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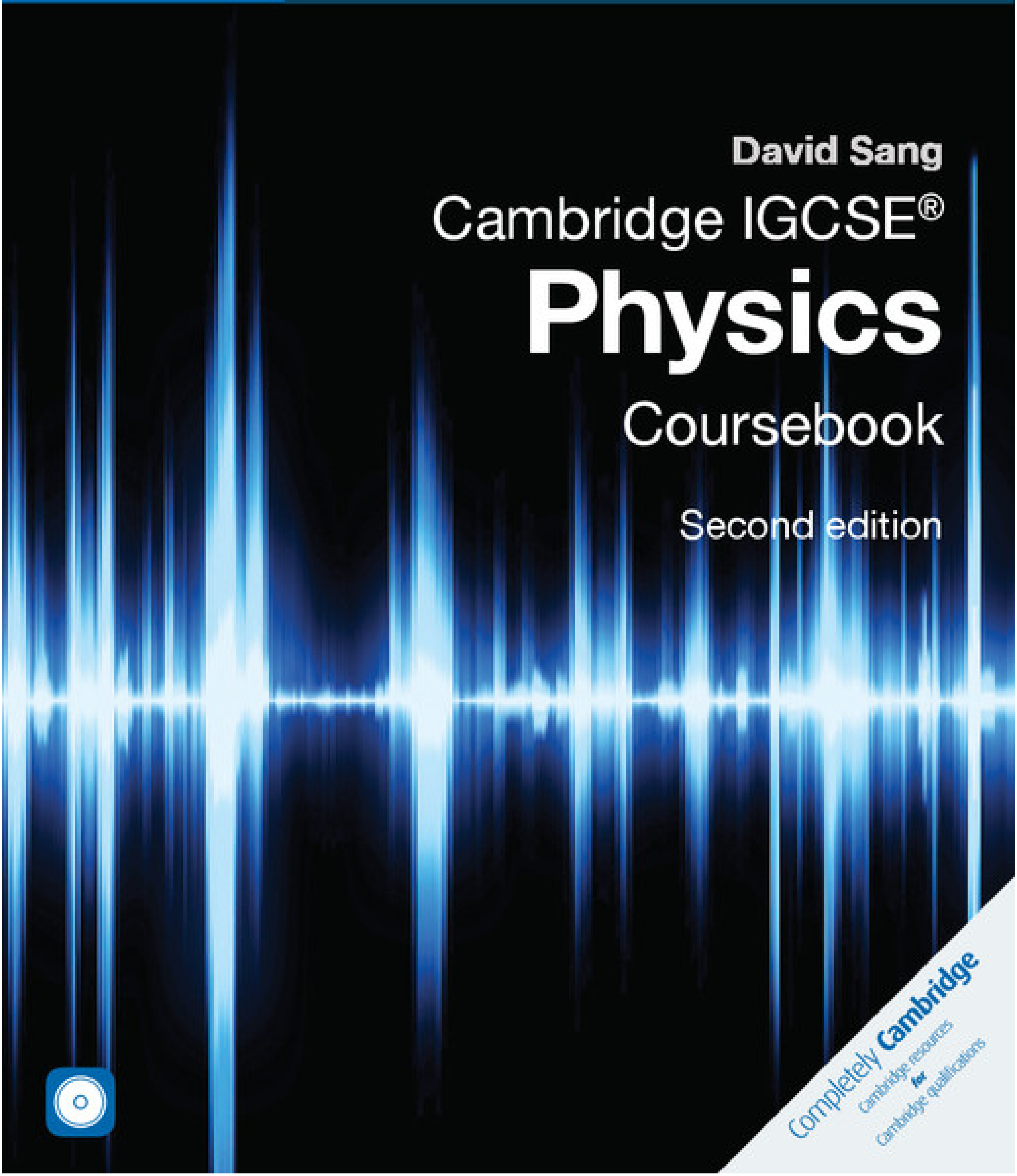

David Sang

Cambridge IGCSE Physics Coursebook

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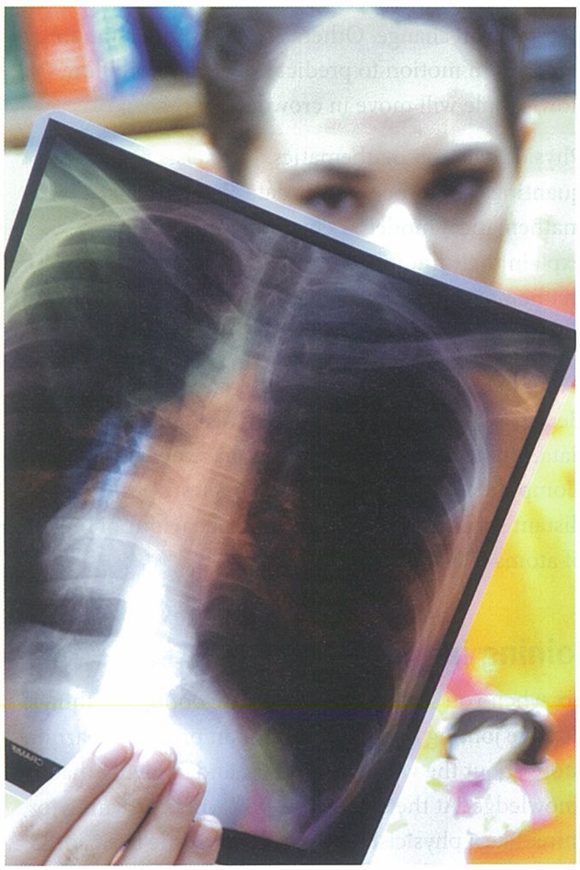
Introduction

Studying physics

Why study physics? Some people study physics for the simple reason that they find it interesting. Physicists study matter, energy and their interactions. They might be interested in the tiniest sub-atomic particles, or the nature of the Universe itself. (Some even hope to discover whether there are more universes than just the one we live in!)



When they were first discovered, X-rays were sometimes treated as an entertaining novelty. Today, they can give detailed views of a patient's bones and organs.

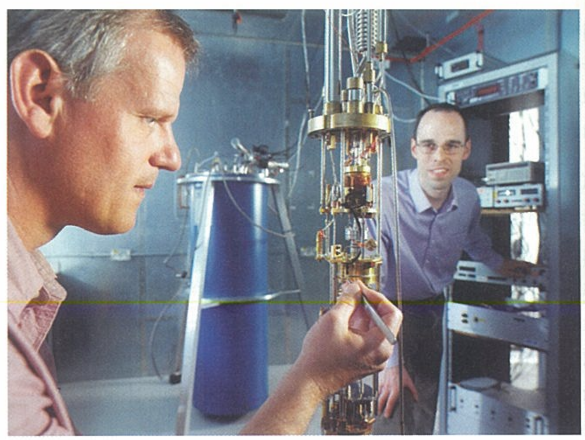
On a more human scale, physicists study materials to try to predict and control their properties. They study the interactions of radiation with matter, including the biological materials we are made of.

Some people don't want to study physics simply for its own sake. They want to know how it can be used, perhaps in an engineering project, or for medical purposes. Depending on how our knowledge is applied, it can make the world a better place.

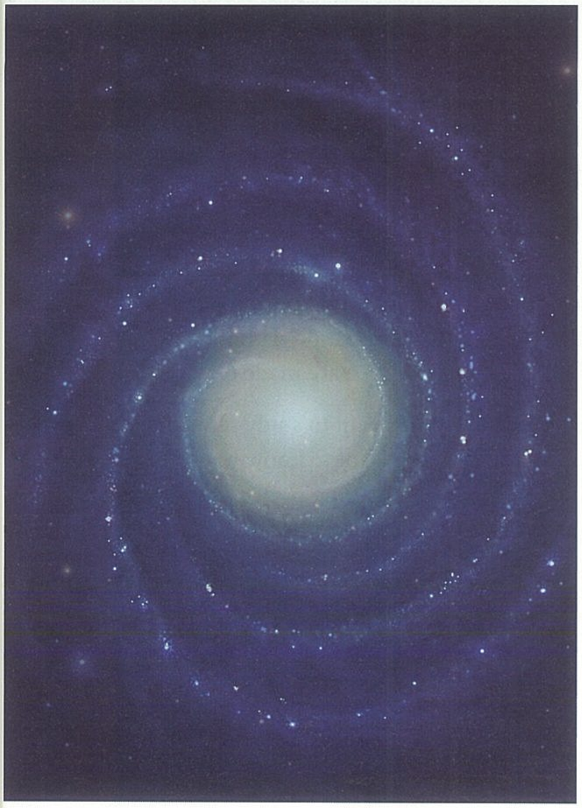
Some people study physics as part of their course because they want to become some other type of scientist – perhaps a chemist, biologist or geologist. These branches of science draw a great deal on ideas from physics, and physics may draw on them.

Thinking physics

How do physicists think? One of the characteristics of physicists is that they try to simplify problems – reduce them to their basics – and then solve them by applying



Physicists often work in extreme conditions. Here, physicists at the UK's National Physical Laboratory prepare a dilution refrigerator, capable of cooling materials down almost to absolute zero, the lowest possible temperature.

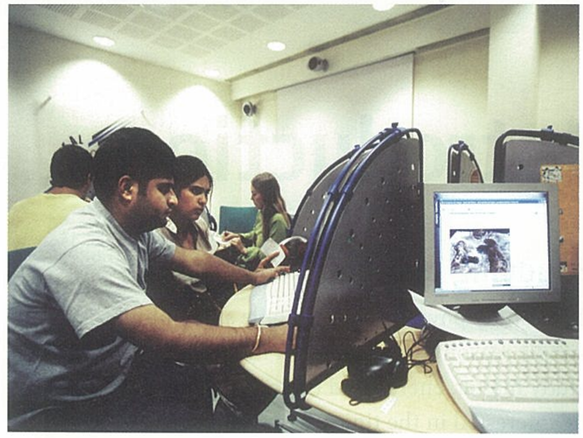


The Milky Way, our Galaxy. Although we can never hope to see it from this angle, careful measurements of the positions of millions of stars has allowed astronomers to produce this computer-generated view.

some very fundamental ideas. For example, you will be familiar with the idea that matter is made of tiny particles that attract and repel each other and move about. This is a very powerful idea, which has helped us to understand the behaviour of matter, how sound travels, how electricity flows, and so on.

Once a fundamental idea is established, physicists look around for other areas where it might help to solve problems. One of the surprises of 20th-century physics was that, once physicists had begun to understand the fundamental particles of which atoms are made, they realised that this helped to explain the earliest moments in the history of the Universe, at the time of the Big Bang.

The more you study physics, the more you will come to realise how the ideas join up. Also, physics is still expanding. Many physicists work in economics and



The Internet, used by millions around the world. Originally invented by a physicist, Tim Berners-Lee, the Internet is used by physicists to link thousands of computers in different countries to form supercomputers capable of handling vast amounts of data.

finance, using ideas from physics to predict how markets will change. Others use their understanding of particles in motion to predict how traffic will flow, or how people will move in crowded spaces.

Physics relies on mathematics. Physicists measure quantities and process their data. They invent mathematical models – equations and so on – to explain their findings. (In fact, a great deal of mathematics was invented by physicists, to help them to understand their experimental results.)

Computers have made a big difference in physics. Because a computer can 'crunch' vast quantities of data, whole new fields of physics have opened up. Computers can analyse data from telescopes, control distant spacecraft and predict the behaviour of billions of atoms in a solid material.

Joining in

So, when you study physics, you are doing two things. You are joining in with a big human project – learning more about the world around us, and applying that knowledge. At the same time, you will be learning to think like a physicist – how to apply some basic ideas, how to look critically at data, and how to recognise underlying patterns. Whatever your aim, these ideas can stay with you throughout your life.

Block 1

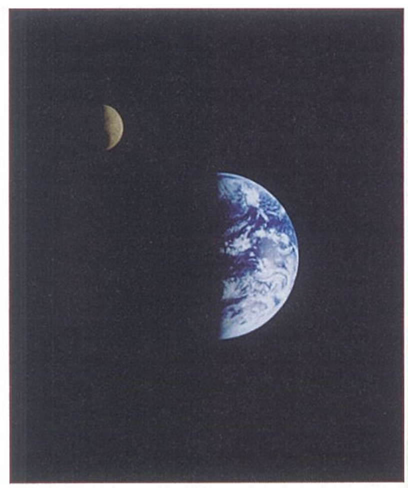
General physics

In your studies of science, you will already have come across many of the fundamental ideas of physics. In this block, you will develop a better understanding of two powerful ideas: (i) the idea of force and (ii) the idea of energy.

Where do ideas in physics come from? Partly, they come from observation. When Galileo looked at the planets through his telescope, he observed the changing face of Venus. He also saw that Jupiter had moons. Galileo's observations formed the basis of a new, more scientific, astronomy.

Ideas also come from thought. Newton (who was born in the year that Galileo died) is famous for his ideas about gravity. He realised that the force that pulls an apple to the ground is the same force that keeps the Moon in its orbit around the Earth. His ideas about forces are explored in this block.

You have probably studied some basic ideas about energy. However, Newton never knew about energy. This was an idea that was not developed until more than a century after his death, so you are already one step ahead of him!



In 1992, a spacecraft named Galileo was sent to photograph Jupiter and its moons. On its way, it looked back to take this photograph of the Earth and the Moon.

1 Making measurements

Core Making measurements of length, volume and time

E **Extension** Increasing the precision of measurements of length and time

Core Determining the densities of solids and liquids

How measurement improves

Galileo Galilei is often thought of as the father of modern science. He did a lot to revolutionise how we think of the world around us, and in particular how we make measurements. In 1582, Galileo was a medical student in Pisa. During a service in the cathedral there, he observed a lamp swinging (Figure 1.1). Galileo noticed that the time it took for each swing was the same, whether the lamp was swinging through a large or a small angle. He realised that a swinging weight – a pendulum – could be used as a timing device. He went on to use it to measure a person's pulse rate, and he also designed a clock regulated by a swinging pendulum.

In Galileo's day, many measurements were based on the human body – for example, the foot and the yard (a pace). Weights were measured in units based on familiar objects such as cereal grains. These 'natural' units are inevitably variable – one person's foot is longer than another's – so efforts were made to standardise them. (It is said that the English 'yard' was defined as the distance from the tip of King Henry I's nose to the end of his outstretched arm.)

Today, we live in a globalised economy. We cannot rely on monarchs to be our standards of measurement. Instead, there are international agreements on the basic units of measurement. For example, the metre is defined as follows:

The metre is the distance travelled by light in $\frac{1}{299\,792\,458}$ second in a vacuum.

Laboratories around the world are set up to check that measuring devices match this standard.

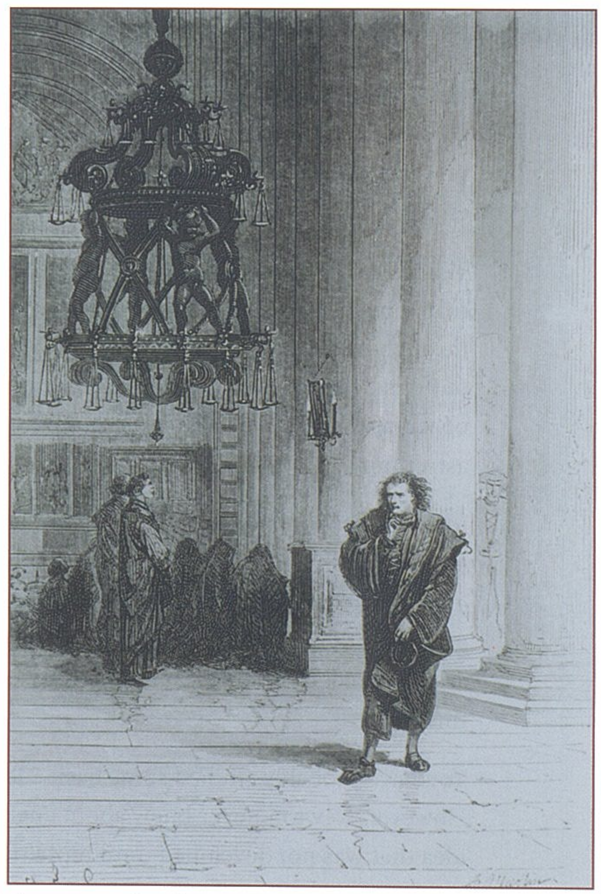


Figure 1.1 An imaginative reconstruction of Galileo with the lamp that he saw swinging in Pisa Cathedral in 1582.

Figure 1.2 shows a new atomic clock, undergoing development at the UK's National Physical Laboratory. Clocks like this are accurate to 1 part in 10^{14}, or one-billionth of a second in a day. You might think that this is far more precise than we could ever need.

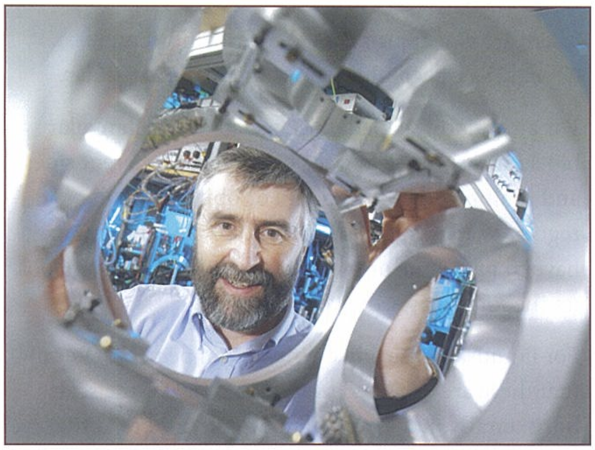


Figure 1.2 Professor Patrick Gill of the National Physical Laboratory is devising an atomic clock that will be one-thousand times more accurate than previous types.

In fact, you may already rely on ultra-precise time measurements if you use a GPS (Global Positioning Satellite) system. These systems detect satellite signals, and they work out your position to within a fraction of a metre. Light travels one metre in about $\frac{1}{300\,000\,000}$ second, or 0.000 000 003 second. So, if you are one metre further away from the satellite, the signal will arrive this tiny fraction of a second later. Hence the electronic circuits of the GPS device must measure the time at which the signal arrives to this degree of accuracy.

1.1 Measuring length and volume

In physics, we make measurements of many different lengths – for example, the length of a piece of wire, the height of liquid in a tube, the distance moved by an object, the diameter of a planet or the radius of its orbit. In the laboratory, lengths are often measured using a rule (such as a metre rule).

Measuring lengths with a rule is a familiar task. But when you use a rule, it is worth thinking about the task and just how reliable your measurements may be. Consider measuring the length of a piece of wire (Figure 1.3).

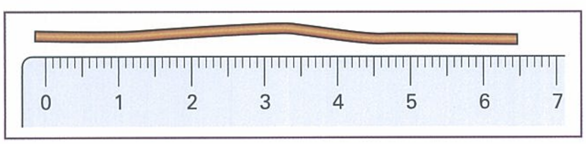


Figure 1.3 Simple measurements – for example, finding the length of a wire – still require careful technique.

- The wire must be straight, and laid closely alongside the rule. (This may be tricky with a bent piece of wire.)
- Look at the ends of the wire. Are they cut neatly, or are they ragged? Is it difficult to judge where the wire begins and ends?
- Look at the markings on the rule. They are probably 1 mm apart, but they may be quite wide. Line one end of the wire up against the zero of the scale. Because of the width of the mark, this may be awkward to judge.
- Look at the other end of the wire and read the scale. Again, this may be tricky to judge.

Now you have a measurement, with an idea of how precise it is. You can probably determine the length of the wire to within a millimetre. But there is something else to think about – the rule itself. How sure can you be that it is correctly calibrated? Are the marks at the ends of a metre rule separated by exactly one metre? Any error in this will lead to an inaccuracy (probably small) in your result.

The point here is to recognise that it is always important to think critically about the measurements you make, however straightforward they may seem. You have to consider the method you use, as well as the instrument (in this case, the rule).

More measurement techniques

If you have to measure a small length, such as the thickness of a wire, it may be better to measure several thicknesses and then calculate the average. You can use

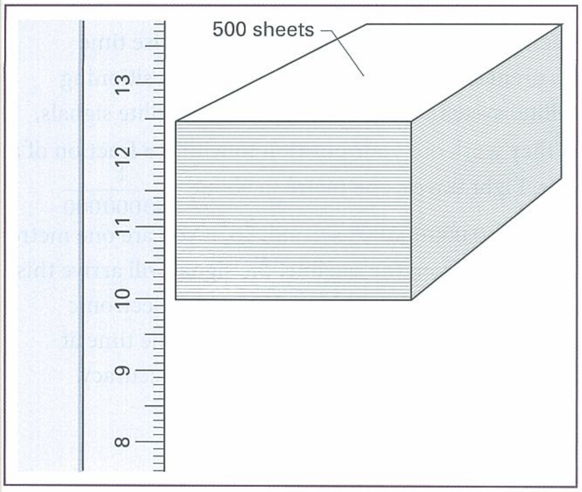


Figure 1.4 Making multiple measurements.

the same approach when measuring something very thin, such as a sheet of paper. Take a stack of 500 sheets and measure its thickness with a rule (Figure **1.4**). Then divide by 500 to find the thickness of one sheet.

For some measurements of length, such as curved lines, it can help to lay a thread along the line. Mark the thread at either end of the line and then lay it along a rule to find the length. This technique can also be used for measuring the circumference of a cylindrical object such as a wooden rod or a measuring cylinder.

Measuring volumes

There are two approaches to measuring volumes, depending on whether or not the shape is regular.

For a regularly shaped object, such as a rectangular block, measure the lengths of the three different sides and multiply them together. For objects of other regular shapes, such as spheres or cylinders, you may have to make one or two measurements and then look up the formula for the volume.

For liquids, measuring cylinders can be used. (Recall that these are designed so that you look at the scale **horizontally**, not at an oblique angle, and read the level of the **bottom** of the meniscus.) Think carefully about the choice of cylinder. A one-litre cylinder is unlikely to be suitable for measuring a small volume such as 5 cm^3. You will get a more accurate answer using a 10 cm^3 cylinder.

Units of length and volume

In physics, we generally use SI units (this is short for *Le Système International d'Unités* or The International System of Units). The SI unit of length is the metre (m). Table **1.1** shows some alternative units of length, together with some units of volume.

Quantity	Units
length	metre (m)
	1 centimetre (cm) = 0.01 m
	1 millimetre (mm) = 0.001 m
	1 micrometre (μm) = 0.000 001 m
	1 kilometre (km) = 1000 m
volume	cubic metre (m^3)
	1 cubic centimetre (cm^3) = 0.000 001 m^3
	1 cubic decimetre (dm^3) = 0.001 m^3
	1 litre (l) = 0.001 m^3
	1 litre (l) = 1 cubic decimetre (dm^3)
	1 millilitre (ml) = 1 cubic centimetre (cm^3)

Table 1.1 Some units of length and volume in the SI system.

QUESTIONS

1 A rectangular block of wood has dimensions 240 mm × 20.5 cm × 0.040 m. Calculate its volume in cm^3.

2 Ten identical lengths of wire are laid closely side-by-side. Their combined width is measured and found to be 14.2 mm. Calculate:

a the radius of a single wire

b the volume in mm^3 of a single wire if its length is 10.0 cm. (Volume of a cylinder = $\pi r^2 h$, where r = radius and h = height.)

