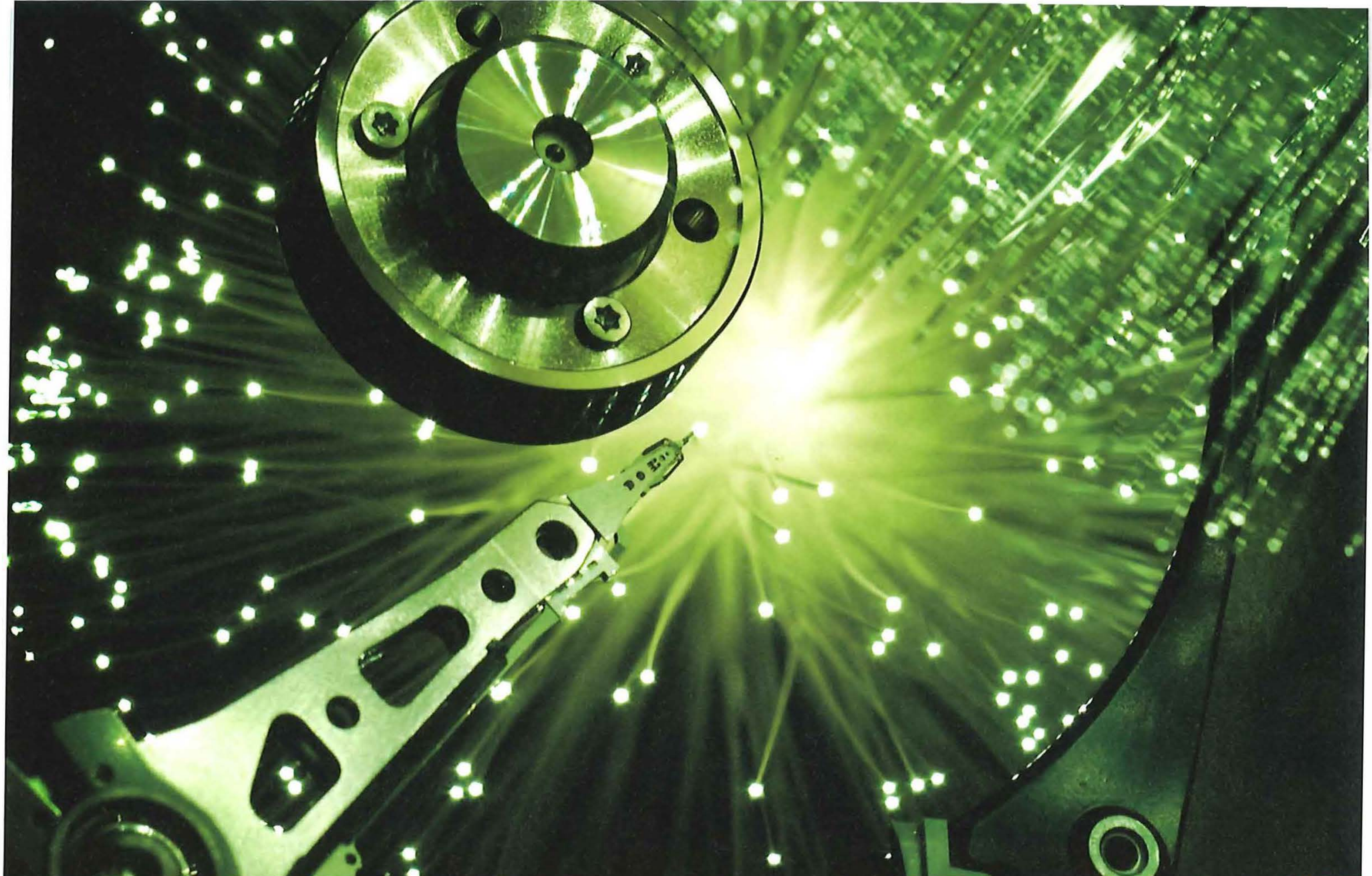

Chapter 8: Memory, Storage Devices and Media

Learning objectives

By the end of this chapter you will:

- understand what is meant by primary, secondary and off-line storage
- know that primary storage is Read Only Memory (ROM) and Random Access Memory (RAM)
- know that secondary storage is hard disk drives (HDD) and Solid State Drives (SSD)
- understand that off-line storage can be optical, magnetic or solid state
- understand the principles of operation of primary memory, secondary memory and off-line storage
- be able to describe how these principles are applied to currently available storage solutions such as HDDs, SSDs, USB flash memory, DVDs, CDs and Blu-ray disks.

