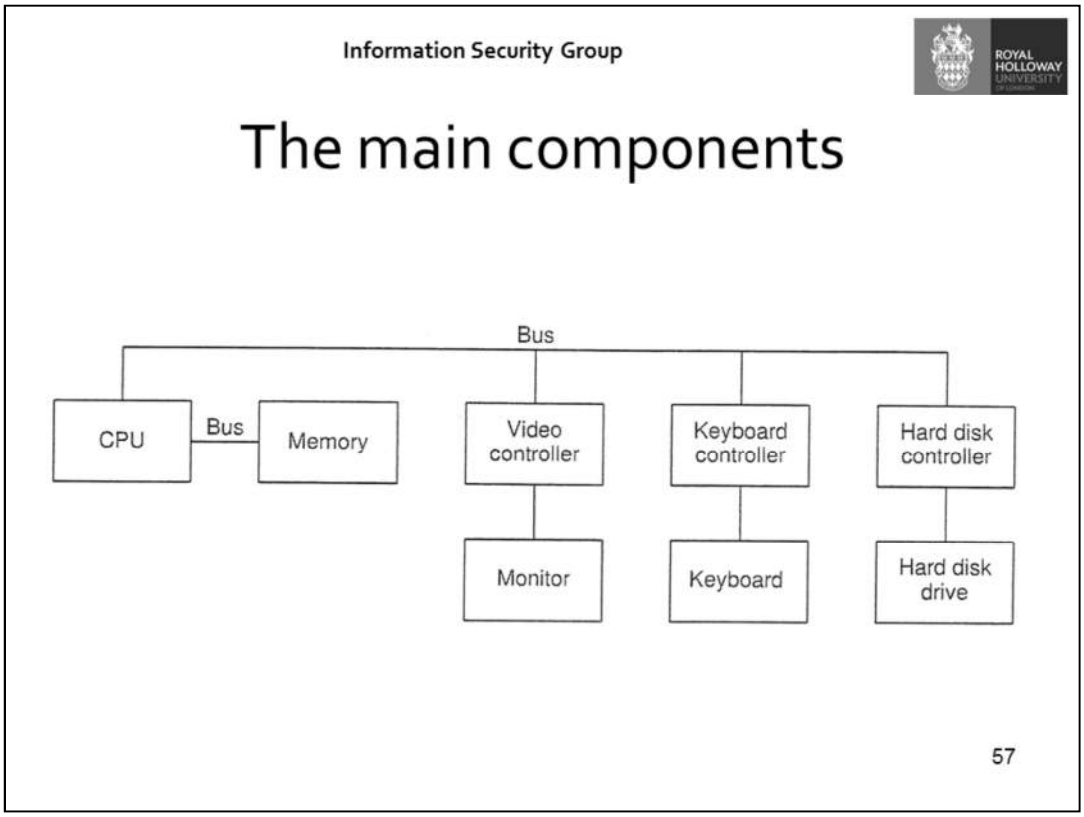
An individual computer (i.e. the hardware component of a computer system) consists of four main elements:

• a **processor** or **central processing unit (CPU)** – controls the operation of the computer and actually performs the computations;

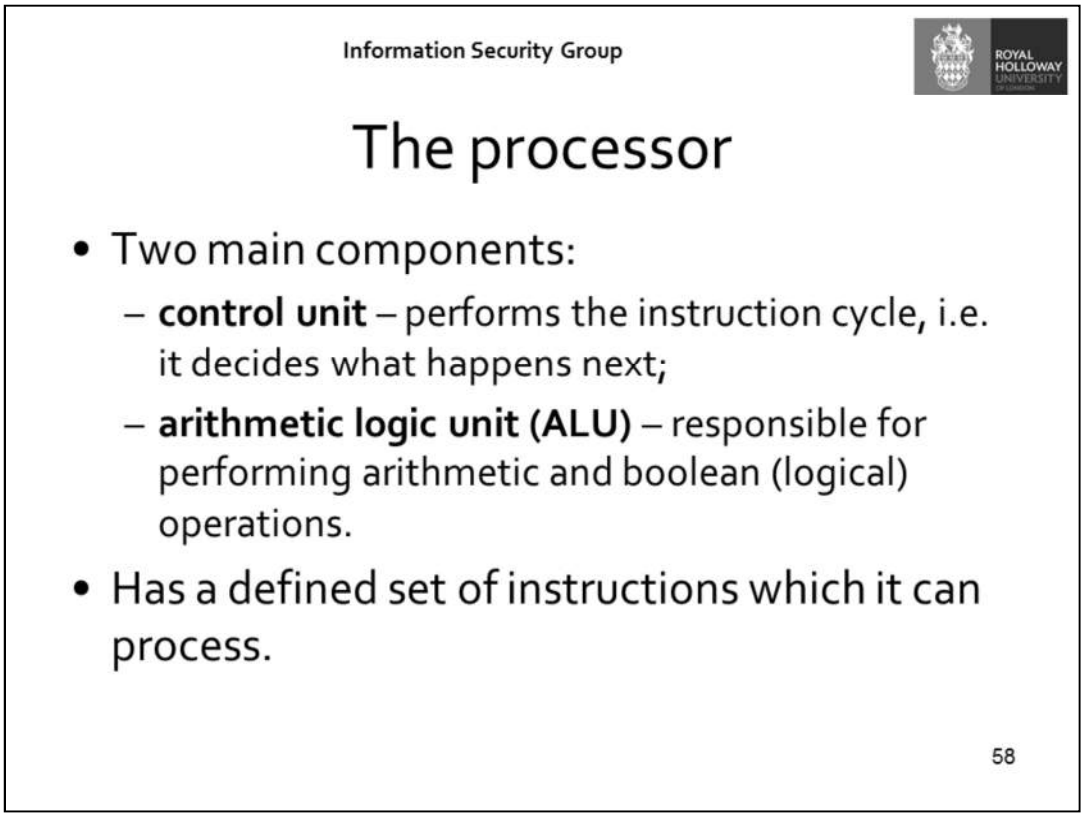
• the **main memory** – stores programs for execution and the data used by the program, i.e. data that the program reads to perform its calculations and writes as its output;

• the **input/output (I/O) controllers** – provide interfaces to peripheral devices (monitors, hard disks, printers, etc.);

• the **system bus** – provides a means of communication between the other components.



This diagram shows a simplified version of the relationships between some of the main components of a computer.

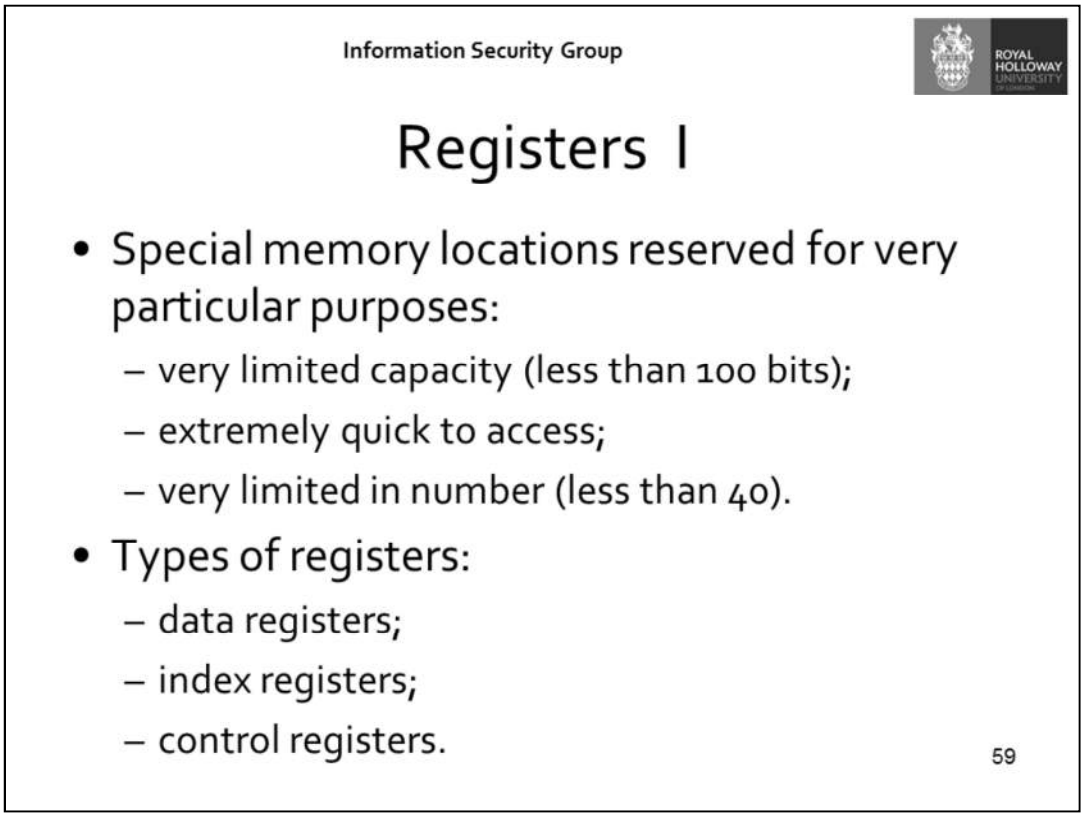


A processor (CPU) incorporates two main components:

• the **control unit** – that is responsible for performing the instruction cycle, i.e. determining what should be done next;

• the **arithmetic logic unit (ALU)** – that is responsible for performing arithmetic and boolean (logical) operations, i.e. actually performing the computations.

Every processor has an associated **instruction set**, which is the collection of instructions that the processor can process. This instruction set is specific to the type of processor.



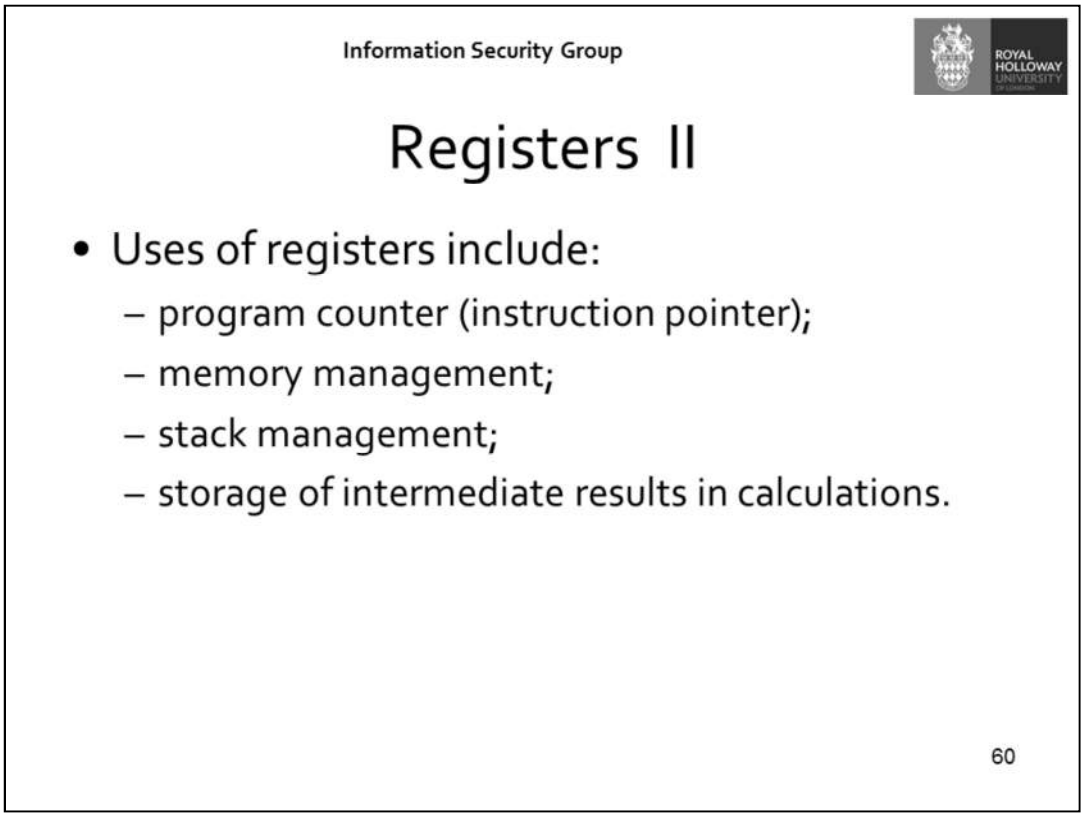
Every processor has a number of special storage locations called **registers**. Registers are reserved for very particular purposes. They:

- have very limited capacity (they have less than 100 bits each);
- can be accessed very quickly by the processor;
- are very limited in number (typically there are less than 40 of them).

Types of registers include:

- data registers;
- index registers; and
- control registers.

The exact nature of the set of registers will depend on the particular type of processor.



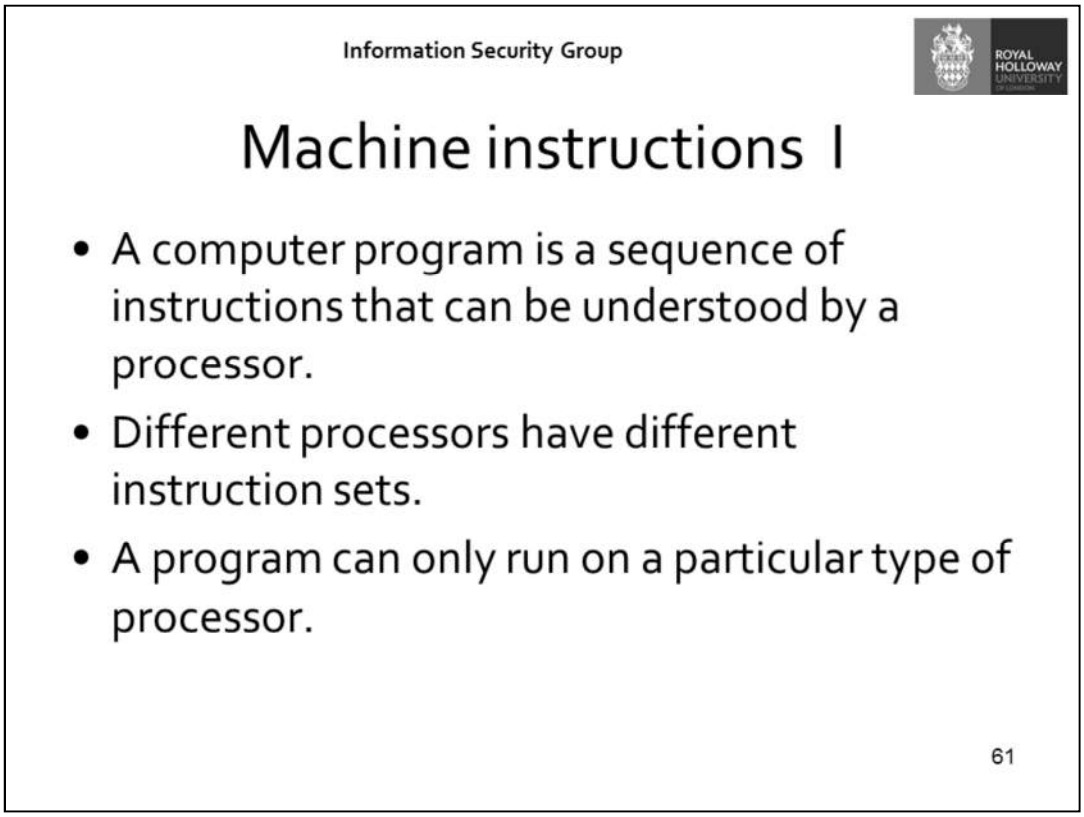
Within a computer, registers are used for a range of purposes, including:

• the program counter (instruction pointer), which points to the memory location containing the instruction currently being executed;

• memory management (i.e. deciding which portions of the computer memory are used for which programs);

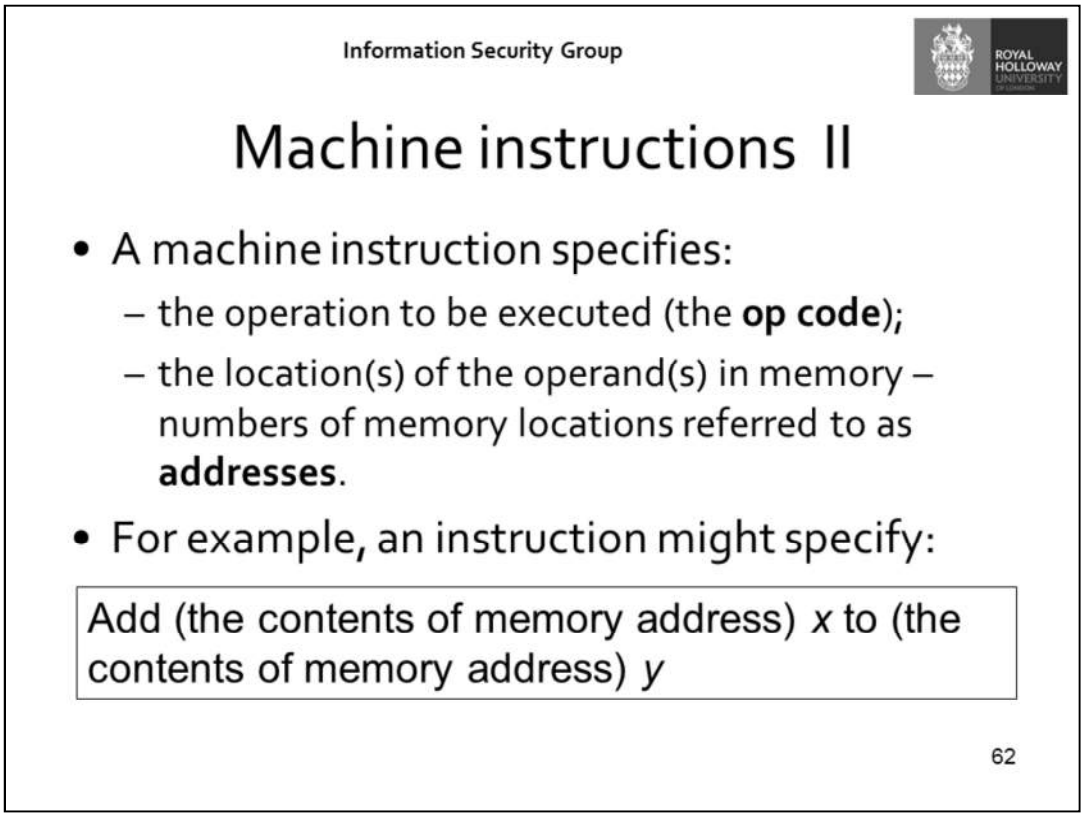
• stack management (where the stack is a special area of memory reserved for temporary storage);

• storage for intermediate results in calculations.



As we have previously outlined, a computer program is a sequence of machine instructions that can be understood by a processor.

Again as mentioned previously, different processors have different instruction sets. As a result, any individual program can only run on a particular type of processor.



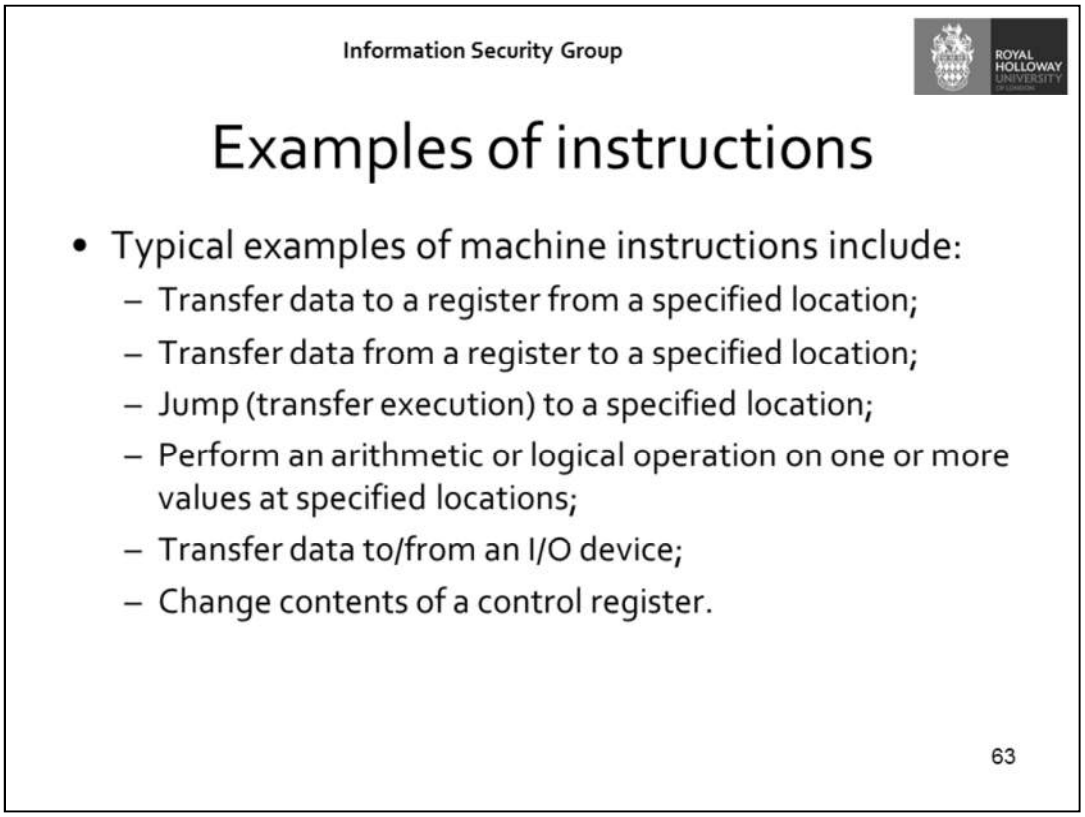
A machine instruction specifies:

• the operation to be executed (the **op code**);

• the location(s) of the **operand**(s) in memory (where the operands are the values used as inputs to the operation). It is important to note that the numbers of memory locations are referred to as **addresses**.

For example, an instruction might specify:

Add (the contents of memory address) *x* to (the contents of memory address) *y*



Typical examples of machine instructions include:

• Transfer data to a register from a specified location in computer memory (recalling that each memory location has a unique address);

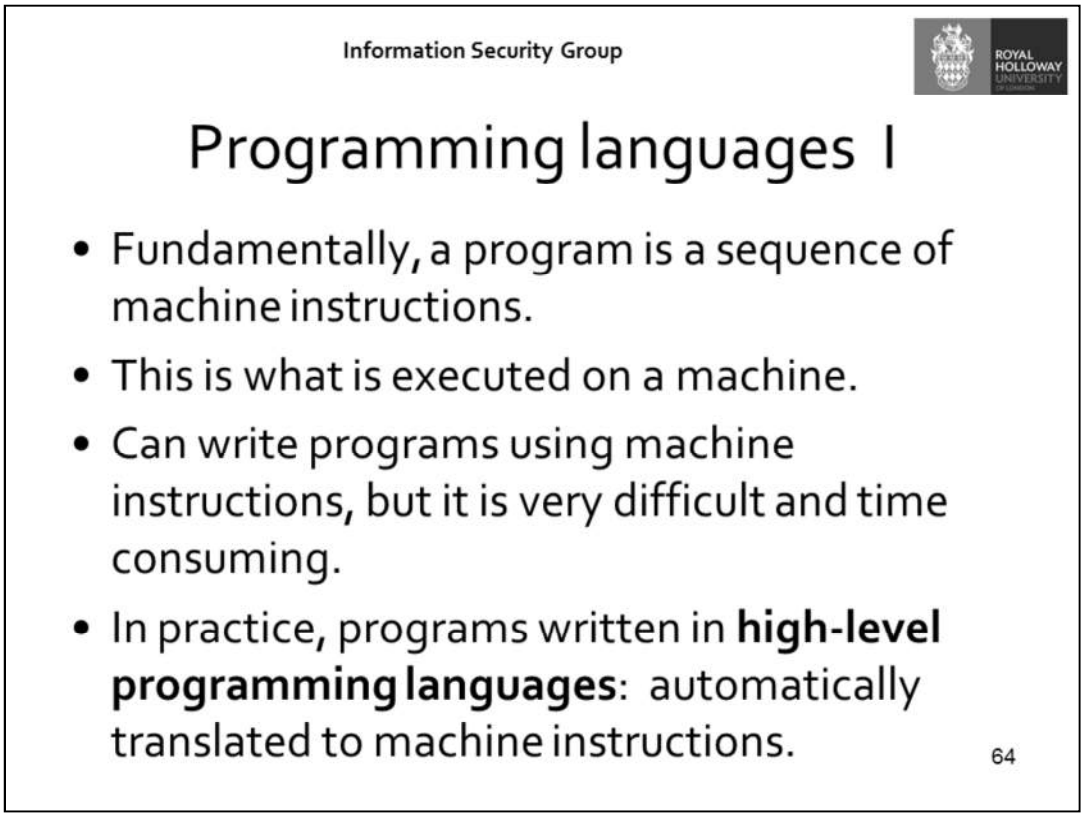
• Transfer data from a register to a specified location in computer memory;

• Jump (transfer execution) to a specified location in computer memory, i.e. modify the program counter, which determines which instruction will be performed next;

• Perform an arithmetic or logical operation on one or more values at specified locations, and store the result somewhere, e.g. in a specific register;

• Transfer data to or from a specified input/output (I/O) device;

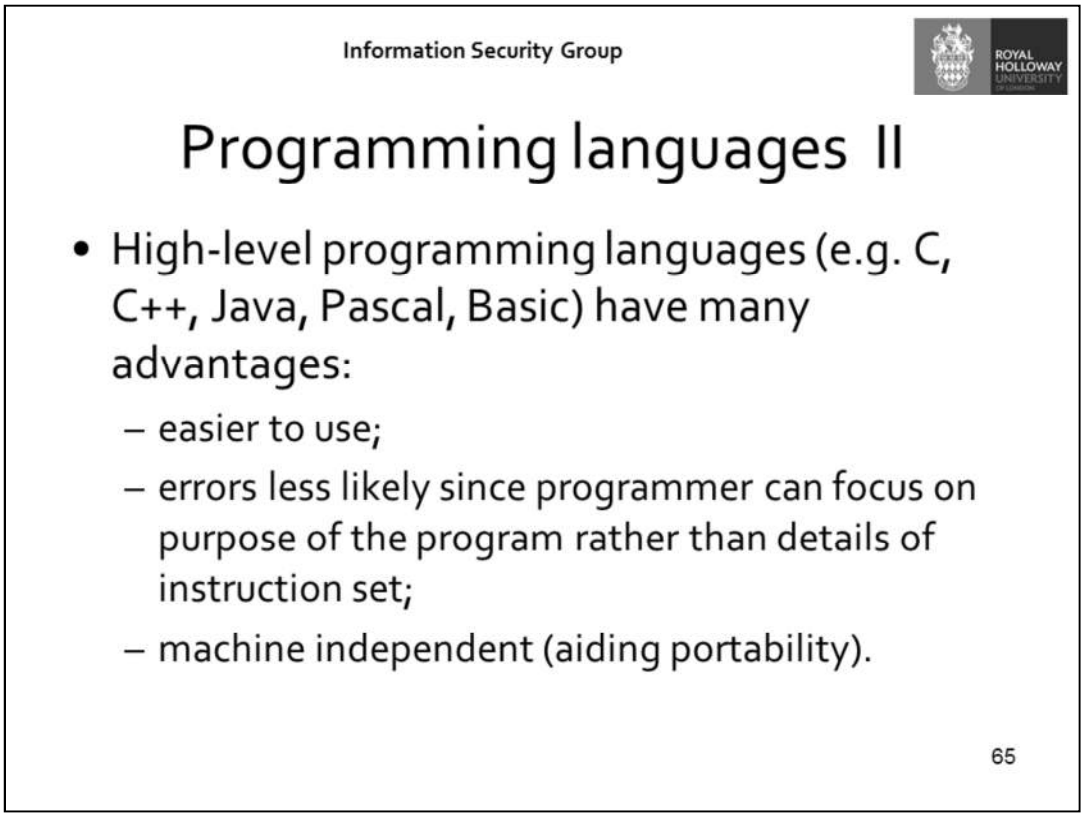
• Change the contents of a control register.