E

1.2 Improving precision in measurements

A rule is a simple measuring instrument, with many uses. However, there are instruments designed to give greater precision in measurements. Here we will look at how to use two of these.

Vernier callipers

The callipers have two scales, the main scale and the vernier scale. Together, these scales give a measurement of the distance between the two inner faces of the jaws (Figure 1.5).

The method is as follows:

- Close the callipers so that the jaws touch lightly but firmly on the sides of the object being measured.
- Look at the zero on the vernier scale. Read the main scale, just to the left of the zero. This tells you the length in millimetres.
- Now look at the vernier scale. Find the point where one of its markings is **exactly** aligned with one of the markings on the main scale. Read the value on the vernier scale. This tells you the fraction of a millimetre that you must add to the main scale reading.

For the example in Figure **1.5**:

thickness of rod
= main scale reading + vernier reading
= 35 mm + 0.7 mm
= 35.7 mm

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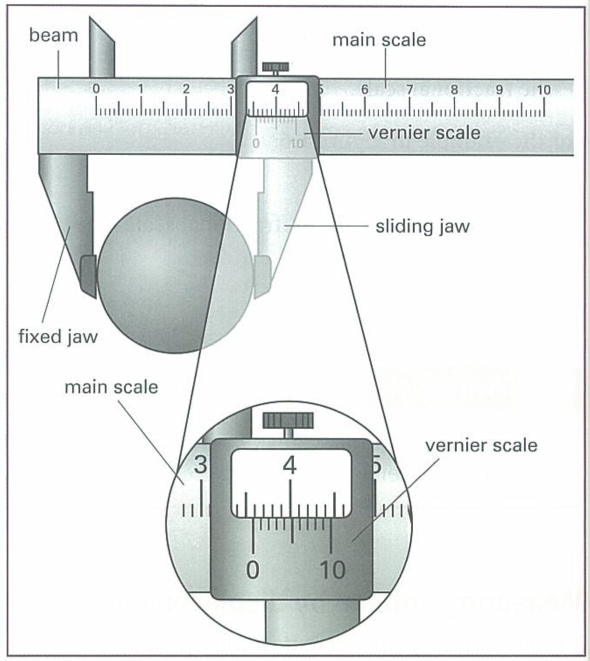

Figure 1.5 Using vernier callipers.

Micrometer screw gauge

Again, this has two scales. The main scale is on the shaft, and the fractional scale is on the rotating barrel. The fractional scale has 50 divisions, so that one complete turn represents 0.50 mm (Figure **1.6**).

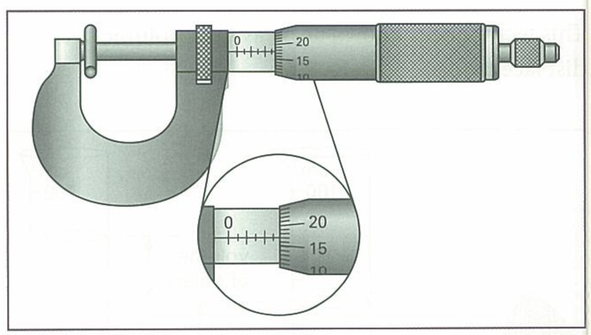

Figure 1.6 Using a micrometer screw gauge.

The method is as follows:

- Turn the barrel until the jaws just tighten on the object. Using the friction clutch ensures just the right pressure.

E

- Read the main scale to the nearest 0.5 mm.
- Read the additional fraction of a millimetre from the fractional scale.

For the example in Figure **1.6**:

thickness of rod
= main scale reading + fractional scale reading
= 2.5 mm + 0.17 mm
= 2.67 mm

Activity 1.1 Precise measurements

Practise reading the scales of vernier callipers and micrometer screw gauges.

Measuring volume by displacement

It is not just instruments that improve our measurements. Techniques also can be devised to help. Here is a simple example, to measure the volume of an irregularly shaped object:

- Select a measuring cylinder that is somewhat (three or four times) larger than the object. Partially fill it with water (Figure **1.7**), enough to cover the object. Note the volume of the water.
- Immerse the object in the water. The level of water in the cylinder will increase. The increase in its volume is equal to the volume of the object.

This technique is known as measuring volume by displacement.

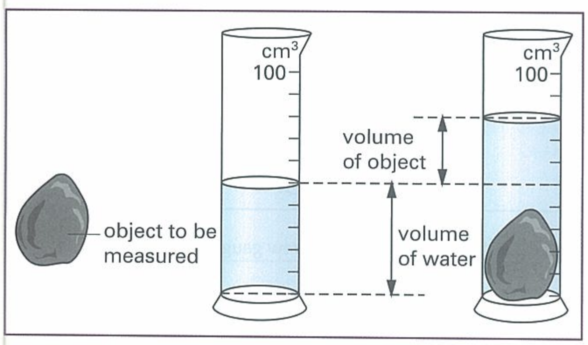

Figure 1.7 Measuring volume by displacement.

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QUESTIONS

3 State the measurements shown in Figure **1.8** on the scale of

a the vernier callipers

b the micrometer screw gauge.

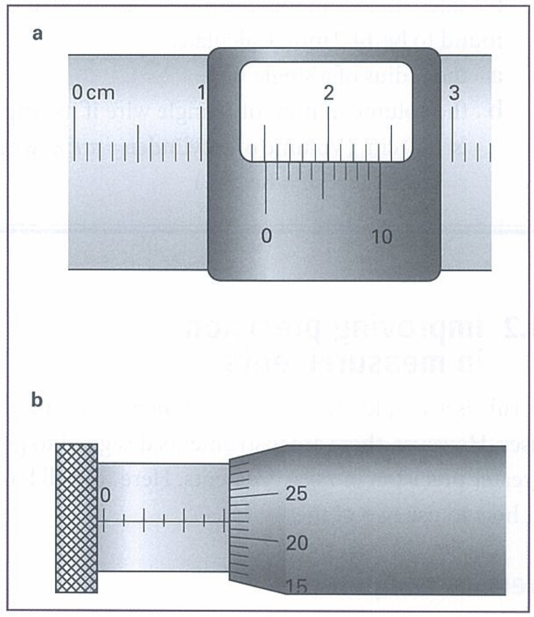

Figure 1.8 For Question **3**.

4 Figure **1.9** shows how the volume of a piece of wood (which floats in water) can be measured. Write a brief paragraph to describe the procedure. State the volume of the wood.

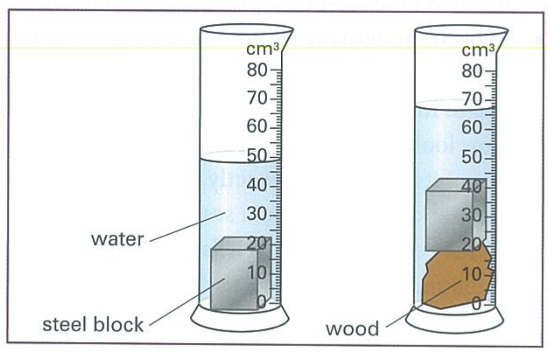

Figure 1.9 For Question **4**.

1.3 Density

Our eyes can deceive us. When we look at an object, we can judge its volume. However, we can only guess its mass. We may guess incorrectly, because we misjudge the density. You may offer to carry someone's bag, only to discover that it contains heavy books. A large box of chocolates may have a mass of only 200 g, a great disappointment!

The **mass** of an object is the amount of matter it is made of. Mass is measured in kilograms. But **density** is a property of a material. It tells us how concentrated its mass is. (There is more about the meaning of **mass** and how it differs from **weight** in Chapter 3.)

In everyday speech, we might say that lead is heavier than wood. We mean that, given equal volumes of lead and wood, the lead is heavier. In scientific terms, the density of lead is greater than the density of wood. So we define density as follows:

$$\text{density} = \frac{\text{mass}}{\text{volume}} \qquad D = \frac{M}{V}$$

The SI unit of density is kg/m^3 (kilograms per cubic metre). You may come across other units, as shown in Table 1.2. A useful value to remember is the density of water (Table 1.3):

density of water = $1000\,kg/m^3$

Unit of mass	Unit of volume	Unit of density	Density of water
kilogram, kg	cubic metre, m^3	kilograms per cubic metre	$1000\,kg/m^3$
kilogram, kg	litre, l	kilograms per litre	1.0 kg/litre
kilogram, kg	cubic decimetre, dm^3	kilograms per cubic decimetre	$1.0\,kg/dm^3$
gram, g	cubic centimetre, cm^3	grams per cubic centimetre	$1.0\,g/cm^3$

Table 1.2 Units of density.

	Material	Density / kg/m^3
gases	air	1.29
	hydrogen	0.09
	helium	0.18
	carbon dioxide	1.98
liquids	water	1 000
	alcohol (ethanol)	790
	mercury	13 600

	Material	Density / kg/m^3
solids	ice	920
	wood	400–1 200
	polythene	910–970
	glass	2 500–4 200
	steel	7 500–8 100
	lead	11 340
	silver	10 500
	gold	19 300

Table 1.3 Densities of some substances. For gases, these are given at a temperature of 0 °C and a pressure of 1.0×10^5 Pa.

Values of density

Some values of density are shown in Table **1.3**. Here are some points to note:

- Gases have much lower densities than solids or liquids.
- Density is the key to floating. Ice is less dense than water. This explains why icebergs float in the sea, rather than sinking to the bottom.
- Many materials have a range of densities. Some types of wood, for example, are less dense than water and will float. Others (such as mahogany) are more dense and sink. The density depends on the composition.
- Gold is denser than silver. Pure gold is a soft metal, so jewellers add silver to make it harder. The amount of silver added can be judged by measuring the density.
- It is useful to remember that the density of water is $1000\,kg/m^3$, $1.0\,g/cm^3$ or $1\,kg/litre$.

Calculating density

To calculate the density of a material, we need to know the mass and volume of a sample of the material.

Worked example 1

A sample of ethanol has a volume of $240\,cm^3$. Its mass is found to be $190.0\,g$. What is the density of ethanol?

Step 1: Write down what you know and what you want to know.

mass $M = 190.0\,g$
volume $V = 240\,cm^3$
density $D = ?$

Step 2: Write down the equation for density, substitute values and calculate D.

$$D = \frac{M}{V}$$
$$= \frac{190}{240}$$
$$= 0.79\,g/cm^3$$

Measuring density

The easiest way to determine the density of a substance is to find the mass and volume of a sample of the substance.

For a solid with a regular shape, find its volume by measurement (see page 4). Find its mass using a balance. Then calculate the density.

Figure **1.10** shows one way to find the density of a liquid. Place a measuring cylinder on a balance. Set the balance to zero. Now pour liquid into the cylinder. Read the volume from the scale on the cylinder. The balance shows the mass.

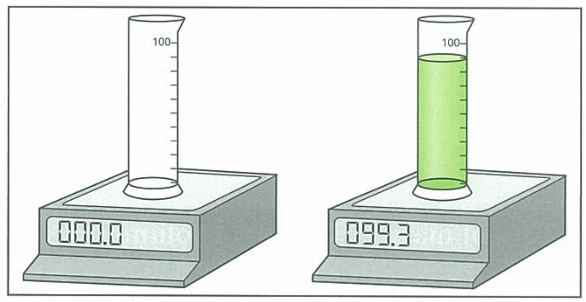

Figure 1.10 Measuring the density of a liquid.

Activity 1.2 Measuring density

Make measurements to find the densities of some blocks of different materials.

QUESTIONS

5 Calculate the density of mercury if $500\,cm^3$ has a mass of $6.60\,kg$. Give your answer in g/cm^3.

6 A steel block has mass $40\,g$. It is in the form of a cube. Each edge of the cube is $1.74\,cm$ long. Calculate the density of the steel.

E 7 A student measures the density of a piece of steel. She uses the method of displacement to find its volume. Figure **1.11** shows her measurements. Calculate the volume of the steel and its density.

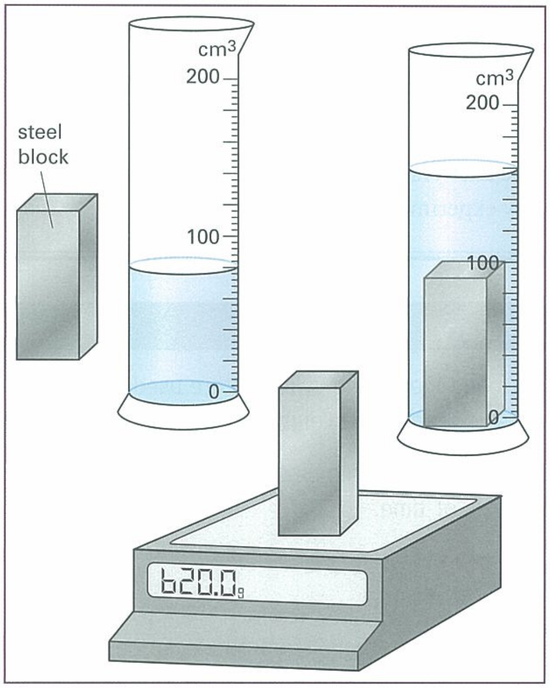

Figure 1.11 For Question 7.

1.4 Measuring time

The athletics coach in Figure **1.12** is using her stopwatch to time a sprinter. For a sprinter, a fraction of a second (perhaps just 0.01 s) can make all the difference between winning and coming second or third. It is different in a marathon, where the race lasts for more than two hours and the runners are timed to the nearest second.

Figure 1.12 The female athletics coach uses a stopwatch to time a sprinter, who can then learn whether she has improved.

In the lab, you might need to record the temperature of a container of water every minute, or find the time for which an electric current is flowing. For measurements like these, stopclocks and stopwatches can be used.

When studying motion, you may need to measure the time taken for a rapidly moving object to move between two points. In this case, you might use a device called a light gate connected to an electronic timer. This is similar to the way in which runners are timed in major athletics events. An electronic timer starts when the marshal's gun is fired, and stops as the runner crosses the finishing line.

There is more about how to use electronic timing instruments in Chapter **2**.

E Measuring short intervals of time

The time for one swing of a pendulum (from left to right and back again) is called its **period**. A single period is usually too short a time to measure accurately. However, because a pendulum swings at a steady rate, you can use a stopwatch to measure the time for a large number of swings (perhaps 20 or 50), and calculate the average time per swing. Any inaccuracy in the time at which the stopwatch is started and stopped will be much less significant if you measure the total time for a large number of swings.

E

Activity 1.3 The period of a pendulum

Figure **1.13** shows a typical lab pendulum. Devise a means of testing Galileo's idea that the period of a pendulum does not depend on the size of its swing.

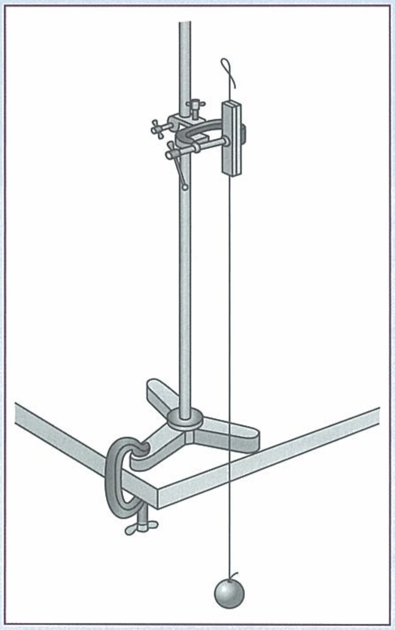

Figure 1.13 A simple pendulum.

E

QUESTIONS

8 Many television sets show 25 images, called 'frames', each second. What is the time interval between one frame and the next?

9 A pendulum is timed, first for 20 swings and then for 50 swings:

time for 20 swings = 17.4 s
time for 50 swings = 43.2 s

Calculate the average time per swing in each case. The answers are slightly different. Can you suggest any experimental reasons for this?

Summary

Rules and measuring cylinders are used to measure length and volume.

Clocks and electronic timers are used to measure intervals of time.

$$\text{Density} = \frac{\text{mass}}{\text{volume}}$$

E

Measurements of small quantities can be improved using special instruments (for example, vernier callipers and micrometer screw gauge) or by making multiple measurements.

End-of-chapter questions

1.1 An ice cube has the dimensions shown in Figure **1.14**. Its mass is 340 g. Calculate:

a its volume [3]

b its density. [3]

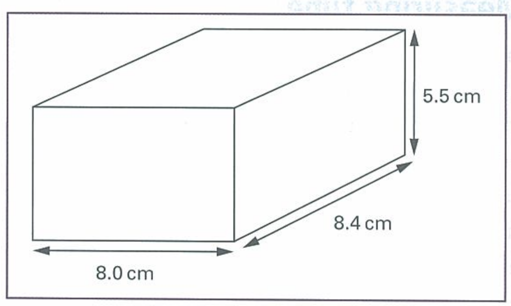

Figure 1.14 A block of ice – for Question **1.1**.

1.2 A student is collecting water as it runs into a measuring cylinder. She uses a clock to measure the time interval between measurements. Figure **1.15** shows the level of water in the cylinder at two times, together with the clock at these times. Calculate:

a the volume of water collected between these two times [2]

b the time interval. [2]

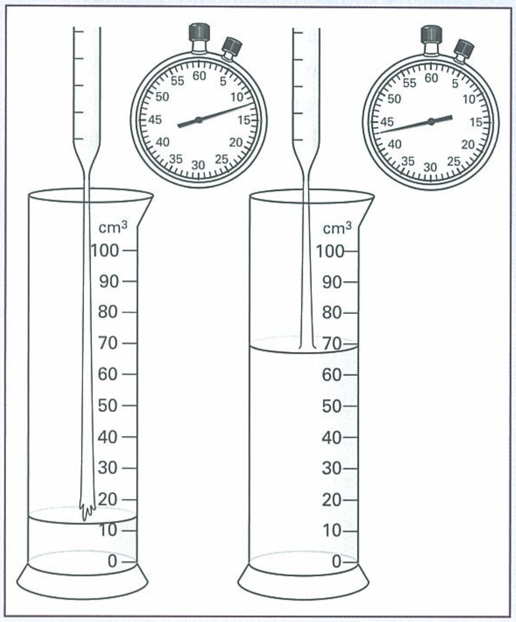

Figure 1.15 For Question **1.2**.

1.3 A student is measuring the density of a liquid. He places a measuring cylinder on a balance and records its mass. He then pours liquid into the cylinder and records the new reading on the balance. He also records the volume of the liquid.

Mass of empty cylinder = 147 g
Mass of cylinder + liquid = 203 g
Volume of liquid = 59 cm^3

Using the results shown above, calculate the density of the liquid. [5]

1.4 The inside of a sports hall measures 80 m long by 40 m wide by 15 m high. The air in it has a density of 1.3 kg/m^3 when it is cool.

a Calculate the volume of the air in the sports hall, in m^3. [3]

b Calculate the mass of the air. State the equation you are using. [3]

E

1.5 A geologist needs to measure the density of an irregularly shaped pebble.

a Describe how she can find its volume by the method of displacement. [4]

b What other measurement must she make if she is to find its density? [1]

1.6 An IGCSE student thinks it may be possible to identify different rocks (A, B and C) by measuring their densities. She uses an electronic balance to measure the mass of each sample and uses the 'displacement method' to determine the volume of each sample. Figure **1.16** shows her displacement results for sample A.

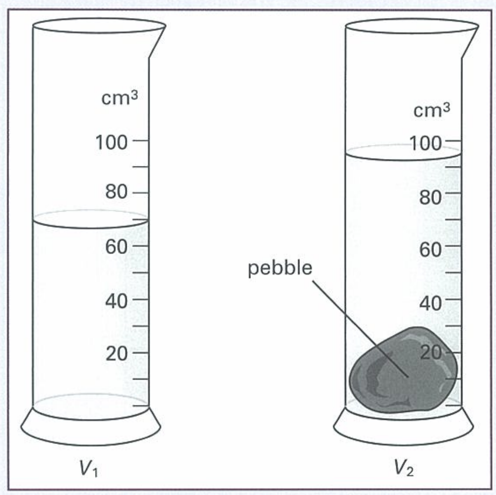

Figure 1.16 For Question **1.6**.

Sample	m / g	...... /......	...... /......	V /......	Density /......
B	144	80	44	......	......
C	166	124	71	......	......

Table 1.4 For Question **1.6.**

a State the volume shown in each measuring cylinder. [2]

b Calculate the volume V of the rock sample A. [2]

c Sample A has a mass of 102 g. Calculate its density. [3]

Table **1.4** shows the student's readings for samples B and C.

d Copy and complete the table by inserting the appropriate column headings and units, and calculating the densities. [12]

2 Describing motion

Core Interpreting distance against time and speed against time graphs
Core Calculating speed and distance
E Extension Calculating acceleration

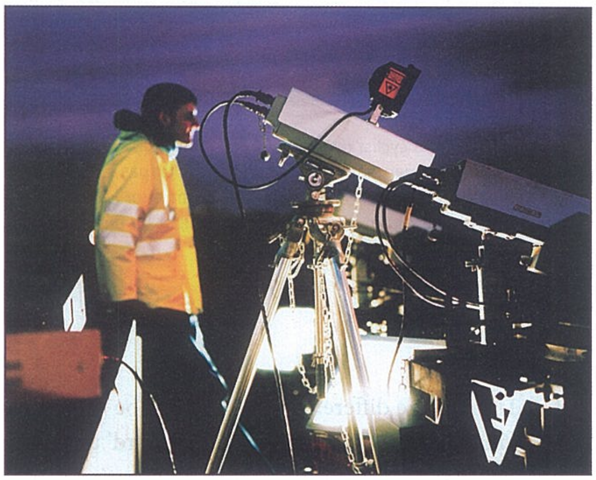

Figure 2.1 Traffic engineers use sophisticated cameras and computers to monitor traffic. Understanding how drivers behave is important not only for safety, but also to improve the flow of traffic.

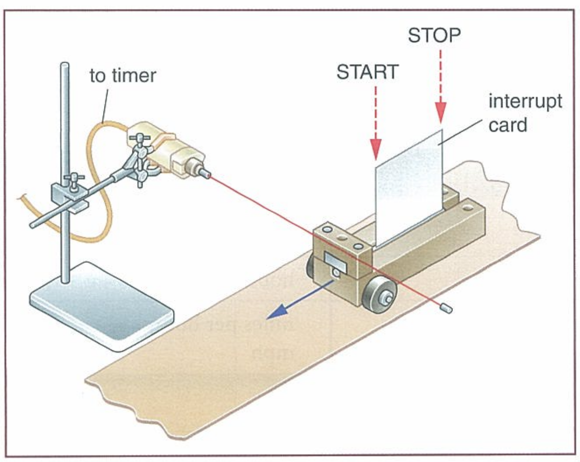

Figure 2.2 Using a light gate to measure the speed of a moving trolley in the laboratory.

Measuring speed

If you travel on a major highway or through a large city, the chances are that someone is watching you (see Figure 2.1). Cameras on the verge and on overhead gantries keep an eye on traffic as it moves along. Some cameras are there to monitor the flow, so that traffic managers can take action when blockages develop, or when accidents occur. Other cameras are equipped with sensors to spot speeding motorists, or those who break the law at traffic lights. In some busy places, traffic police may observe the roads from helicopters.