8.01 Storage media

SYLLABUS CHECK

Show understanding of the difference between: primary, secondary and off-line storage.

In today's world we are used to having computers with a large storage capacity. Even smaller devices, such as smart phones and media players, usually have several gigabytes of data storage. However, it has taken a lot of development to get storage devices to be so small and have such a large capacity. The first storage device (a hard disk) to have a gigabyte of data was created in 1980 by IBM. It was as large as a refrigerator and cost over $80 000 USD.

Figure 8.01 The IBM 3380 was the first storage device to have a capacity of 1 gigabyte

As mentioned in previous chapters, the function of a computer is to input data, process it and output the resulting information. Data is held in storage for processing and so that it can be retrieved for later use.

There are three types of storage that a computer uses:

- primary storage
- secondary storage
- off-line storage

Primary storage

SYLLABUS CHECK

Provide examples of primary storage, such as: Read Only Memory (ROM) and Random Access Memory (RAM).

Primary storage is also known as 'primary memory' or 'memory'. Once data has been input into a computer, it needs to be stored in a place that can be accessed quickly and directly by the computer's processor. Primary storage is a computer's internal storage. It is in this storage where data is held ready for processing. Compared to secondary and off-line storage, the capacity of primary storage is quite small. Primary storage is separated into Random Access Memory (RAM) and Read Only Memory (ROM). Both types are memory chips.

Random Access Memory (RAM)

RAM is primary storage that holds data to be processed and programs that are in use. This means that RAM is storage that data can be written to and read from. Data and programs in RAM are held temporarily and erased when they are no longer needed. RAM also loses its contents when the computer's power is switched off. As a result we say that RAM is 'volatile'.

The amount of RAM built into a computer varies with the type of computer and its purpose. However, RAM can often be expanded to increase storage capacity. **Embedded computers** such as a pocket calculator, digital watch or central heating control system may only have a few kilobytes of RAM. This is because they only need to process small amounts of data at any one time. However, modern **general purpose computers**, such as desktop PCs, laptops, tablets and smartphones, will have a few gigabytes of RAM. This is because at any given time, the RAM in a general purpose computer will hold the operating system, programs that are currently running and data that is being processed.

RAM is often built into peripherals such as printers. Data to be printed is transferred to the printer's RAM, then the printer prints the data whilst the computer moves on to other tasks.

KEY TERM

Embedded computer – a computer that is built into a device and performs one or more specialised tasks.

General purpose computer – a computer used for many different applications.

TEST YOURSELF

Think of three other embedded computers in your school?

Read Only Memory (ROM)

ROM is primary storage that can be read from but not written to. Unlike RAM, ROM does not lose its contents when the computer's power is switched off. As a result we say that ROM is 'non-volatile'.

The contents of ROM vary depending on the type of device. Embedded devices use ROM to hold the software that runs the device. This software is known as **firmware**. General purpose devices use ROM to hold software known as a **bootstrap**. The bootstrap contains instructions that determine the basic hardware structure of the computer and instructions for finding and loading the operating system.

Certain types of ROM can be erased and re-written to. This type of ROM is known as **erasable programmable read only memory (EPROM)**. EPROM is found in situations where a device's firmware may need to be upgraded at some point in the future. For example, modern smart televisions, Blu-ray players and smartphones all have firmware that can be updated by the user. Upgrading firmware is known as **flashing**.

KEY TERM

Firmware – ROM that holds programs that run on an embedded computer.

Bootstrap – ROM that contains start-up instructions for the computer.

Erasable Programmable Read Only Memory (EPROM) – ROM that can be erased and re-written.

Flashing – the process of erasing and re-writing data to ROM.