Up to now we have talked about a program as consisting of a sequence of machine instructions. This is correct in the sense that this is what is executed on a machine.

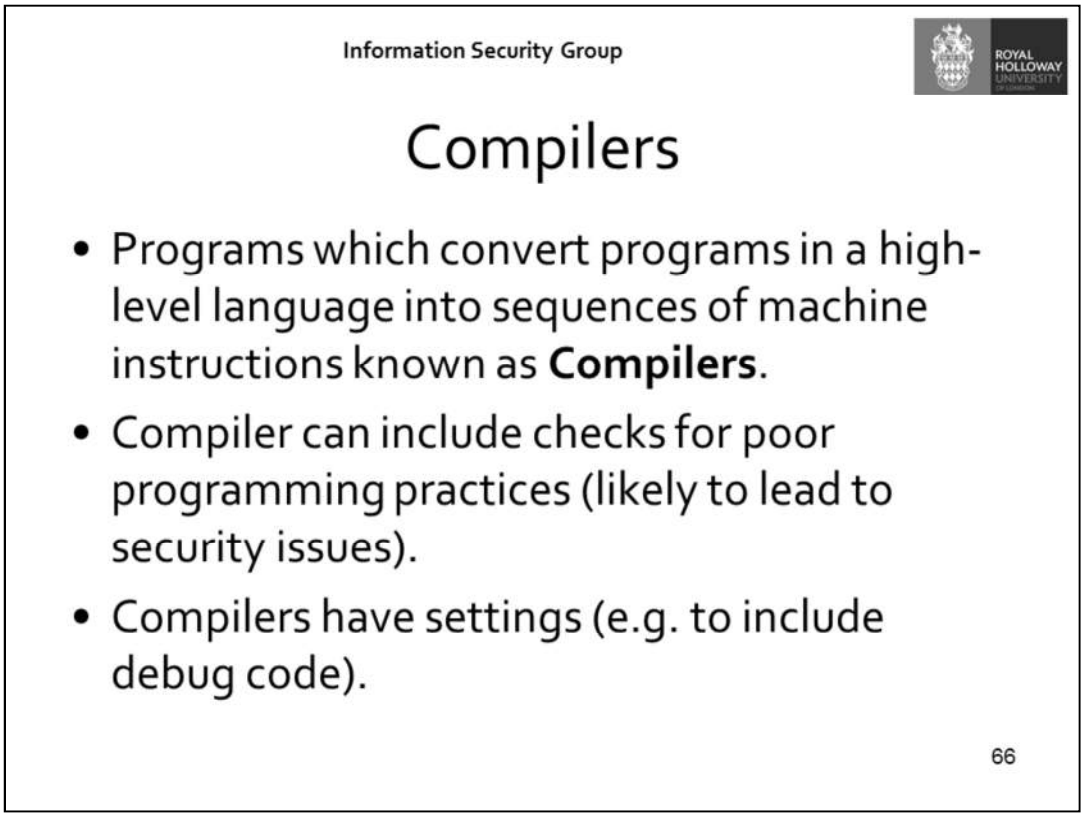
However, whilst it is possible to write programs directly using machine instructions, it is very difficult and time consuming.

In practice, programs are written using **high-level programming languages**, which are subsequently automatically translated into sequences of machine instructions which can then be executed by the processor.



These high-level programming languages (e.g. C, C++, Java, Pascal, Basic) have many advantages:

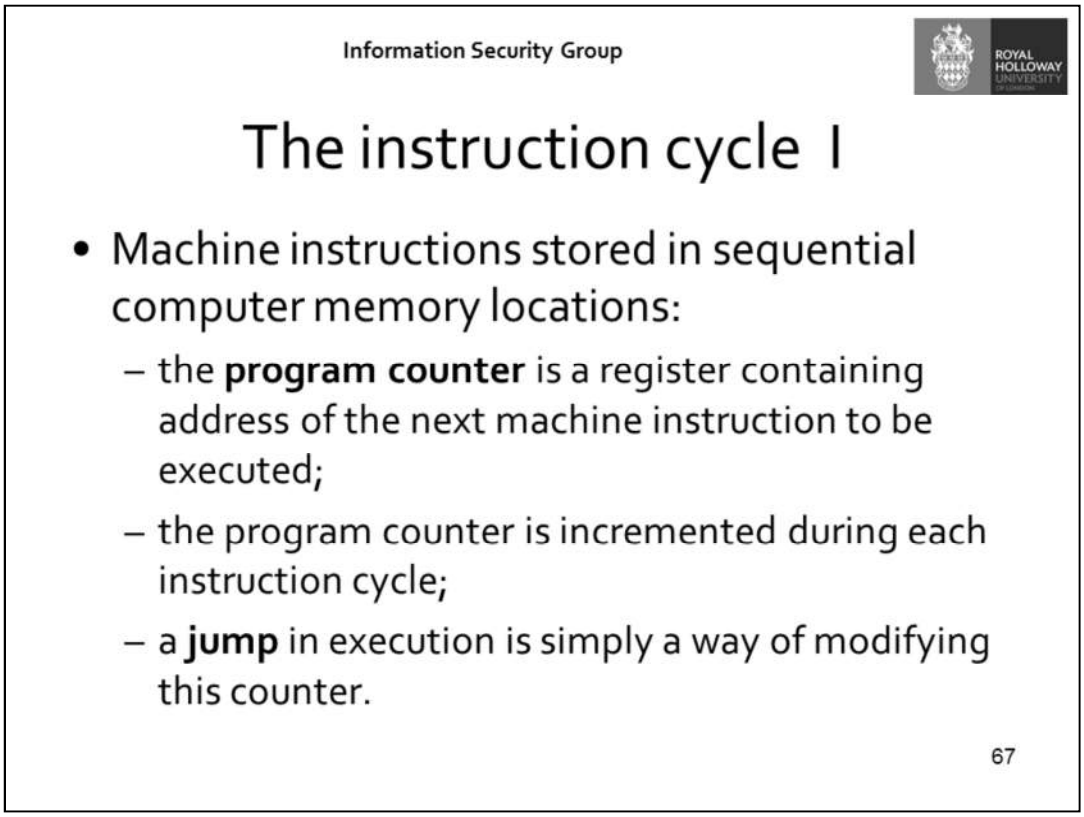
- they are much easier to use;
- errors are less likely since the programmer can focus on the purpose of the program rather than the technicalities of the instruction set;
- they are, to a greater or lesser extent, machine independent, thereby aiding portability.



Programs which can convert programs written in a high-level language into sequences of machine instructions are known as **Compilers**.

A compiler can include checks for poor programming practices (e.g. those which are likely to lead to security issues).

Compilers can have various settings, e.g. so that when developing a new program, the compiler includes lots of extra checks to help in **debugging**, i.e. the process of removing errors from a program while it is being written.

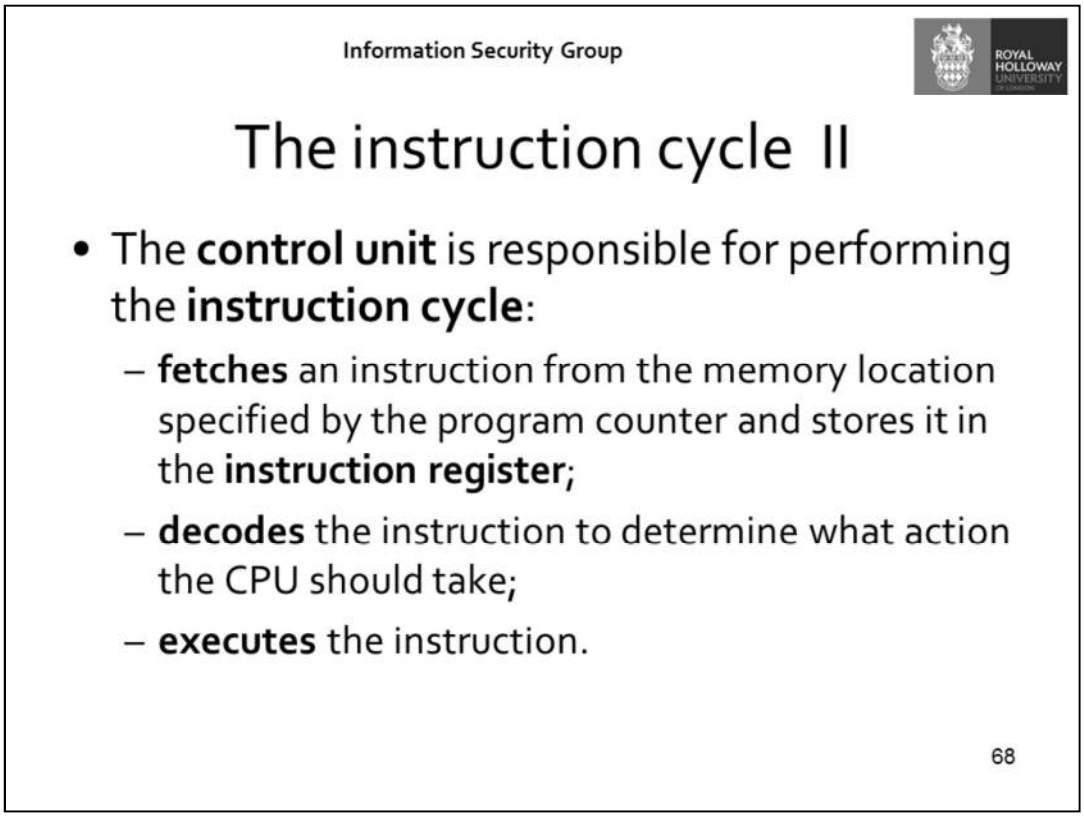


The machine instructions are stored in sequential locations in computer memory:

• the **program counter** is a register that contains the address of the next machine instruction to be executed;

• the program counter is incremented during each instruction cycle;

• a **jump** in execution is simply a way of modifying this counter, so that execution transfers from one part of a program to another part.

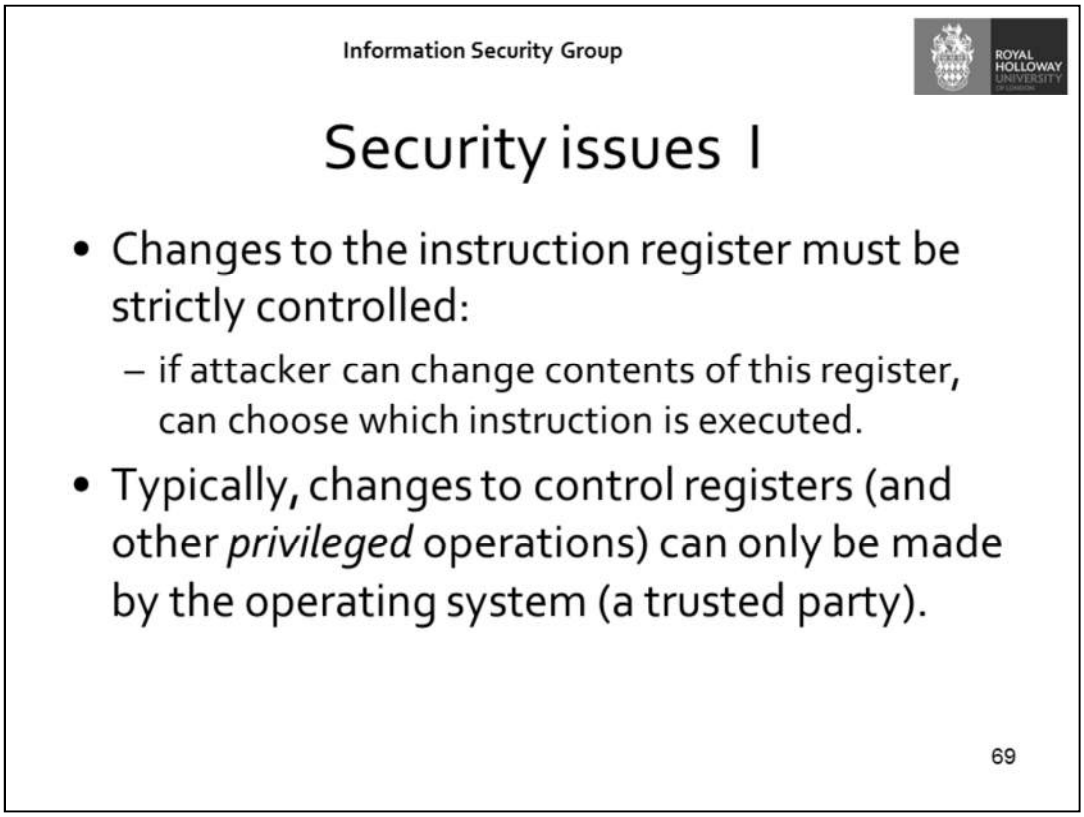


The **control unit** is responsible for performing the **instruction cycle**:

• it **fetches** an instruction from the memory location (address) specified by the program counter and stores it in the **instruction register**;

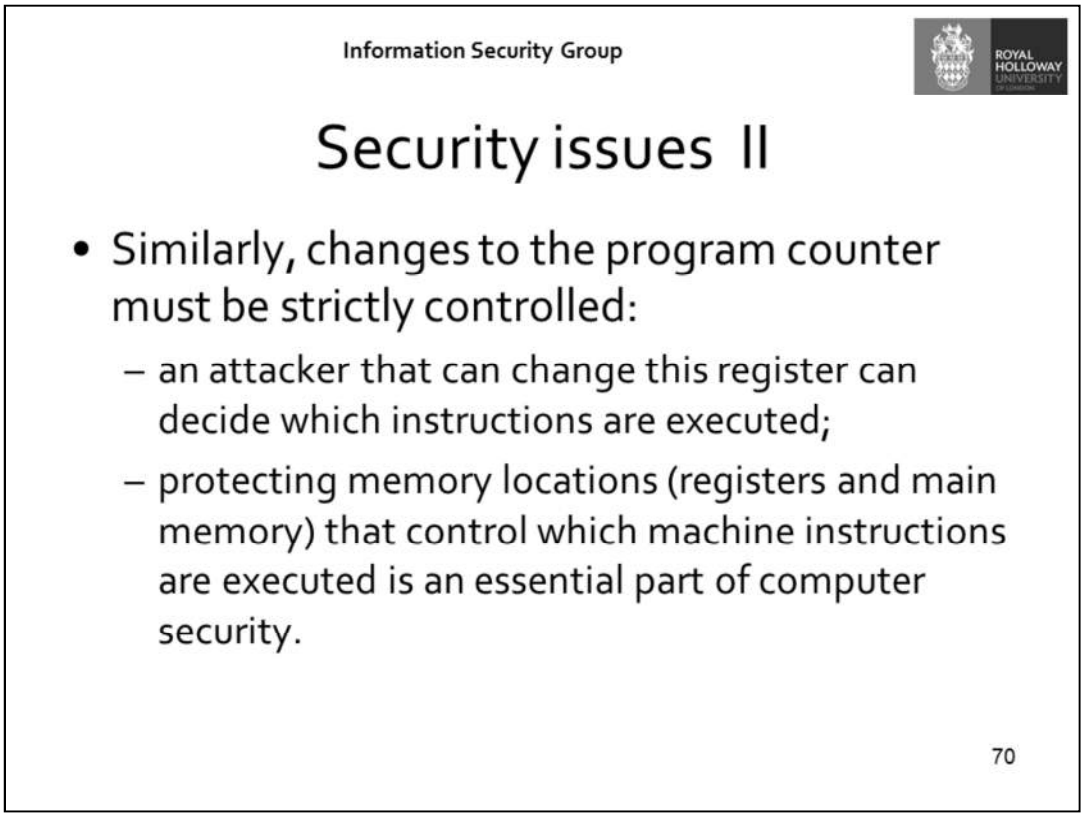
• it **decodes** the instruction to determine what action the CPU should take;

• it **executes** the instruction.



Changes to the instruction register must be strictly controlled. If a malicious party is able to change the contents of this register, then he/she can determine which instruction is executed next.

Typically, things are arranged so that changes to control registers (and other **privileged** operations) can only be made by the operating system, i.e. by a trusted entity.



In a similar way, changes to the program counter must be strictly controlled:

• an attacker that is able to change the contents of this register can decide which machine instructions are executed;

• protecting memory locations (registers and main memory) that control which machine instructions are executed is an essential part of computer security.

Information Security Group

Agenda

- What do computers do?
- Some common notation
- Computer architectures
- Software
- Operating systems
- Resources

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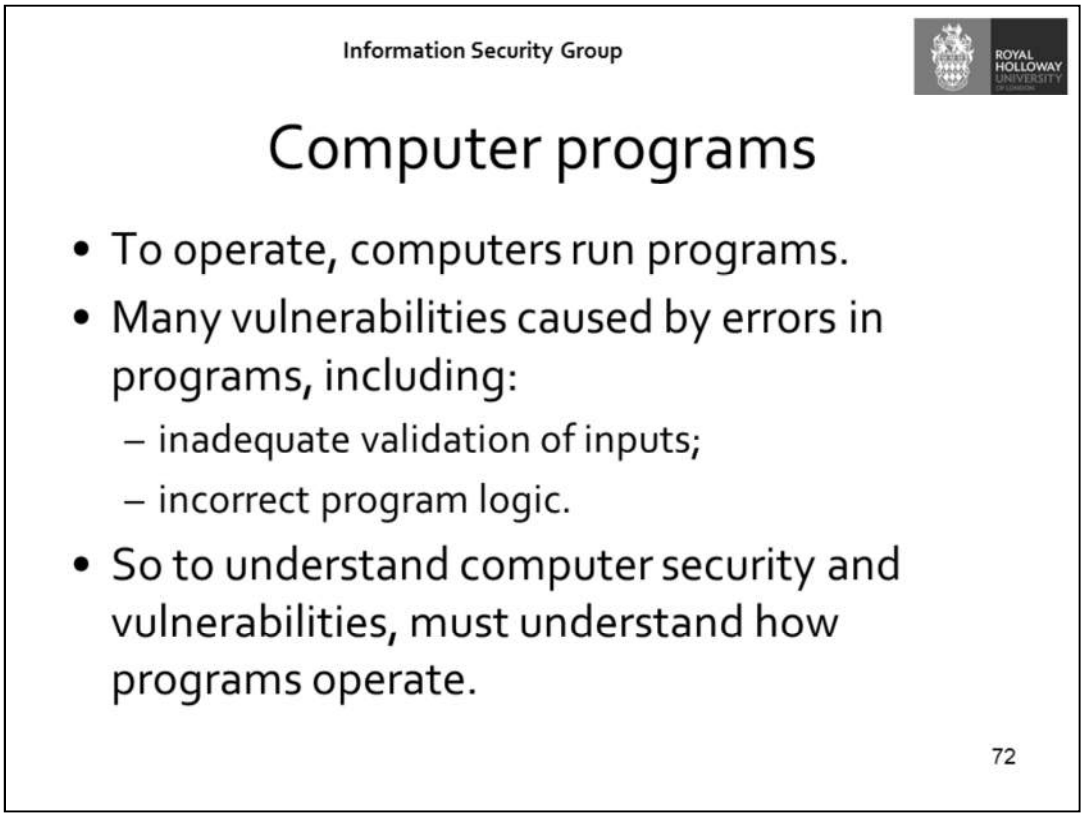
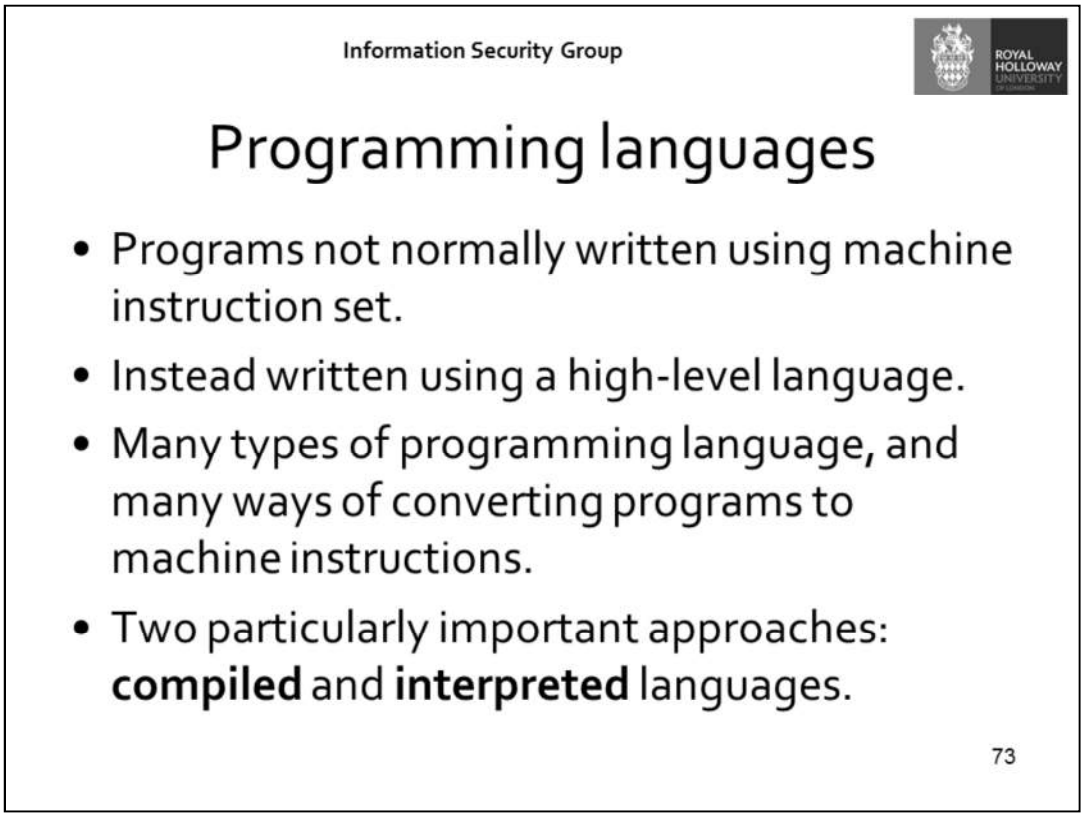


As we have seen, in order to perform tasks, computers run programs.

Many vulnerabilities, i.e. weaknesses in a system that can be exploited to attack the system, are caused by errors in programs, including:

- inadequate validation of inputs;
- incorrect program logic.

In order to fully understand computer security and the vulnerabilities in systems that can give rise to attacks on systems, it is thus necessary to understand how programs operate, at least at a high level.

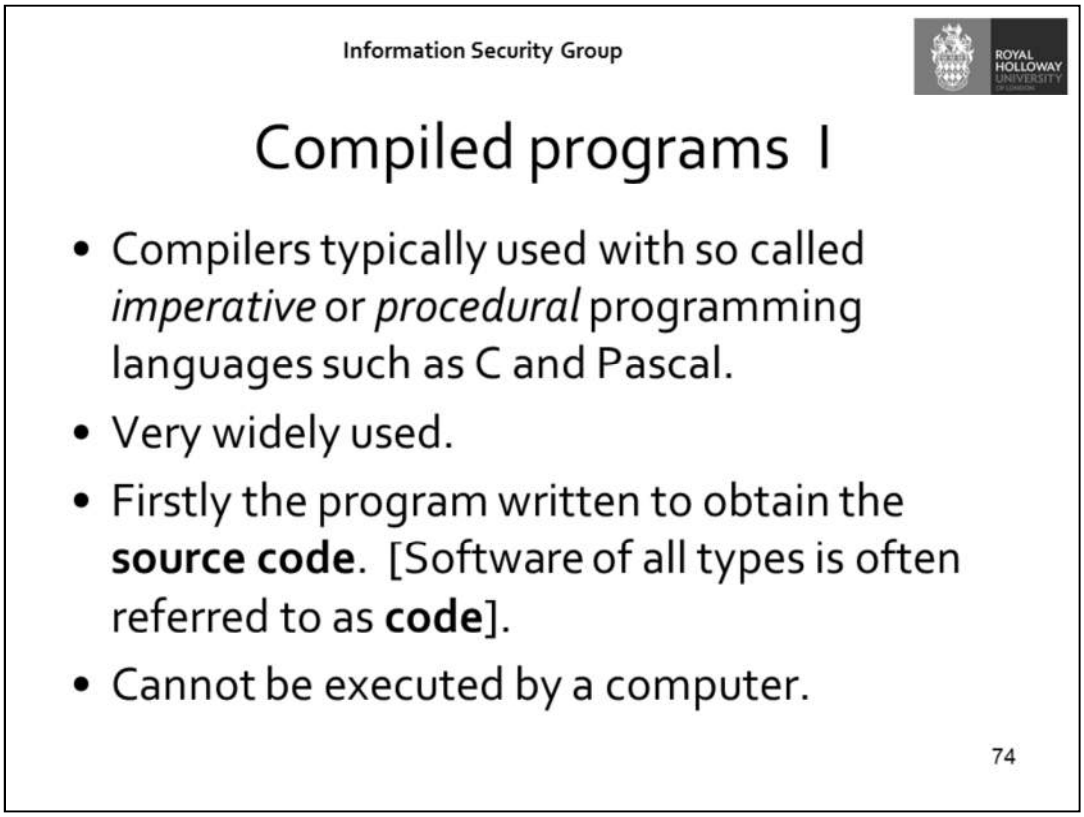


As mentioned previously, although computers have a defined instruction set, programs are not normally written using this instruction set.

They are instead written using a high-level language.

There are many types of programming language, and many ways of converting programs in these high-level languages to machine instructions.

We briefly review two particularly important approaches, namely **compiled** and **interpreted** languages.