Drivers should know how fast they are moving – they have a speedometer to tell them their speed at any instant in time. Traffic police can use a radar speed 'gun' to give them an instant readout of another vehicle's speed (such 'guns' use the Doppler effect to measure a car's speed). Alternatively, they may time a car between two fixed points on the road. Knowing the distance between the two points, they can calculate the car's speed.

In the laboratory, the speed of a moving trolley can be measured using a **light gate** connected to an electronic timer (see Figure 2.2). A piece of card, called an **interrupt card**, is mounted on the trolley. The light gate has a beam of (invisible) infrared radiation. As the trolley passes through the gate, the front edge of the card breaks the beam and starts the timer. When the trailing edge passes the gate, the beam is no longer broken and the timer stops. The faster the trolley is moving, the shorter the time for which the beam is broken. Given the length of the card, the trolley's speed can be calculated.

2.1 Understanding speed

In this chapter, we will look at ideas of motion and speed. In Chapter 3, we will look at how physicists came to understand the forces involved in motion, and how to control them to make our everyday travel possible.

Distance, time and speed

As we have seen, there is more than one way to determine the speed of a moving car or aircraft. Several methods rely on making two measurements:

- the **distance travelled** between two points;
- the **time taken** to travel between these two points.

Then we can work out the average speed between the two points:

$$\textbf{average speed} = \frac{\text{distance travelled}}{\text{time taken}}$$

$$\text{or} \quad \textbf{speed} = \frac{\text{distance}}{\text{time}}$$

Figure 2.3 Timing a cyclist over a fixed distance. Using a stopwatch involves making judgements as to when the cyclist passes the starting and finishing lines. This can introduce an error into the measurements. An automatic timing system might be better.

Notice that this equation tells us the vehicle's average speed. We cannot say whether it was travelling at a steady speed, or if its speed was changing. For example, you could use a stopwatch to time a friend cycling over a fixed distance – say, 100 m (see Figure 2.3). Dividing distance by time would tell you their average speed, but they might have been speeding up or slowing down along the way.

Table 2.1 shows the different units that may be used in calculations of speed. SI units are the 'standard' units used in physics (SI is short for *Système International* or International System). In practice, many other units are used. In US space programmes, heights above the Earth are often given in feet, while the spacecraft's speed is given in knots (nautical miles per hour). These awkward units did not prevent them from reaching the Moon!

Quantity	SI unit	Other units	
distance	metre, m	kilometre, km	miles
time	second, s	hour, h	hour, h
speed	metres per second, m/s, $m\,s^{-1}$	kilometres per hour, km/h	miles per hour, mph

Table 2.1 Quantities, symbols and units in measurements of speed.

Worked example 1

A cyclist completed a 1500 m stage of a race in 37.5 s. What was her average speed?

Step 1: Start by writing down what you know, and what you want to know.

distance = 1500 m
time = 37.5 s
speed = ?

Step 2: Now write down the equation.

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

Step 3: Substitute the values of the quantities on the right-hand side.

$$\text{speed} = \frac{1500\,\text{m}}{37.5\,\text{s}}$$

Step 4: Calculate the answer.

speed = 40 m/s

So the cyclist's average speed was 40 m/s.

QUESTIONS

1 If you measured the distance travelled by a snail in inches and the time it took in minutes, what would be the units of its speed?

2 Which of the following could not be a unit of speed?
km/h, s/m, mph, m/s, m s.

3 Table 2.2 shows information about three cars travelling on a motorway.

a Which car is moving fastest?

b Which car is moving slowest?

Vehicle	Distance travelled / km	Time taken / minutes
car A	80	50
car B	72	50
car C	85	50

Table 2.2 For Question **3**.

Rearranging the equation

The equation

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

allows us to calculate speed from measurements of distance and time. We can rearrange the equation to allow us to calculate distance or time.

For example, a railway signalman might know how fast a train is moving, and need to be able to predict where it will have reached after a certain length of time:

$$\text{distance} = \text{speed} \times \text{time}$$

Similarly, the crew of an aircraft might want to know how long it will take for their aircraft to travel between two points on its flight path:

$$\text{time} = \frac{\text{distance}}{\text{speed}}$$

Worked example 2

A spacecraft is orbiting the Earth at a steady speed of 8 km/s (see Figure 2.4). How long will it take to complete a single orbit, a distance of 40 000 km?

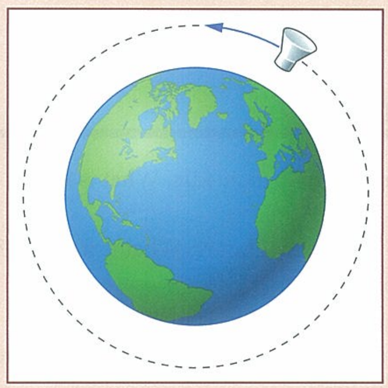

Figure 2.4 A spacecraft orbiting Earth.

Step 1: Start by writing down what you know, and what you want to know.

speed = 8 km/s
distance = 40 000 km
time = ?

Step 2: Choose the appropriate equation, with the unknown quantity 'time' as the subject (on the left-hand side).

$$\text{time} = \frac{\text{distance}}{\text{speed}}$$

Step 3: Substitute values – it can help to include units.

$$\text{time} = \frac{40\,000\,\text{km}}{8\,\text{km/s}}$$

Step 4: Perform the calculation.

$$\text{time} = 5000\,\text{s}$$

This is about 83 minutes. So the spacecraft takes 83 minutes to orbit the Earth once.

Worked example 2 illustrates the importance of keeping an eye on units. Because speed is in km/s and distance is in km, we do not need to convert to m/s and m. We would get the same answer if we did the conversion:

$$\text{time} = \frac{40\,000\,000\,\text{m}}{8000\,\text{m/s}}$$

$$= 5000\,\text{s}$$

QUESTIONS

4 An aircraft travels 1000 m in 4.0 s. What is its speed?

5 A car travels 150 km in 2 hours. What is its speed? (Show the correct units.)

6 An interplanetary spacecraft is moving at 20 000 m/s. How far will it travel in one day? (Give your answer in km.)

7 How long will it take a coach travelling at 90 km/h to travel 300 km along a highway?

2.2 Distance against time graphs

You can describe how something moves in words: 'The coach pulled away from the bus stop. It travelled at a steady speed along the main road, heading out of town. After five minutes, it reached the highway, where it was able to speed up. After ten minutes, it was forced to stop because of congestion.'

We can show the same information in the form of a distance against time graph, as shown in Figure 2.5. This graph is in three sections, corresponding to the three sections of the coach's journey:

A The graph slopes up gently, showing that the coach was travelling at a slow speed.

B The graph becomes steeper. The distance of the coach from its starting point is increasing more rapidly. It is moving faster.

C The graph is flat (horizontal). The distance of the coach from its starting point is not changing. It is stationary.

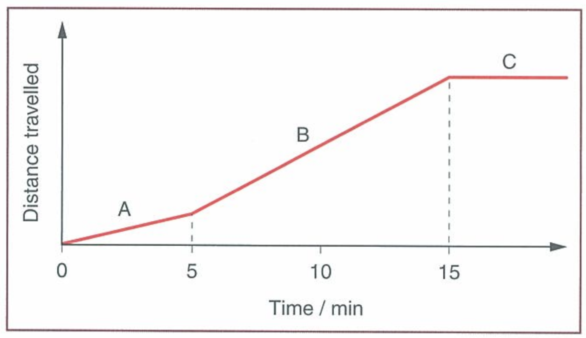

Figure 2.5 A graph to represent the motion of a coach, as described in the text. The slope of the graph tells us about the coach's speed. The steepest section (B) corresponds to the greatest speed. The horizontal section (C) shows that the coach was stationary.

The slope of the distance against time graph tells us how fast the coach was moving. The steeper the graph, the faster it was moving (the greater its speed). When the graph becomes horizontal, its slope is zero. This tells us that the coach's speed was zero. It was not moving.

QUESTION

8 Sketch a distance against time graph to show this: 'The car travelled along the road at a steady speed. It stopped suddenly for a few seconds. Then it continued its journey, at a slower speed than before.'

Activity 2.1 Story graphs

Sketch a distance against time graph. Then ask your partner to write a description of it on a separate sheet of paper.

Choose four graphs and their descriptions. Display them separately and challenge the class to match them up.

Calculating speed

Table 2.3 shows information about a car journey between two cities. The car travelled more slowly at some times than at others. It is easier to see this if we present the information as a graph (see Figure 2.6).

From the graph, you can see that the car travelled slowly at the start of its journey, and also at the end, when it was travelling through the city. The graph is steeper in the middle section, when it was travelling on the open road between the cities.

The graph of Figure 2.6 also shows how to calculate the car's speed. Here, we are looking at the straight section of the graph, where the car's speed was constant. We need to find the value of the gradient (or slope) of the graph, which will tell us the speed:

speed = gradient of distance against time graph

Distance travelled / km	Time taken / h
0	0.0
10	0.5
20	0.8
100	1.8
110	2.3

Table 2.3 Distance and time data for a car journey. This data is represented by the graph in Figure **2.6**

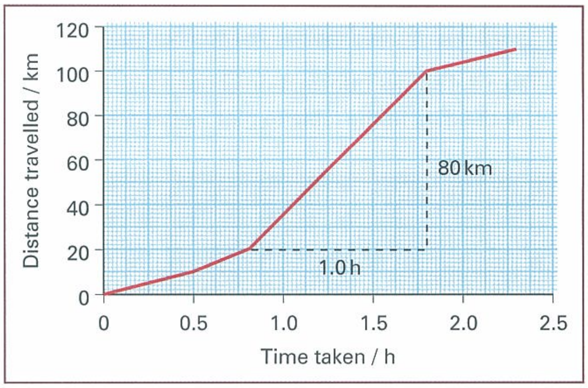

Figure 2.6 Distance against time graph for a car journey, for the data from Table **2.3**.

Worked example 3

These are the steps you take to find the gradient:

Step 1: Identify a straight section of the graph.

Step 2: Draw horizontal and vertical lines to complete a right-angled triangle.

Step 3: Calculate the lengths of the sides of the triangle.

Step 4: Divide the vertical height by the horizontal width of the triangle ('up divided by along').

Here is the calculation for the triangle shown in Figure 2.6:

$$\text{vertical height} = 80\,\text{km}$$
$$\text{horizontal width} = 1.0\,\text{h}$$
$$\text{gradient} = \frac{80\,\text{km}}{1.0\,\text{h}} = 80\,\text{km/h}$$

So the car's speed was 80 km/h for this section of its journey. It helps to include units in this calculation. Then the answer will automatically have the correct units – in this case, km/h.

QUESTION

9 Table 2.4 shows information about a train journey. Use the data in the table to plot a distance against time graph for the train. Find the train's average speed between Beeston and Deeville. Give your answer in km/h.

Station	Distance travelled / km	Time taken / minutes
Ayton	0	0
Beeston	20	30
Seatown	28	45
Deeville	36	60
Eton	44	70

Table 2.4 For Question **9**.

Activity 2.2 Measuring speed

Measure the speed of a cyclist or runner in the school grounds.

Activity 2.3 Measuring speed in the lab

Use lab equipment to measure the speed of a moving trolley or toy car.

Express trains, slow buses

An express train is capable of reaching high speeds, perhaps more than 300 km/h. However, when it sets off on its journey, it may take several minutes to reach this top speed. Then it takes a long time to slow down when it approaches its destination. The famous French TGV trains (Figure 2.7) run on lines that are reserved solely for their operation, so that their high-speed journeys are not disrupted by slower, local trains. It takes time to accelerate (speed up) and decelerate (slow down).

A bus journey is full of accelerations and decelerations (Figure 2.8). The bus accelerates away from the stop. Ideally, the driver hopes to travel at a steady speed until the next stop. A steady speed means that you can sit comfortably in your seat. Then there is a rapid deceleration as the bus slows to a halt. A lot of accelerating and decelerating means that you are likely to be thrown about as the bus changes speed. The gentle acceleration of an express train will barely disturb the drink in your cup. The bus's rapid accelerations and decelerations would make it impossible to avoid spilling the drink.

Figure 2.7 France's high-speed trains, the TGVs (*Trains à Grande Vitesse*), run on dedicated tracks. Their speed has made it possible to travel 600 km from Marseille in the south to Paris in the north, attend a meeting, and return home again within a single day.

Figure 2.8 It can be uncomfortable on a packed bus as it accelerates and decelerates along its journey.

2.3 Understanding acceleration

Some cars, particularly high-performance ones, are advertised according to how rapidly they can accelerate. An advert may claim that a car goes 'from 0 to 60 miles per hour (mph) in 6 s'. This means that, if the car accelerates at a steady rate, it reaches 10 mph after 1 s, 20 mph after 2 s, and so on. We could say that it speeds up by 10 mph every second. In other words, its acceleration is 10 mph per second.

So, we say that an object **accelerates** if its speed increases. Its **acceleration** tells us the rate at which its speed is changing – in other words, the change in speed per unit time.

If an object slows down, its speed is also changing. This is sometimes described as **decelerating**.

Speed against time graphs

Just as we can represent the motion of a moving object by a distance against time graph, we can also represent it by a speed against time graph. (It is easy to get these two types of graph mixed up. Always check out any graph by looking at the axes to see what their labels say.) A speed against time graph shows how the object's speed changes as it moves.

Figure **2.9** shows a speed against time graph for a bus as it follows its route through a busy town. The graph frequently drops to zero because the bus must keep stopping to let people on and off. Then the line slopes up, as the bus accelerates away from the stop. Towards the end of its journey, it manages to move at a steady speed (horizontal graph), as it does not have to stop. Finally, the graph slopes downwards to zero again as the bus pulls into the terminus and stops.

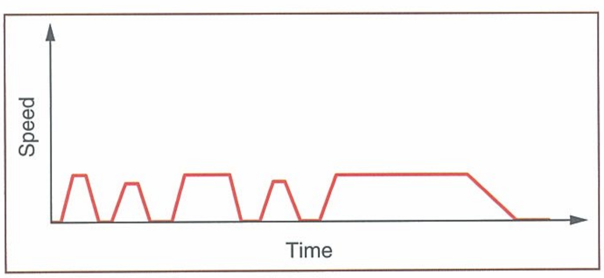

Figure 2.9 A speed against time graph for a bus on a busy route. At first, it has to halt frequently at bus stops. Towards the end of its journey, it maintains a steady speed.

The slope of the speed against time graph tells us about the bus's acceleration:

- The steeper the slope, the greater the acceleration.
- A negative slope means a deceleration (slowing down).
- A horizontal graph (slope = 0) means a constant speed.

Graphs of different shapes

Speed against time graphs can show us a lot about an object's movement. Was it moving at a steady speed, or speeding up, or slowing down? Was it moving at all? The graph shown in Figure **2.10** represents a train journey.

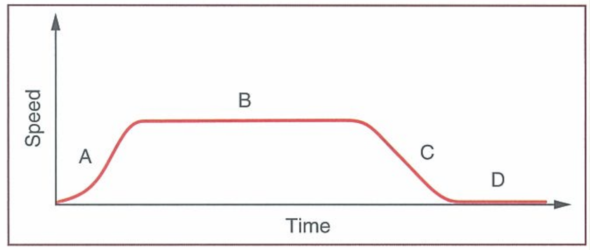

Figure 2.10 An example of a speed against time graph (for a train during part of its journey). This illustrates how such a graph can show acceleration (section A), constant speed (section B), deceleration (section C) and zero speed (section D).

If you study the graph, you will see that it is in four sections. Each section illustrates a different point.

A Sloping upwards – speed increasing – the train was accelerating.

B Horizontal – speed constant – the train was travelling at a steady speed.

C Sloping downwards – speed decreasing – the train was decelerating.

D Horizontal – speed has decreased to zero – the train was stationary.

The fact that the graph lines are curved in sections A and C tells us that the train's acceleration was changing. If its speed had changed at a steady rate, these lines would have been straight.

QUESTIONS

10 A car travels at a steady speed. When the driver sees the red traffic lights ahead, she slows down and comes to a halt. Sketch a speed against time graph for this journey.

11 Look at the speed against time graph in Figure **2.11**. Name the sections that represent:

a steady speed

b speeding up (accelerating)

c being stationary

d slowing down (decelerating).

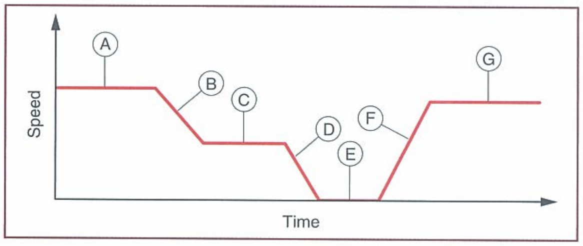

Figure 2.11 For Question **11**.

Finding distance moved

A speed against time graph represents an object's movement. It tells us about how its speed changes. We can use the graph to deduce how far the object moves. To do this, we have to make use of the equation

distance = area under speed against time graph

To understand this equation, consider these two examples.

Example 1

You cycle for 20 s at a constant speed of 10 m/s (see Figure 2.12). The distance you travel is

distance moved = $10\,\text{m/s} \times 20\,\text{s} = 200\,\text{m}$

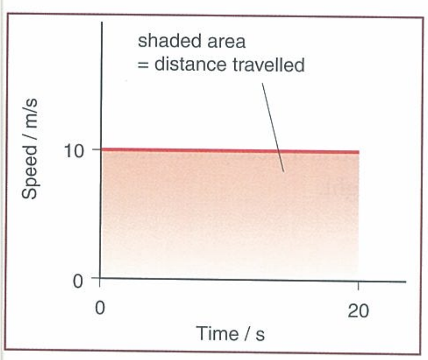

Figure 2.12 Speed against time graph for constant speed. The distance travelled is represented by the shaded area under the graph.

This is the same as the shaded area under the graph. This rectangle is 20 s long and 10 m/s high, so its area is $10\,\text{m/s} \times 20\,\text{s} = 200\,\text{m}$.

Example 2

This is a little more complicated. You set off down a steep ski slope. Your initial speed is 0 m/s. After 10 s you are travelling at 30 m/s (see Figure **2.13**).

To calculate the distance moved, we can use the fact that your average speed is 15 m/s. The distance you travel is

distance moved = $15\,\text{m/s} \times 10\,\text{s} = 150\,\text{m}$

Again, this is represented by the shaded area under the graph. In this case, the shape is a triangle whose height is 30 m/s and whose base is 10 s. Since area of a triangle = $\frac{1}{2} \times$ base $\times$ height, we have

area = $\frac{1}{2} \times 10\,\text{s} \times 30\,\text{m/s} = 150\,\text{m}$.

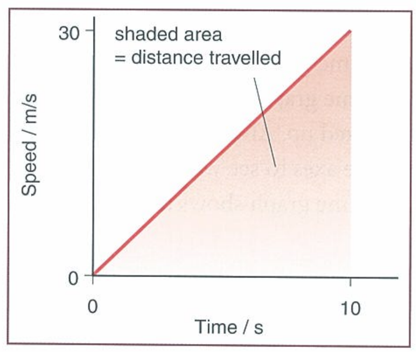

Figure 2.13 Speed against time graph for constant acceleration from rest. Again, the distance travelled is represented by the shaded area under the graph.

Worked example 4

Calculate the distance travelled in 60 s by the train whose motion is represented in Figure **2.14**.

The graph in Figure **2.14** has been shaded to show the area we need to calculate to find the distance moved by the train. This area is in two parts:

- a rectangle (pink) of height 6 m/s and width 60 s

  area = $6\,\text{m/s} \times 60\,\text{s} = 360\,\text{m}$

(this tells us how far the train would have travelled if it had maintained a constant speed of 6 m/s)

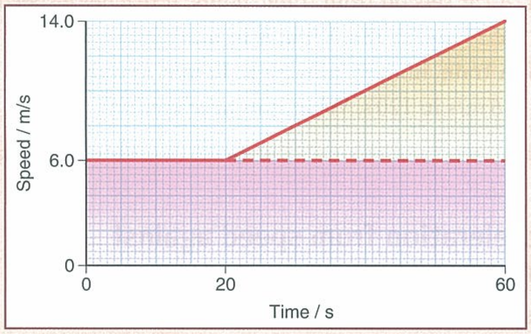

Figure 2.14 Calculating the distance travelled by a train – see Worked example 4. Distance travelled is represented by the area under the graph. To make the calculation possible, this area is divided up into a rectangle and a triangle, as shown.

- a triangle (orange) of base 40 s and height (14 m/s – 6 m/s) = 8 m/s

$$\text{area} = \tfrac{1}{2} \times \text{base} \times \text{height}$$
$$= \tfrac{1}{2} \times 40\,\text{s} \times 8\,\text{m/s}$$
$$= 160\,\text{m}$$

(this tells us the extra distance travelled by the train because it was accelerating).

We can add these two contributions to the area to find the total distance travelled:

$$\text{total distance travelled} = 360\,\text{m} + 160\,\text{m}$$
$$= 520\,\text{m}$$

So, in 60 s, the train travelled 520 m. We can check this result using an alternative approach. The train travelled for 20 s at a steady speed of 6 m/s, and then for 40 s at an average speed of 10 m/s. So

$$\text{distance travelled} = (6\,\text{m/s} \times 20\,\text{s}) + (10\,\text{m/s} \times 40\,\text{s})$$
$$= 120\,\text{m} + 400\,\text{m}$$
$$= 520\,\text{m}$$

QUESTION

12 a Draw a speed against time graph to show the following motion. A car accelerates uniformly from rest for 5 s. Then it travels at a steady speed of 6 m/s for 5 s.

b On your graph, shade the area that shows the distance travelled by the car in 10 s.

c Calculate the distance travelled in this time.

Activity 2.4 Speed against time graphs

Solve some more problems involving speed against time graphs.

E

2.4 Calculating acceleration

An express train may take 300 s to reach a speed of 300 km/h. Its speed has increased by 1 km/h each second, and so we say that its acceleration is 1 km/h per second.

These are not very convenient units, although they may help to make it clear what is happening when we talk about acceleration. To calculate an object's acceleration, we need to know two things:

- its change in speed (how much it speeds up)
- the time taken (how long it takes to speed up).

Then the acceleration of the object is given by

$$\text{acceleration} = \frac{\text{change in speed}}{\text{time taken}}$$

Worked example 5

An aircraft accelerates from 100 m/s to 300 m/s in 100 s. What is its acceleration?

Step 1: Start by writing down what you know, and what you want to know.

$$\text{initial speed} = 100\,\text{m/s}$$
$$\text{final speed} = 300\,\text{m/s}$$
$$\text{time} = 100\,\text{s}$$
$$\text{acceleration} = ?$$

Step 2: Now calculate the change in speed.

$$\text{change in speed} = 300\,\text{m/s} - 100\,\text{m/s}$$
$$= 200\,\text{m/s}$$

Step 3: Substitute into the equation.

$$\text{acceleration} = \frac{\text{change in speed}}{\text{time taken}}$$
$$= \frac{200\,\text{m/s}}{100\,\text{s}} = 2\,\text{m/s}^2$$

E

Units of acceleration

In Worked example 5, the units of acceleration are given as m/s^2 (metres per second squared). These are the standard units of acceleration. The calculation shows that the aircraft's speed increased by 2 m/s every second, or 2 metres per second per second. It is simplest to write this as $2\,m/s^2$, but you may prefer to think of it as 2 m/s per second, as this emphasises the meaning of acceleration.