Table 8.01

RAM	ROM
RAM is like a whiteboard. It can be written to, read from, erased, or left as it is. Its contents are temporary	ROM is like a book. Once written, it can usually only be read from. Its contents are mostly permanent
RAM is volatile. It loses its contents when power is switched off	ROM is non-volatile. It retains its contents when the power is switched off
In embedded devices, RAM holds data for processing. In general purpose computers, RAM hold the operating system, running programs and data for processing	ROM holds firmware and bootstraps
Depending on the device, RAM can range in capacity from a few bytes to several gigabytes	ROM tends to be much smaller in capacity

TEST YOURSELF

1 Research cache memory. What type of memory is it and why is it used?
2 Why does a computer need both RAM and ROM?

Secondary storage

SYLLABUS CHECK

Provide examples of secondary storage, such as: hard disk drive (HDD) and Solid State Drive (SSD).

Although general purpose computers have a large capacity of RAM, the storage requirements of data and software make it very impractical (and sometime impossible) to hold all necessary data and software in RAM at the same time. Software and data also need to be kept for future use, but are lost from RAM when the computer is switched off. Therefore we need secondary storage to hold data and software on a more permanent basis. They can be held in secondary storage until they are erased or over-written when no longer required. General purpose computers such as desktop PCs and laptops also use secondary storage to hold the operating system.

The CPU in a computer can only access data when it is being held in the RAM. Therefore, programs, data and an operating system must first be transferred into RAM from secondary storage before the processor can access them.

As secondary storage needs to hold large volumes of data and software, it is large in capacity, ranging in size from around 500 MB through to a terabyte, or more. Some secondary storage devices are removable. This means they can be transported between computers.

Table 8.02

Primary storage	Secondary storage
Directly accessible by the processor as it is internal to the computer	Not directly accessible to the processor – data first has to be transferred into RAM
Temporarily stores data	Permanently stores data till erased
Can be read from and written to primary storage almost instantly	Slower to read data from and write data to, as it needs to be transferred into RAM first
Normally a few gigabytes in capacity	Can be up to a terabyte or more in capacity
Fixed within the computer	Some devices are removable

There are three types of secondary storage that we need to consider:

- magnetic storage
- optical storage
- solid-state storage.

Each works in a different way and is used for a different purpose.

Magnetic storage

Magnetic storage devices read, write and erase data by using electromagnets and magnetic fields to control tiny magnetic dots of data. The dots represent binary.

Magnetic devices are either tape based or disk based. Tape-based devices use a cartridge of looped magnetic tape. The magnetised data dots are stored in series along the length of the tape. The tape passes over an electromagnetic read/write head that reads, writes or erases the magnetic dots.

Figure 8.02 The magnetised data dots are stored in series along the length of the magnetic tape

Disk-based devices, such as hard disk drives, consist of several disks known as platters. Platters can be made from metal or glass. They have a magnetised coating on which the data dots are stored. The dots lie in tracks that run around a platter. The platters are attached to a rotating spindle. This spindle spins the platters at high speed. Data is read, written or erased as the dots pass under read/write heads that sit on a moving arm. The arm moves back and forth across the platters to access data in different tracks.

Hard disk drives are the most common form of secondary storage device. They can hold up to 8 terabytes of data, although normally far less. A magnetic tape can hold up to 185 terabytes.

Figure 8.03 In a hard disk, an arm moves back and forth across platters to access data in different tracks

The rate at which data is moved to and from a storage device is called the 'data transfer rate'. Data is usually transferred much faster with a hard disk than with tape. Many modern hard disk drives have data transfer rates of up to 185 megabytes per second, whereas tape devices are usually limited to around 30 megabytes per second. This is partly because data can be read quicker using disk technology, but also because of the way data is stored and accessed on the two devices. Data is stored serially on magnetic tape. This means if the data required is near the point at which the tape starts being read, then the data will be quickly found and transferred. However, if the data is far away from that point, the tape has to loop around to the correct place first. Data on disks can be accessed directly as the read/write heads can move directly to the point at which the data is stored. This saves time and increases access speed.

To learn more about different types of data transfer, see Chapter 2.

TEST YOURSELF

Are there any computers in your school that use magnetic storage?