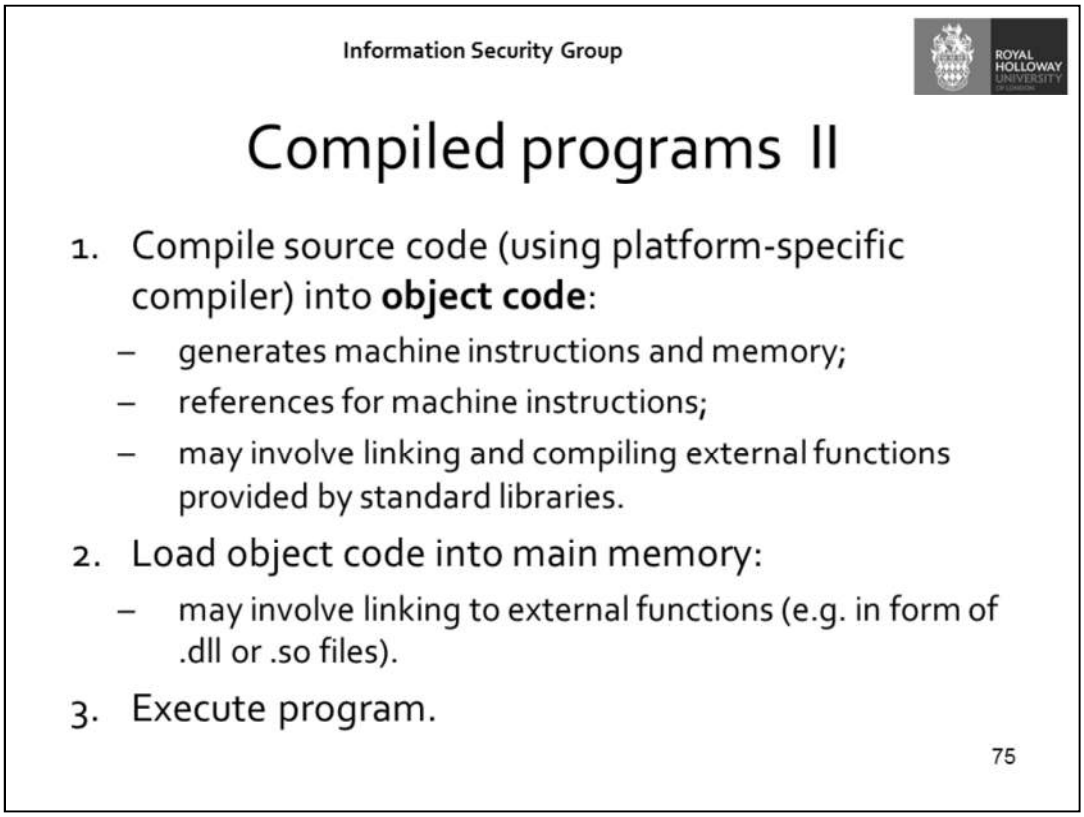


Compilers are typically used with so called *imperative* or *procedural* programming languages, such as C, C++ and Pascal.

Such languages are very widely used.

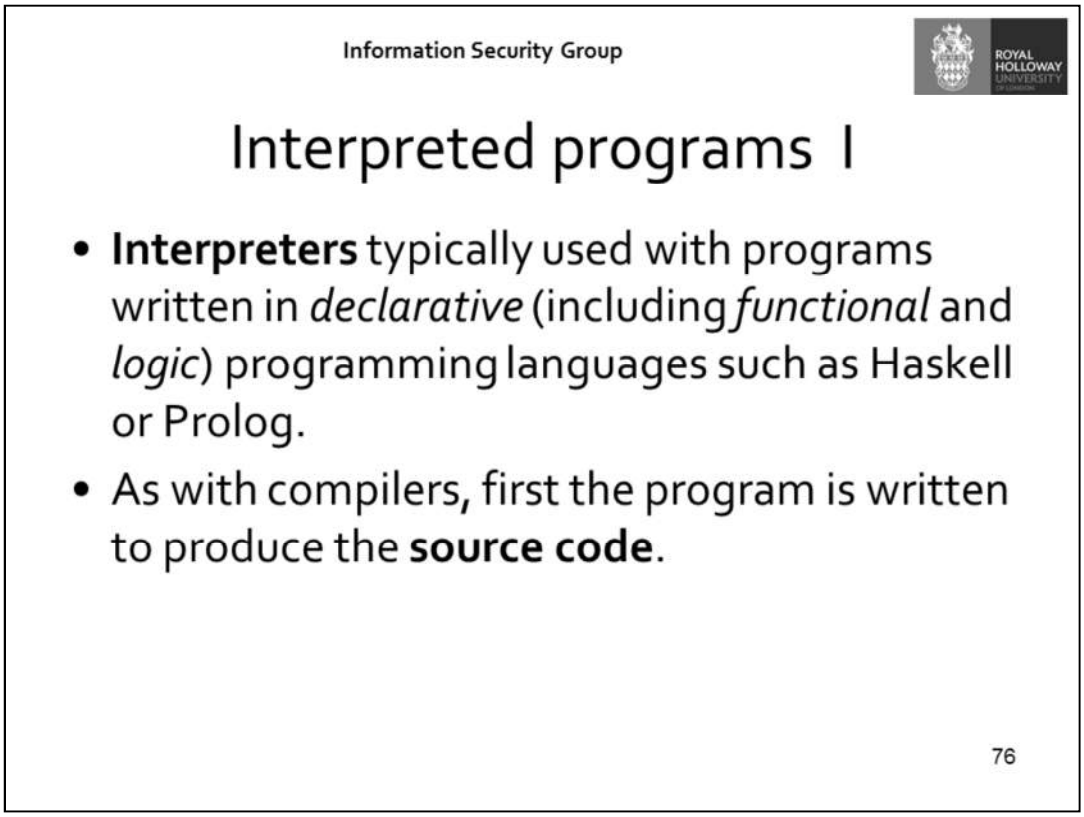
Firstly the program is written to produce the **source code**. Software of all types is often referred to simply as **code**.

This source code cannot be executed directly on a computer.



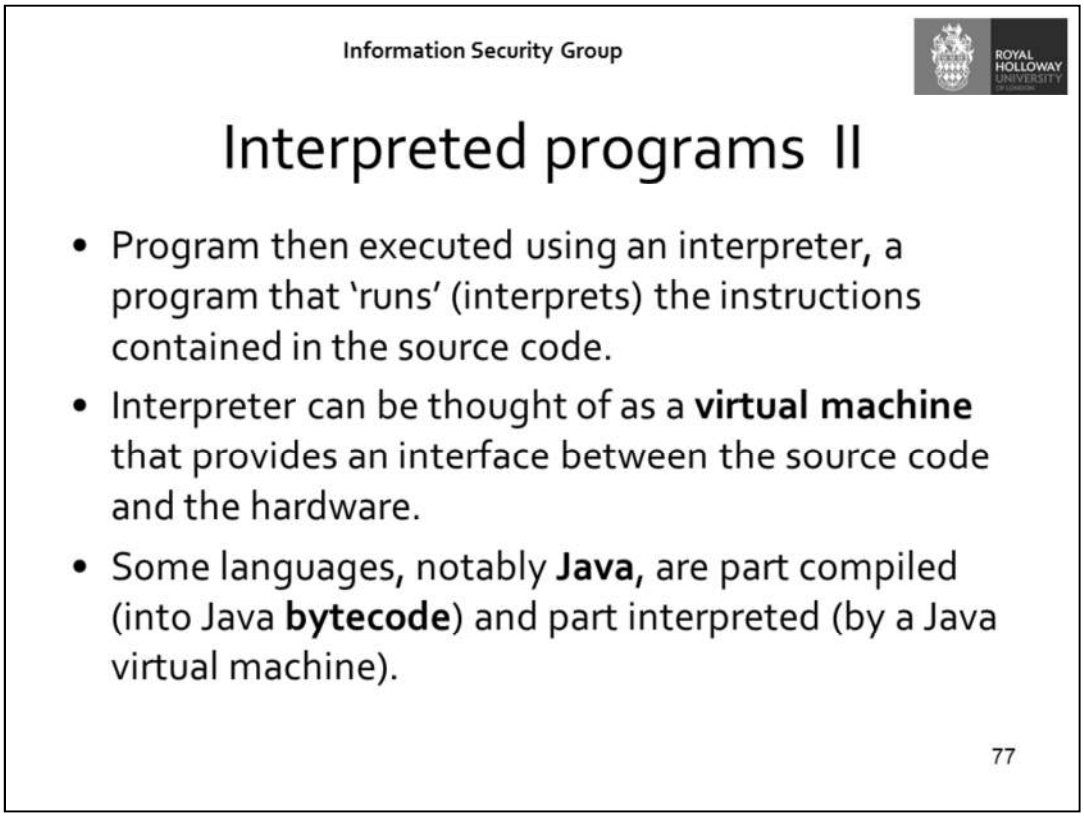
There are three main steps in the use of compiled programs.

1. Compile the source code (using a platform-specific compiler) into **object code**:
   - compiler generates machine instructions and memory references for machine instructions;
   - may involve linking and compiling external functions provided by standard libraries.
2. Load the object code (the program) into the computer's main memory:
   - this may involve **linking** to **external functions**, e.g. provided by the operating system, e.g. in the form of .dll (dynamic linked library) or .so files.
3. Execute the program.



Interpreters are typically used with programs written in *declarative* (including *functional* and *logic*) programming languages such as Haskell or Prolog.

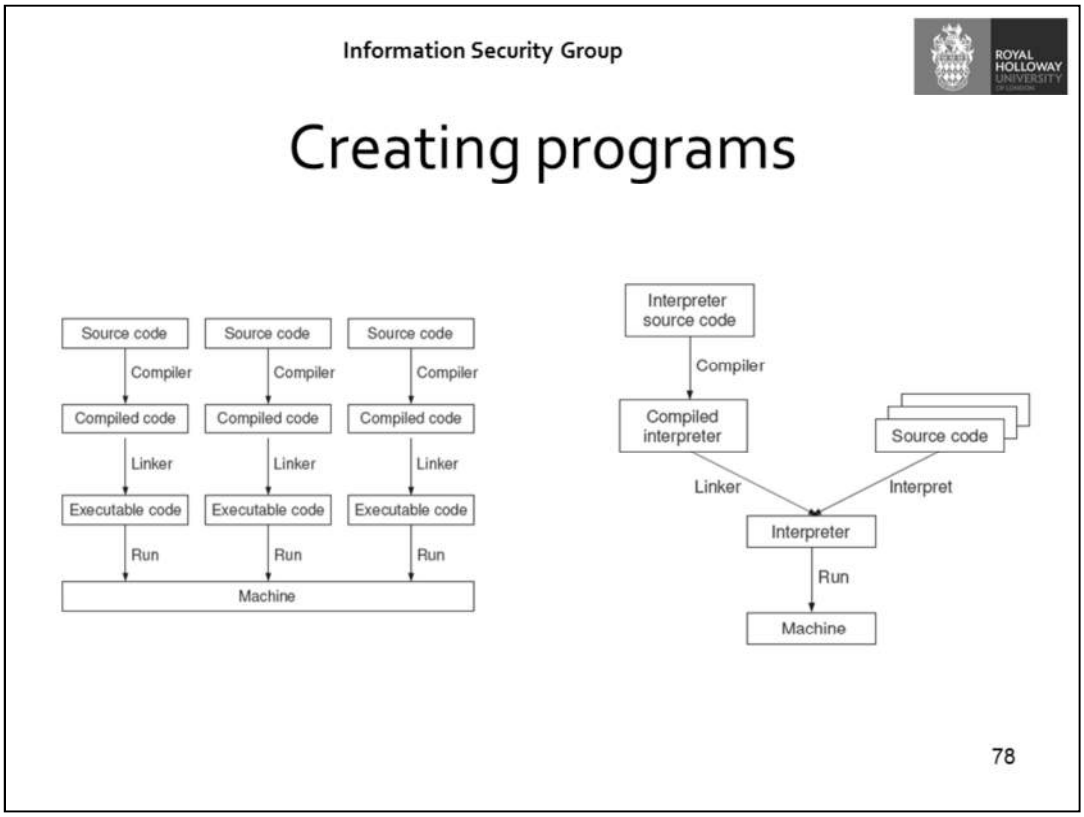
As with the use of compilers, first the program is written to produce the **source code**. It is what happens next that differentiates interpreted from compiled code …



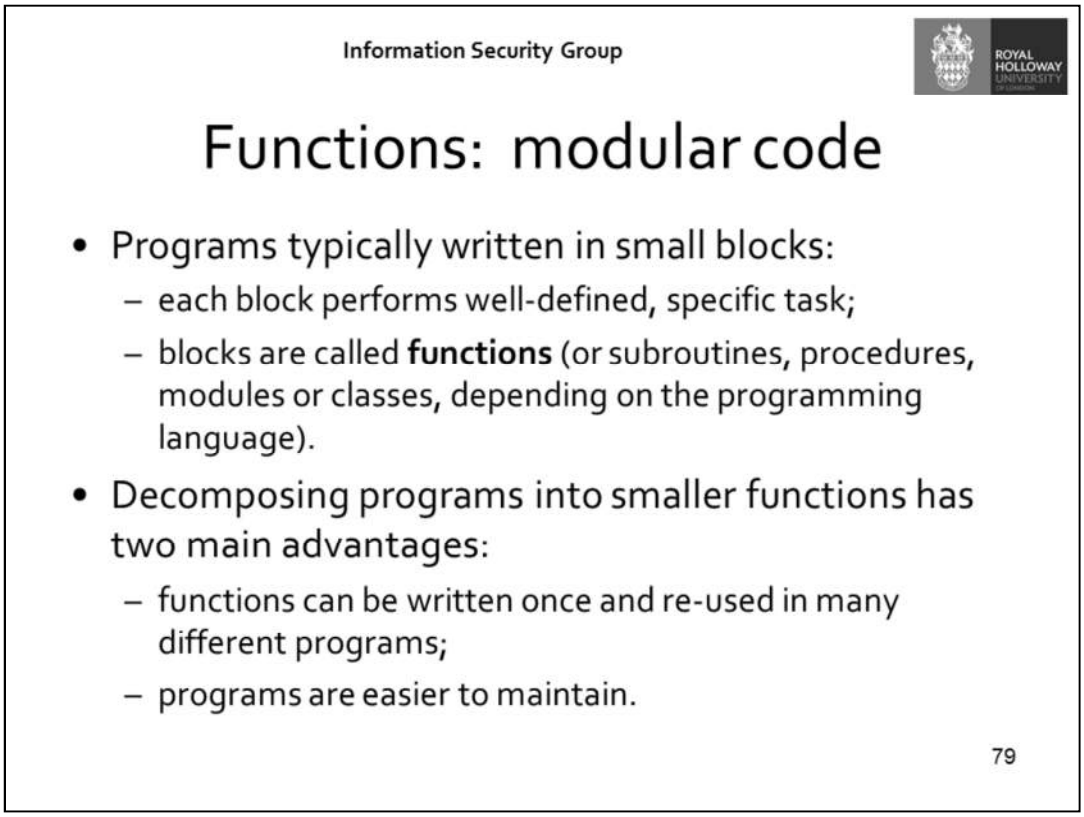
The program is then immediately executed using an interpreter, a program that 'runs' (interprets) the instructions contained in the source code. That is, the instructions in the high level language are translated into machine instructions 'on the fly', instead of in advance.

An interpreter can be thought of as a **virtual machine** that provides an interface between the source code and the hardware. This virtual machine is an imaginary computer that can directly operate on the commands of the high level programming language.

Some languages, notably **Java**, are part compiled (into Java **bytecode**) and part interpreted (by the Java virtual machine).



The diagram shows the two ways in which high-level language programs are converted to machine instructions. The compiler approach is shown on the left, and the interpreter approach on the right.



Computer programs are typically written in small blocks:

• each block performs a well-defined, specific task;

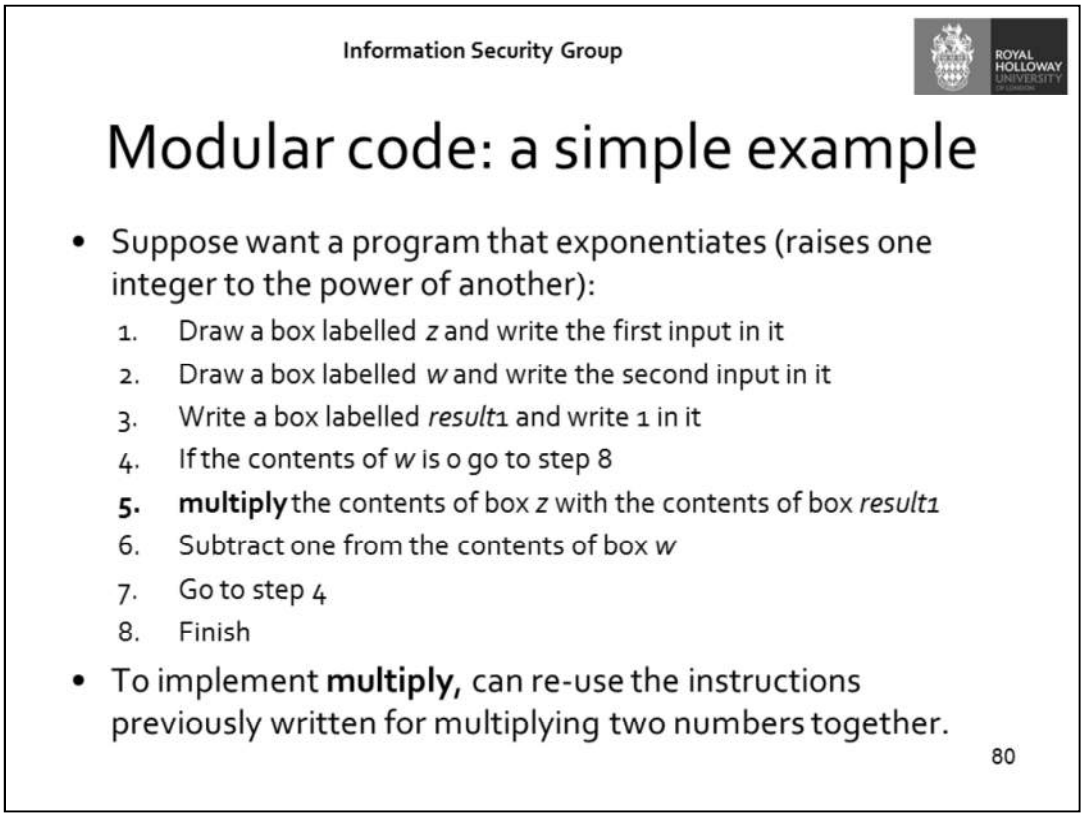
• blocks are called **functions** (or subroutines, procedures, modules or classes, depending on the programming language).

Decomposing programs into smaller functions has two main advantages:

• functions can be written once and re-used in many different programs;

• the resulting programs are easier to maintain, since it is easier to understand, test and maintain a small self-contained piece of code which performs a specific function than a large monolithic program.

Such a **modular approach** is deemed good practice in **software engineering** (the name for the discipline of writing programs).

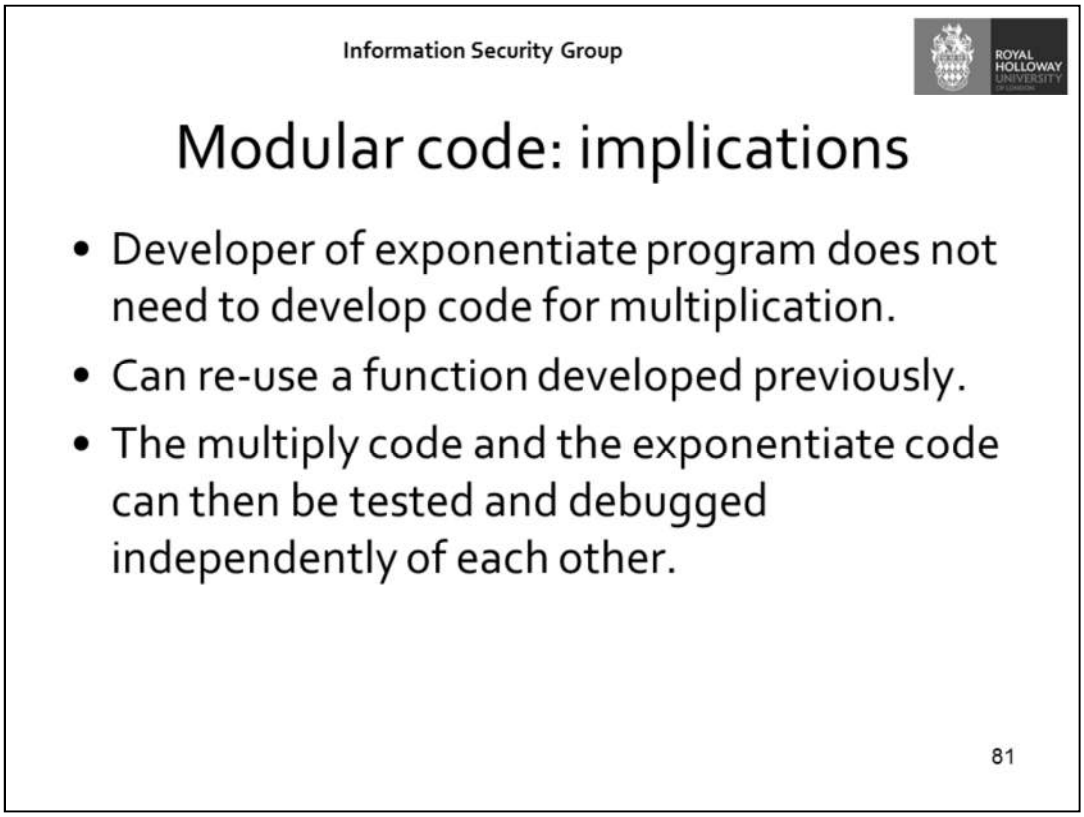


Suppose that you want to develop a program that exponentiates integers (i.e. that raises one integer to the power of another integer). The following program is a possible way of performing such a computation.

1. Draw a box labelled *z* and write the first input in it
2. Draw a box labelled *w* and write the second input in it
3. Write a box labelled *result*1 and write 1 in it
4. If the contents of *w* is 0 go to step 8
5. **multiply** the contents of box *z* with the contents of box *result1*
6. Subtract one from the contents of box *w*
7. Go to step 4
8. Finish

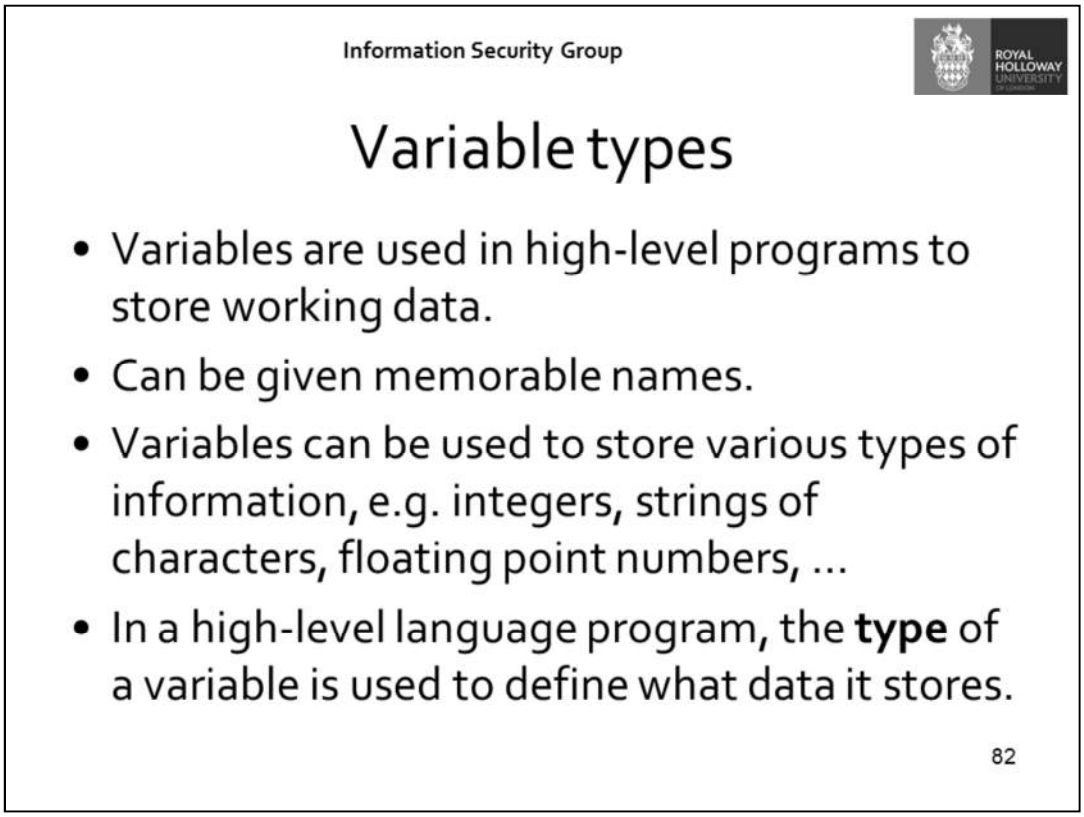
The program works by multiplying the value inserted in *z* by itself over and over again (the number of times this happens is set by the value inserted in *w*).

To implement the **multiply** instruction (in step 5), we can re-use the instructions previously written for multiplying two numbers together.



The developer (author) of the exponentiate program does not need to develop his or her own code for multiplication, and can instead re-use the multiply function developed previously.

The multiply code and the exponentiate code can then be tested and debugged independently of each other.

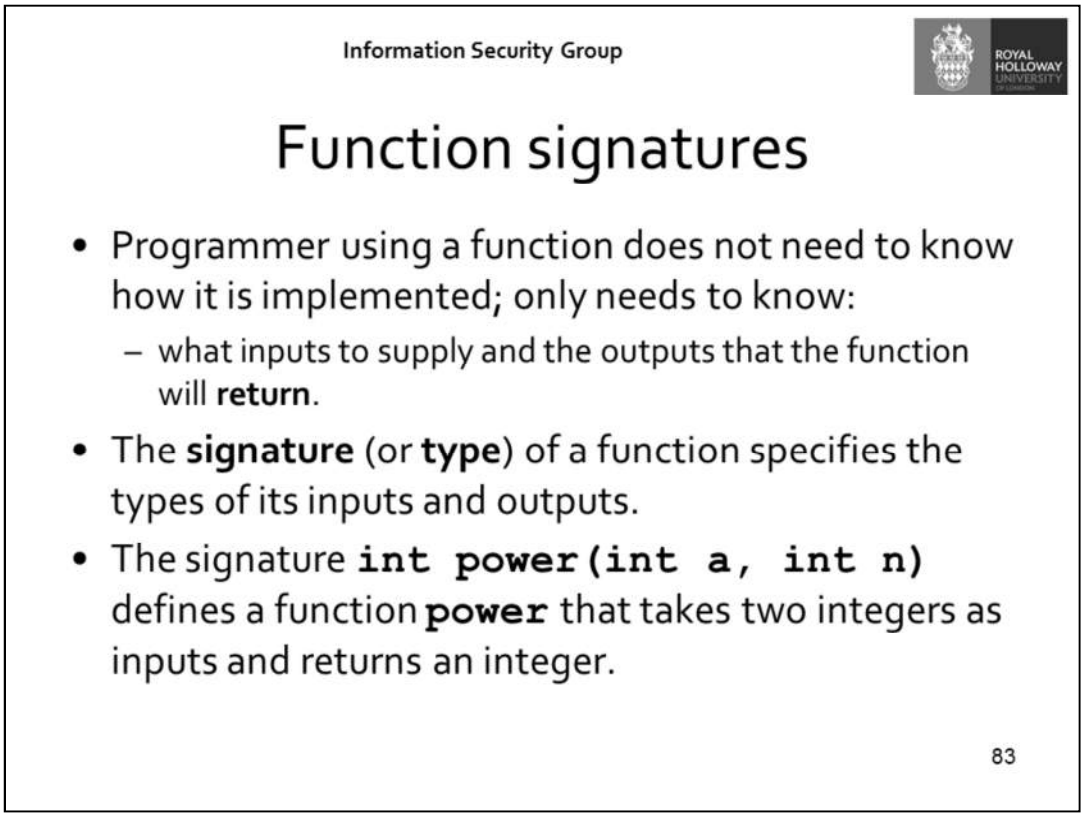


When writing computer programs in a high-level language we use **variables** to store working data. These variables can be given memorable names which reflect their purpose.