Other units for acceleration are possible. Earlier we saw examples of acceleration in mph per second and km/h per second, but these are unconventional. It is usually best to work in m/s^2.

QUESTIONS

13 Which of the following could **not** be a unit of acceleration?
km/s^2, mph/s, km/s, m/s^2

E

14 A car sets off from traffic lights. It reaches a speed of 27 m/s in 18 s. What is its acceleration?

15 A train, initially moving at 12 m/s, speeds up to 36 m/s in 120 s. What is its acceleration?

Acceleration from speed against time graphs

A speed against time graph with a steep slope shows that the speed is changing rapidly – the acceleration is greater. It follows that we can find the acceleration of an object by calculating the gradient of its speed against time graph:

acceleration = gradient of speed against time graph

If the speed against time graph is curved (rather than a straight line), the acceleration is changing.

Worked example 6

A train travels slowly as it climbs up a long hill. Then it speeds up as it travels down the other side. Table 2.5 shows how its speed changes. Draw a speed against time graph to show this data. Use the graph to calculate the train's acceleration during the second half of its journey.

Before starting to draw the graph, it is worth looking at the data in the table. The values of speed are given at equal intervals of time (every 10 s). The speed is constant at first (6.0 m/s). Then it increases in equal steps (8.0, 10.0, and so on). In fact, we can see that the speed increases by 2.0 m/s every 10 s. This is enough to tell us that the train's acceleration is $0.2\,m/s^2$. However, we will follow through the detailed calculation to illustrate how to work out acceleration from a graph.

Step 1: Figure **2.15** shows the speed against time graph drawn using the data in the table.

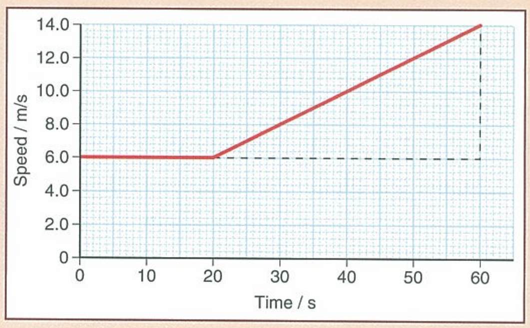

Figure 2.15 Speed against time graph for a train, based on the data in Table **2.5**. The triangle is used to calculate the slope of the second section of the graph. This tells us the train's acceleration.

Speed / m/s	6.0	6.0	6.0	8.0	10.0	12.0	14.0
Time / s	0	10	20	30	40	50	60

Table 2.5 Speed against time data for a train.

E

You can see that it falls into two parts.

- the initial horizontal section shows that the train's speed was constant (zero acceleration)
- the sloping section shows that the train was then accelerating.

Step 2: The triangle shows how to calculate the slope of the graph. This gives us the acceleration.

$$\text{acceleration} = \frac{14.0\,\text{m/s} - 6.0\,\text{m/s}}{60\,\text{s} - 20\,\text{s}}$$

$$= \frac{8.0\,\text{m/s}}{40\,\text{s}}$$

$$= 0.2\,\text{m/s}^2$$

So, as we expected, the train's acceleration down the hill is $0.2\,\text{m/s}^2$

QUESTION

16 A car travels for 10 s at a steady speed of 20 m/s along a straight road. The traffic lights ahead change to red, and the car slows down with a constant deceleration, so that it halts after a further 8 s.

a Draw a speed against time graph to represent the car's motion during the 18 s described.

b Use the graph to deduce the car's deceleration as it slows down.

c Use the graph to deduce how far the car travels during the 18 s described.

Activity 2.5 Acceleration problems

Solve some more problems involving acceleration.

Speed and velocity, vectors and scalars

In physics, the words **speed** and **velocity** have different meanings, although they are closely related. **Velocity** is an object's speed in a particular direction.

So, we could say that an aircraft has a speed of 200 m/s but a velocity of 200 m/s due north. We must give the direction of the velocity or the information is incomplete.

E

Velocity is an example of a **vector quantity**. Vectors have both magnitude (size) and direction. Another example of a vector is weight – your weight is a force that acts downwards, towards the centre of the Earth.

Speed is an example of a **scalar quantity**. Scalars only have magnitude. Temperature is an example of another scalar quantity.

There is more about vectors and scalars in Chapter 3.

Summary

We can represent an object's motion using distance against time and speed against time graphs.

$$\text{Speed} = \frac{\text{distance}}{\text{time}}$$

Speed = gradient of distance against time graph

Distance travelled = area under speed against time graph

E

$$\text{Acceleration} = \frac{\text{change in speed}}{\text{time taken}}$$

Acceleration = gradient of speed against time graph

End-of-chapter questions

2.1 A runner travels 400 m in 50 s. What is her average speed? [3]

2.2 Figure 2.16 represents the motion of a bus. It is in two sections, A and B. What can you say about the motion of the bus during these two sections? [2]

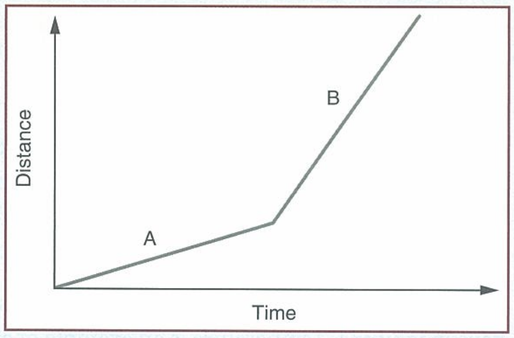

Figure 2.16 For Question 2.2.

2.3 How far will a bus travel in 30 s at a speed of 15 m/s? [3]

2.4 Table 2.6 shows the distance travelled by a car at intervals during a short journey.

a Draw a distance against time graph to represent this data. [4]

b What does the shape of the graph tell you about the car's speed? [2]

Distance / m	0	200	400	600	800
Time / s	0	10	20	30	40

Table 2.6 For Question 2.4.

2.5 Figure 2.17 shows the distance travelled by a car on a rollercoaster ride, at different times along its trip. It travels along the track, and then returns to its starting position. Study the graph and decide which point best fits the following descriptions. In each case, give a reason to explain why you have chosen that point.

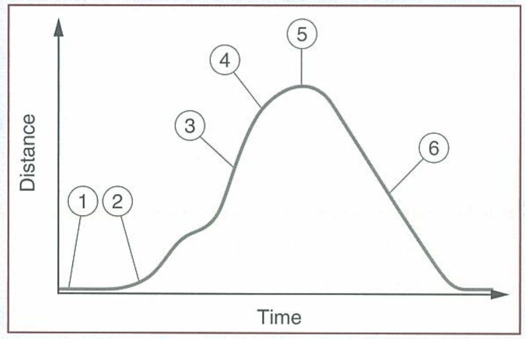

Figure 2.17 Distance against time graph for a rollercoaster car – for Question 2.5.

a The car is stationary. [2]

b The car is travelling its fastest. [2]

c The car is speeding up. [2]

d The car is slowing down. [2]

e The car starts on its return journey. [2]

2.6 Scientists have measured the distance between the Earth and the Moon by reflecting a beam of laser light off the Moon. They measure the time taken for light to travel to the Moon and back.

a What other piece of information is needed to calculate the Earth–Moon distance? [1]

b How would the distance be calculated? [1]

2.7 Table 2.7 shows information about the motion of a number of objects. Copy and complete the table. [4]

Object	Distance travelled	Time taken	Speed
bus	20 km	0.8 h	……
taxi	6 km	……	30 m/s
aircraft	……	5.5 h	900 km/h
snail	3 mm	10 s	……

Table 2.7 For Question 2.7.

2.8 The speed against time graph for part of a train journey is a horizontal straight line. What does this tell you about the train's speed, and about its acceleration? [2]

2.9 Sketch speed against time graphs to represent the following two situations.

a An object starts from rest and moves with constant acceleration. [3]

b An object moves at a steady speed. Then it slows down and stops. [3]

E

2.10 A runner accelerates from rest to 8 m/s in 2 s. What is his acceleration? [3]

2.11 A runner accelerates from rest with an acceleration of 4 m/s^2 for 2.3 s. What will her speed be at the end of this time? [4]

2.12 A car can accelerate at 5.6 m/s^2. Starting from rest, how long will it take to reach a speed of 24 m/s? [3]

2.13 Table 2.8 shows how the speed of a car changed during a section of a journey.

a Draw a speed against time graph to represent this data. [4]

Use your graph to calculate:

b the car's acceleration during the first 30 s of the journey [3]

c the distance travelled by the car during the journey. [5]

E

Speed / m/s	0	9	18	27	27	27
Time / s	0	10	20	30	40	50

Table 2.8 For Question **2.13**.

2.14 Figure 2.18 shows how a car's speed changed as it travelled along.

a In which section(s) was its acceleration zero? [2]

b In which section(s) was its acceleration constant? [2]

c What can you say about its acceleration in the other section(s)? [2]

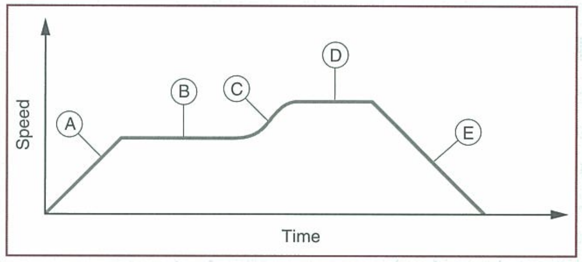

Figure 2.18 A speed against time graph for a car – for Question **2.14**.

2.15 A bus travels 1425 m in 75 s.

a What is its speed? [3]

b What other piece of information do we need in order to state its velocity? [1]

3 Forces and motion

Core Identifying the forces acting on an object
Core Describing how a resultant force changes the motion of an object
E **Extension** Describing how a resultant force can give rise to motion in a circle
Extension Using the relationship between force, mass and acceleration
Core Explaining the difference between mass and weight
E **Extension** Describing the effect of drag on a moving object
Extension Calculating the resultant of two or more vectors

Roller-coaster forces

Some people get a lot of pleasure out of sudden acceleration and deceleration. Many fairground rides involve sudden changes in speed. On a roller-coaster (Figure 3.1), you may speed up as the car runs downhill. Then, suddenly, you veer off to the left – you are accelerated sideways. A sudden braking gives you a large, negative acceleration (a deceleration). You will probably have to be fastened in to your seat to avoid being thrown out of the car by these sudden changes in speed.

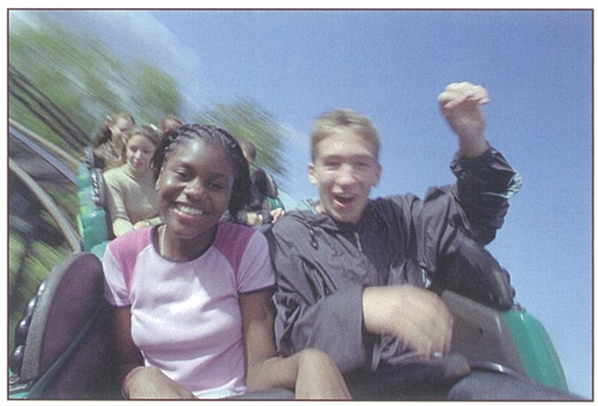

Figure 3.1 A roller-coaster ride involves many rapid changes in speed. These accelerations and decelerations give the ride its thrill. The ride's designers have calculated the accelerations carefully to ensure that the car will not come off its track, and the riders will stay in the car.

What are the forces at work in a roller-coaster? If you are falling downwards, it is gravity that affects you. This gives you an acceleration of about $10\,m/s^2$. We say that the G-force acting on you is 1 (that is, one unit of gravity). When the brakes slam on, the G-force may be greater, perhaps as high as 4. The brakes make use of the force of **friction**.

Changing direction also requires a force. So when you loop the loop or veer to the side, there must be a force acting. This is simply the force of the track, whose curved shape pushes you round. Again, the G-force may reach as high as 4.

Roller-coaster designers have learned how to surprise you with sudden twists and turns. You can be scared or exhilarated. However you feel, you can release the tension by screaming.

3.1 We have lift-off

It takes an enormous force to lift the giant space shuttle off its launch pad, and to propel it into space (Figure 3.2). The booster rockets that supply the initial thrust provide a force of several million newtons. As the spacecraft accelerates upwards, the crew experience the sensation of being pressed firmly back into their seats. That is how they know that their craft is accelerating.

Figure 3.2 The space shuttle accelerating away from its launch pad. The force needed is provided by several rockets. Once each rocket has used all its fuel, it will be jettisoned, to reduce the mass that is being carried up into space.

Forces change motion. One moment, the shuttle is sitting on the ground, stationary. The next moment, it is accelerating upwards, pushed by the force provided by the rockets.

In this chapter, we will look at how forces – pushes and pulls – affect objects as they move. You will be familiar with the idea that forces are measured in **newtons (N)**. To give an idea of the sizes of various forces, here are some examples:

- You lift an apple. The force needed to lift an apple is roughly 1 newton (1 N).
- You jump up in the air. Your leg muscles provide the force needed to do this, about 1000 N.
- You reach the motorway in your high-performance car, and 'put your foot down'. The car accelerates forwards. The engine provides a force of about 5000 N.
- You are crossing the Atlantic in a Boeing 777 jumbo jet. The four engines together provide a thrust of about 500 000 N. In total, that is about half the thrust provided by each of the space shuttle's booster rockets.

Some important forces

Forces appear when two objects interact with each other. Figure **3.3** shows some important forces. Each force is represented by an arrow to show its direction.

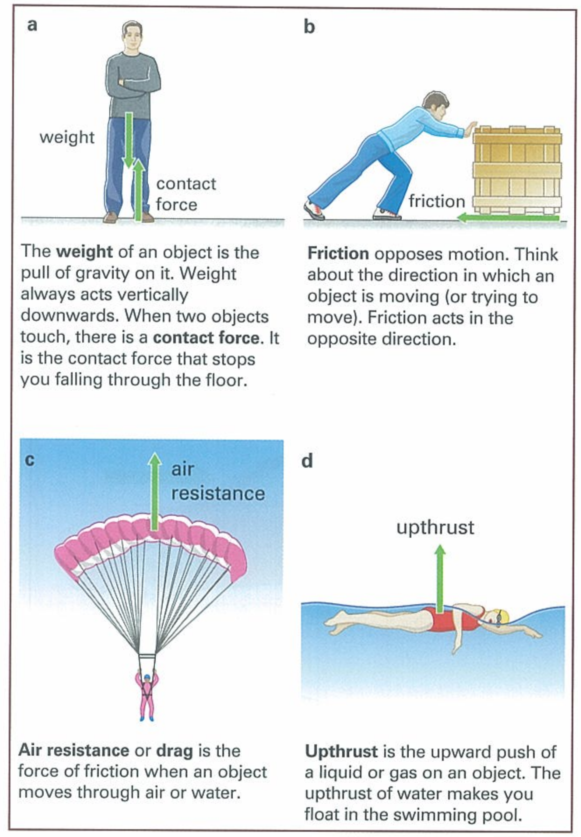

Figure 3.3 Some common forces.

Forces produce acceleration

The car driver in Figure **3.4a** is waiting for the traffic lights to change. When they go green, he moves forwards. The force provided by the engine causes the car to accelerate. In a few seconds, the car is moving quickly along the road. The arrow in the diagram shows the force pushing the car forwards. If the driver wants to get away from the lights more quickly, he can press harder on the accelerator. The forward force is then bigger, and the car's acceleration will be greater.

The driver reaches another junction, where he must stop. He applies the brakes. This provides another force to slow down the car (see Figure **3.4b**). The car is moving forwards, but the force needed to make it decelerate is directed backwards. If the driver wants to stop in a hurry, a bigger force is needed. He must press hard on the brake pedal, and the car's deceleration will be greater.

Finally, the driver wants to turn a corner. He turns the steering wheel. This produces a sideways force on the car (Figure **3.4c**), so that the car changes direction.

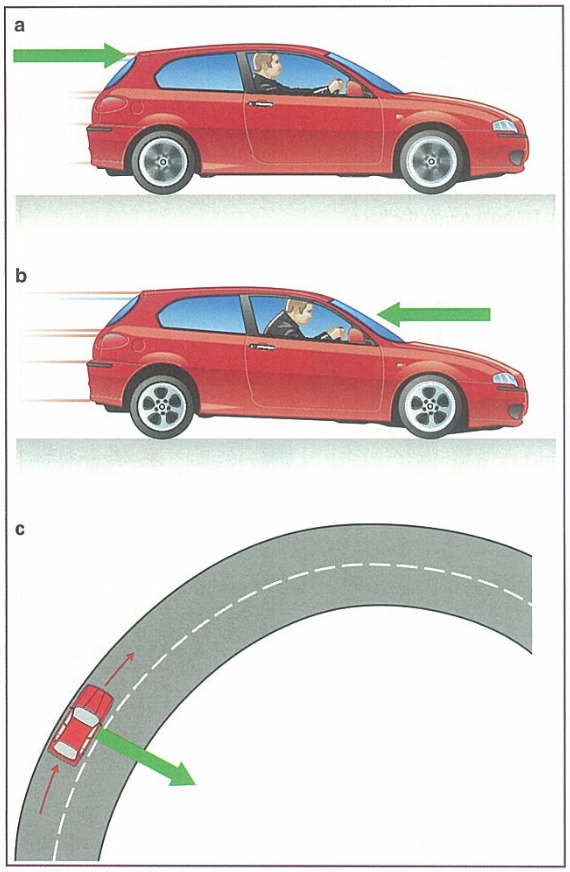

Figure 3.4 A force can be represented by an arrow. **a** The forward force provided by the engine causes the car to accelerate forwards. **b** The backward force provided by the brakes causes the car to decelerate. **c** A sideways force causes the car to change direction.

To summarise, we have seen several things about forces:

- They can be represented by arrows. A force has a direction, shown by the direction of the arrow.
- A force can make an object change speed (accelerate). A forward force makes it speed up, while a backward force makes it slow down.
- A force can change the direction in which an object is moving.

QUESTION

1 Figure **3.5** shows three objects that are moving. A force acts on each object. For each, say how its movement will change.

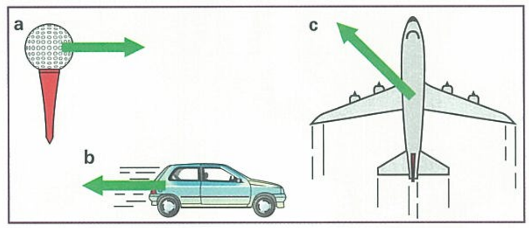

Figure 3.5 Three moving objects – for Question **1**.

Two or more forces

The car shown in Figure **3.6a** is moving rapidly. The engine is providing a force to accelerate it forwards, but there is another force acting, which tends to slow down the car. This is **air resistance**, a form of friction caused when an object moves through the air. (This frictional force is also called **drag**, especially for motion through fluids other than the air.) The air drags on the object, producing a force that acts in the opposite direction to the object's motion. In Figure **3.6a**, these two forces are:

- push of engine = 600 N to the right
- drag of air resistance = 400 N to the left.

We can work out the combined effect of these two forces by subtracting one from the other to give the **resultant force** acting on the car.

> The resultant force is the single force that has the same effect as two or more forces.

So in Figure **3.6a**:

resultant force = 600 N – 400 N
= 200 N to the right

This resultant force will make the car accelerate to the right, but not as much as if there was no air resistance.

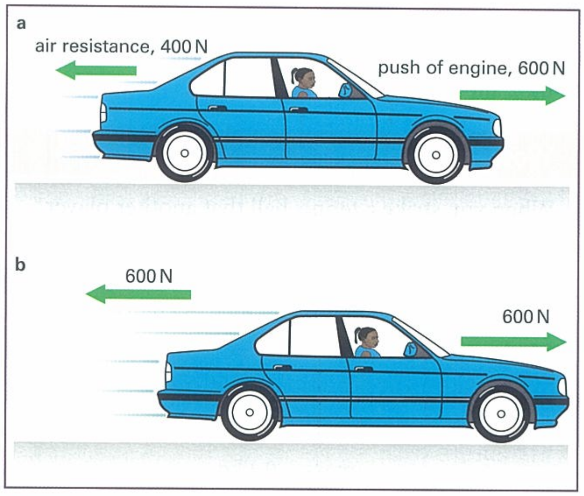

Figure 3.6 A car moves through the air. Air resistance acts in the opposite direction to its motion.

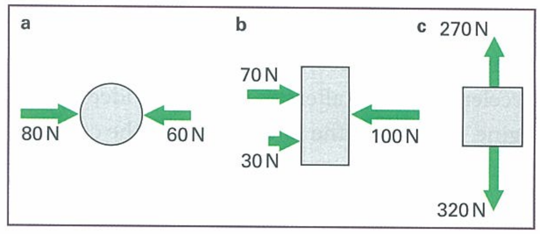

Figure 3.7 For Question **2**.

In Figure **3.6b**, the car is moving even faster, and air resistance is greater. Now the two forces cancel each other out. So in Figure **3.6b**:

resultant force = 600 N – 600 N = 0 N

We say that the forces on the car are **balanced**, and it no longer accelerates.

QUESTION

2 Figure **3.7** shows the forces acting on three objects. For each, say whether the forces are balanced or unbalanced. If the forces are unbalanced, calculate the resultant force and give its direction. Say how the object's motion will change.

Activity 3.1 Balanced forces

Solve some problems involving two or more forces acting on an object.

E

Going round in circles

When a car turns a corner, it changes direction. Any object moving along a circular path is changing direction as it goes. A force is needed to do this. Figure **3.8** shows three objects following curved paths, together with the forces that act to keep them on track.

a The boy is whirling an apple around on the end of a piece of string. The tension in the string pulls on the apple, keeping it moving in a circle.

b An aircraft 'banks' (tilts) to change direction. The lift force on its wings provides the necessary force.

c The Moon is held in its orbit around the Earth by the pull of the Earth's gravity.

For an object following a circular path, the object is acted on by a force at right angles to its velocity.

E

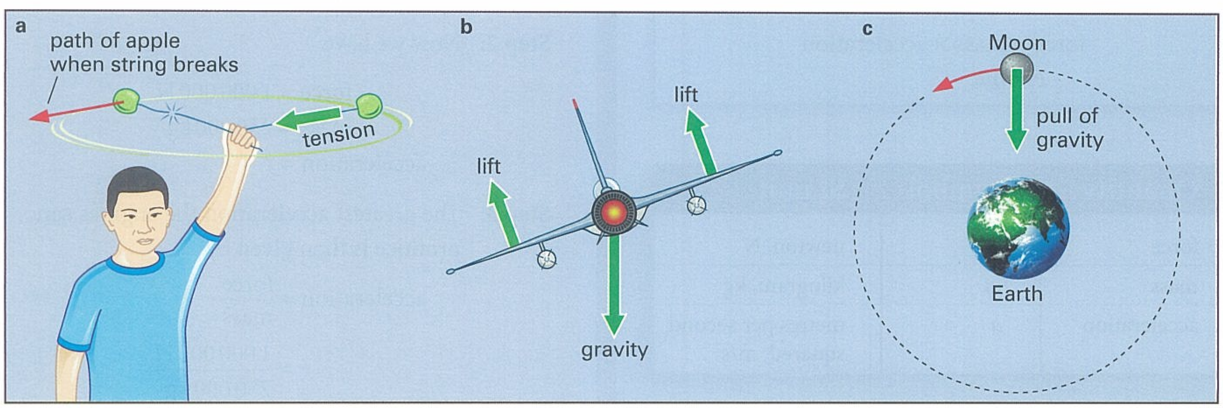

Figure 3.8 Examples of motion along a curved path. In each case, there is a sideways force holding the object in its circular path.