Optical storage

Optical storage devices read data by shining a laser beam onto the surface of plastic disks. The disks are coated with aluminium to make them reflective. The reflective surface is covered in one large track that spirals outwards from the centre of the disk. Data is written on the track by using a laser to make indentations known as **pits**. These pits represent binary data. The areas in between pits are known as **land**. As a pit reflects light back differently from land, the optical device is able to differentiate between binary 1s and 0s. For example, supposing we recorded the binary data 11101001. This would be recorded on the disk as:

Table 8.03

Disk	Pit			Land	Pit	Land		Pit
Binary Representation	1	1	1	0	1	0	0	1

The process of recording data onto an optical disk is known as 'burning'. This is because the laser burns the pits into the disk surface.

Optical disks have a good data transfer rate with speeds ranging between 10 and 72 megabytes per second. Newer formats, such as Blu-ray, are far quicker than older formats such as compact disk. There are different types of optical disk including **compact disks (CDs), digital versatile disks (DVDs)** and **Blu-ray disks**.

KEY TERM

Pit – an indentation on the surface of an optical disk, used to represent data.

Land – the raised surface between pits on an optical disk.

Compact disk (CD) – an early, but still used, optical medium.

Digital versatile disk (DVD) – a later, higher capacity optical medium.

Blu-ray disk – a modern, extremely high capacity optical medium.

DVD devices use a higher frequency laser than CD devices. The higher frequency allows the pits and land to be packed tighter onto the tracks. This allows more data to be stored.

Blu-ray devices use a blue-violet laser that operates at a shorter wavelength than the red lasers used in CD and DVD devices. This gives more precision when writing to and reading from a disk. This mean that data can be packed even closer together than when using a DVD device. DVDs and Blu-ray disks can have more than one reflective layer on which data can be stored.

Each type of optical disk has a different storage capacity for data, as shown in Table 8.04.

Table 8.04

Optical disk type	Capacity
CD	700 MB – equivalent of 80 mins of music
DVD single layer	4.7 GB – equivalent of 1.5 hr of standard-definition video and sound
DVD dual layer	9.4 GB – equivalent of 3 hr of standard-definition video and sound
Blu-ray single layer	25 GB – equivalent of 2.5 hr of high-definition video and sound
Blu-ray dual layer	50 GB – equivalent of 5 hr of high-definition video and sound
Blu-ray triple layer	100 GB – equivalent of 10 hr of high-definition video and sound
Blu-ray quadruple layer	128 GB – equivalent of 13 hr of high-definition video and sound

Optical media come in different types:

- ROM – read only. The data stored is already burned onto the disk by a manufacturer or another user. This data can only be read.
- -R. The disk is initially empty of data. It can be written to once and once only. Once written, the data can be read. There is a similar format called +R.
- -RW. The disk is initially empty of data. It can be written to and read from repeatedly. This type of disk has a reflective surface that can have pits burned in to it. By using a higher power laser the surface can be made to flow and cover the pits. This will return the disk to a blank state. There is a similar format called +RW.

Data stored on an optical medium is more portable than that on a hard disk drive. This is because the disk can easily be carried from one location to another. However, optical disks tend to have slower data transfer rates than hard disks and a far lower storage capacity. Most desktop PCs and laptops have a built-in optical disk drive, usually one that is able to burn media as well as read from it. Smaller computers, such as tablets and smartphones, tend to not have an optical disk drive as they are unable to accommodate the physical size of them.

Solid-state storage

Unlike magnetic and optical devices, solid-state storage has no moving parts. Instead, high-speed flash memory is used to store data. Examples of solid-state storage include USB **RAM sticks**, **solid-state hard drives** and **SD cards**.

KEY TERM

RAM stick – small solid-state medium used to transport data.

Solid-state drive (SSD) – a solid-state equivalent of a hard disk drive.

SD card – a solid-state card used to store and transfer data.

Solid-state devices are physically quite small in size, but their data transfer rate is much quicker than other types of storage. They are capable of rates up to 230 megabytes per second. They are normally no larger than 4 terabytes in capacity. This is because flash memory is expensive to produce.