Variables can be used to store various types of information, e.g. integers, strings of characters, floating point numbers, …

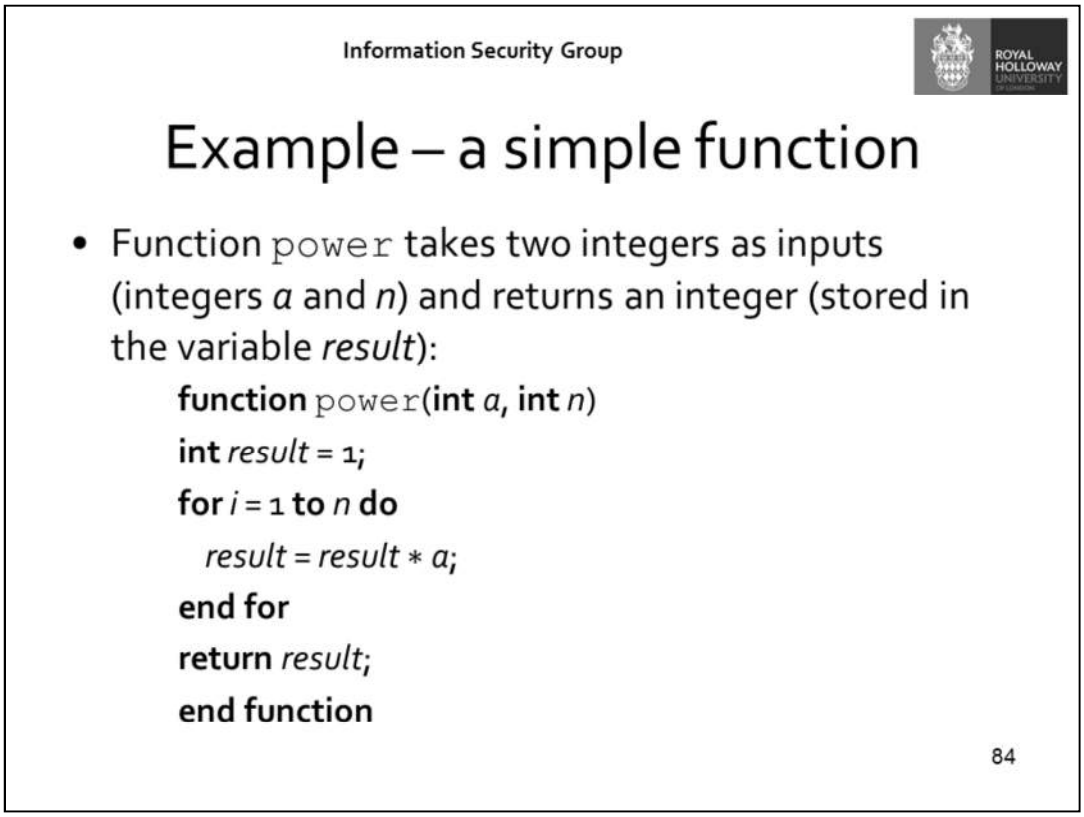
In a high-level language program, the **type** of a variable is used to define the nature of the data stored in that variable.

When a high-level language program is translated into a sequence of machine instructions, the variable names are converted into numerical memory addresses.



A computer programmer using a pre-written function does not need to know how the function is implemented. The programmer only needs to know what inputs to supply to a function, and the outputs that the function will **return**. That is, the programmer can treat a function as a 'back box', with known inputs and outputs.

The **signature** (or **type**) of a function specifies the types of its inputs and outputs. The signature `int power(int a, int n)` defines a function `power` that takes two integers as inputs and returns an integer.

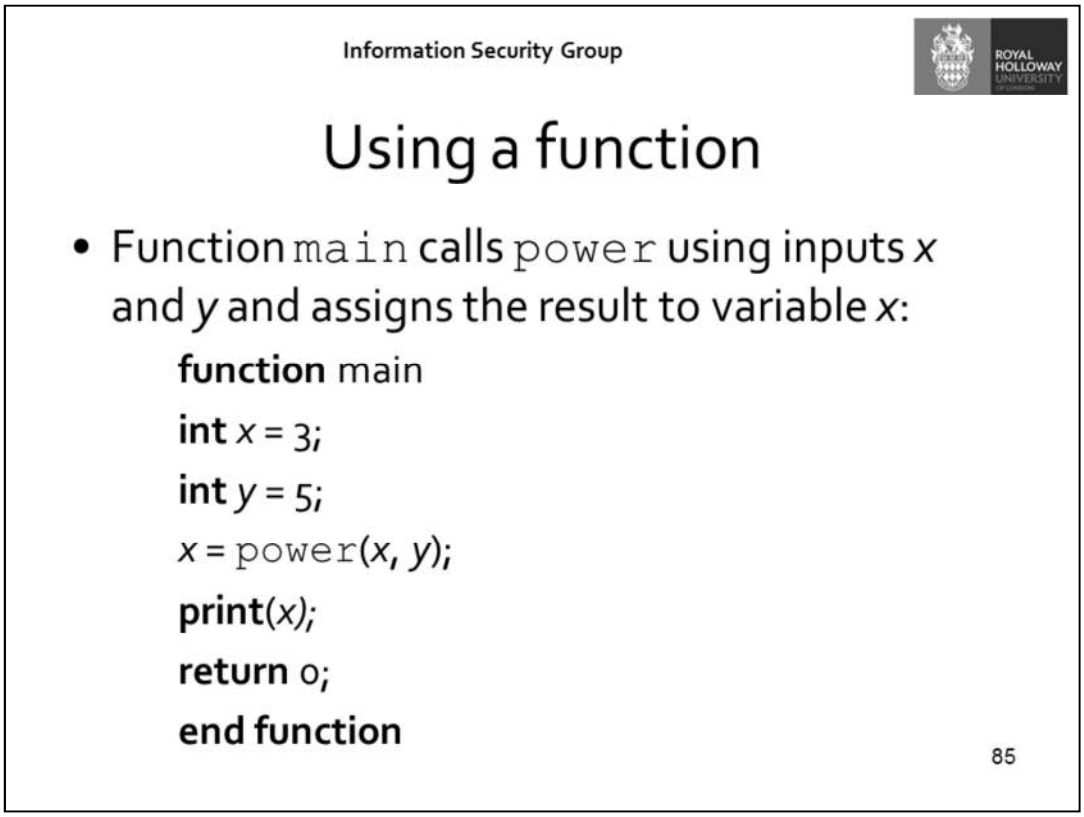


The `power` function takes two integers as inputs (integers *a* and *n*) and returns an integer (stored in the variable *result*):

```
function power(int a, int n)
int result = 1;
for i = 1 to n do
   result = result * a;
end for
return result;
end function
```

In this function there is a 'for loop', terminated by the 'end for' statement The syntax shown simply means execute the instructions in the loop a total of *n* times – firstly with *i*=1, secondly with *i*=2, and so on, until the last time when *i*=*n*.

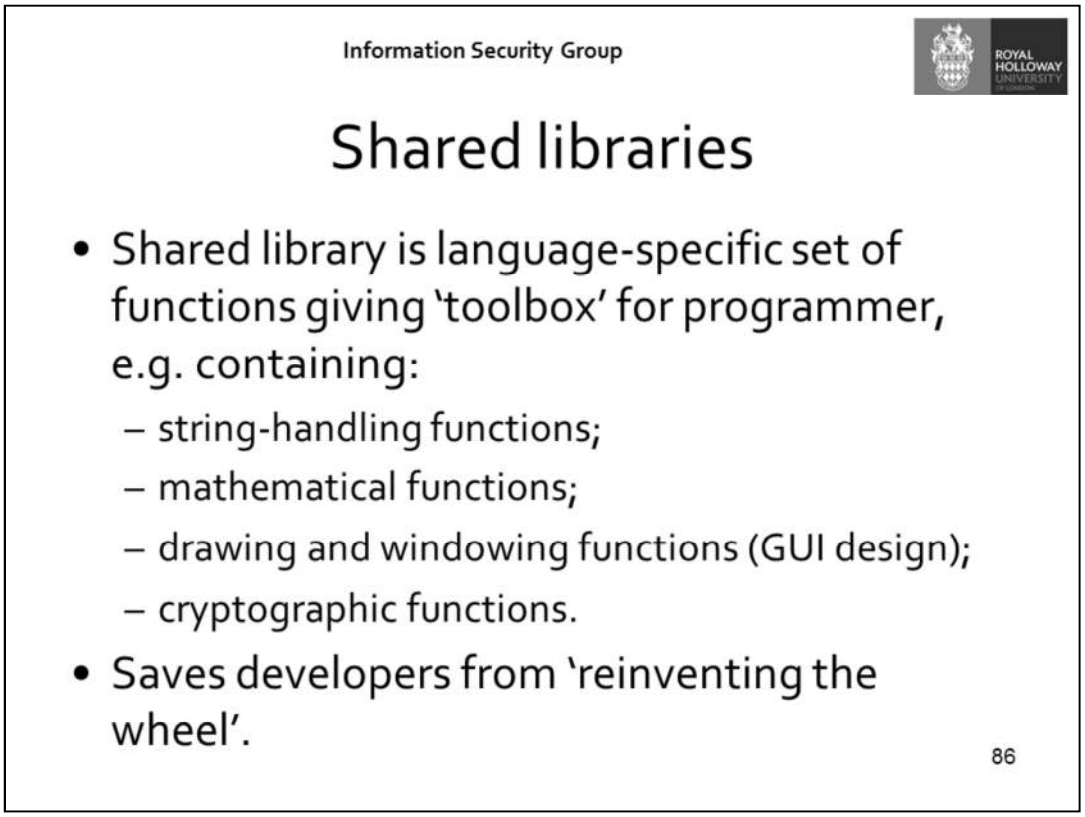
The function computes the exponential a^n, i.e. *a* raised to the power *n.*



The program `main` (which is itself a function) calls the function `power` using inputs *x* and *y*, and assigns the result to the variable *x*:

function main
int *x* = 3;
int *y* = 5;
x = `power`(*x*, *y*);
print(*x);*
return 0;
end function

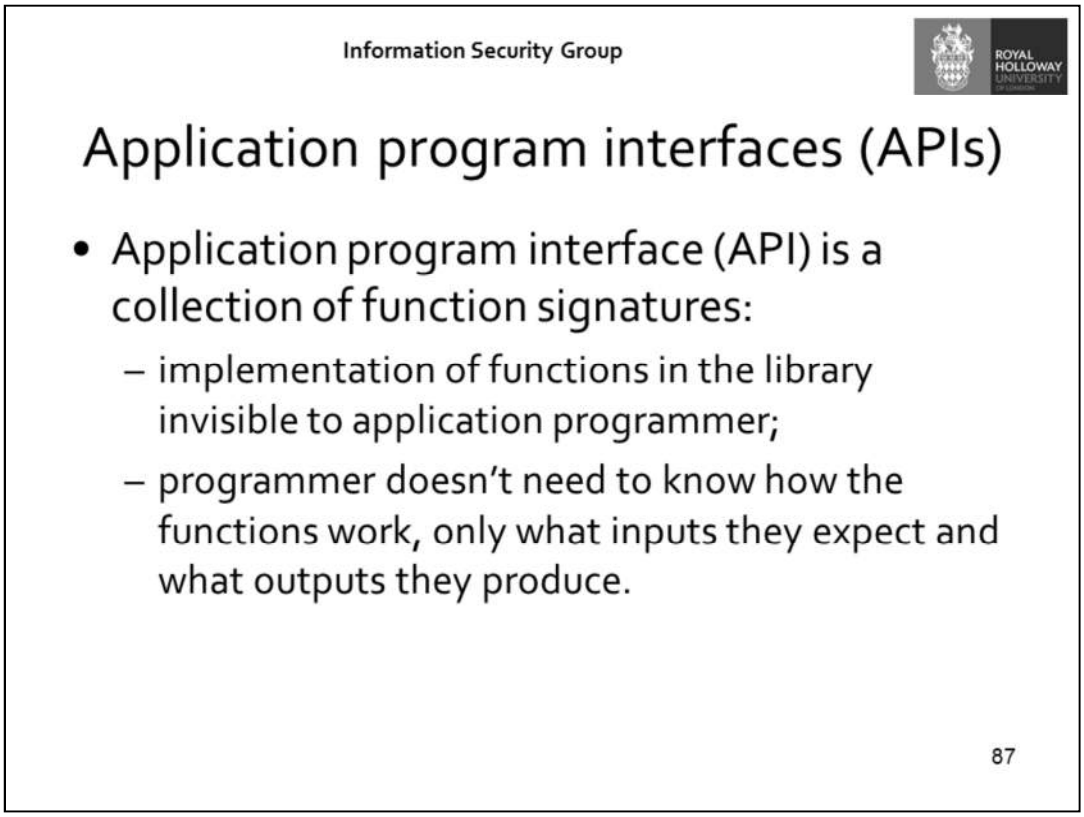
Note that the 'return 0' line is just a programmatic convenience. It doesn't mean anything, since no function calls main – it is the 'top level' function.



A shared library is a language-specific suite of functions that provides a 'toolbox' for programmers. The functions in such a library will be designed to do things that are needed by many programs. Examples of types of functions in such a library include:

- string-handling functions;
- mathematical functions;
- drawing and windowing functions (for Graphical User Interface (GUI) design);
- cryptographic functions.

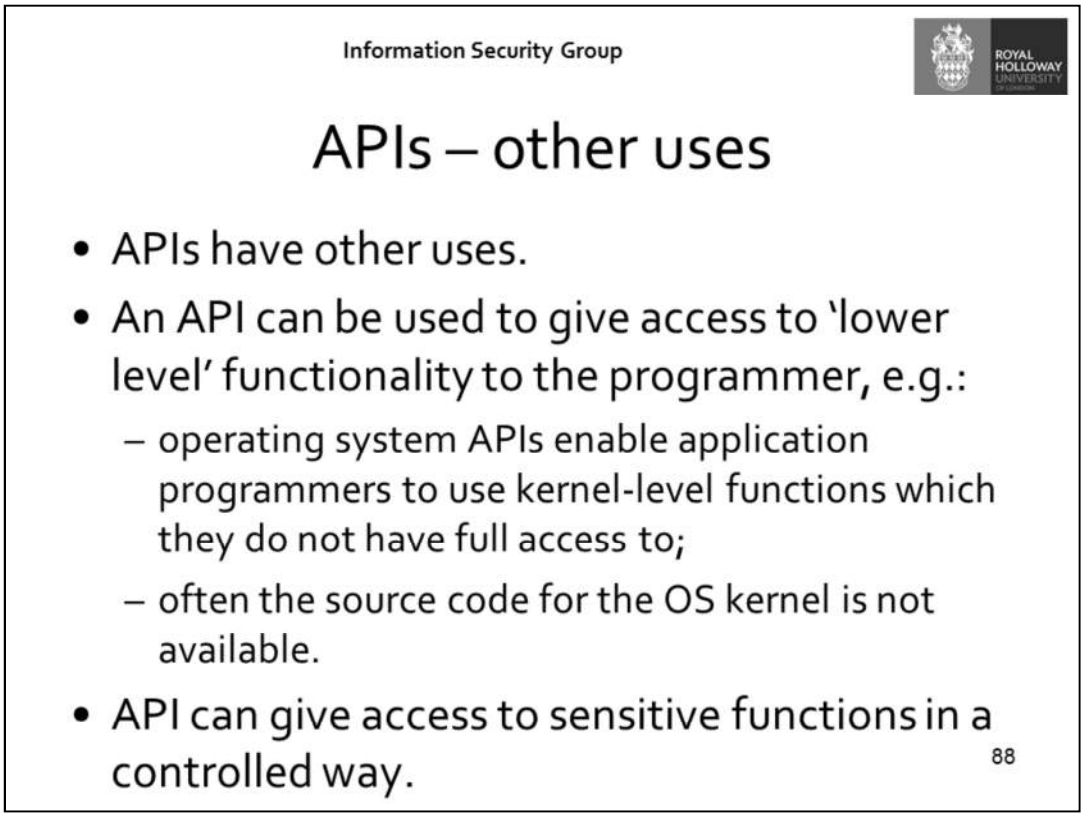
Such a library saves developers from 'reinventing the wheel'. That is, a developer can write a program which calls these functions, without having to write new code to implement them.



An application program interface (API) is a collection of function signatures:

• the implementation of the functions in the library is typically invisible to the application programmer;

• the programmer doesn't need to know how the functions work, only what inputs they expect and what outputs they produce.

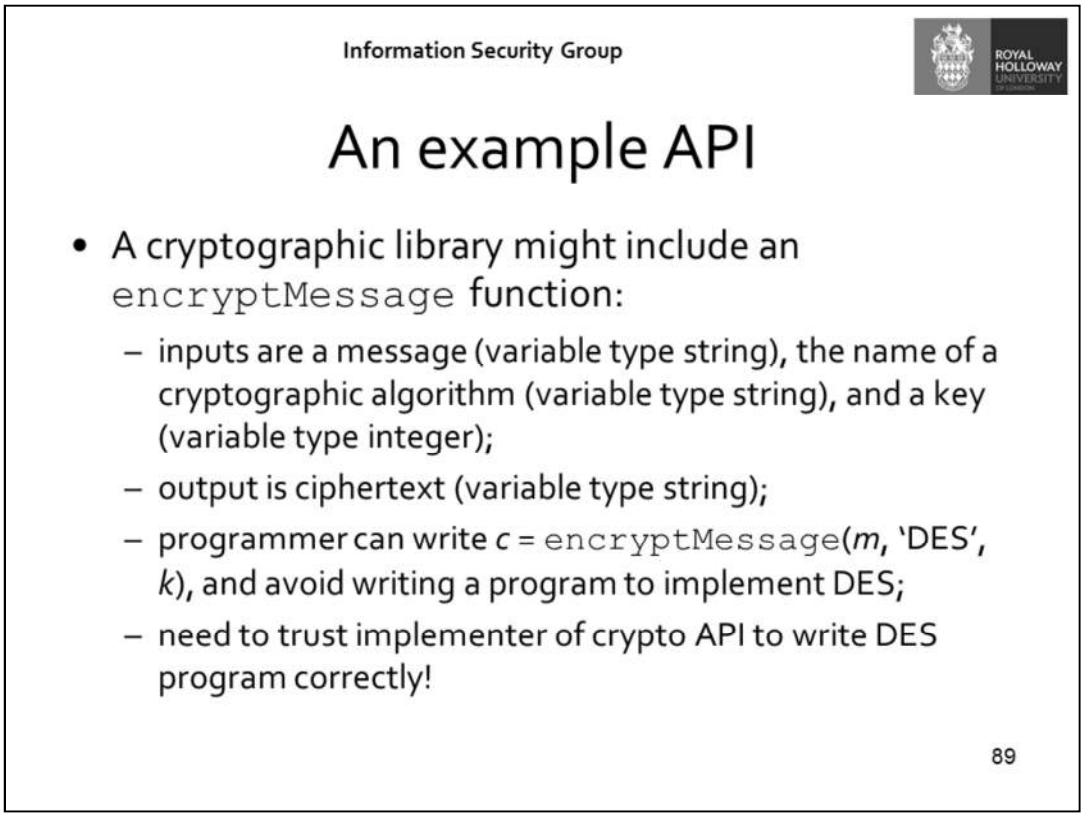


Apart from giving access to 'useful functions, APIs have other uses. An API is often used to 'expose', i.e. give access to, so called lower level functionality to the programmer. For example:

• operating system APIs enable application programmers to use kernel-level functions, to which they do not have full access (since they are very powerful);

• often the source code for the OS kernel is not available.

That is, an API can give access to sensitive functions in a controlled way.



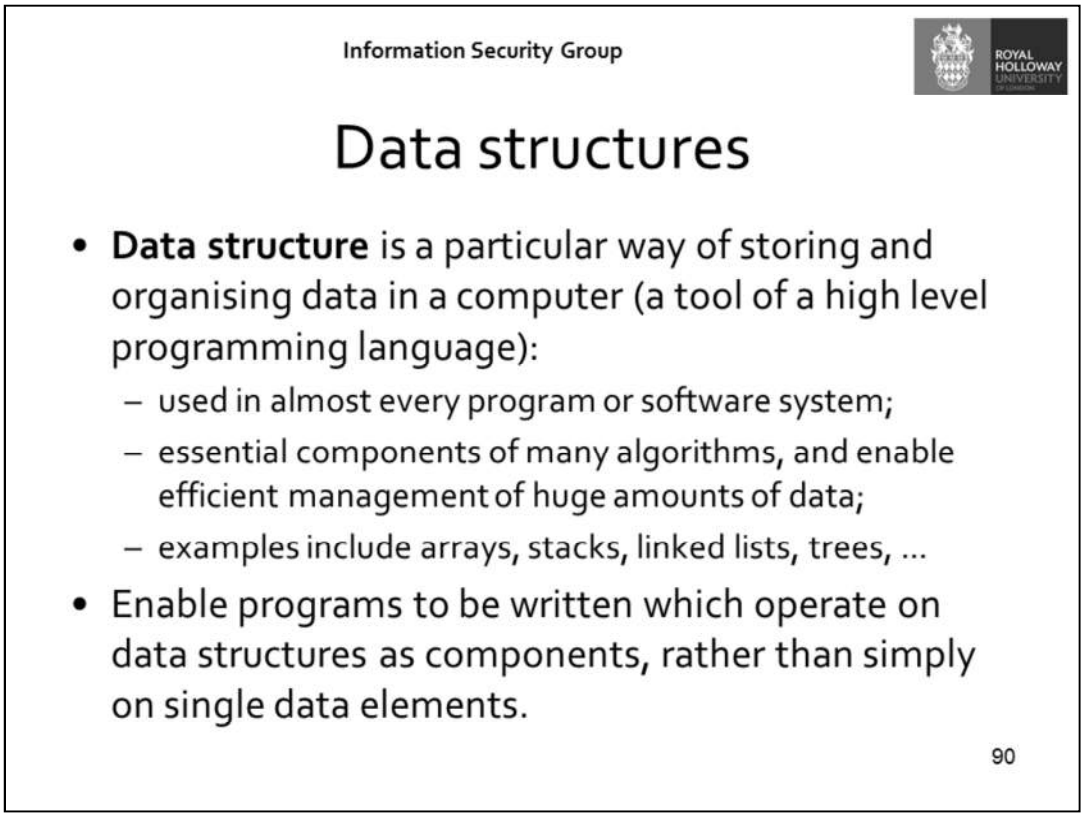
A cryptographic library might include an `encryptMessage` function:

• the inputs are a message (variable type string), the name of a cryptographic algorithm (variable type string), and a key (variable type integer);

• the output is the ciphertext (variable type string);

• a programmer can write *c* = `encryptMessage`(*m*, 'DES', *k*), and avoid writing a program to implement DES;

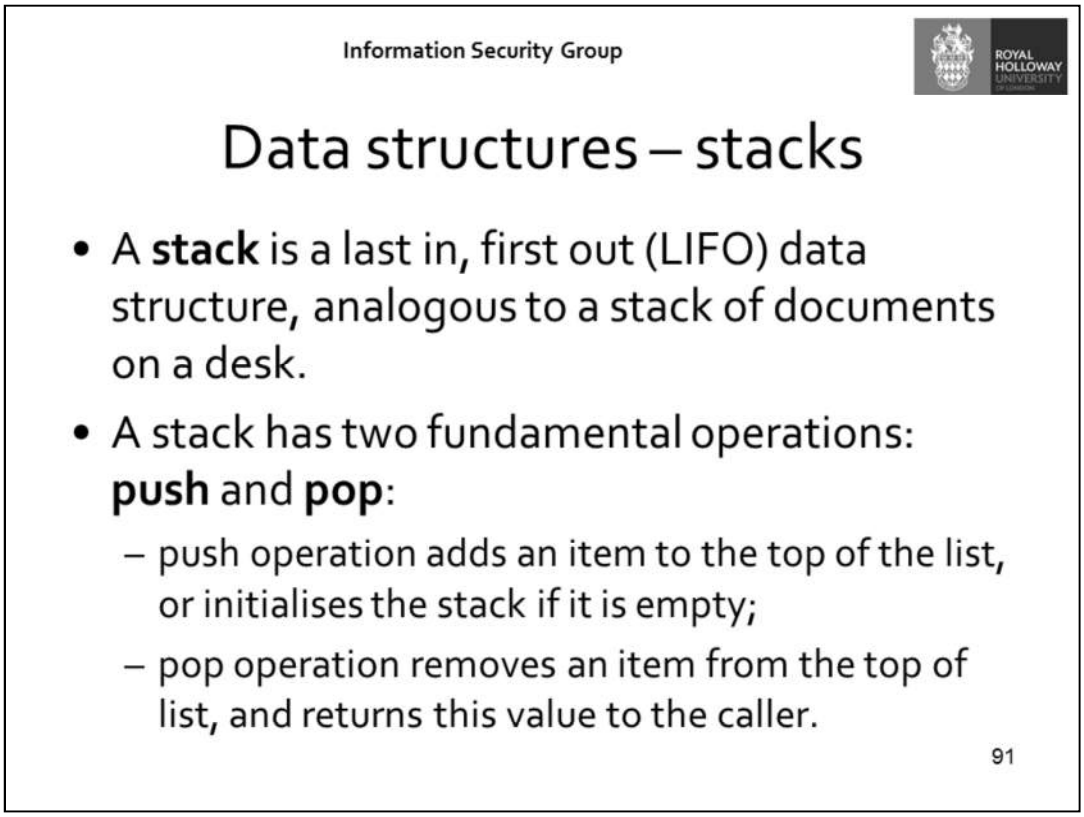
The user of a library needs to trust the implementer of the crypto API to write the DES program correctly!



A **data structure** is a particular way of storing and organising data in a computer (a tool of a high level programming language). Data structures are used in almost every program or software system. They are essential components of many algorithms, and they make possible to manage and process large volumes of data in efficient and simple ways.

Examples of data structures include arrays, stacks, linked lists, trees, heaps, etc.

The use of data structures enables programs to be written which operate on the data structures as components, rather than simply on single data elements. This can greatly simplify and clarify the task of the programmer.