3.2 Force, mass and acceleration

A car driver uses the accelerator pedal to control the car's acceleration. This alters the force provided by the engine. The bigger the force acting on the car, the bigger the acceleration it gives to the car. Doubling the force produces twice the acceleration, three times the force produces three times the acceleration, and so on.

There is another factor that affects the car's acceleration. Suppose the driver fills the boot with a lot of heavy boxes and then collects several children from college. He will notice the difference when he moves away from the traffic lights. The car will not accelerate so readily, because its mass has been increased. Similarly, when he applies the brakes, it will not decelerate as readily as before. The mass of the car affects how easily it can be accelerated or decelerated. Drivers learn to take account of this.

> The greater the mass of an object, the smaller the acceleration it is given by a particular force.

So big (more massive) objects are harder to accelerate than small (less massive) ones. If we double the mass of the object, its acceleration for a given force will be halved. We need double the force to give it the same acceleration.

This tells us what we mean by **mass**. It is the property of an object that resists changes in its motion.

Force calculations

These relationships between force, mass and acceleration can be combined into a single, very useful, equation:

$$\text{force} = \text{mass} \times \text{acceleration}$$
$$F = ma$$

Quantity	Symbol	SI unit
force	F	newton, N
mass	m	kilogram, kg
acceleration	a	metres per second squared, m/s^2

Table 3.1 The three quantities related by the equation force = mass × acceleration.

The quantities involved in this equation, and their units, are summarised in Table **3.1**. Worked examples **1** and **2** show how to use the equation.

Worked example 1

When you strike a tennis ball that another player has hit towards you, you provide a large force to reverse its direction of travel and send it back towards your opponent. You give the ball a large acceleration. What force is needed to give a ball of mass 0.1 kg an acceleration of $500\,m/s^2$?

Step 1: We have

$$\text{mass} = 0.1\,\text{kg}$$
$$\text{acceleration} = 500\,\text{m/s}^2$$
$$\text{force} = ?$$

Step 2: Substituting in the equation to find the force gives

$$\text{force} = \text{mass} \times \text{acceleration}$$
$$= 0.1\,\text{kg} \times 500\,\text{m/s}^2$$
$$= 50\,\text{N}$$

Worked example 2

A Boeing 777 jumbo jet (Figure **3.9**) has four engines, each capable of providing 250 000 N of thrust. The mass of the aircraft is 250 000 kg. What is the greatest acceleration that the aircraft can achieve?

Step 1: The greatest force provided by all four engines working together is 4 × 250 000 N = 1 000 000 N.

Step 2: Now we have

$$\text{force} = 1\,000\,000\,\text{N}$$
$$\text{mass} = 250\,000\,\text{kg}$$
$$\text{acceleration} = ?$$

Step 3: The greatest acceleration the engines can produce is then given by

$$\text{acceleration} = \frac{\text{force}}{\text{mass}}$$
$$= \frac{1\,000\,000\,\text{N}}{250\,000\,\text{kg}}$$
$$= 4.0\,\text{m/s}^2$$

Figure 3.9 A jumbo jet has four engines, each capable of providing a quarter of a million newtons of thrust. When the aircraft lands, the engines are put into 'reverse thrust' mode, so that they provide a decelerating force to bring it to a halt.

QUESTIONS

3 What force is needed to give a car of mass 600 kg an acceleration of 2.5 m/s^2?

4 A stone of mass 0.2 kg falls with an acceleration of 10.0 m/s^2. How big is the force that causes this acceleration?

5 What acceleration is produced by a force of 2000 N acting on a person of mass 80 kg?

6 One way to find the mass of an object is to measure its acceleration when a force acts on it. If a force of 80 N causes a box to accelerate at 0.1 m/s^2, what is the mass of the box?

Activity 3.2 *F*, *m* and *a*

Change the force acting on an object, and see how its acceleration changes.

Change the mass of an object, and see how its acceleration changes.

3.3 Mass, weight and gravity

If you drop an object, it falls to the ground. It is difficult to see how a falling object moves. However, a multi-flash photograph can show the pattern of movement when an object falls.

Figure **3.10** shows a ball falling. There are seven images of the ball, taken at equal intervals of time. The ball falls further in each successive time interval. This shows that its speed is increasing – it is accelerating.

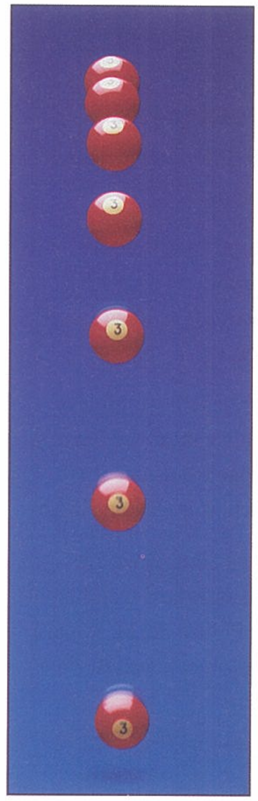

Figure 3.10 The increasing speed of a falling ball is captured in this multi-flash image.

If an object accelerates, there must be a force that is causing it to do so. In this case, the force of **gravity** is pulling the ball downwards. The name given to the force of gravity acting on an object is its **weight**. Because weight is a force, it is measured in newtons (N).

Every object on or near the Earth's surface has weight. This is caused by the attraction of the Earth's gravity. The Earth pulls with a force of 10 N (approximately) on each kilogram of matter, so an object of mass 1 kg has a weight of 10 N:

weight of 1 kg mass = 10 N

Because the Earth pulls with the same force on every kilogram of matter, every object falls with the same acceleration close to the Earth's surface. If you drop a 5 kg ball and a 1 kg ball at the same time, they will reach the ground at the same time.

The acceleration caused by the pull of the Earth's gravity is called the **acceleration of free fall** or the **acceleration due to gravity**, and its value is $10\ m/s^2$ close to the surface of the Earth:

acceleration of free fall = $10\ m/s^2$

Distinguishing mass and weight

It is important to understand the difference between the two quantities, mass and weight.

- The **mass** of an object, measured in kilograms, tells you how much matter it is composed of.
- The **weight** of an object, measured in newtons, is the force of gravity that acts on it.

If you take an object to the Moon, it will weigh less, because the Moon's gravity is weaker than the Earth's. However, its mass will be **unchanged** because it is made of just as much matter as when it was on Earth.

When we weigh an object using a balance, we are comparing its weight with that of standard weights on the other side of the balance (Figure **3.11**). We are making use of the fact that, if two objects weigh the same, their masses will be the same.

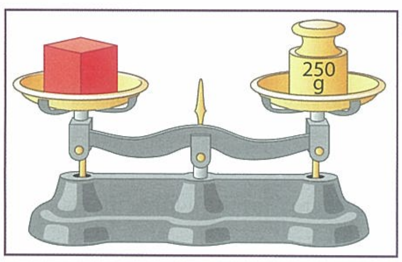

Figure 3.11 When the balance is balanced, we know that the weights on opposite sides are equal, and so the masses must also be equal.

Activity 3.3 Comparing masses

You can compare the masses of two objects by holding them. How good are you at judging mass?

QUESTION

7 A book is weighed on Earth. It is found to have a mass of 1 kg. So its weight on the Earth is 10 N. What can you say about its mass and its weight if you take it:
  - **a** to the Moon, where gravity is weaker than on Earth?
  - **b** to Jupiter, where gravity is stronger?

E

3.4 Falling through the air

The Earth's gravity is equally strong at all points close to the Earth's surface. If you climb to the top of a tall building, your weight will stay the same. We say that there is a **uniform gravitational field** close to the Earth's surface. This means that all objects fall with the same acceleration as the ball shown above in Figure **3.10**, provided there is no other force acting to reduce their acceleration. For many objects, the force of air resistance can affect their acceleration.

Parachutists make use of air resistance. A free-fall parachutist (Figure **3.12**) jumps out of an aircraft and accelerates downwards. Figure **3.13** shows the forces on a parachutist at different points in his fall. At first, air resistance has little effect. However, air resistance increases as he falls, and eventually this force balances his weight. Then the parachutist stops accelerating – he falls at a steady rate known as the **terminal velocity**.

Figure 3.12 Free-fall parachutists, before they open their parachutes. They can reach a terminal velocity of more than 50 m/s.

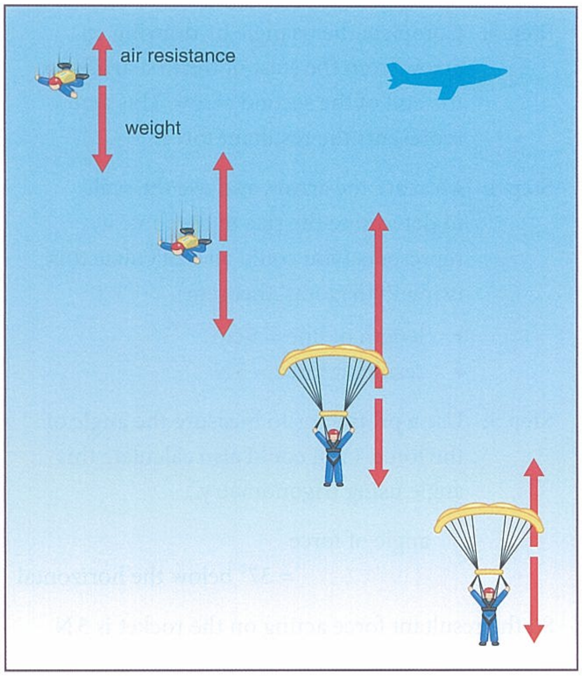

Figure 3.13 The forces on a falling parachutist. Notice that his weight is constant. When air resistance equals weight, the forces are balanced and the parachutist reaches a steady speed. The parachutist is always falling (velocity downwards), although his acceleration is upwards when he opens his parachute.

Opening the parachute greatly increases the area and hence the air resistance. Now there is a much bigger force upwards. The forces on the parachutist are again unbalanced, and he slows down. The idea is to reach a new, slower, terminal velocity of about 10 m/s, at which speed he can safely land. At this point, weight = drag, and so the forces on the parachutist are balanced.

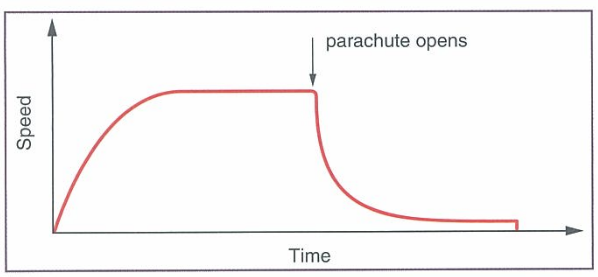

Figure 3.14 A speed against time graph for a falling parachutist.

The graph in Figure **3.14** shows how the parachutist's speed changes during a fall.

- When the graph is horizontal, speed is constant and forces are balanced.
- When the graph is sloping, speed is changing. The parachutist is accelerating or decelerating, and forces are unbalanced.

QUESTION

8 Look at the graph of Figure **3.14**. Find a point where the graph is sloping upwards.
  a Is the parachutist accelerating or decelerating?
  b Which of the two forces acting on the parachutist is greater?
  c Explain the shape of the graph after the parachute has opened.

3.5 More about scalars and vectors

We can represent forces using arrows because a force has a **direction** as well as a **magnitude**. This means that force is a **vector quantity** (see Chapter 2). Table **3.2** lists some scalar and vector quantities.

Scalar quantities	Vector quantities
speed	velocity
mass	force
energy	weight
density	acceleration
temperature	

Table 3.2 Some scalar and vector quantities.

Adding forces

What happens if an object is acted on by two or more forces? Figure **3.15a** shows someone pushing a car. Friction opposes their pushing force. Because the forces are acting in a straight line, it is simple to calculate the resultant force, provided we take into account the directions of the forces:

$$\text{resultant force} = 500\,\text{N} - 350\,\text{N}$$
$$= 150\,\text{N to the right}$$

Note that we must give the direction of the resultant force, as well as its magnitude. The car will accelerate towards the right.

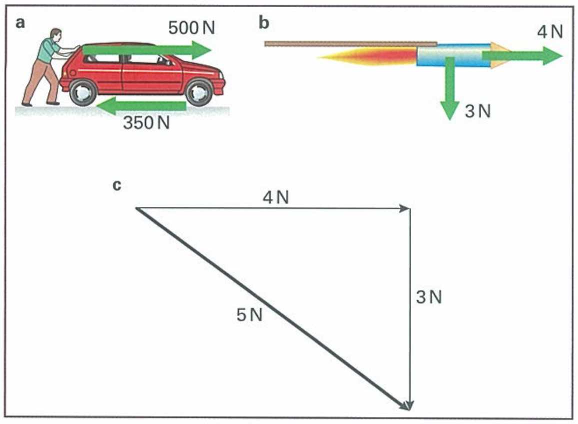

Figure 3.15 Adding forces: **a** two forces in a straight line; **b** two forces in different directions; **c** a vector triangle shows how to add the forces in **b**.

Figure **3.15b** shows a more difficult situation. A firework rocket is acted on by two forces.

- The thrust of its burning fuel pushes it towards the right.
- Its weight acts vertically downwards.

Worked example **3** shows how to find the resultant force by the method of drawing a **vector triangle** (graphical representation of vectors).

Worked example 3

Find the resultant force acting on the rocket shown in Figure **3.15b**. What effect will the resultant force have on the rocket?

Step 1: Look at the diagram. The two forces are 4 N horizontally and 3 N vertically.

Step 2: Draw a scale diagram to represent these forces, as follows (see Figure **3.15c**). In Figure **3.15c** we are using a scale of 1 cm to represent 1 N.

- Draw a horizontal arrow, 4 cm long, to represent the 4 N force. Mark it with an arrow to show its direction.
- Using the end of this arrow as the start of the next arrow, draw a vertical arrow, 3 cm long, to represent the 3 N force.

Step 3: Complete the triangle by drawing an arrow from the start of the first arrow to the end of the second arrow. This arrow represents the resultant force.

Step 4: Measure the arrow, and use the scale to determine the size of the force it represents (you could also calculate this using Pythagoras' theorem).

- length of line = 5 cm
- resultant force = 5 N

Step 5: Use a protractor to measure the angle of the force. (You could also calculate this angle using trigonometry.)

angle of force
= 37° below the horizontal

So the resultant force acting on the rocket is 5 N acting at 37° below the horizontal. The rocket will be given an acceleration in this direction.

Rules for vector addition

You can add two or more forces by the following method – simply keep adding arrows end-to-end:

- Draw arrows end-to-end, so that the end of one is the start of the next.
- Choose a scale that gives a large triangle.
- Join the start of the first arrow to the end of the last arrow to find the resultant.

Other vector quantities (for example, two velocities) can be added in this way. Imagine that you set out to swim across a fast-flowing river. You swim towards the opposite bank, but the river's velocity carries you downstream. Your resultant velocity will be at an angle to the bank.

Airline pilots must understand vector addition. Aircraft fly at high speed, but the air they are moving through is also moving fast. If they are to fly in a straight line towards their destination, the pilot must take account of the wind speed.

E

QUESTION

9 An aircraft can fly at a top speed of 600 km/h.

a What will its speed be if it flies into a head-wind of 100 km/h? (A head-wind blows in the opposite direction to the aircraft.)

b The pilot directs the aircraft to fly due north at 600 km/h. A side-wind blows at 100 km/h towards the east. What will be the aircraft's resultant velocity? (Give both its speed and direction.)

Summary

A force can cause a body to accelerate, decelerate, or change direction.

The resultant force on a body is the single force that has the same effect as all of the forces acting on it.

When combining forces, we must take account of their directions.

The force of gravity on an object is its weight.

E Force, mass and acceleration are related by

force = mass × acceleration

$F = ma$

An object following a circular path is acted on by a force at right angles to its velocity.

End-of-chapter questions

3.1 What are the units of **a** mass, **b** force and **c** acceleration? [3]

3.2 a Why is it sensible on diagrams to represent a force by an arrow? [1]

b Why should mass not be represented by an arrow? [1]

3.3 Which will produce a bigger acceleration: a force of 10 N acting on a mass of 5 kg, or a force of 5 N acting on a mass of 10 kg? [2]

3.4 An astronaut is weighed before he sets off to the Moon. He has a mass of 80 kg.

a What will his weight be on Earth? [3]

b When he arrives on the Moon, will his mass be more, less, or the same? [1]

c Will his weight be more, less, or the same? [1]

3.5 Figure **3.16** shows the forces acting on a lorry as it travels along a flat road.

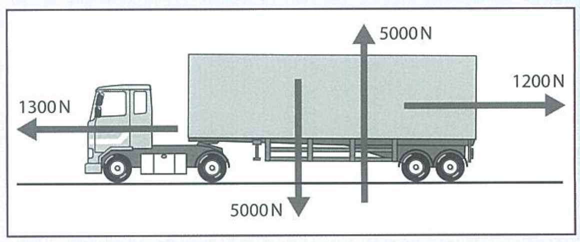

Figure 3.16 For Question **3.5**.

a Two of the forces have effects that cancel each other out. Which two? Explain your answer. [2]

b What is the resultant force acting on the lorry? Give its magnitude and direction. [3]

c What effect will this resultant force have on the speed at which the lorry is travelling? [1]

E **3.6** What force is needed to give a mass of 20 kg an acceleration of 5 m/s^2? [3]

3.7 A train of mass 800 000 kg is slowing down. What acceleration is produced if the braking force is 1 400 000 N? [3]

3.8 A car speeds up from 12 m/s to 20 m/s in 6.4 s. If its mass is 1200 kg, what force must its engine provide? [6]

3.9 The gravitational field of the Moon is weaker than that of the Earth. It pulls on each kilogram of mass with a force of 1.6 N. What will be the weight of a 50 kg mass on the Moon? [3]

E **3.10** Figure 3.17 shows a diver underwater.

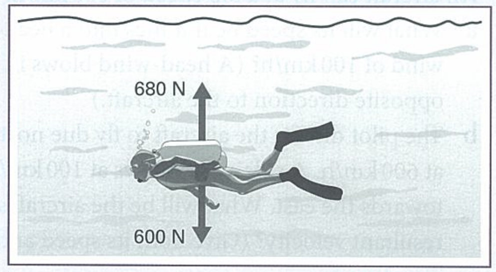

Figure 3.17 For Question **3.10.**

a Calculate the resultant force on the diver. [3]

b Explain how his motion will change. [1]

4 Turning effects of forces

Core Describing the turning effect of a force
Core Stating the conditions for equilibrium of an object
E Extension Calculating moments, forces and distances
Core Understanding centre of mass and stability

Keeping upright

Human beings are inherently unstable. We are tall and thin and walk upright. Our feet are not rooted into the ground. So you might expect us to keep toppling over. Human children learn to stand and walk at the age of about 12 months. It takes a lot of practice to get it right. We have to learn to coordinate our muscles so that our legs, body and arms move correctly. There is a special organ in each of our ears (the semicircular canals) that keeps us aware of whether we are vertical or tilting. Months of practice and many falls are needed to develop the skill of walking.

We have the same experience later in life if we learn to ride a bicycle (Figure 4.1). A bicycle is even more unstable than a person. If you ride a bicycle, you are constantly adjusting your position to maintain your stability and to remain upright. If the bicycle tilts slightly to the left, you automatically lean slightly to the right to provide a force that tips it back again. You make these adjustments unconsciously. You know intuitively that if you let the bicycle tilt too far, you will not be able to recover the situation, and you will end up sprawling on the ground.

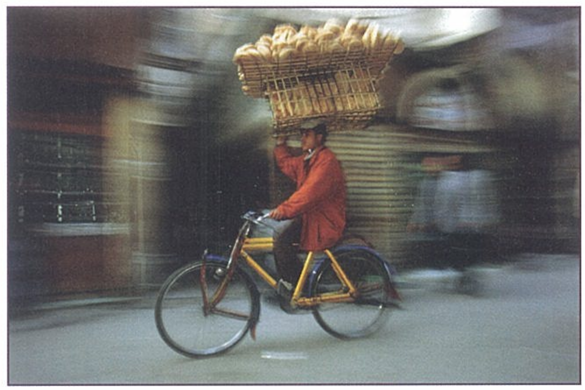

Figure 4.1 This cyclist must balance with great care because the load he is carrying on his head makes him even more unstable.

4.1 The moment of a force

Figure 4.2 shows a boy who is trying to open a heavy door by pushing on it. He must make the **turning effect** of his force as big as possible. How should he push?

First of all, look for the **pivot** – the fixed point about which the door will turn. This is the hinge of the door. To open the door, push with as big a force as possible, and as far as possible from the pivot – at the other edge of the door. (That's why the door handle is fitted there.)

Figure 4.2 Opening a door – how can the boy have a big turning effect?

To have a big turning effect, the person must push hard at **right angles** to the door. Pushing at a different angle gives a smaller turning effect.

The quantity that tells us the turning effect of a force about a pivot is its **moment**.

- The moment of a force is bigger if the force is bigger.
- The moment of a force is bigger if it acts further from the pivot.
- The moment of a force is greatest if it acts at 90° to the object it acts on.

Making use of turning effects

Figure **4.3** shows how understanding moments can be useful.

- Using a crowbar to lift a heavy paving slab – pull near the end of the bar, and at 90°, to have the biggest possible turning effect.
- Lifting a load in a wheelbarrow – the long handles help to increase the moment of the lifting force.

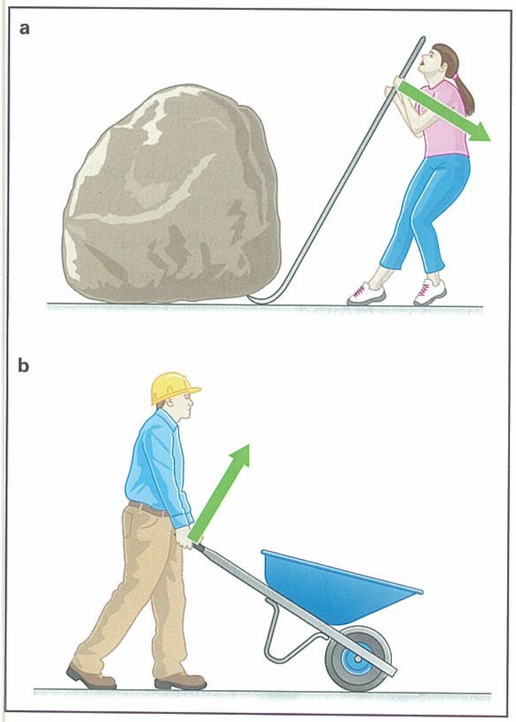

Figure 4.3 Understanding moments can help in some difficult tasks.