A solid-state storage device can be written to and read from many times. This, combined with their physically small size, makes them useful as portable storage device. Many portable devices such as tablets and smartphones make use of solid-state storage. They are also used in compact media players, cameras and computers such as the Raspberry Pi.

Off-line storage

Off-line storage is any non-volatile storage device or medium that can be disconnected (off-line), or removed, from a computer. Typical examples of off-line storage include optical media (CD, DVD and Blu-ray disks), USB RAM sticks, external hard drives and magnetic tape.

SYLLABUS CHECK

Provide examples of off-line storage, such as: Digital Versatile Disk (DVD), Compact Disk (CD), Blu-ray disk, USB flash memory and removable HDD.

Describe the principles of operation of a range of storage devices and media including magnetic, optical and solid-state.

TEST YOURSELF

Why might off-line storage be necessary for a business?

8.02 Choosing an appropriate secondary storage device

There are many different types of secondary storage medium. Some types are more suitable for certain situations than others. Selecting the wrong format can have consequences.

SYLLABUS CHECK

Describe how the principles of operation are applied to currently available storage solutions, such as SSDs, HDDs, USB flash memory, DVDs, CDs and Blu-ray disks.

There are several factors to take into account when choosing an appropriate secondary storage medium:

- Capacity – The amount of data that can be stored with the medium.
- Transfer speed – The rate at which data can be transferred to and from the medium.
- Portability – How easily the medium can be transported from one location to another
- Durability – How resistant the medium is to data loss and damage from wear, tear and pressure.
- Cost – How expensive is the medium (this is often calculated as cost per megabyte or cost per gigabyte).

Table 8.05 gives a general comparison of differing media.

Table 8.05

Format/ Device	Capacity	Transfer speed	Portable	Durability	Cost per megabyte
Magnetic					
Hard disk drive	Up to 8 TB	Fast, up to 128 MB per second	Often fixed within a computer Portable versions exist	Very durable	Very cheap
Magnetic tape	Up to 185 TB	Medium, up to 30 MB per second	Yes	Case is quite durable, although tape can be easily damaged	Extremely cheap
Optical					
CD	700 MB	Slow, up to 10 MB per second	Yes	Reflective surface is quite easily scratched Disk is easily broken	Cheap for small volumes, expensive for large data storage
DVD	4.7–9.4 GB	Medium, up to 33 MB per second	Yes	Reflective surface is quite easily scratched Disk is easily broken	Cheap for small volumes, expensive for large data storage
Blu-ray	25–128 GB	Quite quick, up to 72 MB per second	Yes	Reflective surface is quite easily scratched Disk is easily broken	Cheap for small volumes, expensive for large data storage
Solid-state					
USB RAM stick	Up to 1 TB	Very quick, up to 180 MB per second	Yes	Fairly durable, but easily lost	Very cheap
Solid-state drive	Up to 4 TB	Extremely quick, up to 230 MB per second	Yes	Very durable as no moving parts	Expensive
SD card	Up to 2 TB	Medium, up to 48 MB per second	Yes	Fairly durable, but easily lost	Very cheap

Since different secondary storage media have different capabilities, some types are better suited to certain situations than others. Table 8.06 give some uses of the different media.

Table 8.06

Situation	Secondary storage medium	Reasons
Storing operating system, data and programs	Hard disk drive Solid-state drive	• Large capacity • High data transfer rate • Data can be read and written
Distribution of software	CD-ROM DVD-ROM	• Cheap • Easily duplicated • Portable • Once written data cannot be erased or changed
Distribution of films	DVD-ROM Blu-ray ROM	• Larger capacity to deal with large file size of films • Easily duplicated • Portable • Once written data cannot be erased or changed

Situation	Secondary storage medium	Reasons
Transferring data from one computer to another	USB RAM stick SD card	• Cheap • Very portable
Backing up data	Magnetic tape Portable hard disk drive	• Large capacity • Easy to remove and store elsewhere for safe keeping • Data can be over-written to make a new back-up
Archiving data	CD-R DVD-R Blu-ray R	• Easy to remove and store elsewhere for safe keeping • Once written, data cannot be erased or changed

TEST YOURSELF

1 What kind of secondary storage devices do you mostly use?
2 Do you think they are the best choice?
3 Would another type of secondary storage be more suitable?