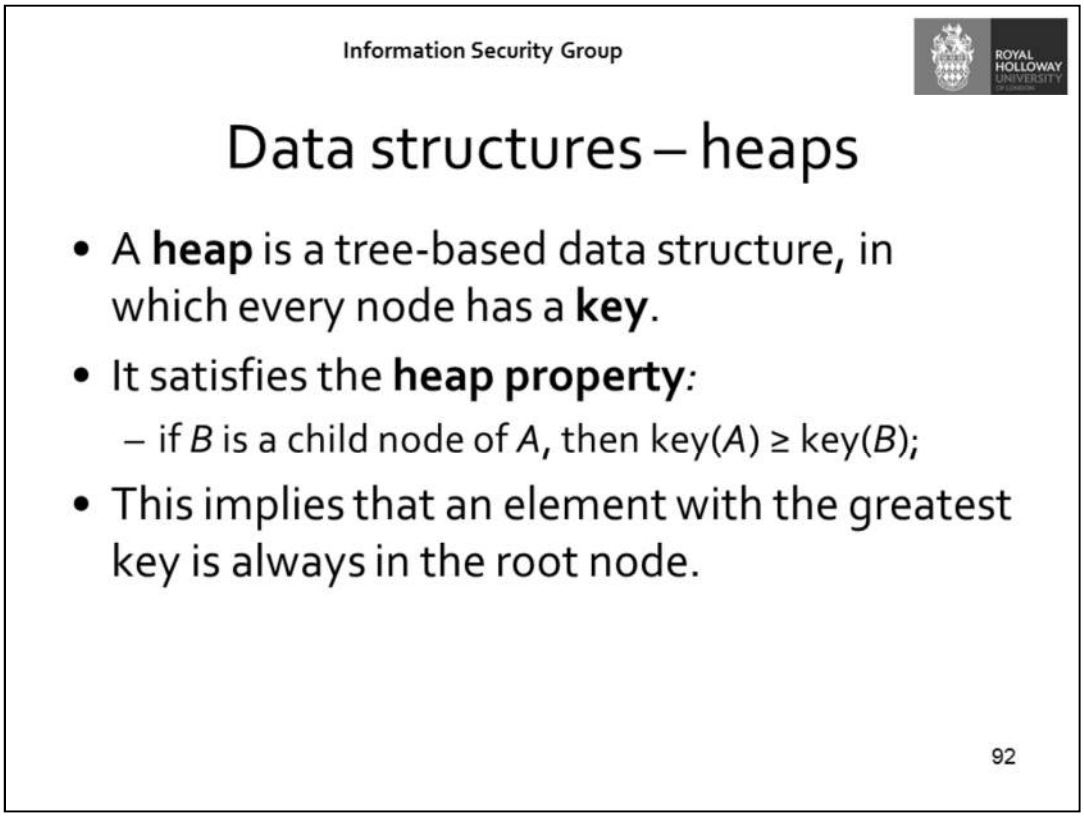


A **stack** is a last in, first out (LIFO) data structure, analogous to a stack of documents on a desk.

A stack has two fundamental operations associated with it: **push** and **pop**:

• the push operation adds an item to the top of the list, or initialises the stack if it is empty;

• the pop operation removes an item from the top of the list, and returns this value to the caller.



A **heap** is a tree-based data structure, in which every node in the tree has an associated **key**.

It satisfies the **heap property***:*

- if *B* is a child node of *A*, then key(*A*) ≥ key(*B*);

This implies that an element with the greatest key is always in the root node.

Note that a tree is a special type of graph. A graph consists of a set of nodes (vertices) and a set of edges between defined pairs of nodes. A tree has the property that there are no circuits in the graph.

Information Security Group

Agenda

- What do computers do?
- Some common notation
- Computer architectures
- Software
- Operating systems
- Resources

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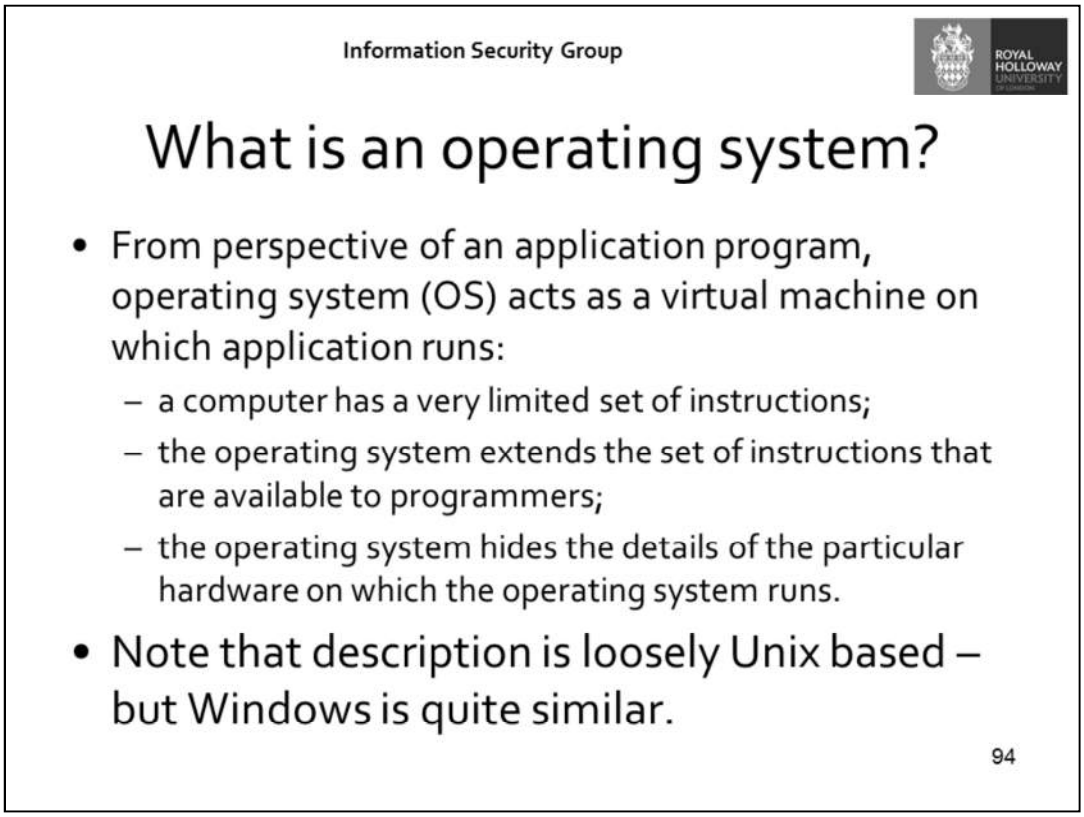
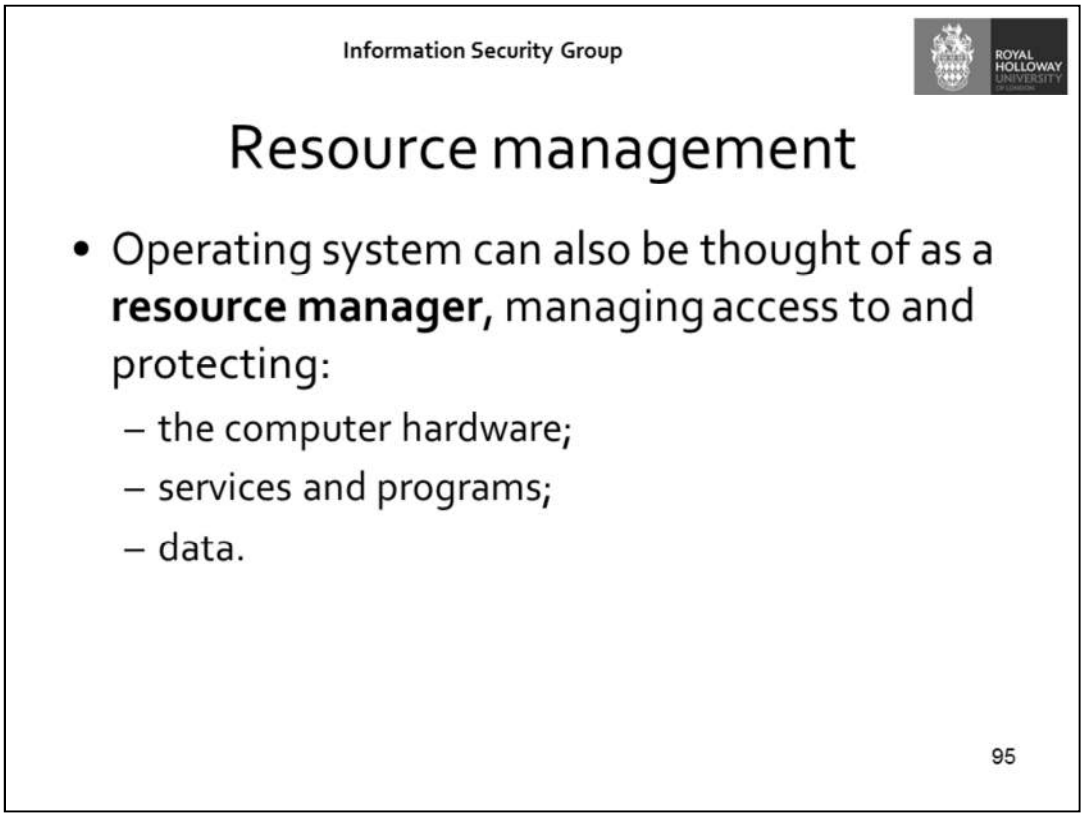


From the perspective of an application program, we can think of the operating system (OS) as an extended or virtual machine:

- a computer has a very limited set of instructions;
- the operating system extends the set of instructions that are available to programmers;
- the operating system hides the details of the particular hardware on which the operating system runs.

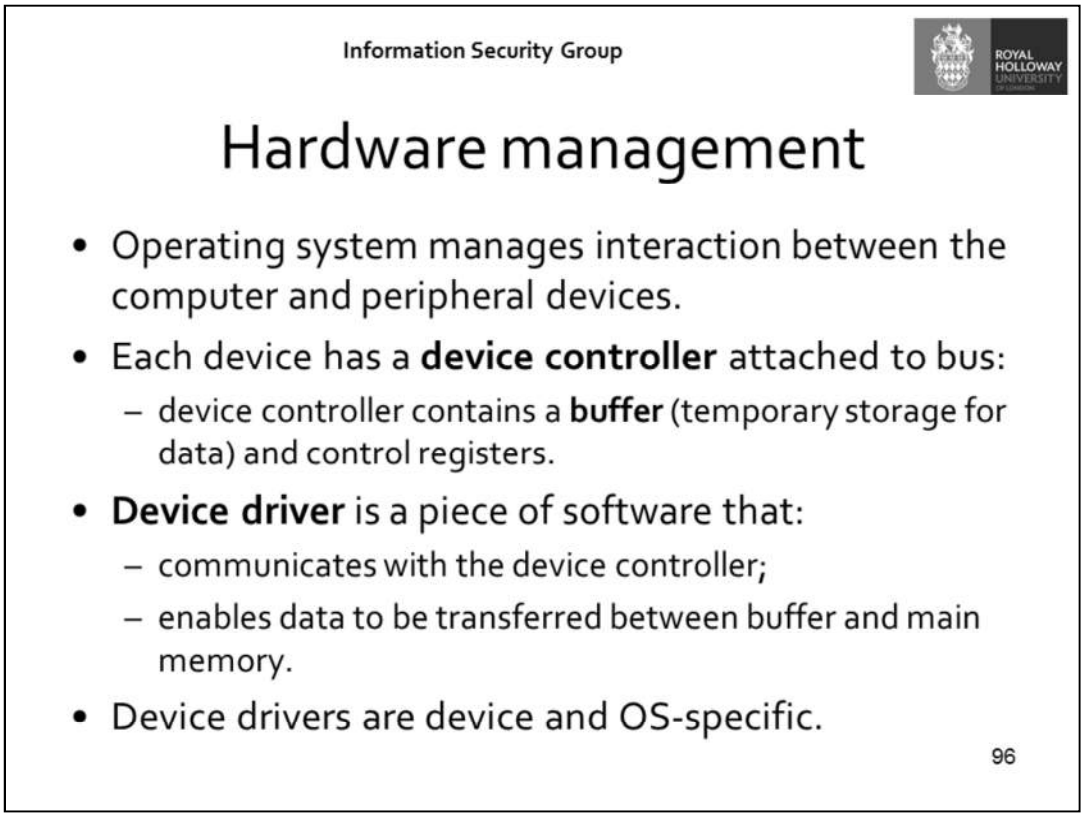
Note that the descriptions in the next few slides are loosely based on Unix; however, at least at this high level, Windows is quite similar.



The operating system can also be thought of as a **resource manager**, that manages access to and protects:

- the computer hardware;
- a set of services and programs;
- stored data.

It also typically provides a user interface (e.g. in the form of a **shell** or **desktop**), so that a human user can choose which applications run, manage files, install and remove applications, etc.



An operating system manages the interaction between the computer and peripheral devices.

Each device has an associated **device controller** attached to the system bus:

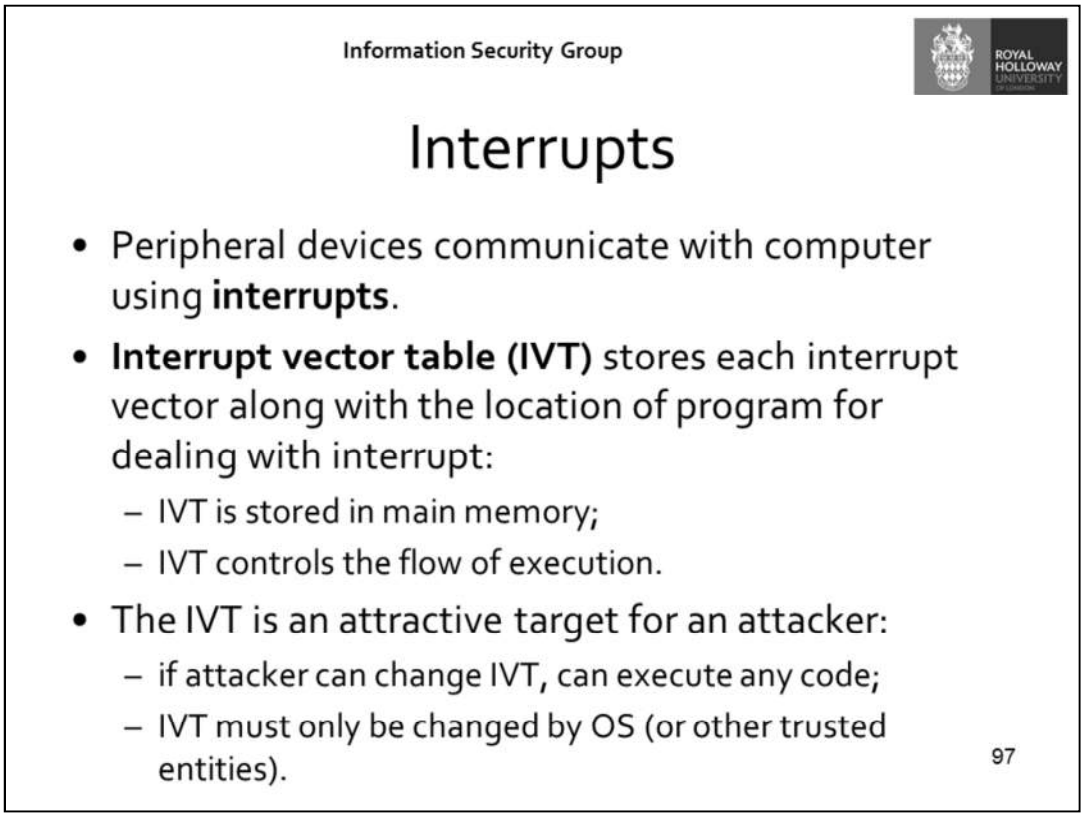
• the device controller contains a buffer (temporary storage for data) and control registers.

A **device driver** is a piece of software that:

• communicates with the device controller; and

• provides functions to write data to the buffer from main memory and read data from the buffer and write it to main memory.

Device drivers are device and OS-specific.



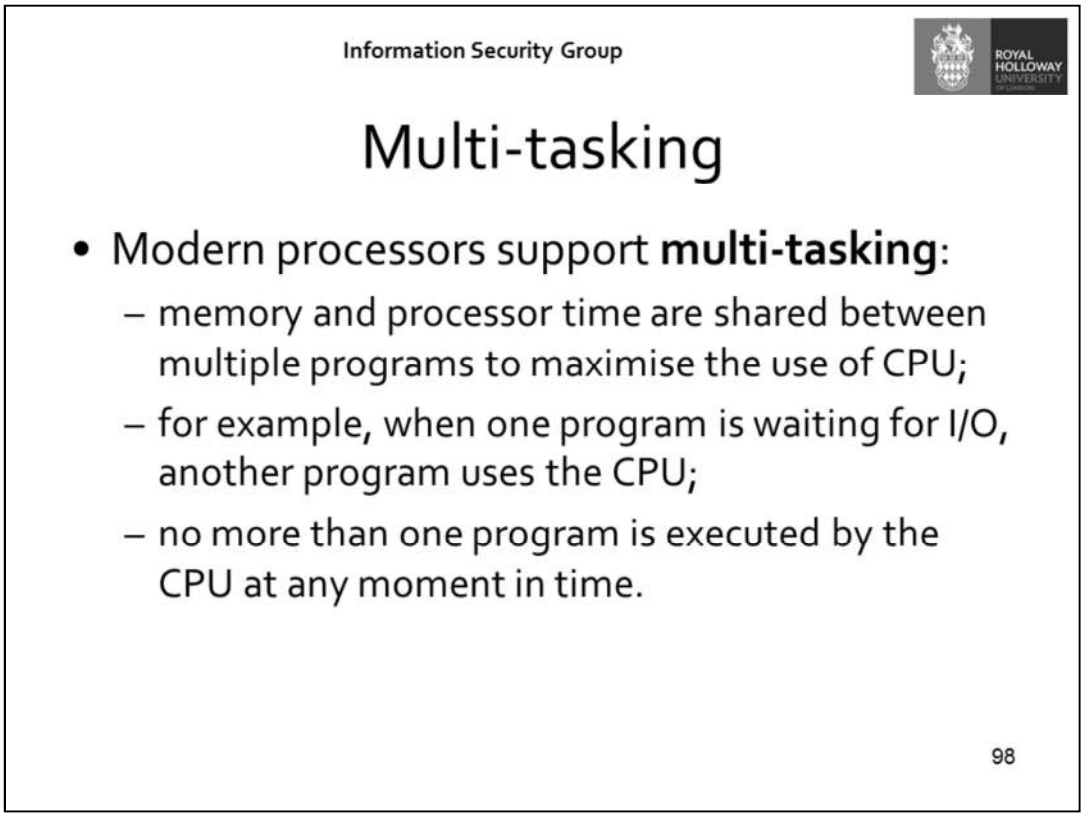
Peripheral devices communicate with the computer by means of special processor functions known as **interrupts**. As the name suggests, interrupts interrupt (stop) the current flow of execution of a program, and cause a different program to run. Each type of interrupt has a unique interrupt vector, i.e. a numerical value which indicates the type of interrupt

The **interrupt vector table (IVT)** stores each interrupt vector along with the location of the program for dealing with the interrupt:

- the IVT is stored in main memory (in an area reserved for use by the OS);
- the IVT controls the flow of execution.

The IVT is an attractive target for an attacker:

- if an attacker can change the IVT he can execute code of his choosing;
- the IVT must only be changed by the operating system (or other trusted entities).

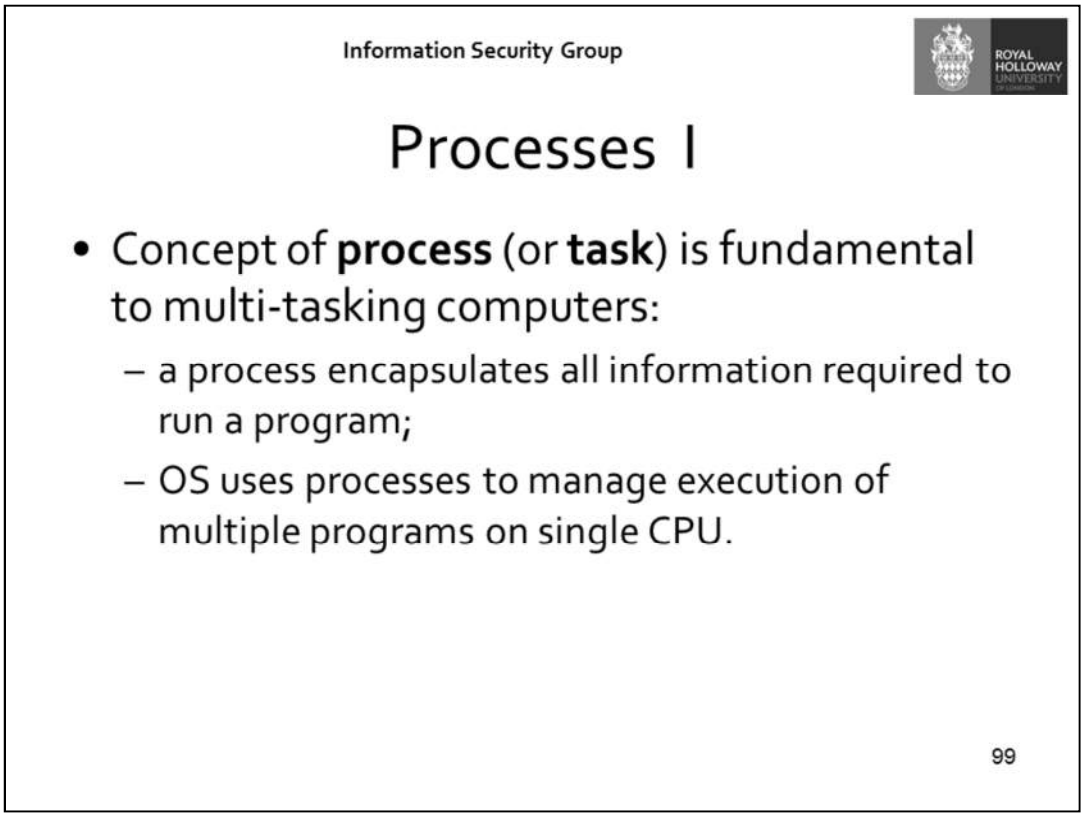


All modern processors support **multi-tasking**:

• memory and processor time are shared between multiple programs to maximise the use of CPU processing cycles;

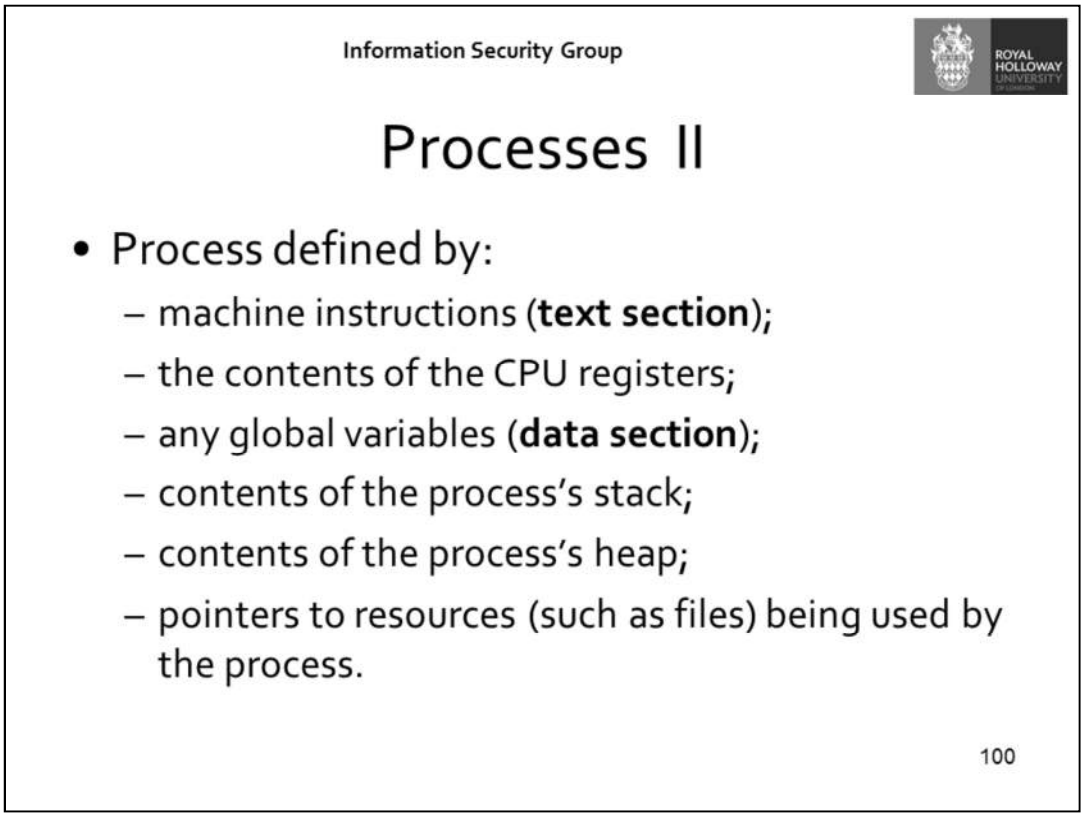
• for example, when one program is waiting for I/O, another program can use the CPU;

Although it may appear as if multiple processes are operating in parallel at the same time, in fact no more than one program is executed by the CPU at any moment in time. [This situation changes in modern **multi-core** processors which have more than one CPU – one processor chip can contain many CPUs].



The concept of a **process** (or **task**) is fundamental to multi-tasking computers:

- a process encapsulates all the information required to run a program;
- the OS uses processes to manage the execution of multiple programs on the same CPU.

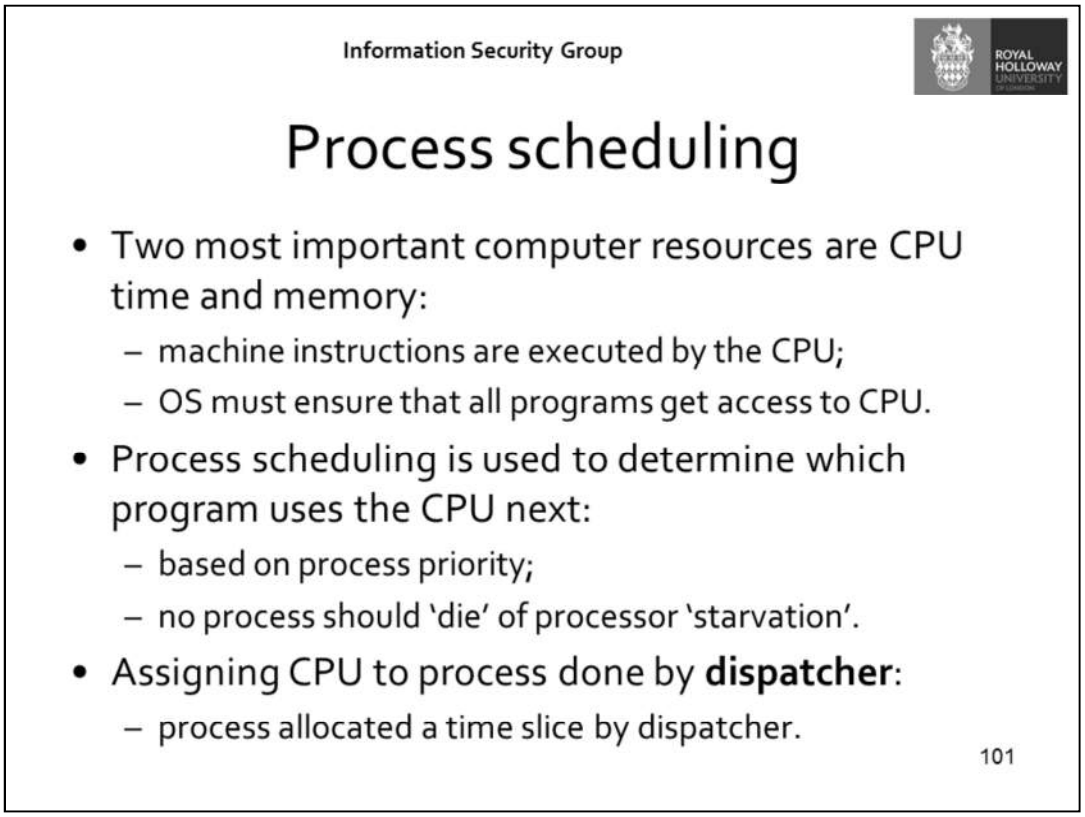


A process is defined by:

- the machine instructions (the **text section**);
- the contents of the CPU registers;
- any global variables (the **data section**);
- the contents of the process-specific stack;
- the contents of the process-specific heap;
- pointers to resources (such as files) that are currently being used by the process.