Balancing a beam

Figure **4.4** shows a small child sitting on the left-hand end of a see-saw. Her weight causes the see-saw to tip down on the left. Her father presses down on the other end. If he can press with a force greater than her weight, the see-saw will tip to the right and she will come up in the air.

Now, suppose the father presses down closer to the pivot. He will have to press with a greater force if the turning effect of his force is to overcome the turning effect of his daughter's weight. If he presses at half the distance from the pivot, he will need to press with twice the force to balance her weight.

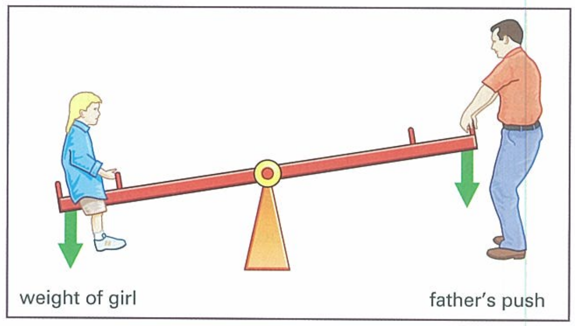

Figure 4.4 Two forces are causing this see-saw to tip. The girl's weight causes it to tip to the left, while her father provides a force to tip it to the right. He can increase the turning effect of his force by increasing the force, or by pushing down at a greater distance from the pivot.

A see-saw is an example of a **beam**, a long, rigid object that is pivoted at a point. The girl's weight is making the beam tip one way. The father's push is making it tip the other way. If the beam is to be balanced, the moments of the two forces must cancel each other out.

Equilibrium

When a beam is balanced, we say that it is in **equilibrium**. If an object is in equilibrium:

- the forces on it must be balanced (no resultant force)
- the turning effects of the forces on it must also be balanced (no resultant turning effect).

If a resultant force acts on an object, it will start to move off in the direction of the resultant force. If there is a resultant turning effect, it will start to rotate.

Activity 4.1 Balancing

Can you make a beam balance?

QUESTIONS

1 Figure 4.5 shows a heavy trapdoor. Three different forces are shown pulling on the trapdoor. Which force will have the biggest turning effect? Explain your answer.

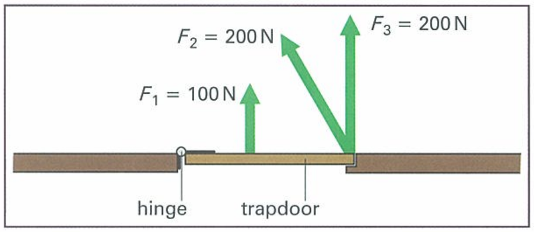

Figure 4.5 For Question **1**.

2 A tall tree can survive a gentle breeze but it may be blown over by a high wind. Explain why a tall tree is more likely to blow over than a short tree.

4.2 Calculating moments

We have seen that, the greater a force and the further it acts from the pivot, the greater is its moment. We can write an equation for calculating the moment of a force:

moment of a force = force × perpendicular distance from pivot to force

Units: since moment is a force (in N) multiplied by a distance (in m), its unit is simply the newton metre (N m). There is no special name for this unit in the SI system.

Figure 4.6 shows an example. The 40 N force is 2.0 m from the pivot, so:

$$\text{moment of force} = 40\,\text{N} \times 2.0\,\text{m} = 80\,\text{N m}$$

Balancing moments

The three children in Figure 4.7 have balanced their see-saw – it is in equilibrium. The weight of the child

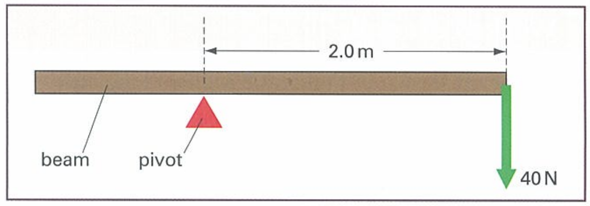

Figure 4.6 Calculating the moment of a force.

on the left is tending to turn the see-saw anticlockwise. So the weight of the child on the left has an anticlockwise moment. The weights of the two children on the right have clockwise moments.

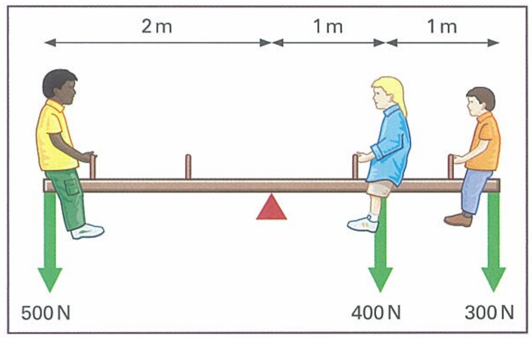

Figure 4.7 A balanced see-saw. On her own, the child on the left would make the see-saw turn anticlockwise; her weight has an anticlockwise moment. The weight of each child on the right has a clockwise moment. Since the see-saw is balanced, the sum of the clockwise moments must equal the anticlockwise moment.

From the data in Figure 4.7, we can calculate these moments:

$$\begin{aligned}\text{anticlockwise moment} &= 500 \times 2.0 = 1\,000\,\text{N m}\\ \text{clockwise moments} &= (300 \times 2.0) + (400 \times 1.0)\\ &= 600\,\text{N m} + 400\,\text{N m}\\ &= 1000\,\text{N m}\end{aligned}$$

(The brackets are included as a reminder to perform the multiplications before the addition.) We can see that in this situation:

total clockwise moment = total anticlockwise moment

So the see-saw in Figure 4.7 is balanced.

We can use this idea to find the value of an unknown force or distance, as shown in Worked example 1.

Worked example 1

The beam shown in Figure **4.8** is 2.0 m long and has a weight of 20 N. It is pivoted as shown. A force of 10 N acts downwards at one end. What force F must be applied downwards at the other end to balance the beam?

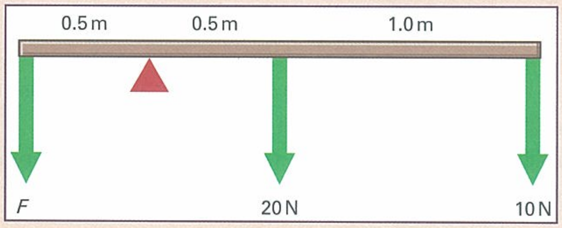

Figure 4.8 A balanced beam. Note that the weight of the beam (20 N) is represented by a downward arrow at its midpoint.

Step 1: Identify the clockwise and anticlockwise forces. Two forces act clockwise: 20 N at a distance of 0.5 m, and 10 N at 1.5 m. One force acts anticlockwise: the force F at 0.5 m.

Step 2: Since the beam is in equilibrium, we can write

total clockwise moment
= total anticlockwise moment

Step 3: Substitute in the values from Step 1, and solve.

$$(20\,\text{N} \times 0.5\,\text{m}) + (10\,\text{N} \times 1.5\,\text{m}) = F \times 0.5\,\text{m}$$

$$10\,\text{N m} + 15\,\text{N m} = F \times 0.5\,\text{m}$$

$$25\,\text{N m} = F \times 0.5\,\text{m}$$

$$F = \frac{25\,\text{N m}}{0.5\,\text{m}} = 50\,\text{N}$$

So a force of 50 N is needed.

(You might have been able to work this out in your head, by looking at the diagram. The 20 N weight requires 20 N to balance it, and the 10 N at 1.5 m needs 30 N at 0.5 m to balance it. So the total force needed is 50 N.)

In equilibrium

In the drawing of the three children on the see-saw (Figure **4.7**), three forces are shown acting downwards. There is also the weight of the see-saw itself, 200 N, to consider, which also acts downwards, through its midpoint. If these were the **only** forces acting, they would make the see-saw accelerate downwards. Another force acts to prevent this from happening. There is an upward **contact force** where the see-saw sits on the pivot. Figure **4.9** shows all five forces.

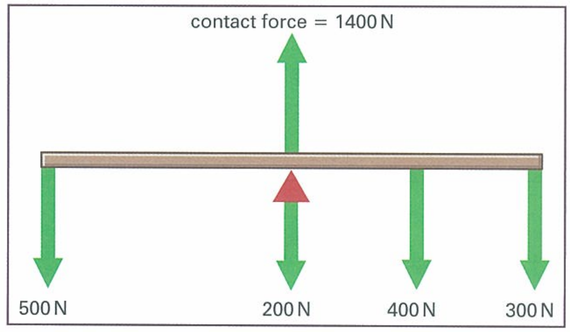

Figure 4.9 A force diagram for the see-saw shown in Figure **4.7**. The upward contact force of the pivot on the see-saw balances the downward forces of the children's weights and the weight of the see-saw itself. The contact force has no moment about the pivot because it acts through the pivot. The weight of the see-saw is another force that acts through the pivot, so it also has no moment about the pivot.

Because the see-saw is in equilibrium, we can calculate this contact force. It must balance the four downwards forces, so its value is (500 + 200 + 400 + 300) N = 1400 N, upwards. This force has no turning effect because it acts through the pivot. Its distance from the pivot is zero, so its moment is zero.

Now we have satisfied the two conditions that must be met if an object is to be in equilibrium:

- there must be no resultant force acting on it
- total clockwise moment = total anticlockwise moment.

You can use these two rules to solve problems concerning the forces acting on objects in equilibrium.

Activity 4.2 A question of balance

Predict the forces on a balanced beam.

Activity 4.3 Balancing problems

Solve some more problems for systems in equilibrium.

E

QUESTIONS

3 Figure **4.10** shows a balanced beam. Calculate the unknown forces *X* and *Y*.

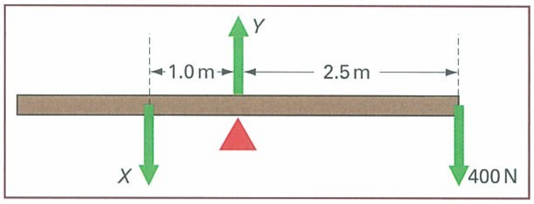

Figure 4.10 For Question **3**.

4 Figure **4.11** shows a beam, balanced at its midpoint. The weight of the beam is 40 N. Calculate the unknown force *Z*, and the length of the beam.

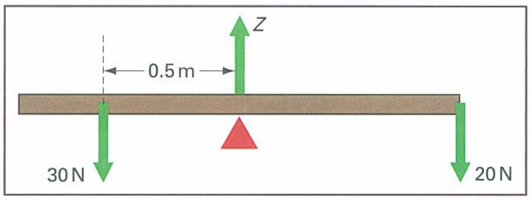

Figure 4.11 For Question **4**.

4.3 Stability and centre of mass

People are tall and thin, like a pencil standing on end. Unlike a pencil, we do not topple over when touched by the slightest push. We are able to remain upright, and to walk, because we make continual adjustments to the positions of our limbs and body. We need considerable brain power to control our muscles for this. The advantage is that, with our eyes about a metre higher than if we were on all-fours, we can see much more of the world.

Circus artistes such as tightrope walkers (Figure **4.12**) have developed the skill of remaining upright to a high degree. They use items such as poles or parasols to help them maintain their balance. The idea of moments can help us to understand why some objects are stable while others are more likely to topple over.

A tall glass is easily knocked over – it is unstable. It could be described as top-heavy, because most of its mass is concentrated high up, above its stem. Figure **4.13** shows what happens if the glass is tilted.

Figure 4.12 This high-wire artiste is using a long pole to maintain her stability on the wire. If she senses that her weight is slightly too far to the left, she can redress the balance by moving the pole to the right. Frequent, small adjustments allow her to walk smoothly along the wire.

a When the glass is upright, its weight acts downwards and the contact force of the table acts upwards. The two forces are in line, and the glass is in equilibrium.

b If the glass is tilted slightly to the right, the forces are no longer in line. There is a pivot at the point where the base of the glass is in contact with the table. The line of the glass's weight is to the left of this pivot, so it has an anticlockwise moment, which tends to tip the glass back to its upright position.

c Now the glass is tipped further. Its weight acts to the right of the pivot, and has a clockwise moment, which makes the glass tip right over.

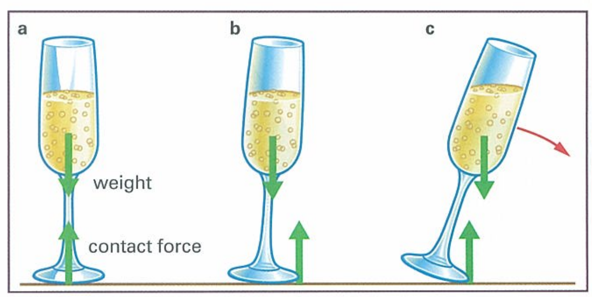

Figure 4.13 A tall glass is easily toppled. Once the line of action of its weight is beyond the edge of the base, as in **c**, the glass tips right over.

Centre of mass

In Figure **4.13**, the weight of the glass is represented by an arrow starting at a point inside the liquid in the bowl of the glass. Why is this? The reason is that the glass behaves as if all of its mass were concentrated at this point, known as the **centre of mass**. The glass is top-heavy because its centre of mass is high up. The force of gravity acts on the mass of the glass – each bit of the glass is pulled by the Earth's gravity. However, rather than drawing lots of weight arrows, one for each bit of the glass, it is simpler to draw a single arrow acting through the centre of mass. (Because we can think of the weight of the glass acting at this point, it is sometimes known as the centre of gravity.)

Figure **4.14** shows the position of the centre of mass for several objects. A person is fairly symmetrical, so their centre of mass must lie somewhere on the axis of symmetry. (This is because half of their mass is on one side of the axis, and half on the other.) The centre of mass is in the middle of the body, roughly level with the navel. A ball is much more symmetrical, and its centre of mass is at its centre.

For an object to be stable, it should have a low centre of mass and a wide base. The pyramid in Figure **4.14** is an example of this. (The Egyptian pyramids are among the Wonders of the World. It has been suggested that, if they had been built the other way up, they would have been even greater wonders!) The tightrope walker shown in Figure **4.12** has to adjust her position so that her centre of mass remains above her 'base' – the point where her feet make contact with the rope.

Finding the centre of mass

Balancing is the clue to finding an object's centre of mass. A metre rule balances at its midpoint, so that is where its centre of mass must lie.

The procedure for finding the centre of mass of a more irregularly shaped object is shown in Figure **4.15**. In this case, the object is a piece of card, described as a plane **lamina**. The card is suspended from a pin. If it is free to move, it hangs with its centre of mass below the point of suspension. (This is because its weight pulls it round until the weight and the contact force at the pin are lined up. Then there is no moment about the pin.) A plumb-line is used to mark a vertical line below the pin. The centre of mass must lie on this line.

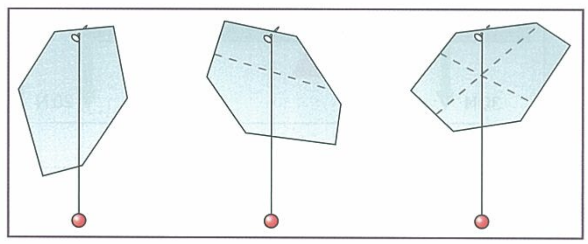

Figure 4.15 Finding the centre of mass of an irregularly shaped piece of card. The card hangs freely from the pin. The centre of mass must lie on the line indicated by the plumb-line hanging from the pin. Three lines are enough to find the centre of mass.

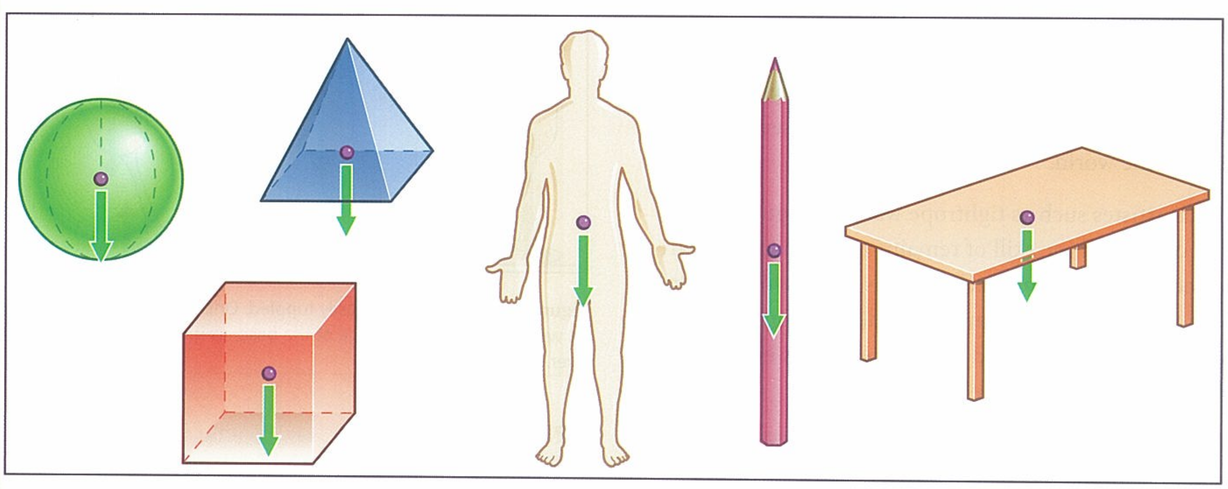

Figure 4.14 The weight of an object acts through its centre of mass. Symmetry can help to judge where the centre of mass lies. An object's weight can be considered to act through this point. Note that, for the table, its centre of mass is in the air below the tabletop.

The process is repeated for two more pinholes. Now there are three lines on the card, and the centre of mass must lie on all of them, that is, at the point where they intersect. (Two lines might have been enough, but it is advisable to use at least three points to show up any inaccuracies.)

Activity 4.4 Centre of mass of a plane lamina

Use the method described in the text to find the centre of mass of a sheet of card.

QUESTIONS

5 Use the ideas of **stability** and **centre of mass** to explain the following.
  - **a** Double-decker buses have heavy weights attached to their undersides.
  - **b** The crane shown in Figure **4.16** has a heavy concrete block attached to one end of its arm, and others placed around its base.

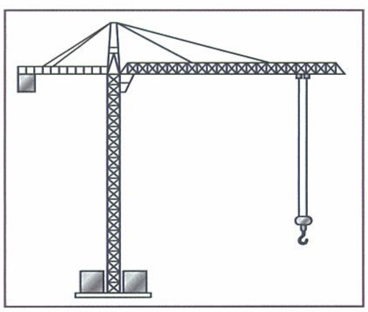

Figure 4.16 For Question **5**.

6 Figure **4.17** shows the forces acting on a cyclist. Look at part **a** of the diagram.
  - **a** Explain how you can tell that the cyclist shown in part **a** is in equilibrium.

  Now look at part **b** of the diagram.
  - **b** Are the forces on the cyclist balanced now? How can you tell?
  - **c** Would you describe the cyclist as **stable** or **unstable**? Explain your answer.

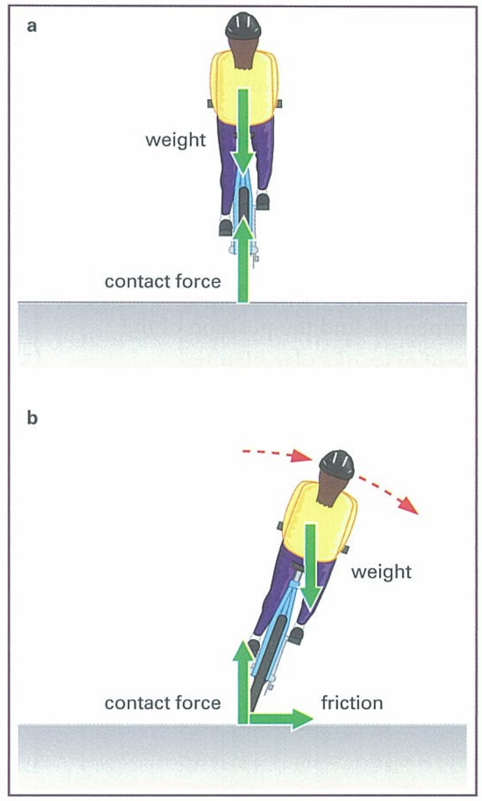

Figure 4.17 Forces on a cyclist – for Question **6**.

E

Summary

The moment of a force is a measure of its turning effect.

When a system is in equilibrium, the resultant force is zero and the resultant turning effect is zero.

For an object to be stable, its centre of mass must be low down and it must have a large base.

Moment of a force = force × perpendicular distance from pivot to force

When an object is in equilibrium:
total clockwise moment = total anticlockwise moment

End-of-chapter questions

4.1 What quantity is a measure of the turning effect of a force? [1]

4.2 What **two** conditions must be met if an object is to be in equilibrium? [2]

4.3 Write out step-by-step instructions for an experiment to find the position of the centre of mass of a plane lamina. [5]

E **4.4** The diagram (Figure **4.18**) shows a 3 m uniform beam AB, pivoted 1.0 m from the end A. The weight of the beam is 200 N.

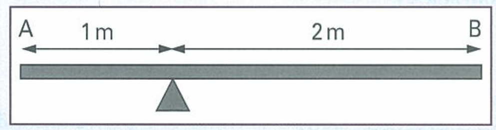

Figure 4.18 For Question **4.4**.

a Copy the diagram and mark the beam's centre of mass. [1]

b Add arrows to show the following forces: the weight of the beam; the contact force on the beam at the pivot. [2]

c A third force *F* presses down on the beam (at end point A). What value of *F* is needed to balance the beam? [5]

d When this force is applied, what is the value of the contact force that the pivot exerts on the beam? [3]

5 Forces and matter

Core Using forces to change the shape and size of a body
Core Carrying out experiments to produce extension against load graphs
E Extension Interpreting extension against load graphs
Extension Using Hooke's law
Core Understanding the factors that affect pressure
E Extension Calculating pressure

5.1 Forces acting on solids

Forces can change the size and shape of an object. They can stretch, squash, bend or twist it. Figure **5.1** shows the forces needed for these different ways of deforming an object. You could imagine holding a cylinder of foam rubber, which is easy to deform, and changing its shape in each of these ways.

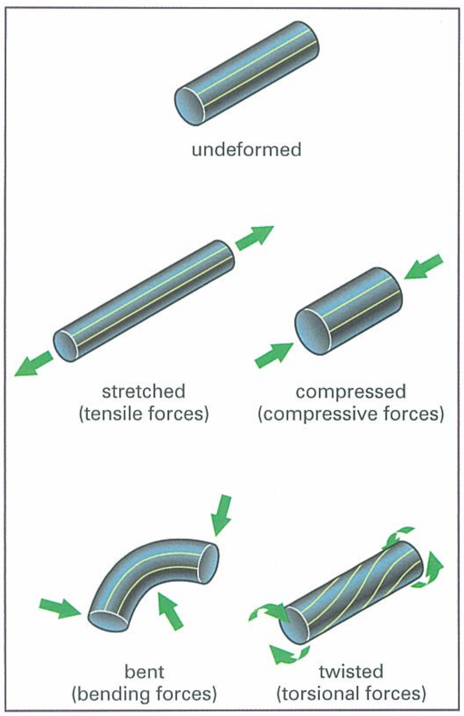

Figure 5.1 Forces can change the size and shape of a solid object. These diagrams show four different ways of deforming a solid object.