8.03 Calculating the storage requirement of a file

SYLLABUS CHECK

Calculate the storage requirement of a file.

Data is represented as bits. Data is stored in files and file sizes are represented in units:

8 bits = 1 byte, or 1 B
1024 bytes = 1 kilobyte (1 KB)
1024 kilobytes = 1 megabyte (1 MB) or 1 048 576 bytes
1024 megabytes = 1 gigabyte (1 GB) or 1 073 741 824 bytes
1024 gigabytes = 1 terabyte (1 TB) or 1 099 511 627 776 bytes

The number of bits required for data storage depends on the amount of data and the type of data to be stored.

Table 8.07

Data to be stored	Storage requirements
Pixels in a black and white image	1 bit per pixel
Pixels in an 8-bit colour image	8 bits (1 byte) per pixel
Characters in an ASCII text string	1 byte per character
Sound in a wave file	86 kilobytes per second
Uncompressed frame of standard-definition TV	27 megabytes per frame
Uncompressed frame of high-definition TV	182 megabytes per frame

Compression can be used to reduce file storage requirements.

To learn more about data representation and compression, see Chapter 1.

To calculate the storage requirements of a file we need to know the type and amount of data to be stored.

Example 1: Storing a string of text

The following message is stored in a file:

I LOVE IGCSE COMPUTER SCIENCE!

This message contains 30 characters (including spaces). Each character requires 1 byte for storage. Therefore, the size of the file for this data would be:

30 characters × 1 byte per character = **30 bytes**

Example 2: Storing a simple black-and-white image

The graphic in Figure 8.04 is stored in a file.

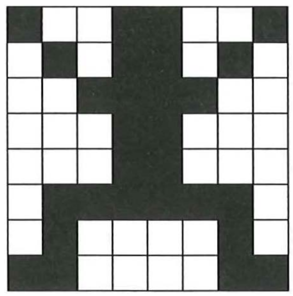

Figure 8.04 Stored simple black-and-white image

The graphic contains 8 rows and 8 columns giving 64 pixels in total: 8 × 8 = 64.

A black and white image requires 1 bit per pixel. Therefore, excluding metadata, the size of the file for this data would be:

64 pixels × 1 bit per pixel = **64 bits or 8 bytes**

Example 3: Storing a simple 8-bit colour image

The 8-bit colour graphic in Figure 8.05 is to be stored in a file.

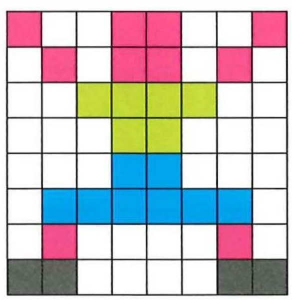

Figure 8.05 Stored 8-bit colour image

The graphic contains 8 rows and 8 columns giving 64 pixels in total. However, this graphic is in 8-bit colour (unlike the black-and-white image of Example 2). This requires 8 bits (1 byte) per pixel. Therefore, excluding metadata, the size of the file for this data would be:

64 pixels × 8 bits = 512 bits
512 bits ÷ 8 = **64 bytes**

Example 4: Calculating a file size from image size and resolution

The file size of an image can be calculated as long as its size and resolution are known. For example, consider a 24-bit colour image that is 2 inches high and 3 inches wide, with a resolution of 300 dots per inch.

First, the number of pixels are calculated. If the resolution is 300 dots per inch then the pixel grid for a 2-inch by 3-inch image will measure 600 pixels (2 × 300) by 900 pixels (3 × 300). As a 24-bit colour image requires 24 bits for each pixel, excluding metadata the size of the file would be:

300 pixels × 900 pixels = 270 000 pixels
270 000 pixels × 24 bits per pixel = 6 480 000 bits
6 480 000 bits ÷ 8 = 810 000 bytes
810 000 bytes ÷ 1024 = **791.02 kilobytes**
792.02 ÷ 1024 = **0.77 megabytes**

Example 5: Storing a database

A university holds student data in a simple flat file database with the structure shown in Table 8.08.