A **call stack** (also known as an **execution stack**, **control stack**, **function stack**, or **run-time stack**, and often referred to as just **the stack**) stores information about the active functions of a program. Although maintenance of the call stack is important for the proper functioning of most software, the details are normally transparent to the author of a program written in a high-level language. The main purpose of a call stack is to keep track of the address to which each active function should return control when it finishes executing. There is usually a single call stack for each running program (or, more accurately, with each thread of a process).

More generally, the **stack** is a section of computer memory used to store all the variables that are declared and initialised before a program is run. The **heap** is the section of computer memory used to store the variables created or initialised during execution of a program. That is, heap is an area of memory used for **dynamic memory allocation**. Blocks of memory can be allocated and freed in an arbitrary order. The pattern of allocation and size of blocks is not known until run time.



The two most important resources of a computer are CPU time and memory:

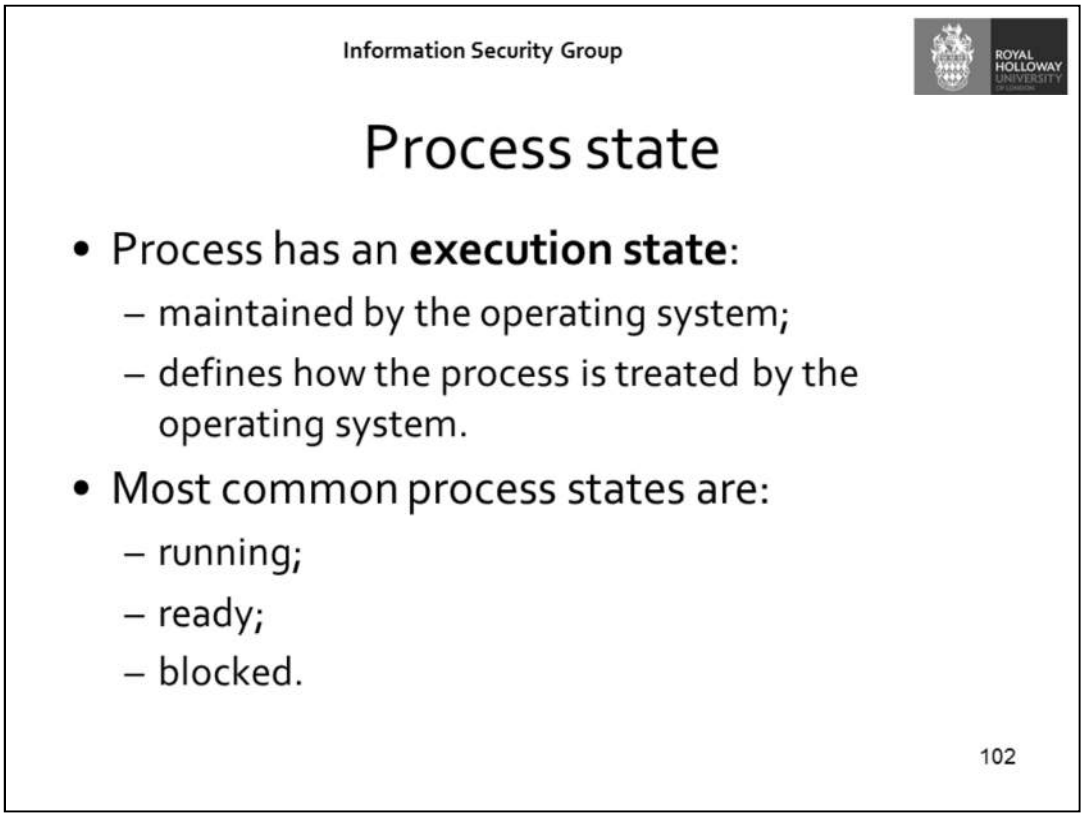
- machine instructions are executed by the CPU;
- the OS must ensure that all programs gain access to the CPU.

Process scheduling is used to determine which program next uses the CPU:

- this is typically based on the priority of a process (a numerical value indicating how important the process is), as well as some kind of 'round robin' system, i.e. so that processes of equal priority are given CPU time in turn;
- no process should 'die' of processor 'starvation'.

The assignment of the CPU to a process is done by the **dispatcher**:

- the process is allocated a time slice (i.e. a specific period of time for it to execute) by the dispatcher.

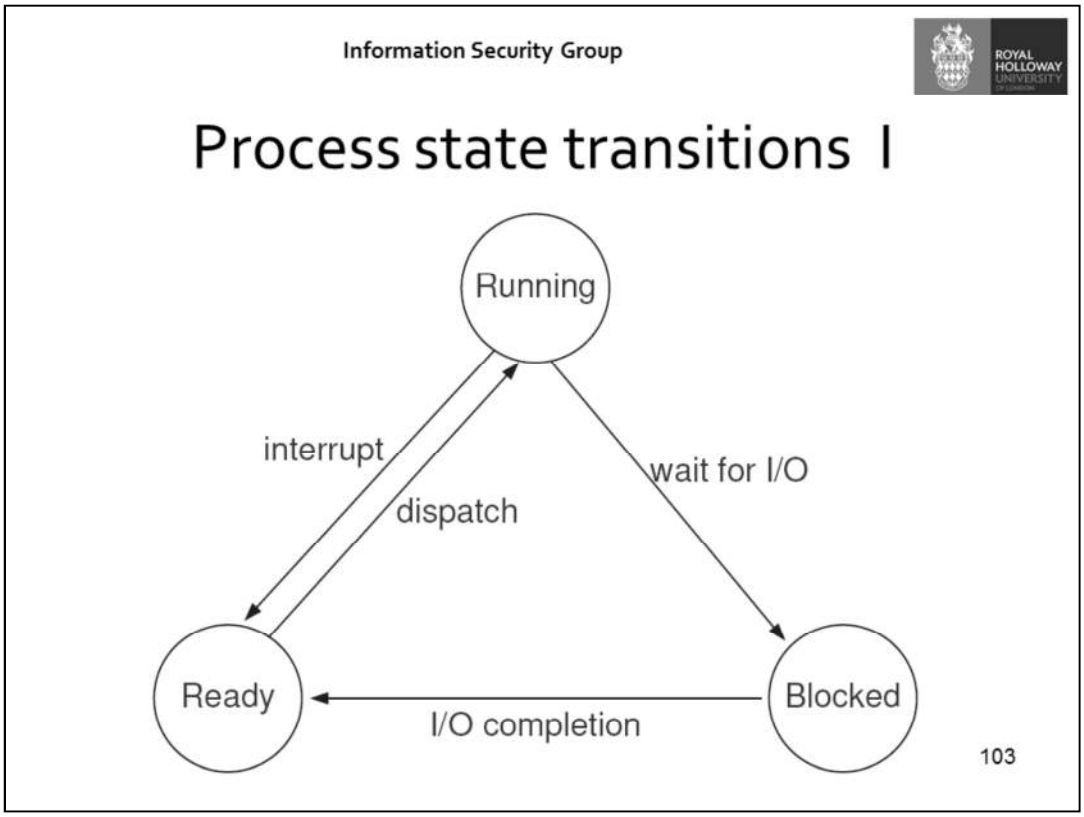


Every process has an **execution state**. This state:

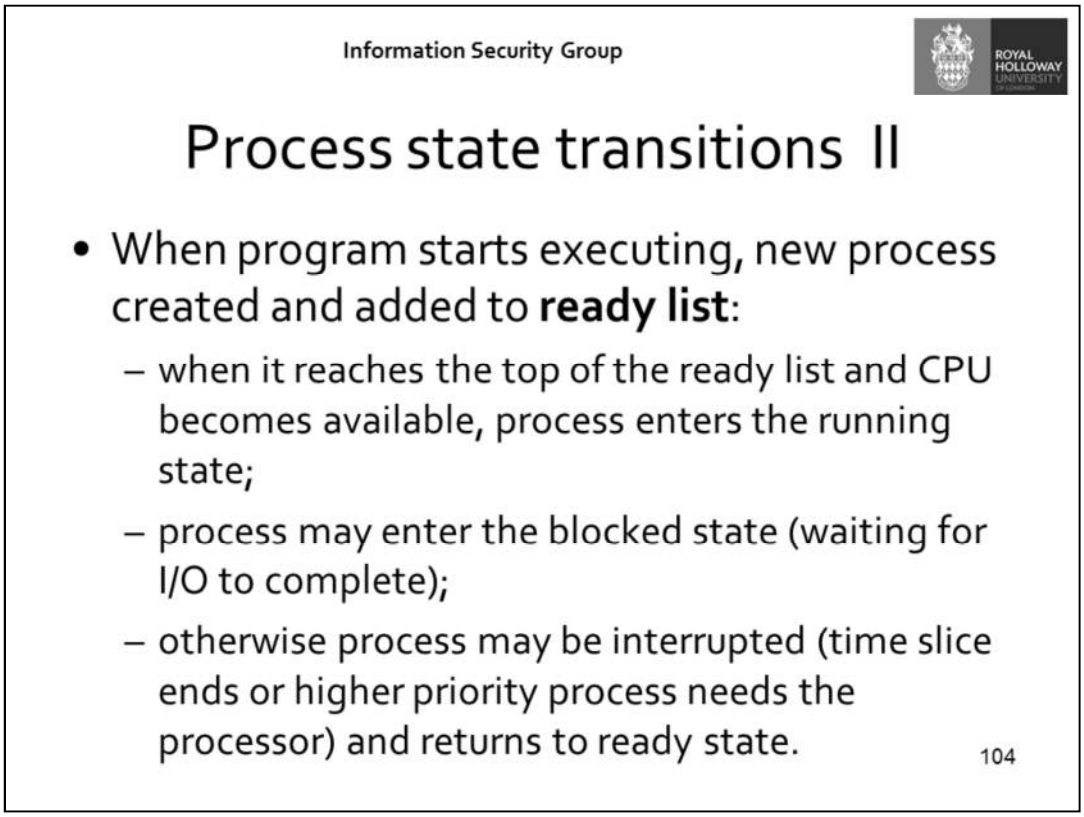
- is maintained by the operating system;
- defines how the process should be treated by the operating system.

The most common process states are:

- running;
- ready (to run);
- blocked (waiting for something to occur before it can run).



The diagram shows the three common execution states of a process, as well as the possible transitions between these states.

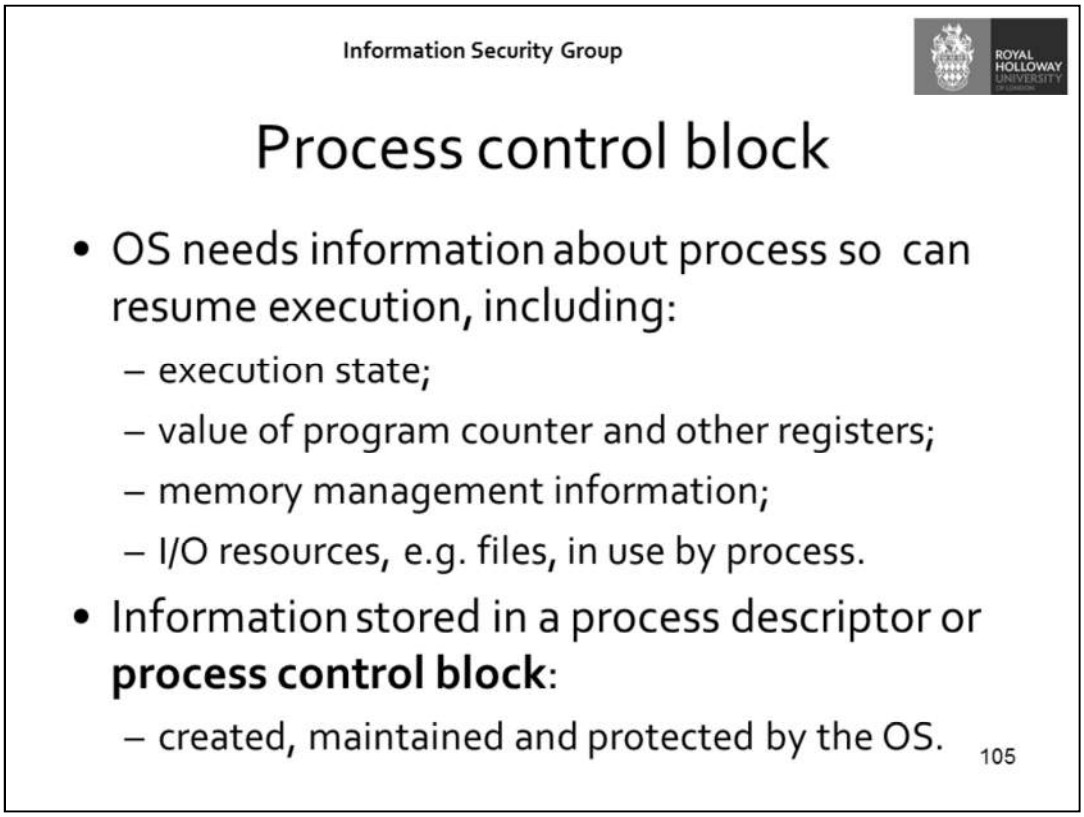


When a program starts executing, a new process is created and added to the list of processes in the ready state, the **ready list**.

When it reaches the head of the ready list and the CPU becomes available the process enters the running state;

The process may enter the blocked state (waiting for I/O to complete);

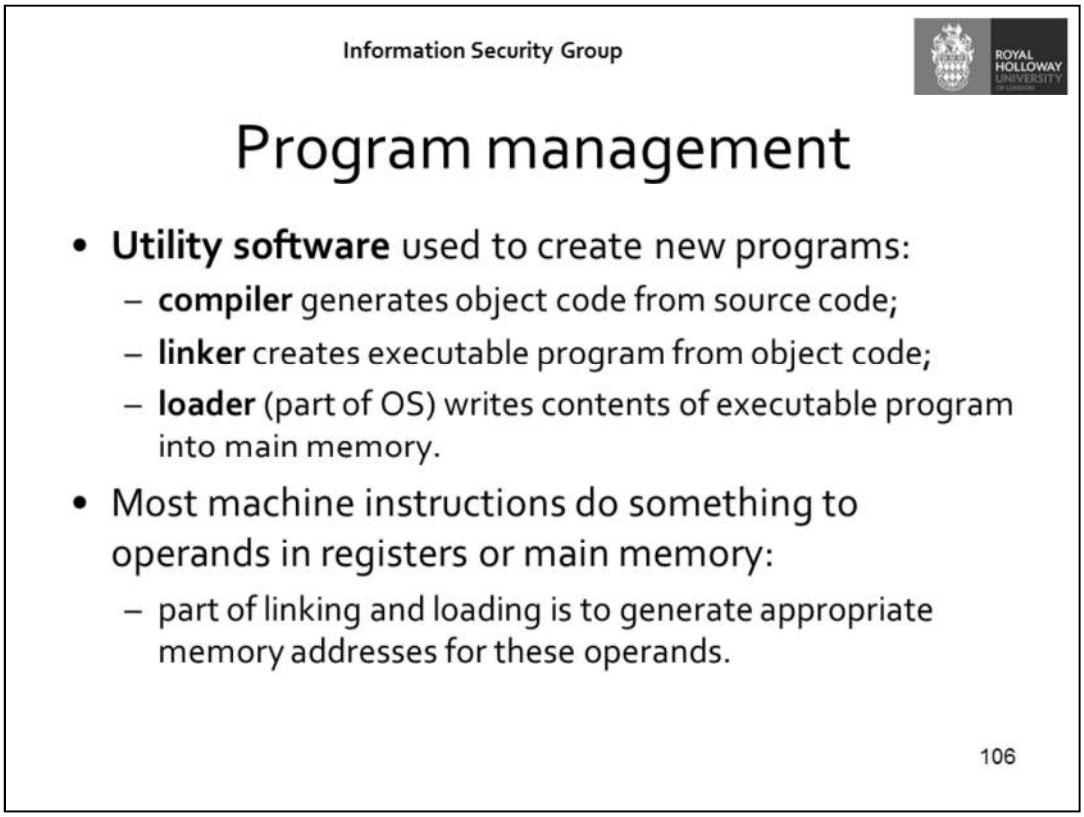
Otherwise the process may be interrupted (time slice ends or higher priority process needs the processor) and returns to the ready state, and would typically be added to the bottom of the ready list (depending on its priority).



The operating system requires a lot of information about each process so that it can resume execution when that process enters the ready state, including:

- the execution state of the process (i.e. whether it is running, blocked or ready);
- the value of the program counter and other registers;
- memory management information (i.e. which areas of main memory are being sued by the process);
- references to I/O resources such as the set of files in use by the process.

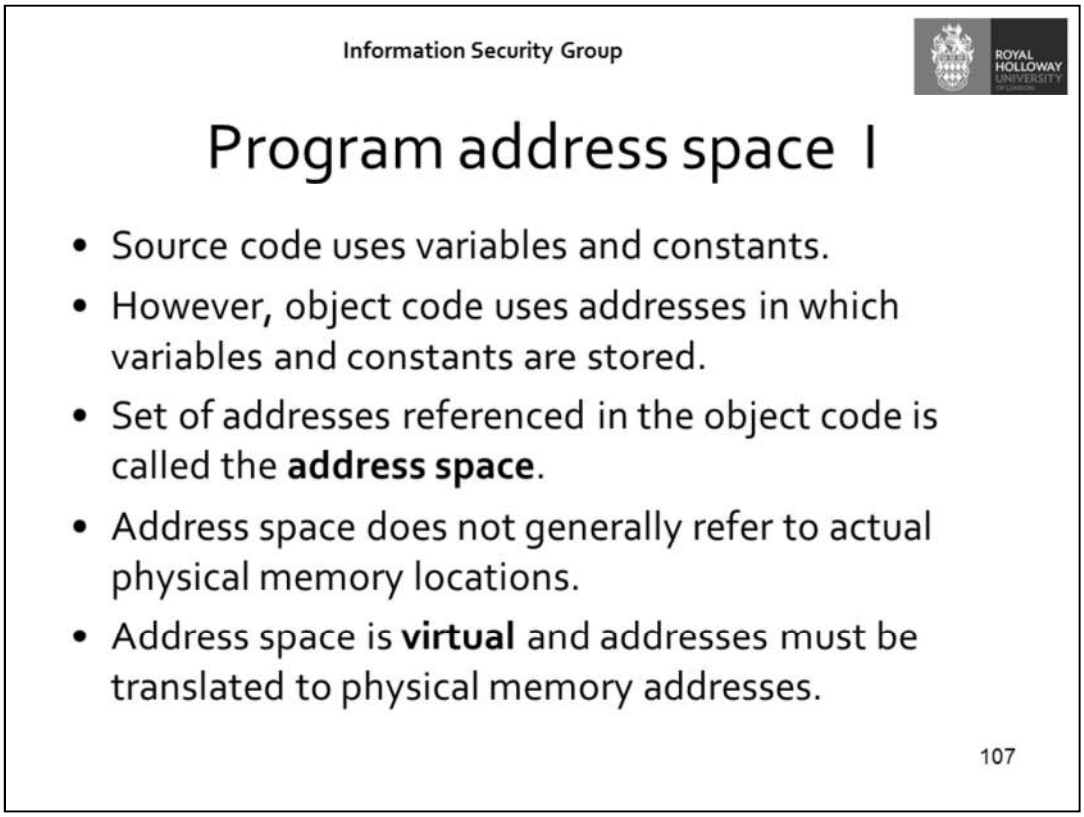
This information is stored in a process descriptor or **process control block**, which is created, maintained and protected by the operating system.



Utility software is used to create new programs. Such software includes:

- a **compiler**, which generates object code from source code;
- a **linker**, which creates an executable program from object code;
- a **loader** (part of the OS), which is responsible for loading the contents of an executable program (typically in a file) into main memory.

Recall that most machine instructions do something to operands, which are values that are stored either in registers or in main memory. Part of the linking and loading processes is to generate appropriate memory addresses for these operands.

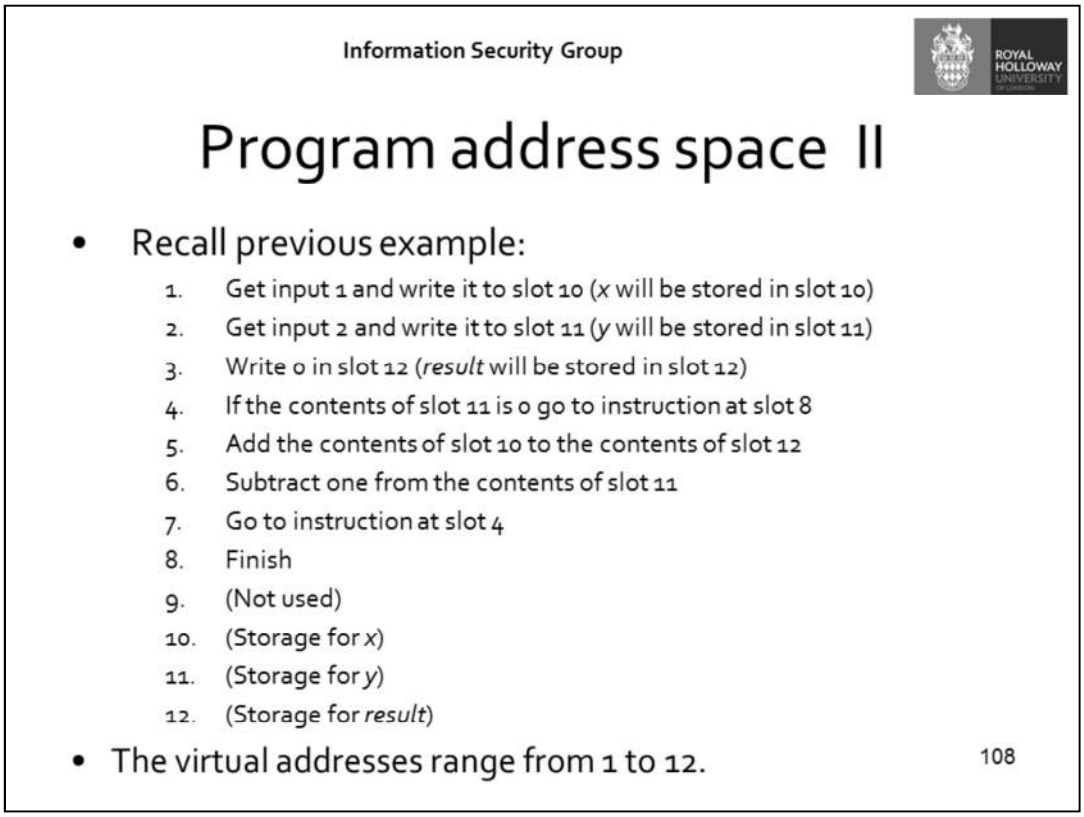


Source code makes references to variables and constants. By contrast, object code makes references to addresses in which variables and constants are stored.

The set of addresses referenced in the object code is called the **address space**.

The address space does not generally refer to actual physical memory locations.

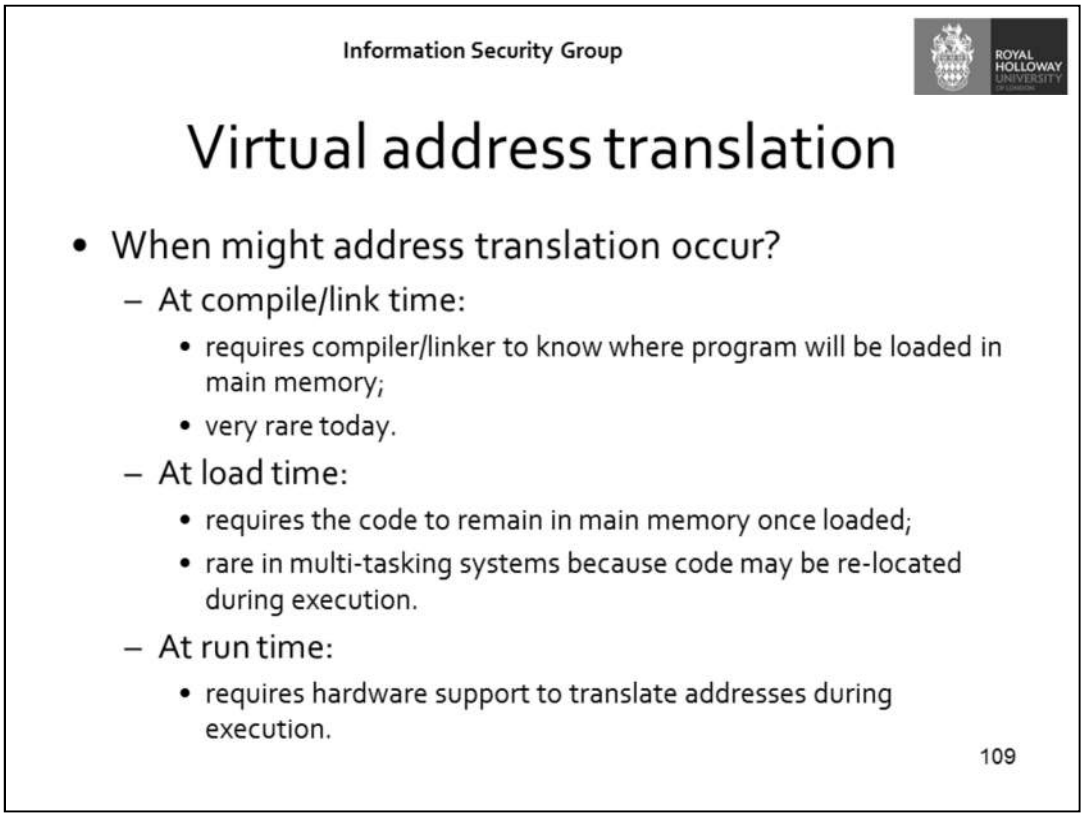
The address space is **virtual** and addresses must be translated to physical computer memory locations at some stage. That is, an piece of software (an **executable**) will be constructed in such a way that it is designed to work in a fixed address space – however, it may be loaded into any part of the computer's main memory.