Foam rubber is good for investigating how things deform because, when the forces are removed, it springs back to its original shape. Here are two more examples of materials that deform in this way:

- When a football is kicked, it is compressed for a short while (see Figure **5.2**). Then it springs back to its original shape as it pushes itself off the foot of the player who has kicked it. The same is true for a tennis ball when struck by a racket.
- Bungee jumpers rely on the springiness of the rubber rope, which breaks their fall when they jump from a height. If the rope became permanently stretched, they would stop suddenly at the bottom of their fall, rather than bouncing up and down and gradually coming to a halt.

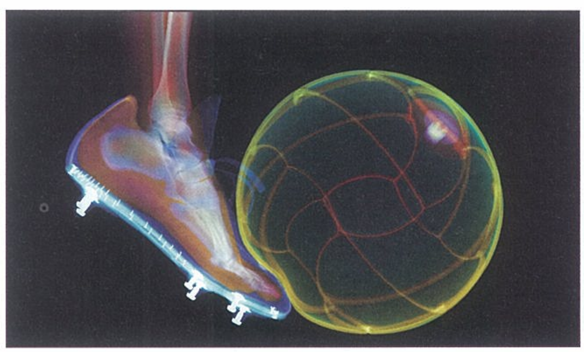

Figure 5.2 This remarkable X-ray image shows how a football is compressed when it is kicked. It returns to its original shape as it leaves the player's boot. (This is an example of an elastic deformation.) The boot is also compressed slightly but, because it is stiffer than the ball, the effect is less noticeable.

Some materials are less springy. They become permanently deformed when forces act on them.

- When two cars collide, the metal panels of their bodywork are bent. In a serious crash, the solid metal sections of the car's chassis are also bent.
- Gold and silver are metals that can be deformed by hammering them (see Figure 5.3). People have known for thousands of years how to shape rings and other ornaments from these precious metals.

Figure 5.3 A Tibetan silversmith making a wrist band. Silver is a relatively soft metal at room temperature, so it can be hammered into shape without the need for heating.

5.2 Stretching springs

To investigate how objects deform, it is simplest to start with a spring. Springs are designed to stretch a long way when a small force is applied, so it is easy to measure how their length changes.

Figure 5.4 shows how to carry out an investigation on stretching a spring. The spring is hung from a rigid clamp, so that its top end is fixed. Weights are hung on the end of the spring – these are referred to as the **load**. As the load is increased, the spring stretches and its length increases.

Figure 5.5 shows the pattern observed as the load is increased in regular steps. The length of the spring increases (also in regular steps). At this stage the spring will return to its original length if the load is removed. However, if the load is increased too far, the spring becomes permanently stretched and will not return to its original length. It has been **inelastically deformed**.

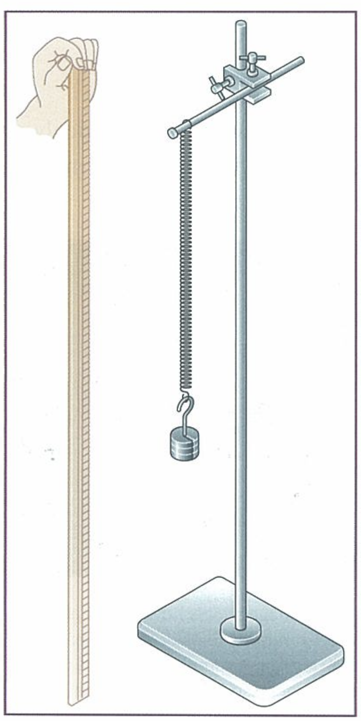

Figure 5.4 Investigating the stretching of a spring.

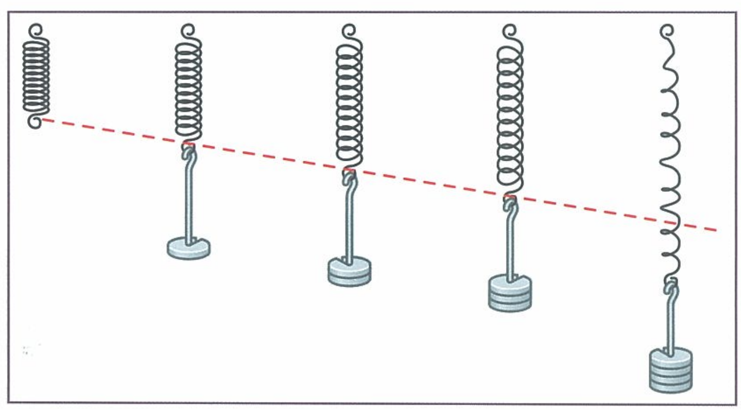

Figure 5.5 Stretching a spring. At first, the spring deforms elastically. It will return to its original length when the load is removed. Eventually, however, the load is so great that the spring is damaged.

Extension of a spring

As the force stretching the spring increases, it gets longer. It is important to consider the increase in length of the spring. This quantity is known as the **extension**.

length of stretched spring
= original length + extension

Table 5.1 shows how to use a table with three columns to record the results of an experiment to stretch a spring. The third column is used to record the value of the extension, calculated by subtracting the original length from the value in the second column.

Load / N	Length / cm	Extension / cm
0.0	24.0	0.0
1.0	24.6	0.6
2.0	25.2	1.2
3.0	25.8	1.8
4.0	26.4	2.4
5.0	27.0	3.0
6.0	27.6	3.6
7.0	28.6	4.6
8.0	29.5	5.6

Table 5.1 Results from an experiment to find out how a spring stretches as the load on it is increased.

To see how the extension depends on the load, we draw an extension against load graph (Figure 5.6). You can see that the graph is in two parts.

- At first, the graph slopes up steadily. This shows that the extension increases in equal steps as the load increases.
- Then the graph bends. This happens when the load is so great that the spring has become permanently damaged. It will not return to its original length.

(You can see the same features in Table 5.1. Look at the third column. At first, the numbers go up in equal steps. The last two steps are bigger.)

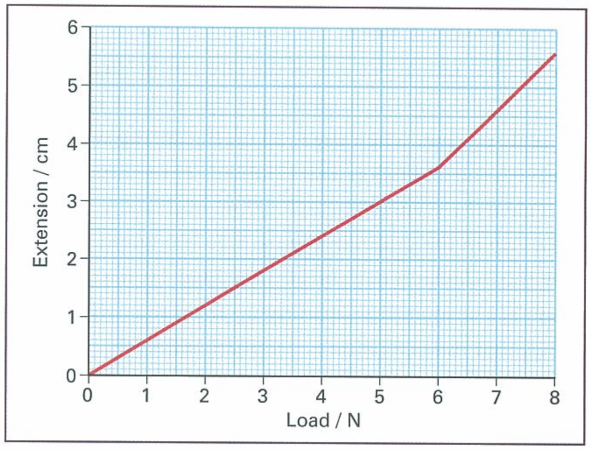

Figure 5.6 An extension against load graph for a spring, based on the data in Table 5.1.

Activity 5.1 Investigating springs

Use weights to stretch a spring, and then plot a graph to show the pattern of your results.

QUESTIONS

1 A piece of elastic cord is 80 cm long. When it is stretched, its length increases to 102 cm. What is its extension?

2 Table 5.2 shows the results of an experiment to stretch an elastic cord. Copy and complete the table, and draw a graph to represent this data.

Load / N	Length / mm	Extension / mm
0.0	50	0
1.0	54	
2.0	58	
3.0	62	
4.0	66	
5.0	70	
6.0	73	
7.0	75	
8.0	76	

Table 5.2 For Question 2.

5.3 Hooke's law

The mathematical pattern of the stretching spring was first described by the English scientist Robert Hooke. He realised that, when the load on the spring was doubled, the extension also doubled. Three times the load gave three times the extension, and so on. This shows up in the graph in Figure 5.7. The graph shows how the extension depends on the load. At first, the graph is a straight line, leading up from the origin. This shows that the extension is proportional to the load.

At a certain point, the graph bends and the line slopes up more steeply. This point is called the **limit of proportionality**. If the spring is stretched beyond this point, it will be permanently damaged. If the load is removed, the spring will not return all the way to its original, undeformed length. (This point is also known as the **elastic limit**.)

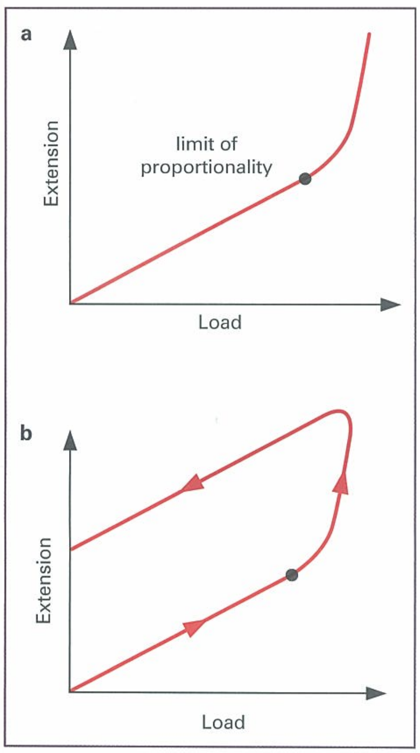

Figure 5.7 **a** An extension against load graph for a spring. Beyond the limit of proportionality, the graph is no longer a straight line, and the spring is permanently deformed. **b** This graph shows what happens when the load is removed. The extension does not return to zero, showing that the spring is now longer than at the start of the experiment.

The behaviour of the spring is represented by the graph of Figure 5.7**a** and is summed up by **Hooke's law**:

> The extension of a spring is proportional to the load applied to it, provided the limit of proportionality is not exceeded.

We can also write Hooke's law as an equation:

$$F = kx$$

In this equation, F is the load (force) stretching the spring, k is the stiffness of the spring, and x is the extension of the spring.

Worked example 1

A spring has a stiffness $k = 20\,\mathrm{N/cm}$. What load is needed to produce an extension of 2.5 cm?

Step 1: Write down what you know and what you want to find out.

load $F = ?$
stiffness $k = 20\,\mathrm{N/cm}$
extension = 2.5 cm

Step 2: Write down the equation linking these quantities, substitute values and calculate the result.

$F = kx$
$F = 20 \times 2.5 = 50\,\mathrm{N}$

So a load of 50 N will stretch the spring by 2.5 cm.

How rubber behaves

A rubber band can be stretched in a similar way to a spring. As with a spring, the bigger the load, the bigger the extension. However, if the weights are added with great care, and then removed one by one without releasing the tension in the rubber, the following can be observed:

- The graph obtained is not a straight line. Rather, it has a slightly S-shaped curve. This shows that the extension is not exactly proportional to the load. Rubber does not obey Hooke's law.

- Eventually, increasing the load no longer produces any extension. The rubber feels very stiff. When the load is removed, the graph does not come back exactly to zero.

Activity 5.2 Stretching rubber

Carry out an investigation into the stretching of a rubber band. This is a good test of your experimental skills. You will need to work carefully if you are to see the effects described above.

Hooke and springs

Why was Robert Hooke so interested in springs? Hooke was a scientist, but he was also a great inventor. He was interested in springs for two reasons:

- Springs are useful in making weighing machines, and Hooke wanted to make a weighing machine that was both very sensitive (to weigh very light objects) and very accurate (to measure very precise quantities).
- He also realised that a spiral spring could be used to control a clock or even a wristwatch.

Figure 5.8 shows a set of diagrams drawn by Hooke, including a long spring and a spiral spring, complete with pans for carrying weights. You can also see some of his graphs.

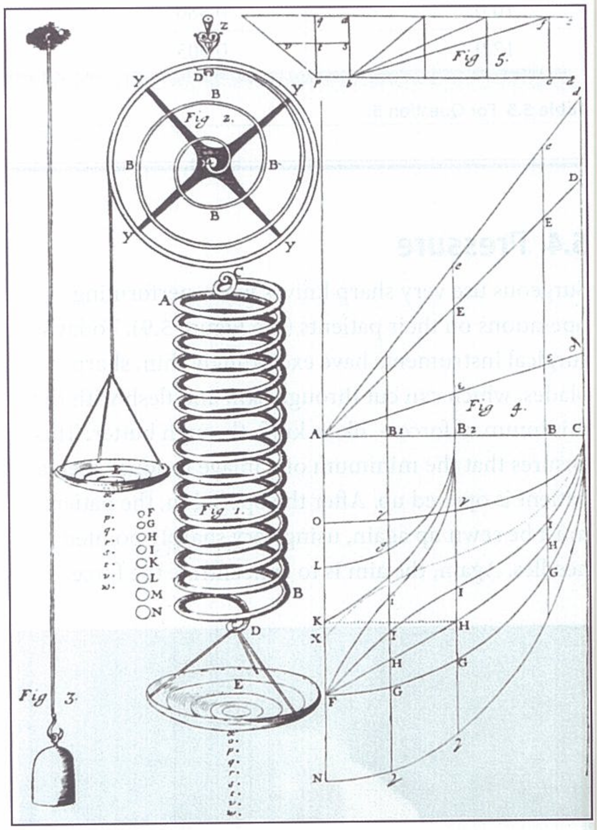

Figure 5.8 Robert Hooke's diagrams of springs.

For scientists, it is important to publish results so that other scientists can make use of them. Hooke was very secretive about some of his findings, because he did not want other people to use them in their own inventions. For this reason, he published some of his findings in code. For example, instead of writing his law of springs as given above, he wrote this: "ceiiinosssttuv". Later, when he felt that it was safe to publish his ideas, he revealed that this was an anagram of a sentence in Latin. Decoded, it said:

Ut tensio, sic vis.

In English, this is:

As the extension increases, so does the force.

In other words, the extension is proportional to the force producing it. You can see Hooke's straight-line graph in Figure 5.8.

QUESTIONS

3 A spring requires a load of 2.5 N to increase its length by 4 cm. The spring obeys Hooke's law. What load will give it an extension of 12 cm?

4 A spring has an unstretched length of 12.0 cm. Its stiffness k is 8 N/cm. What load is needed to stretch the spring to a length of 15.0 cm?

5 Table 5.3 shows the results of an experiment to stretch a spring. Use the results to plot an extension against load graph. On your graph, mark the limit of proportionality and state the value of the load at this point.

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Load / N	Length / m
0.0	0.800
2.0	0.815
4.0	0.830
6.0	0.845
8.0	0.860
10.0	0.880
12.0	0.905

Table 5.3 For Question **5**.

5.4 Pressure

Surgeons use very sharp knives when performing operations on their patients (see Figure 5.9). Today's surgical instruments have exceedingly thin, sharp blades, which can cut through skin and flesh with the minimum of force – 'like a knife through butter'. This ensures that the minimum of damage is done when a patient is opened up. After the operation, the patient must be sewn up again, using very sharply pointed needles. Again, the aim is to concentrate the force pushing the needle onto a very small area. Then a small force is needed to pass through the skin.

Figure 5.9 Surgeons aim to minimise the damage to a patient during an operation. Surgical instruments are made from special steels, which can be sharpened to give very fine points and edges. This means that less force is needed to cut through a patient's skin, or to cut into an organ.

Knives and needles have sharp blades and tips in order to concentrate the force that is being applied onto a small area. This means that the **pressure** that is being applied is as large as possible. Pressure tells us how concentrated a force is. If a force is spread out over a large area, its pressure is low. If a force is concentrated on a small area, its pressure is high.

High pressure, low pressure

Knives have sharp blades to give a high pressure. Ice skates also have 'blades', the part that is in contact with the ice. This is narrow, so that the skater's weight is concentrated on a small area. The effect of this high pressure is to melt the ice just below the blade. This gives a thin film of water, which provides lubrication for the skate as it skims over the ice. As the skate moves on, the water re-freezes. On very cold days, the pressure may not be enough to melt the ice, and skating is impossible.

If you are unlucky enough to find yourself standing on thin ice, it is advisable to lie down on it to spread out your weight. This reduces the pressure, and the ice is less likely to break. The same principle is used elsewhere. 'Crawling boards' are often used to climb over a glass roof. These spread out the weight of anyone needing to climb on the roof. Some vehicles are fitted with very wide tyres (Figure 5.10) so that they exert less pressure on soft ground.

Figure 5.10 This truck has wide tyres to spread its weight as it travels over the sand dunes. Camels have big, flat feet for the same reason, to reduce the pressure on the sand so that they are less likely to sink in and become bogged down.

QUESTION

6 Use the idea of pressure to explain the following.
   a Sharks and crocodiles have sharp teeth.
   b Camels have wide, flat feet.
   c If you walk on a wooden floor wearing stilettos (shoes with very narrow heels), you may damage the floor.

Calculating pressure

A large force pressing on a small area gives a high pressure. We can think of **pressure** as the force per unit area acting on a surface:

$$\text{pressure} = \frac{\text{force}}{\text{area}} \qquad p = \frac{F}{A}$$

Units: if force F is measured in newtons (N) and area A in square metres (m^2), pressure p is in newtons per square metre (N/m^2). In the SI system of units, this is given the name **pascal** (**Pa**).

Worked example 2

Shoes with stiletto heels go in and out of fashion. ('Stiletto' is an Italian word meaning a small and murderous dagger.) Such heels can damage floors, and dance halls often have notices requiring them to be removed. Calculate the pressure exerted by a woman dancer weighing 600 N standing on a single heel of area 1 cm^2. If the surface of the dancefloor is broken by pressures over five million pascals (5 MPa), will it be damaged?

Step 1: To calculate the pressure, we need to know the force, and the area on which the force acts, in m^2.

$$\text{force } F = 600\,\text{N}$$
$$\text{area } A = 1\,\text{cm}^2 = 0.0001\,\text{m}^2 = 10^{-4}\,\text{m}^2$$

Step 2: Now we can calculate the pressure p.

$$p = \frac{F}{A} = \frac{600\,\text{N}}{0.0001\,\text{m}^2}$$
$$= 6\,000\,000\,\text{Pa} = 6\,\text{MPa}$$

The pressure is thus 6×10^6 Pa, or 6 MPa. This is more than the minimum pressure needed to break the surface of the floor, so it will be damaged.

QUESTIONS

7 Write down an equation that defines pressure.
8 What are the SI units of pressure?
9 Which exerts a greater pressure, a force of 100 N acting on 1 cm^2, or the same force acting on 2 cm^2?
10 What pressure is exerted by a force of 40 000 N acting on 2 m^2?
11 A swimming pool has a level, horizontal, bottom of area 10.0 m by 4.0 m. If the pressure of the water on the bottom is 15 000 Pa, what total force does the water exert on the bottom of the pool?

Pressure in fluids

In a fluid such as water or air, pressure does not simply act downwards – it acts equally in all directions. This is because the molecules of the fluid move around in all directions, causing pressure on every surface they collide with.

If you dive into a swimming pool, you will experience the pressure of the water on you. It provides the upthrust on you, which pushes you back to the surface. The deeper you go, the greater the pressure acting on you. Deep-sea divers have to take account of this. They wear protective suits, which will stop them being crushed by the pressure. Submarines and marine exploring vehicles (Figure **5.11**) must be designed to withstand very great pressures. They have curved surfaces, which are less likely to buckle under pressure, and they are made of thick metal.

This pressure comes about because any object under water is being pressed down on by the weight of water above it. The deeper you go, the greater the amount of water pressing down on you (see Figure **5.12a**). In a similar way, the atmosphere exerts pressure on us, although we are not normally conscious of this. The Earth's gravity pulls it downwards, so that

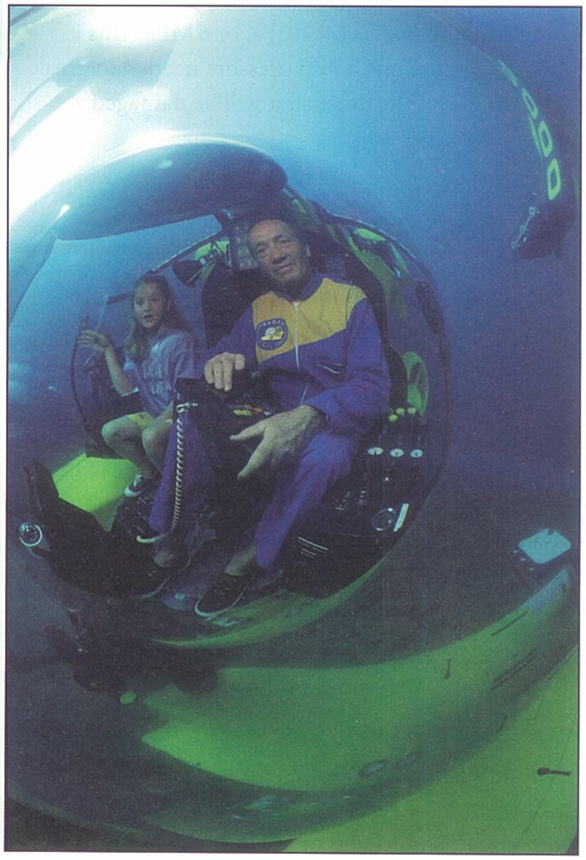

Figure 5.11 This underwater exploring vehicle is used to carry tourists to depths of 600 m, where the pressure is 60 times that at the surface. The design makes use of the fact that spherical and cylindrical surfaces stand up well to pressure. The viewing window is made of acrylic plastic and is 9.5 cm thick.

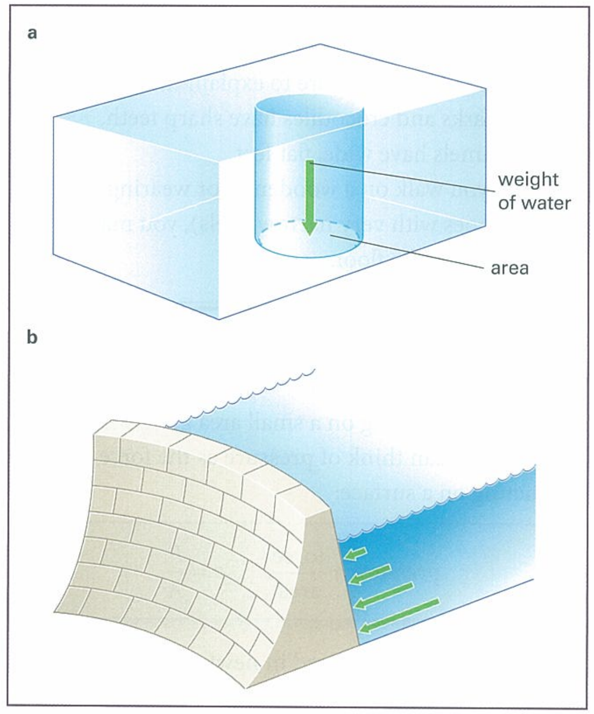

Figure 5.12 **a** Pressure is caused by the weight of water (or other fluid) above an object, pressing down on it. **b** This dam is thickest near its base, because that is where the pressure is greatest.

the atmosphere presses downwards on our heads. Mountaineers climbing to the top of Mount Everest rise through two-thirds of the atmosphere, so the pressure is only about one-third of the pressure down at sea-level. There is much less air above them, pressing down.

The pressure caused by water is much greater than that caused by air because water is much denser than air. Figure **5.12b** shows how a dam is designed to withstand the pressure of the water behind it. Because the pressure is greatest at the greatest depth, the dam must be made thickest at its base.

Pressure measurements

A **manometer** is a simple instrument for showing the difference in pressure between two gases or liquids.

Figure **5.13** shows how a manometer is used to measure the pressure of the laboratory gas supply. This pressure must be higher than atmospheric pressure, or gas would not flow out of the pipe.