Table 8.08

Field Name	Type	Field size	Sample record
StudentID	Number	4	1509
FamilyName	Text	30	Scott
Firstname	Text	20	Heather
Address	Text	30	34 Brampton Rd
Town	Text	20	Swindon
Postcode	Text	8	SN5 5DS
Gender	Text	6	Female
Date of birth	Date	6	01/03/98
Course Name	Text	20	Computer Art

The university's database currently holds data for 27 000 students. In this example, we can only estimate the size of the data. This is because we don't know exactly what data each record has, only what the field size in database structure will allow. The database has nine fields and each record should allow for a total of 144 bytes

(4 + 30 + 20 + 30 + 20 + 8 + 6 + 6 + 20).

Each data character requires 1 byte for storage. Therefore, the estimated size of the file for this data would be:

144 characters per record × 1 byte per character = 144 bytes
144 bytes × 27 000 records = 3 888 000 bytes
3 888 000 ÷ 1024 = 3796.875 kilobytes
3796.875 ÷ 1024 = **3.71 megabytes**

Example 6: Calculating the size of an audio file

There are four main pieces of data that are used in calculating the size of an audio file:

- The length of the audio track (this needs to be in seconds)
- The number of samples taken per second (sample rate)
- The number of bits used to store each sample (sample depth)
- The number of channels used to play the track (mono has 1, stereo has 2)

The following calculation can then be carried out to find the size of the file:

sample rate x sample depth × track length × number of tracks

If an audio track is 3 minutes and 30 seconds (210 seconds in total) in length, recorded in stereo, samples at 44 Khz (44000 Hz) with a sample depth of 16 bits, this is how we would calculate the file size:

$$44000 \times 16 \times 210 \times 2 = 295680000 \text{ bits}$$
$$295680000 \div 8 = 36960000 \text{ bytes}$$
$$36960000 \div 1024 = 36093.75 \text{ kilobytes}$$
$$36093.75 \div 1024 = \textbf{35.25 megabytes}$$

Summary

- Data is held in storage for processing and so that it can be retrieved for later use.
- There are three types of storage, primary storage, secondary storage and off-line storage.
- Primary storage is storage internal to the computer that is directly accessible by the processor.
- Random Access Memory (RAM) is primary storage that temporarily holds running programs and data for processing. It is volatile, meaning it loses its contents when switched off.
- Read Only Memory (ROM) is primary storage that can be read from but not written to. ROM is non-volatile, meaning it keeps its contents when power is switched off.
- Secondary storage is non-volatile storage that is not directly accessible by the processor that is used to hold data permanently, till deleted:
  - Magnetic storage uses electromagnets and magnetic fields to read, write and erase data. Magnetic devices are either tape based or disk based.
  - Optical devices shine a laser beam onto a disk with a reflective surface. Data is stored on the disk in the form of indentations (pits) and raised areas (land). Optical devices generally have less capacity and slower data transfer rates than magnetic devices.
  - Solid-state devices have no moving parts. They use high-speed flash memory to store data. SSDs are very fast at transferring data, but generally smaller in capacity and far more expensive than equivalent hard disk drives.
- Off-line storage is any non-volatile storage device or medium that is disconnected (off-line), or removed, from the computer.
- A user must take into account several factors when choosing an appropriate medium such as capacity, data transfer rate, portability, durability and cost per megabyte.
- When calculating the storage requirements for data, the user must take into account the type of data and the amount of data to be stored.

Exam-style questions

1. Explain the difference between primary storage and secondary storage. (2 marks)
2. Describe three ways in which RAM differs from ROM. (3 marks)
3. Explain how a hard disk drive reads and writes data. (4 marks)
4. What enables a Blu-ray disk to hold more data than a compact disk? (2 marks)
5. A company sends out an electronic catalogue its customers. Suggest a suitable storage medium and justify your choice with reasons. (2 marks)
6. A 16-bit colour image is 4 inches × 1 inch in size, with a resolution of 600 dots per inch. Calculate the storage requirements for this image. (1 mark)
7. Explain why data on a magnetic tape may be accessed quickly or slowly. (2 marks)
8. Explain two reasons why solid-state storage is not as common in desktop PCs and laptops as hard disk drives. (2 marks)