We recall the previous example:

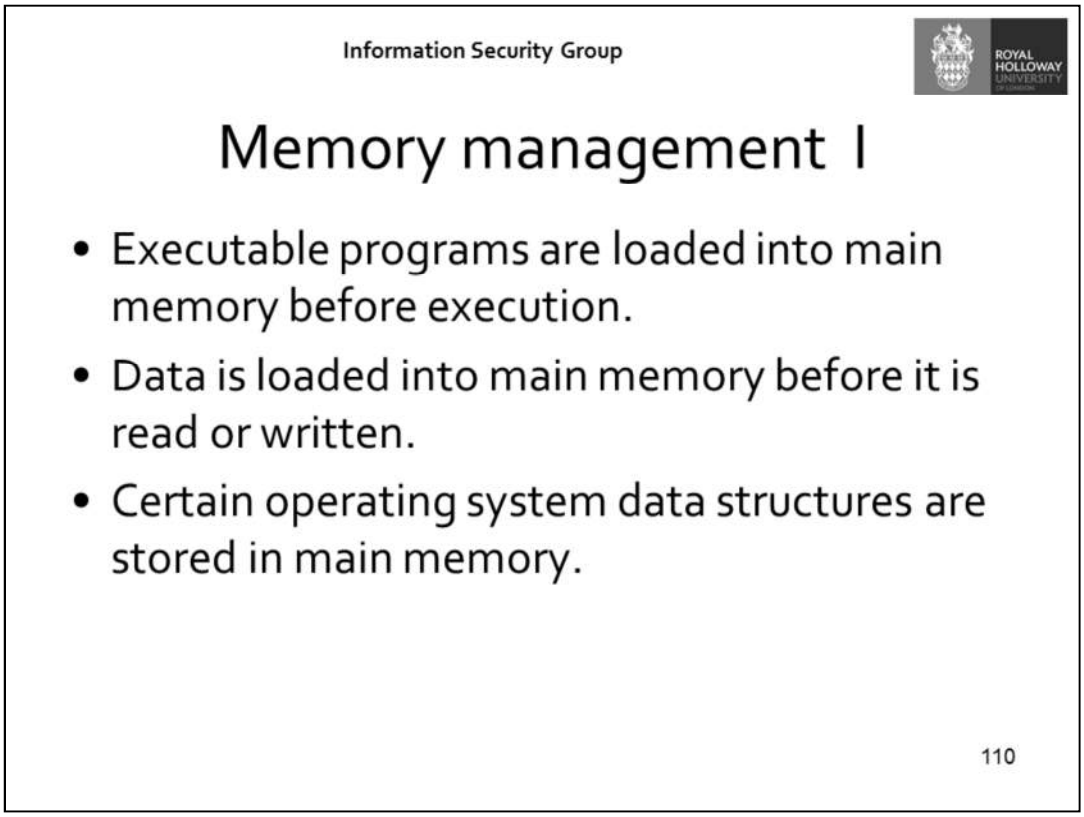
1. Get input 1 and write it to slot 10 (*x* will be stored in slot 10)
2. Get input 2 and write it to slot 11 (*y* will be stored in slot 11)
3. Write 0 in slot 12 (*result* will be stored in slot 12)
4. If the contents of slot 11 is 0 go to instruction at slot 8
5. Add the contents of slot 10 to the contents of slot 12
6. Subtract one from the contents of slot 11
7. Go to instruction at slot 4
8. Finish
9. (Not used)
10. (Storage for *x*)
11. (Storage for *y*)
12. (Storage for *result*)

In this example, the virtual addresses range from 1 to 12. However, this does not mean that the program must always be located in the part of the computer memory with these addresses (this would be very inflexible).



There are various possible occasions when address translation might occur.

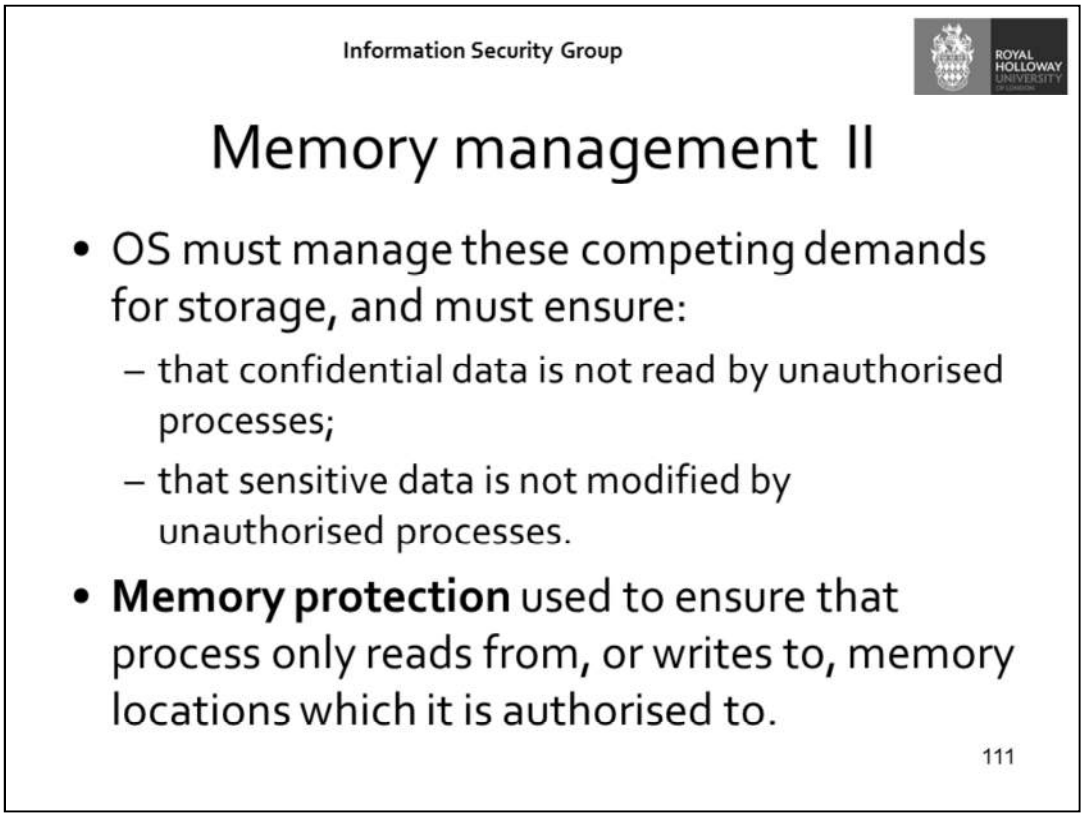
- At compile/link time:
  - this requires the compiler/linker to know where in main memory the program will be loaded;
  - such an approach is very rare today, since it is very inflexible (it means a program must always occupy same part of physical memory).
- At load time:
  - this requires the code to remain in main memory once it has been loaded;
  - this is rare in multi-tasking systems because code may be re-located during execution.
- At run time:
  - this requires hardware support to translate addresses during the execution cycle;
  - modern processors provide support for run-time address translation, which is how modern computers work.



Executable programs are loaded into main memory before execution.

Data is loaded into main memory before it is read or written.

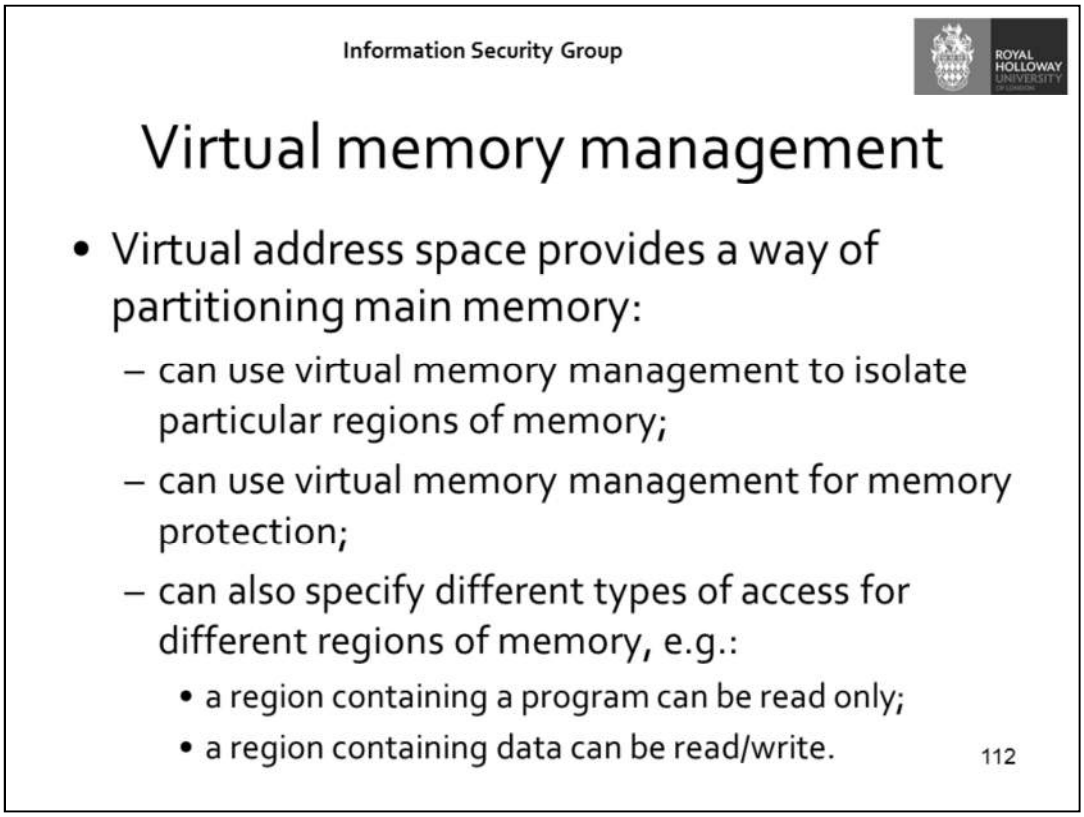
Certain operating system data structures are also stored in the computer's main memory.



The operating system has to manage all these competing demands for storage. In particular, the operating system has to ensure that:

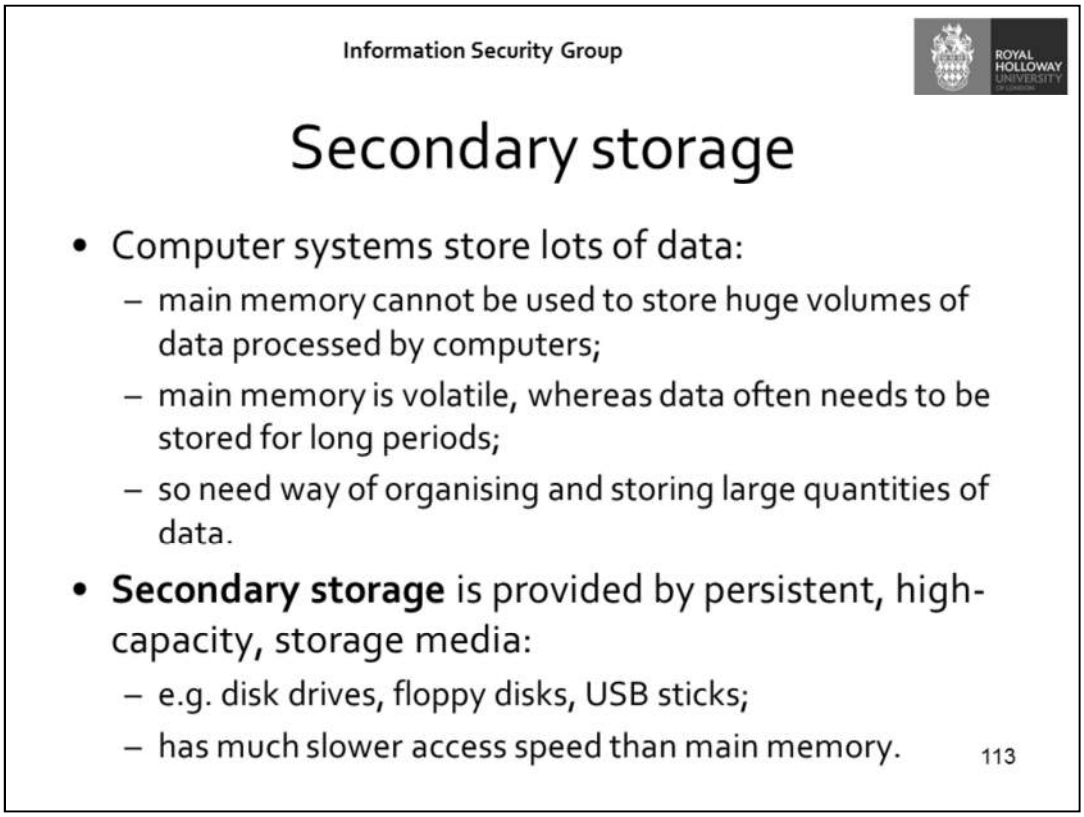
- confidential data is not read by unauthorised processes;
- sensitive data is not modified by unauthorised processes.

Memory protection is used to ensure that a process only reads from, or writes to, memory locations for which it has the necessary authorisation.



A virtual address space provides a way of partitioning main memory:

- can use virtual memory management to isolate particular regions of memory;
- can use virtual memory management for memory protection;
- can also specify different types of access for different regions of memory, e.g.:
    - a region containing a program can be read only;
    - a region containing data can be read/write.



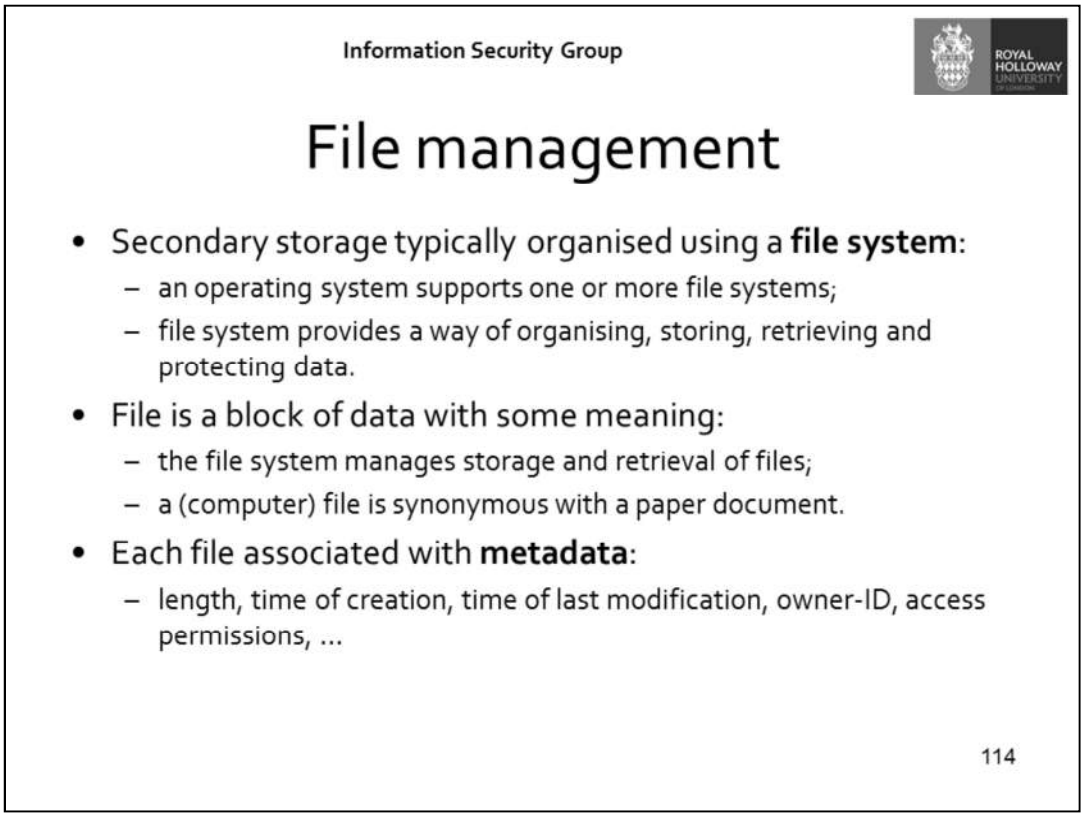
Computer systems typically store large volumes of data:

• main memory cannot be used to store the huge volumes of data processed by computers;

• main memory is volatile, whereas a data typically needs to be stored for long periods of time;

• hence we need a way of organising and storing large quantities of data.

Secondary storage consists of persistent, high-capacity storage media such as disk drives, floppy disks, USB sticks. These forms of secondary storage have much slower access speeds than main memory (particularly in terms of latency, i.e. delay).



Secondary storage is typically organised using a **file system**:

• an operating system will support one or more file systems;

• a file system provides a way of organising, storing, retrieving and protecting data.

A file represents a block of data that forms a logical unit:

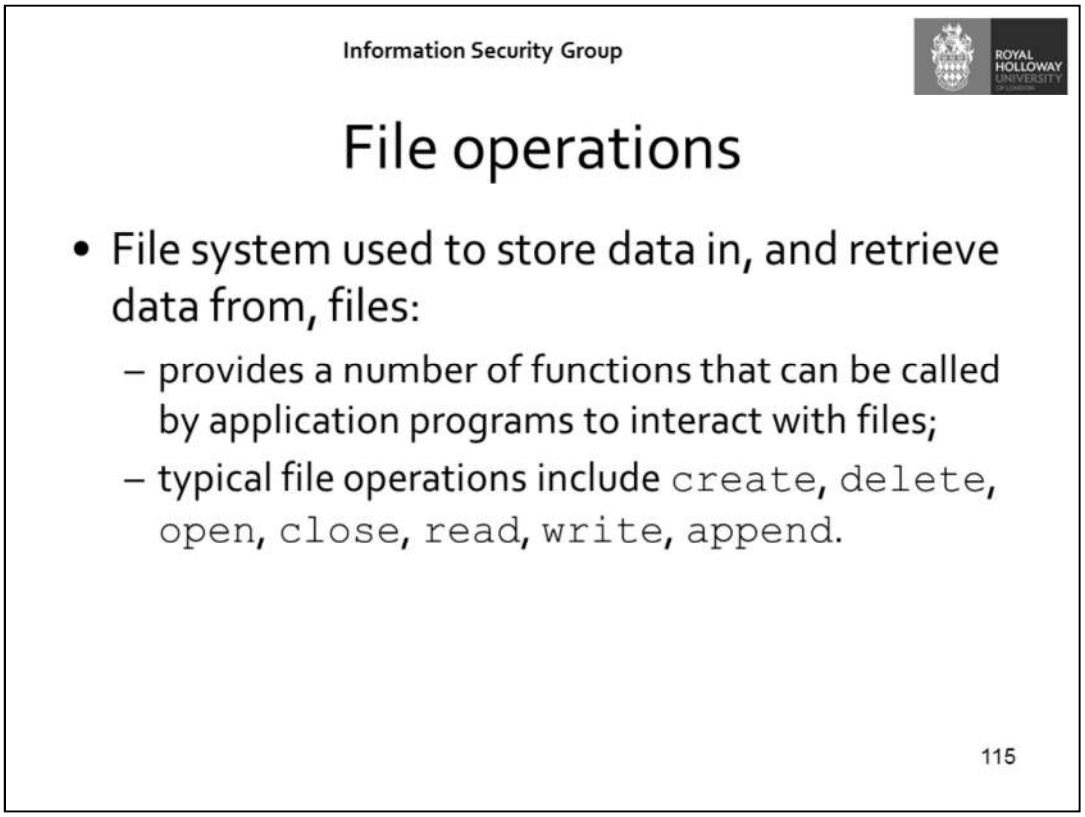
• the file system manages the storage and retrieval of files;

• a (computer) file is synonymous with a paper document.

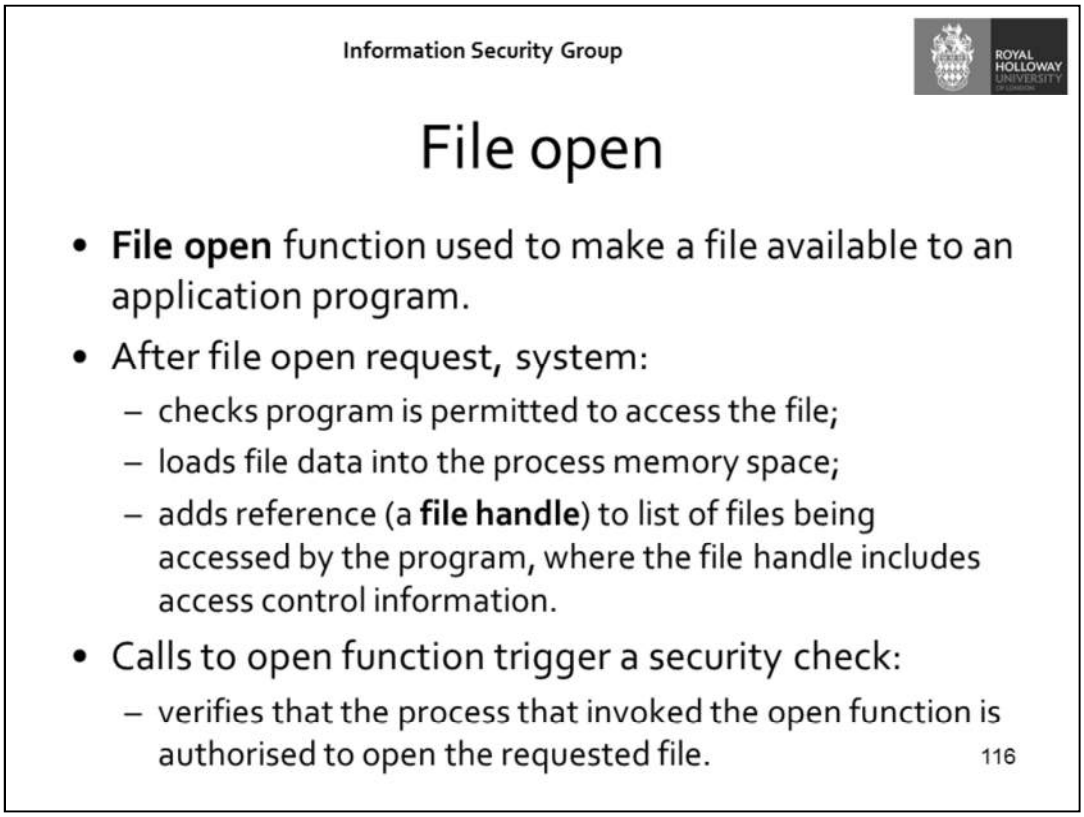
Every file is associated with a range of **metadata** containing information about the file, such as:

• length, time of creation, time of last modification, owner-ID, access permissions, …

Different types of file will have different associated metadata types.



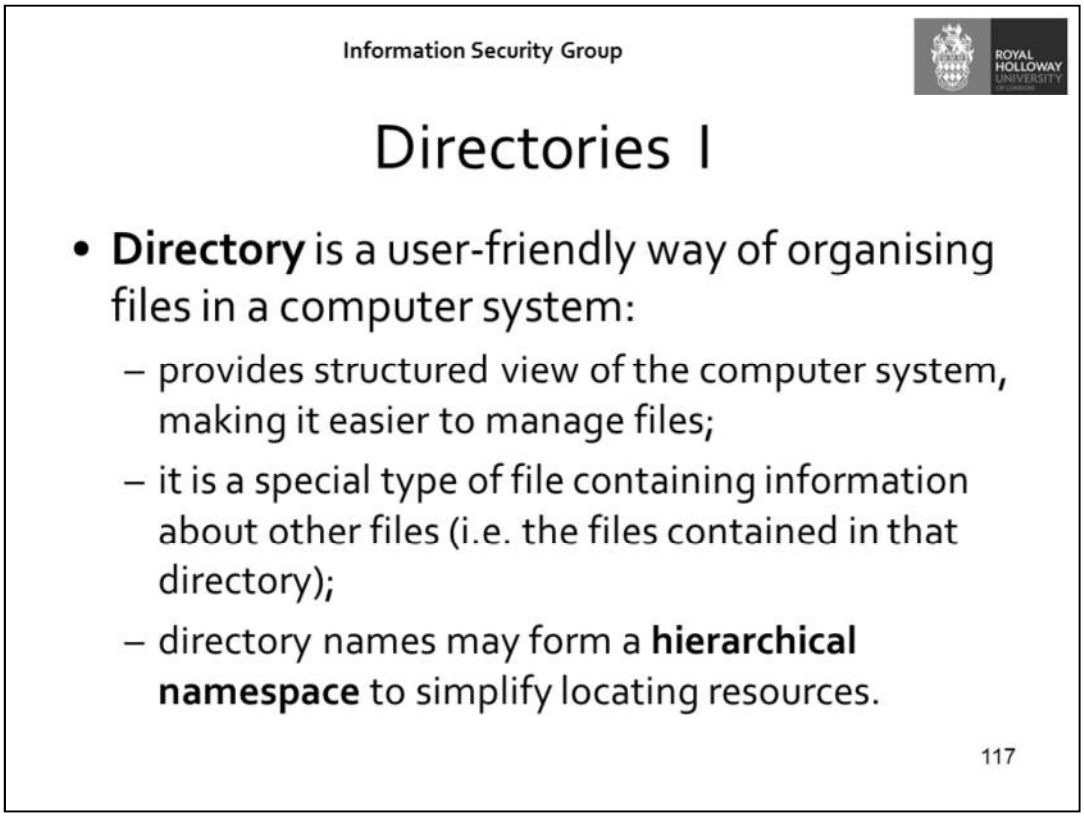
The file system is used to store data in, and retrieve data from, files. It provides a number of functions that can be called by application programs to interact with files. Typical operations provided by a file system include `create`, `delete`, `open`, `close`, `read`, `write`, `append`.



The **file open** function (a **system call**) is used to make a file available to an application program. When it receives a file open request, the system:

- checks that the program is permitted to access the file (**authorisation**);
- loads the file data into the process memory space;
- adds a reference (a **file handle**) to the list of files being accessed by the program, where the file handle includes access control information that governs how the program can access the file (e.g. the program may be allowed to read the file but not modify it).

All calls to the open function will trigger a security check. This check will verify that the process that invoked the open function is authorised to open the requested file.

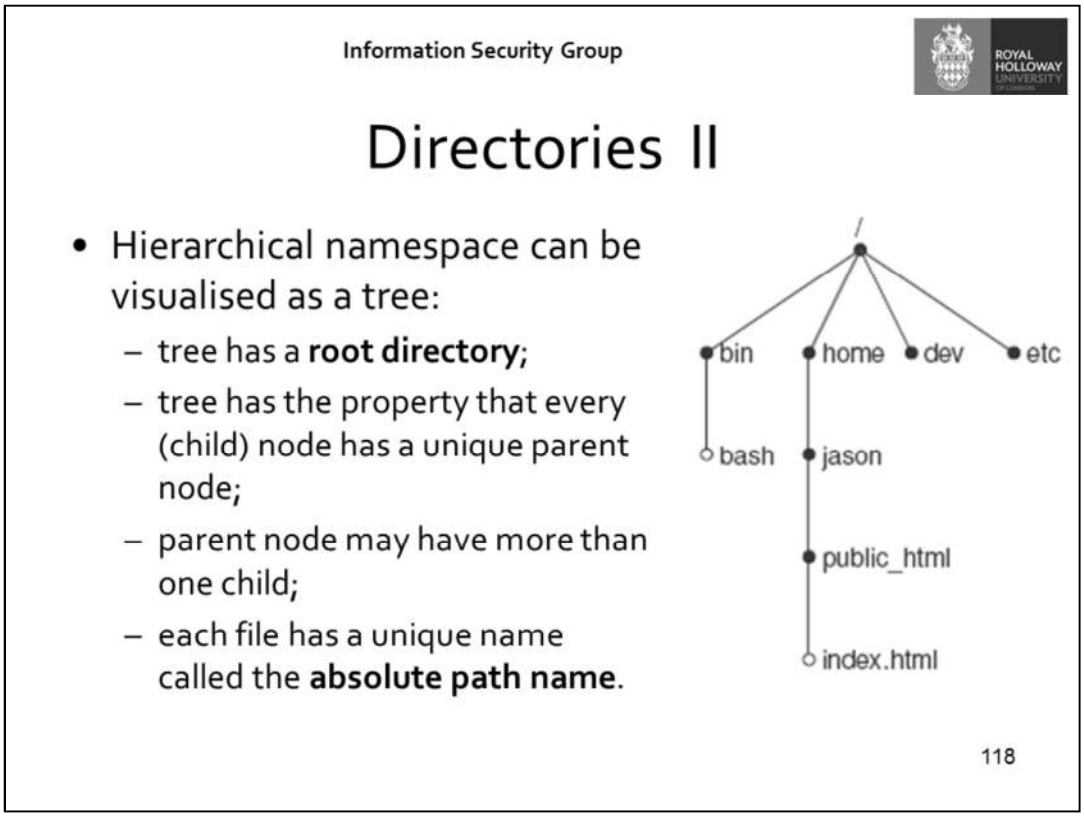


A **directory** is a user-friendly way of organising files in a computer system:

• it provides a structured view of the computer system, making it easier to manage files;

• the directory is itself a special type of file that contains information about other files (namely the files contained in that directory);

• directory names will typically form a **hierarchical namespace** to make it easier to locate resources.



A hierarchical namespace can be visualised as a tree-like structure:

- the tree has a **root directory**;
- the tree has the property that every (child) node has a unique parent node;
- the parent node may have more than one child;
- each file has a unique name called the **absolute path name**, derived from the nodes on the path from the root to the node corresponding to the file.

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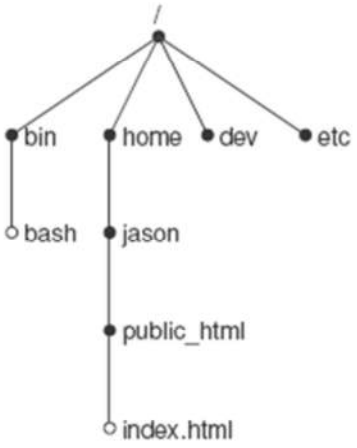
Directories III

- Each process has a working directory or current directory:
  - determined by the user account information at authentication time;
  - default current directory of a new process is that of its parent process;
  - relative path name defines a path from the current directory;
  - in example shown, /public_html/index.html is the path name relative to the directory /home/jason



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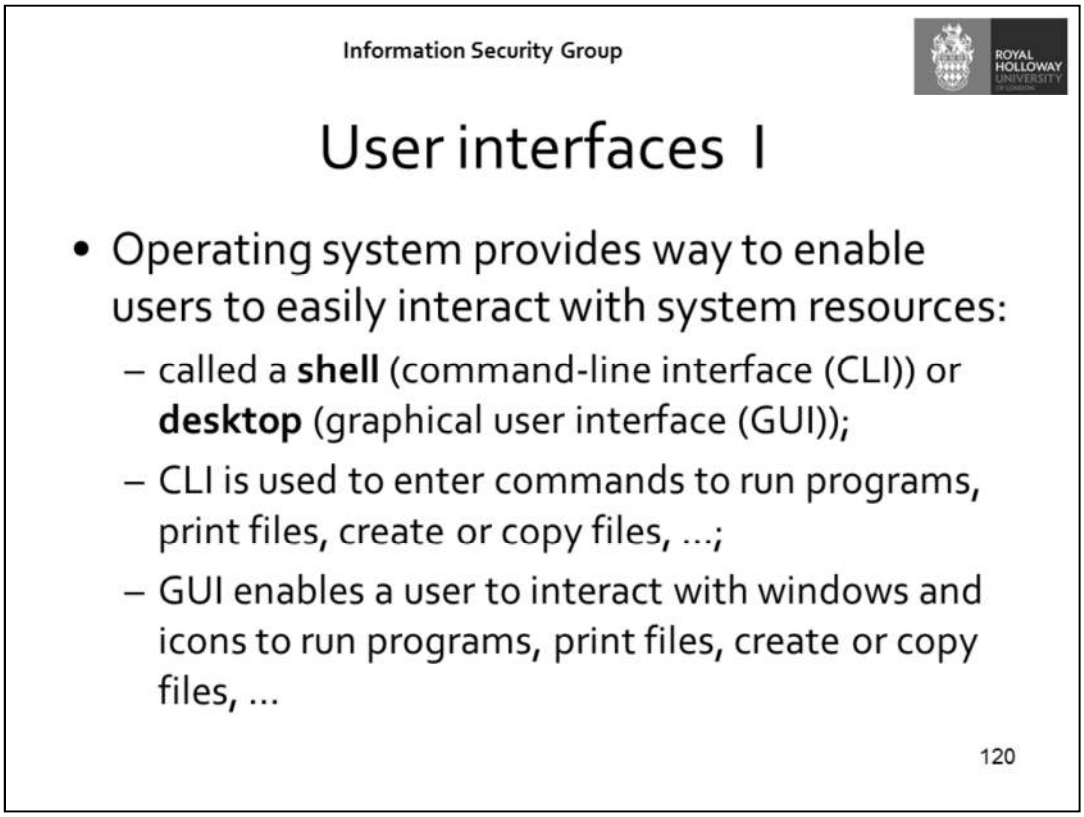
Each process has a working directory or current directory:

• this working/current directory is determined by the user account information at authentication time;

• the default current directory of a new process is that of its parent process;

• a relative path name defines a path from the current directory;

• in the example shown, /public_html/index.html is the path name relative to the directory /home/jason

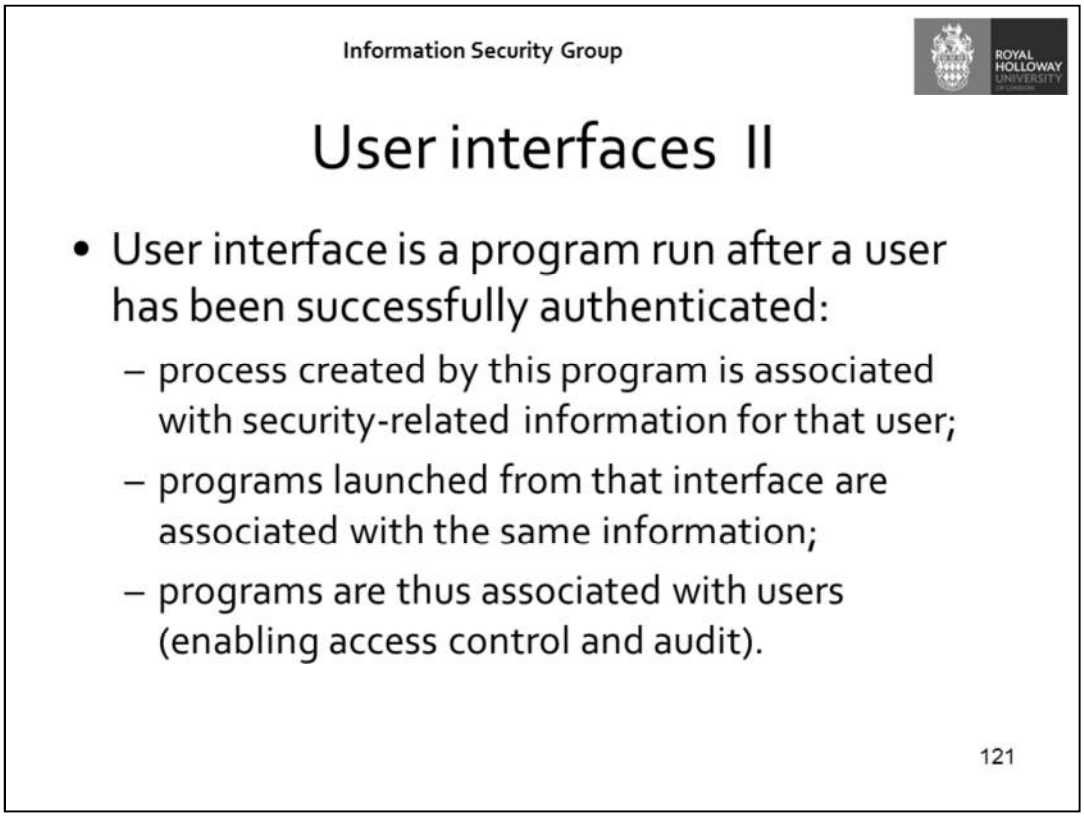


The operating system provides an environment that enables the user to easily interact with system resources:

• often called a **shell** (in the case of a command-line interface (CLI)) or **desktop** (in the case of a graphical user interface (GUI));

• a CLI is used to enter commands to run programs, print files, create or copy files, …;

• a GUI enables a user to interact with windows and icons to run programs, print files, create or copy files, …

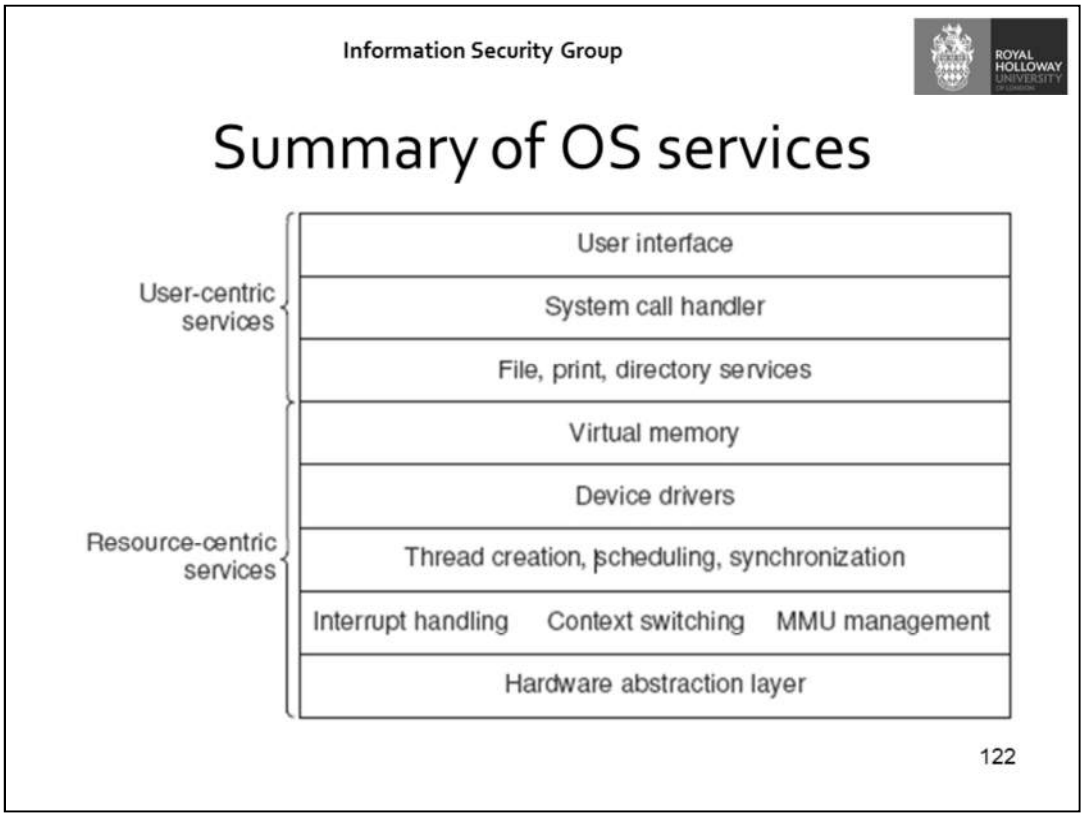


The user interface is a program that is run after a user has been successfully authenticated:

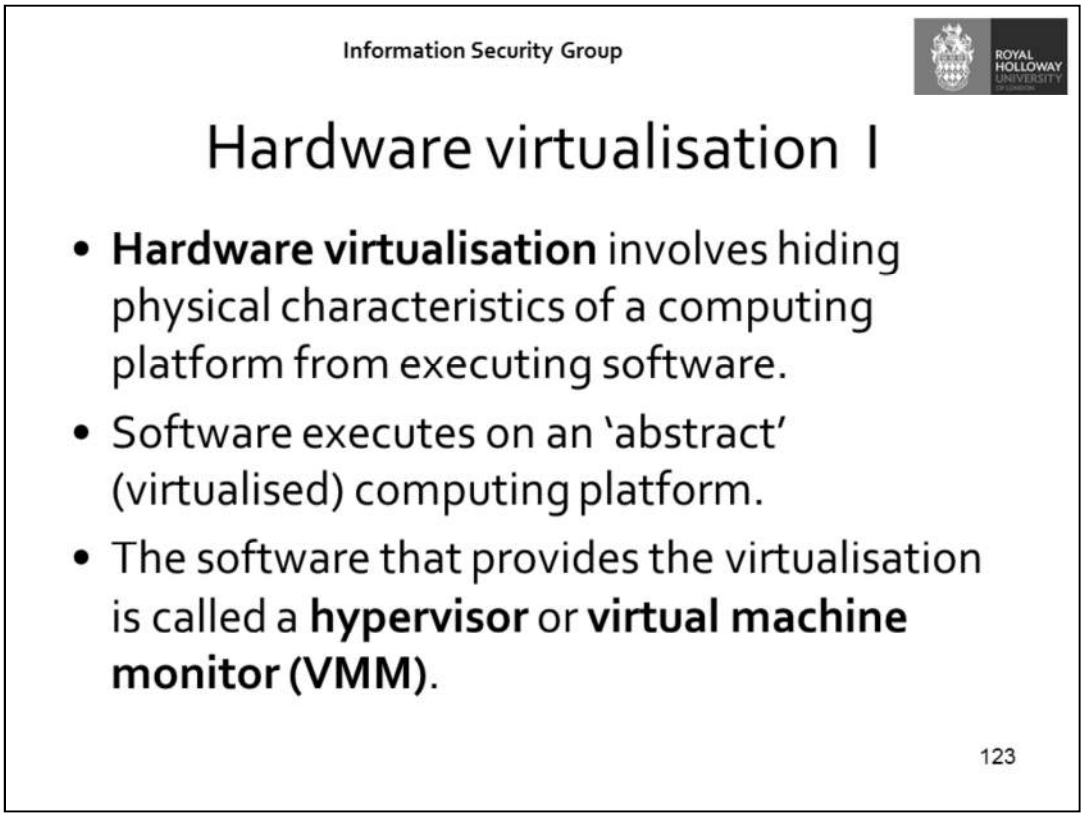
• the process that is created when this program is run (recall that running any program involves creating a process) is associated with the security-related information for the user that has been authenticated;

• any programs launched from that interface are associated with the same information;

• in this way programs are associated with users, and so user-based access control and audit can be achieved.

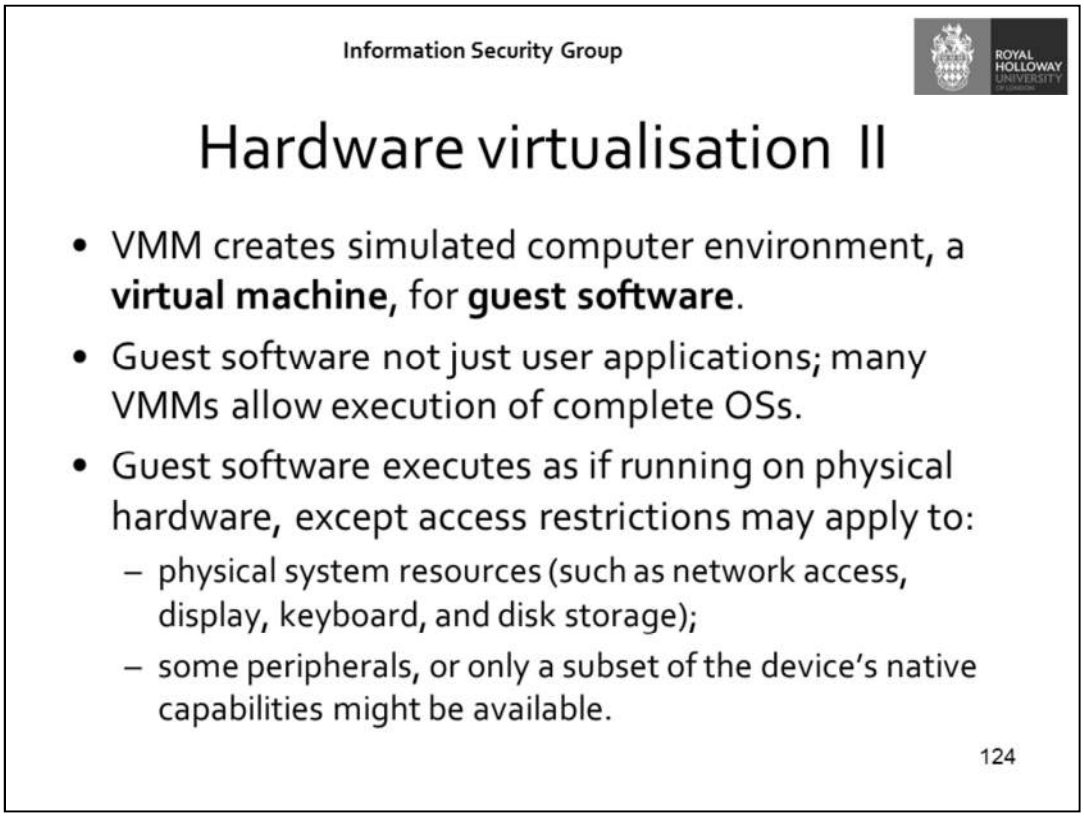


The picture summarises the services provided by a ‘typical’ OS.



Hardware virtualisation involves hiding the physical characteristics of a computing platform from executing software. In such a case, the software executes on an 'abstract' (virtualised) computing platform.

The software that provides the virtualisation layer is called a **hypervisor** or **virtual machine monitor (VMM)**.



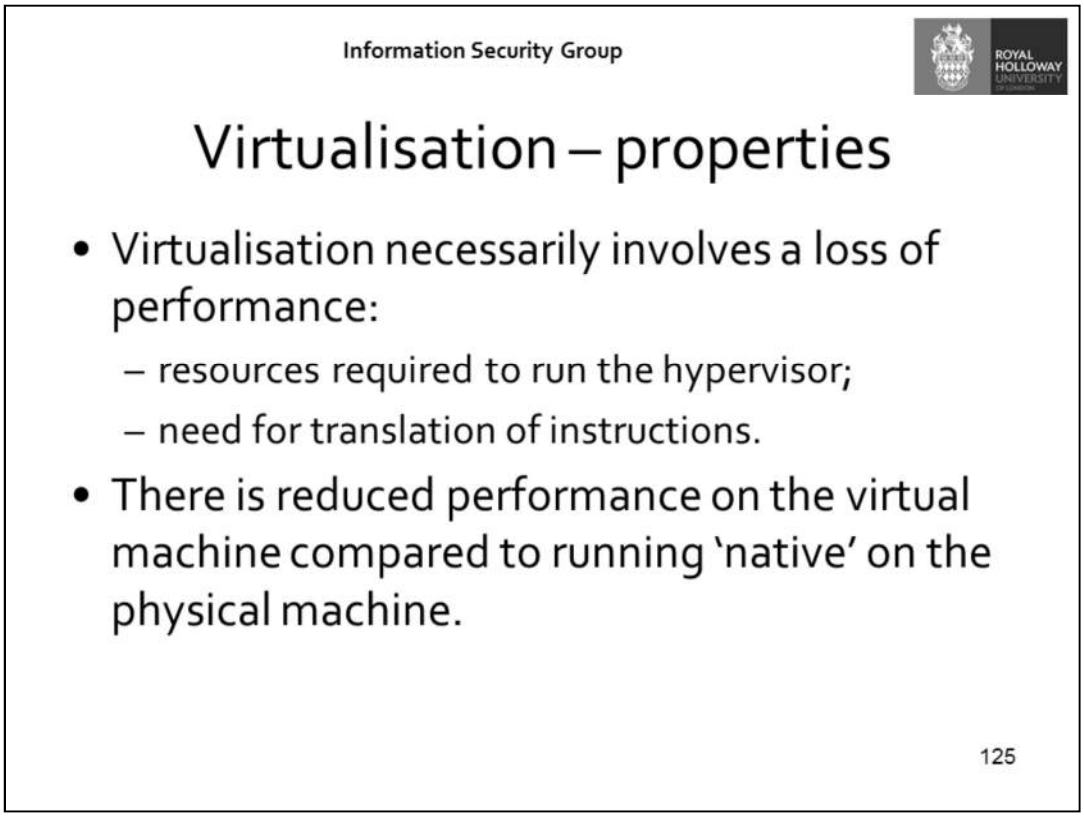
A VMM creates a simulated computer environment, known as a **virtual machine**, for its **guest software**.

The guest software is not limited to user applications; many VMMs allow the execution of complete operating systems.

The guest software executes as if it were running directly on the physical hardware, except that certain access restrictions may apply to:

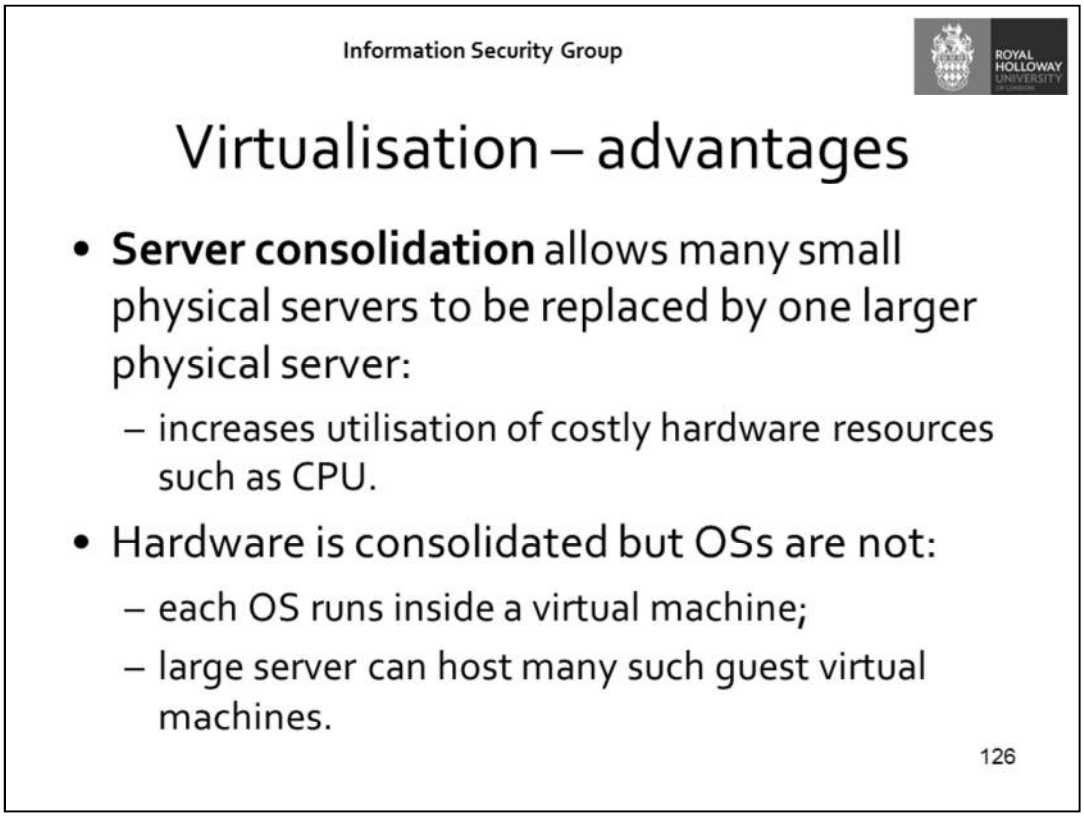
• physical system resources (such as network access, display, keyboard, and disk storage);

• some peripherals, or only a subset of the device's native capabilities may be available.



Virtualisation necessarily involves a loss of performance, because of the resources required to run the hypervisor/VMM, and the need for translation of instructions.

As a result, there is reduced performance on the virtual machine compared to running 'native' (i.e. in the non-virtualised way) on the physical machine.



Server consolidation allows many small physical servers to be replaced by one larger physical server:

- increases utilisation of costly hardware resources such as CPU.

The hardware is consolidated, but OSs are not:

- each OS runs inside a virtual machine;
- a large server can host many such guest virtual machines.

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Agenda

- What do computers do?
- Some common notation
- Computer architectures
- Software
- Operating systems
- Resources

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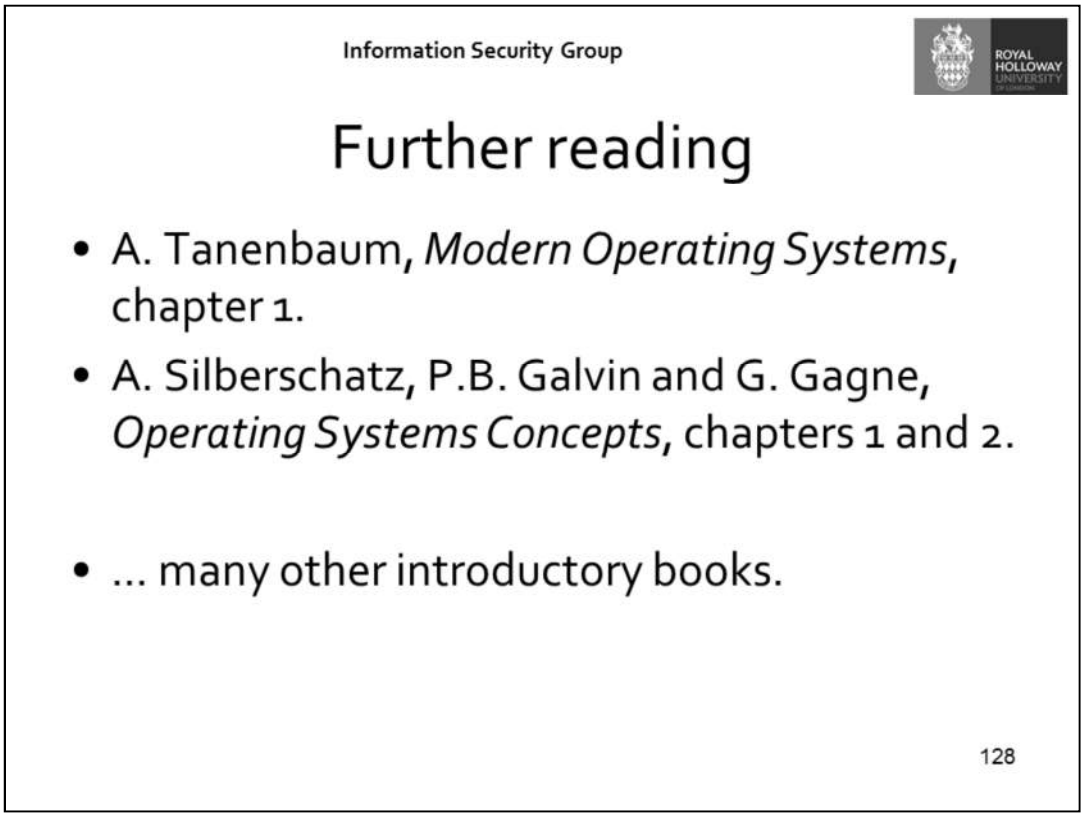

The following books are recommended:

• A. Tanenbaum, *Modern Operating Systems*, chapter 1.

• A. Silberschatz, P.B. Galvin and G. Gagne, *Operating Systems Concepts*, chapters 1 and 2.

However, there are many other textbooks covering similar ground, and of course there are many very valuable resources on the web.