- A manometer is a U-shaped tube, holding a small amount of liquid.
- When both ends are open, the levels of the liquid in the two sides are the same.
- If one side is connected to the gas supply, the gas pushes down on the liquid and forces it round the bend. The levels are now unequal, showing that there is a difference in pressure.

A **barometer** can be used to measure atmospheric pressure. One simple type, the mercury barometer, is shown in Figure **5.14**. It consists of a long glass tube, at least 80 cm in length. The tube is filled with mercury and then carefully inverted into a trough containing mercury. This must be done carefully, so that no air enters the tube.

Once the tube is safely inverted, the level of mercury in the tube drops. The length l of the mercury column,

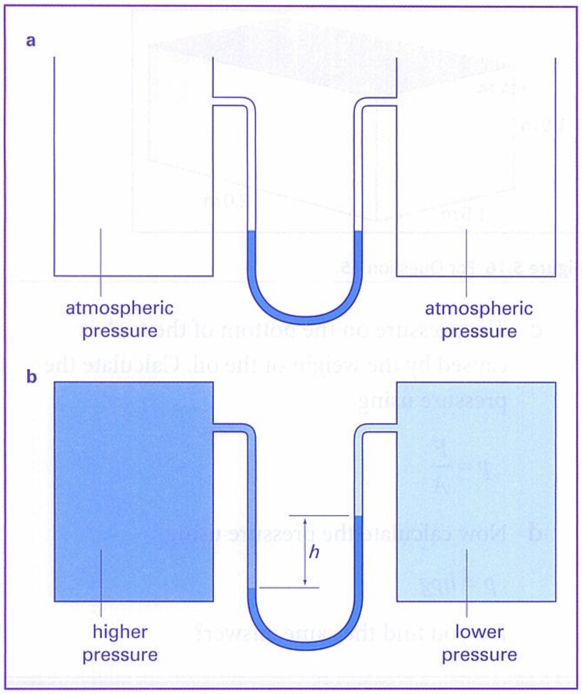

Figure 5.13 Using a manometer to measure the pressure difference between two gases. **a** With atmospheric pressure on both sides of the U-tube, the liquid is at the same level in both sides. **b** With higher pressure on one side, the liquid is pushed round. The greater the pressure difference, the greater is the difference in levels, *h*.

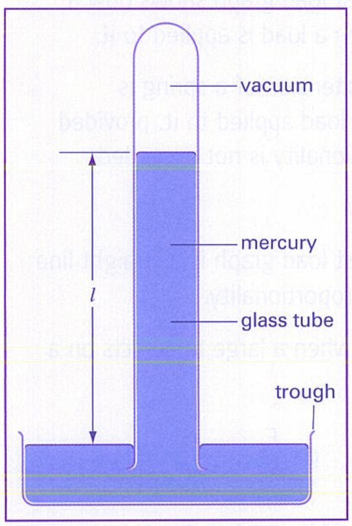

Figure 5.14 A mercury barometer is used to measure atmospheric pressure.

measured from the surface of the mercury in the trough, is about 76 cm. The space above the mercury column is a vacuum (with a small amount of mercury vapour).

The column length l depends on the atmospheric pressure. On a day when the atmospheric pressure is high, the air presses more strongly on the mercury in the trough, so that it rises further in the tube. If the pressure falls, the force on the mercury decreases, and the level in the tube decreases.

Mercury is used in barometers like this because it has a high density (more than 13 times the density of water). A barometer made using water would require a much taller tube, over 10 m in height!

Activity 5.3 Pressure experiments

Try out some simple experiments to explore the idea of pressure.

QUESTIONS

12 Name an instrument used to measure:

a atmospheric pressure

b differences in pressure.

13 Figure 5.15 shows two tanks, A and B. Each tank contains gas and is fitted with a manometer to show how the pressure compares with atmospheric pressure outside the tank.

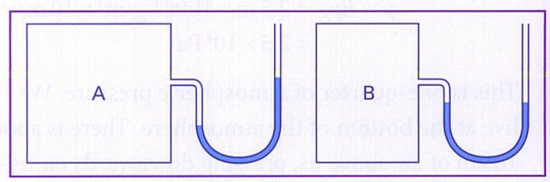

Figure 5.15 For Question **13**.

a In which tank is the gas pressure greater than atmospheric pressure? Explain how you can tell.

b What can you say about the pressure of the gas in the other tank?

Pressure, depth and density

E

We have seen that the deeper one dives into water, the greater the pressure. Pressure p is proportional to depth h (we use the letter h, for height). Twice the depth means twice the pressure. Pressure also depends

E on the density ρ of the material (here ρ is the Greek letter rho). If you dive into mercury, which is more than ten times as dense as water, the pressure will be more than ten times as great.

We can write an equation for the pressure at a depth h in a fluid of density ρ:

> pressure = depth × density × acceleration due to gravity
>
> $p = h\rho g$

Worked example 3

Calculate the pressure on the bottom of a swimming pool 2.5 m deep. How does the pressure compare with atmospheric pressure, 10^5 Pa? (Density of water = 1000 kg/m^3.)

Step 1: Write down what you know, and what you want to know.

$h = 2.5\,\text{m}$
$\rho = 1000\,\text{kg/m}^3$
$g = 10\,\text{m/s}^2$
$p = ?$

Step 2: Write down the equation for pressure, substitute values and calculate the answer.

$$p = h\rho g = 2.5\,\text{m} \times 1000\,\text{kg/m}^3 \times 10\,\text{m/s}^2 = 2.5 \times 10^4\,\text{Pa}$$

This is one-quarter of atmospheric pressure. We live at the bottom of the atmosphere. There is about 10 km of air above us, pressing downwards on us – that is the origin of atmospheric pressure.

QUESTIONS

14 A water tank holds water to a depth of 80 cm. What is the pressure on the bottom of the tank? (Density of water = 1000 kg/m^3.)

15 Figure 5.16 shows a tank that is filled with oil. The density of the oil is 920 kg/m^3.

a Calculate the volume of the tank from the dimensions shown in the diagram.

b Calculate the weight of the oil in the tank.

E

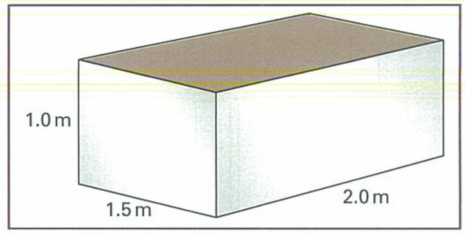

Figure 5.16 For Question **15**.

c The pressure on the bottom of the tank is caused by the weight of the oil. Calculate the pressure using

$$p = \frac{F}{A}$$

d Now calculate the pressure using

$$p = h\rho g$$

Do you find the same answer?

Summary

Forces can change the size and shape of a body.

An extension against load graph shows how a body stretches when a load is applied to it.

E Hooke's law: The extension of a spring is proportional to the load applied to it, provided the limit of proportionality is not exceeded.

Hooke's law: $F = kx$.

An extension against load graph is a straight line up to the limit of proportionality.

Pressure is greater when a large force acts on a small area.

E Pressure = $\frac{\text{force}}{\text{area}}$ $\quad p = \frac{F}{A}$

The pressure in a fluid is greater at greater depths, and when the fluid has a greater density.

E Pressure = depth × density × acceleration due to gravity

$p = h\rho g$

End-of-chapter questions

5.1 When a spring is stretched, its length increases from 58 cm to 66 cm. Calculate its extension. [3]

5.2 A student has a short spring. He is required to investigate how the length of the spring changes as the load stretching it increases. Describe the experimental procedure he should follow, stating the equipment he should use and the measurements he should make. [6]

5.3 Table 5.4 shows the results of an experiment in which a long piece of plastic foam was stretched by hanging weights from one end.

Load / N	Length / cm	Extension / cm
0.0	83.0	0.0
5.0	87.0	……
10.0	91.0	……
15.0	95.0	……
20.0	99.0	……

Table 5.4 For Question **5.3**.

a Copy the table and complete the third column to show the value of the extension produced by each load. [4]

b Use your completed table to plot an extension against load graph. [3]

5.4 a Draw a labelled diagram to show a simple mercury barometer. [3]

b Describe how such a barometer shows changes in atmospheric pressure. [1]

5.5 Your friend has fallen through the thin ice on a frozen pond. You come to the rescue by laying a ladder across the ice and crawling along the ladder to reach your friend. Use the idea of **pressure** to explain why it is safer to use the ladder than to walk on the ice. [3]

E

5.6 An unstretched spring is 12 cm long. A load of 5 N stretches it to 15 cm. How long will it be under a load of 15 N? (Assume that the spring obeys Hooke's law.) [3]

5.7 A group of students carried out an experiment in which they stretched a length of wire by hanging weights on the end. For each value of the load, they measured the length of the wire. Table 5.5 shows their results.

a Copy the table and add a row showing the extension for each load. [4]

b Use the data in your table to draw an extension against load graph for the wire. [4]

c From your graph, determine the extension produced by a load of 25 N. [2]

d Determine the value of the load at the limit of proportionality. [2]

5.8 The pressure of the atmosphere is 100 000 Pa.

a Calculate the force with which the atmosphere presses on the outside of a large window 2.0 m high and 1.25 m wide. [3]

b Explain why this force does not break the window. [1]

5.9 On a particular day, the height of the mercury column in a simple barometer is 760 mm. Calculate the atmospheric pressure on this day. (Density of mercury = 13 600 kg/m^3, $g = 10\ m/s^2$.) [3]

E

Load / N	0	10	20	30	40	50	60	70
Length / m	3.200	3.207	3.215	3.222	3.230	3.242	3.255	3.270

Table 5.5 For Question **5.7**.

6 Energy transformations and energy transfers

Core Identifying forms of energy
Core Describing energy conversions
Core Applying the principle of conservation of energy
Core Explaining energy efficiency
E Extension Calculating percentage efficiency
Extension Calculating kinetic and potential energy

Energy for life

Crocodiles (Figure **6.1**) are efficient creatures. Their jaws snap down on their prey, and there is no escape. You might imagine that a crocodile has a big appetite, but that is not so. A crocodile needs very little food. It can exist on just one-quarter of its own body weight each year. For a human being, this is equivalent to surviving on fish and chips once a week!

There are several reasons for this. It does not take much energy to lie in wait in a water-hole. The water supports your weight, and you do not have to move around a lot. Also, crocodiles (like all reptiles) are cold-blooded, so that their body temperature is close to that of their surroundings. On a cold day, they are sluggish and much more approachable. On hot days, their system is more active, and they are much more agile and dangerous. Finally, their bodies make good use of the food they consume. Unlike humans, they do not have much of a brain (which uses a lot of a human's energy supply). Instead, their energy is stored efficiently and only released when it is time to grab a snack.

In this chapter, we will look at how energy is used in various forms, and how we can use energy efficiently to avoid wasting it.

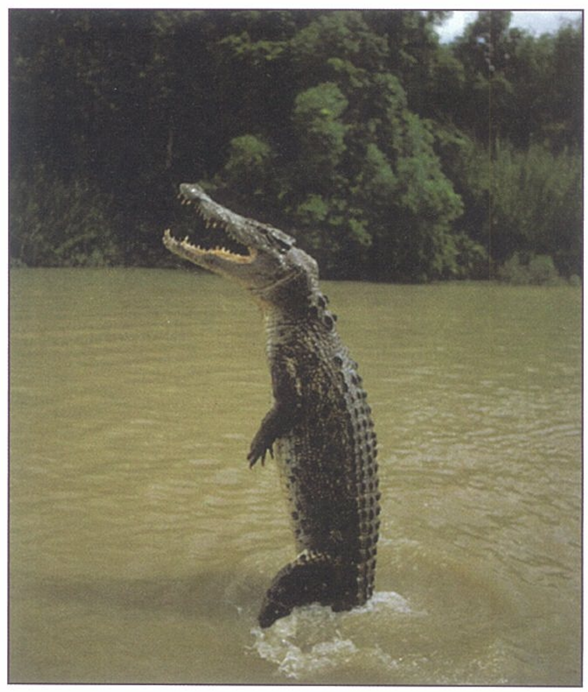

Figure 6.1 Crocodiles are cold-blooded creatures, so it is relatively safe to approach them on a cold day. On a hot day, they are much more active. Crocodiles are not big eaters, but they make very efficient use of the energy supplied by their food.

6.1 Forms of energy

Energy, and energy changes, are involved in all sorts of activities. We will look at two examples and see how we can describe them in terms of energy. We need to have the idea of forms of **energy**.

Example 1: running

At the start of a race, you are stationary, waiting for the starter's pistol. Energy is stored in your toned-up muscles, ready to be released. As you set off, the energy from your muscles gets you moving. If you are running a marathon, you will need to make use of the energy in the longer-term stores in the fatty tissues of your body.

The energy changes involved are shown in Figure **6.2**. Your muscles store **chemical energy**. The energy is stored by chemicals in your muscles, ready to be released at a moment's notice. Your muscles start you moving, and you then have **kinetic energy**. Running makes you hot. This tells us that some of the energy released in your muscles is wasted as **thermal (heat) energy**, rather than becoming useful kinetic energy. Fitness training helps people to reduce this waste.

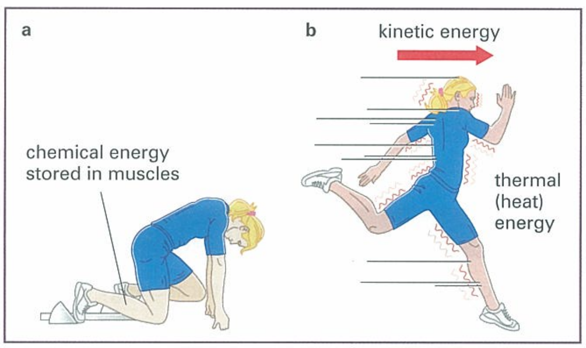

Figure 6.2 **a** At the start of a race, the runner's muscles are stores of chemical energy. **b** As the runner starts to move, chemical energy is transformed to kinetic energy and thermal (heat) energy.

Example 2: switching on a light

It is evening, and the daylight is fading. You switch on the light. Your electricity meter starts to turn a little faster, recording the fact that you are drawing more energy from the distant power station.

The energy changes involved are shown in Figure **6.3**. Electricity is useful because it brings energy, available at the flick of a switch. We can think of the energy it brings as **electrical energy**. In the light bulb, this energy is transformed into **light energy**. Every light bulb also produces **thermal (heat) energy**.

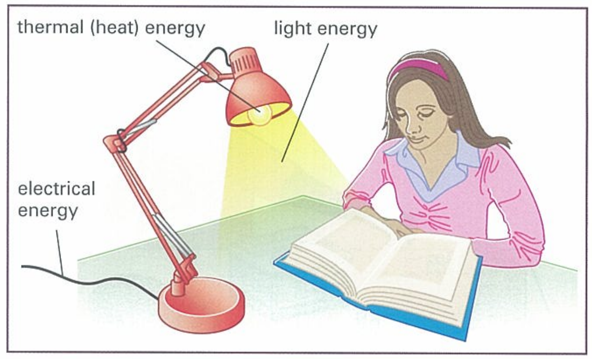

Figure 6.3 Switching on the light requires a supply of electrical energy. In the light bulb, electrical energy is transformed to light energy and thermal (heat) energy.

Naming forms of energy

The examples above highlight some of the various forms of energy. We now take a brief look at further examples of all of these forms.

A moving object has **kinetic energy (k.e.)**. The faster an object moves, the greater its k.e. We know this because we need to transfer energy to an object to get it moving, and we need to transfer more energy to get it moving faster. Also, if you stand in the path of a moving object so that it runs into you, it will move more slowly. It has transferred some of its energy to you.

If you lift an object upwards, you give it **gravitational potential energy (g.p.e.)**. The higher an object is above the ground, the greater its g.p.e. If you let the object fall, you can get the energy back again. This is exploited in many situations. The water stored behind a hydro-electric dam has g.p.e. As the water falls, it can be used to drive a turbine to generate electricity. A grandfather clock has weights that must be pulled upwards once a week. Then, as they gradually fall, they drive the pendulum to operate the clock's mechanism.

Fuels such as coal or petrol are stores of **chemical energy**. We know that a fuel is a store of energy because, when the fuel burns, the stored energy is released, usually as heat and light. There are many other stores of chemical energy (see Figure **6.4**). As we saw above,

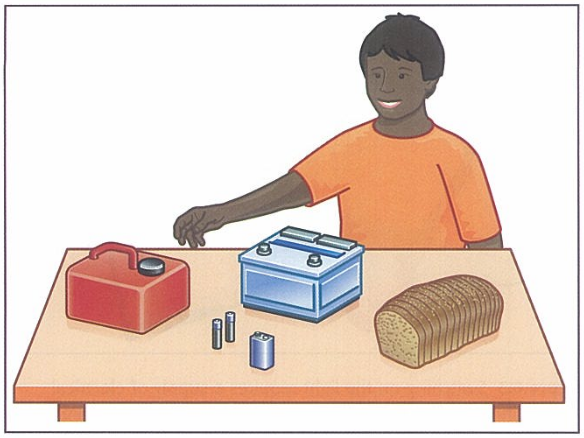

Figure 6.4 Some stores of chemical energy – petrol, batteries and bread. Our bodies have long-term stores of energy in the form of fatty tissues.

energy is stored by chemicals in our bodies. Batteries are also stores of energy. When a battery is part of a complete circuit, the chemicals start to react with one another and an electric current flows. The current carries energy to the other components in the circuit.

An electric current is a good way of transferring energy from one place to another. It carries **electrical energy**. When the current flows through a component such as a heater, it gives up some of its energy.

A close relation of chemical energy is **nuclear energy**. Uranium is an example of a nuclear fuel, which is a store of nuclear energy. All radioactive materials are also stores of nuclear energy. In these substances, the energy is stored in the nucleus of the atoms – the tiny positively charged core of the atom. A nuclear power station is designed to release the nuclear energy stored in uranium.

If you stretch a rubber band, it becomes a store of **strain energy**. The band can give its energy to a paper pellet and send it flying across the room. Strain energy is the energy stored by an object that has been stretched or squashed in an elastic way (so that it will spring back to its original dimensions when the stretching or squashing forces are removed). The metal springs of a car are constantly storing and releasing elastic energy as the car travels along, so that the occupants have a smoother ride. A wind-up clock stores energy in a spring, which is the energy source needed to keep its mechanism operating.

If you heat an object so that it gets hotter, you are giving energy to its atoms. The energy stored in a hot object is called **internal energy**. We can picture the atoms of a hot object jiggling rapidly about – they have a lot of energy. This picture is developed further in Chapter **9**.

If you get close to a hot object, you may feel **thermal (heat) energy** coming from it. This is energy travelling from a hotter object to a colder one. The different ways in which this can happen are described in Chapter **11**.

Very hot objects glow brightly. They are giving out **light energy**. Light radiates outwards all around the hot object.

Another way in which energy can be transferred to an object's surroundings is as **sound energy**. An electric current brings electrical energy to a loudspeaker – sound energy and some thermal energy are produced (see Figure **6.5**).

Energy stores, energy transfers

Energy can be stored in an object, or it can be transferred from one object to another. Table **6.1** lists the forms of energy described above under two headings, **energy stores** and **energy transfers**. An energy transfer is 'energy on the move', from one place to another.

Energy stores	Energy transfers
kinetic energy	electrical energy
gravitational potential energy	thermal (heat) energy
chemical energy	light energy
nuclear energy	sound energy
strain energy	
internal energy	

Table 6.1 Different forms of energy can be classified as stores or transfers.

Energy can be transferred from one object to another, or from place to place. (Remember that a 'ferry' transfers people from place to place.) Here are four different ways in which energy can be transferred:

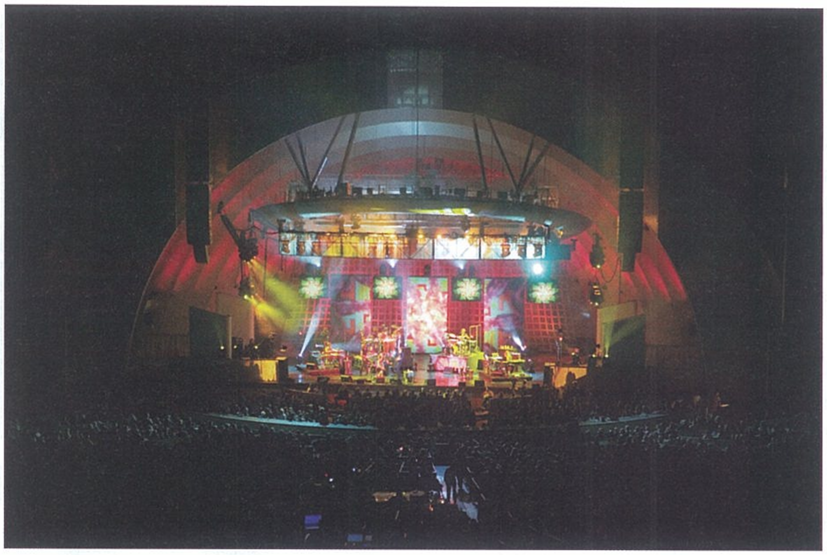

Figure 6.5 At a major rock concert, giant loudspeakers pour out sound energy to the audience. Extra generators may have to be brought on to the site to act as a source of electrical energy to power the speaker systems. Much of the energy supplied is wasted as heat energy, because only a fraction of the electrical energy is transformed into sound energy.

- **By a force.** If you lift something, you give it gravitational potential energy – you provide the force that lifts it. Alternatively, you can provide the force needed to start something moving – you give it kinetic energy. When energy is transferred from one object to another by means of a force, we say that the force is **doing work**. This is discussed in detail in Chapter **8**.
- **By heating.** We have already seen how thermal (heat) energy spreads out from hot objects. No matter how good the insulation, energy is transferred from a hot object to its cooler surroundings. This is discussed in detail in Chapter **11**.
- **By radiation.** Light reaches us from the Sun. That is how energy is transferred from the Sun to the Earth. Some of the energy is also transferred as infrared and ultraviolet radiation. These are all forms of **electromagnetic radiation** (see Chapter **15**).
- **By electricity.** An electric current is a convenient way of transferring energy from place to place. The electricity may be generated in a power station many kilometres away from where the energy is required. Alternatively, a torch battery provides the energy needed to light a bulb. Electricity transfers the energy from the battery to the bulb. This is covered in Chapter **19**.

QUESTIONS

1 What name is given to the energy of a moving object?
2 The Sun is a very hot object. Name **two** forms of energy that arrive at the Earth from the Sun.
3 What form of energy is stored by a stretched spring?
4 What do the letters g.p.e. stand for? How can an object be given g.p.e.?
5 Name a device that transforms electrical energy to sound energy. (It may also produce thermal (heat) energy.)
6 Name **three** forms of energy that are given out by a television set.
7 Look at the list of energy stores, shown in Table **6.1**. For each, give an example of an object or material that stores energy in this form.

6.2 Energy conversions

When energy changes from one form to another, we say that it has been **converted** or **transformed**. We have already mentioned several examples of **energy conversions**. Now we will look at a few more and think a little about the forms of energy that are involved.

The rocket in Figure **6.6a** is lifting off from the ground as it carries a new spacecraft up into space. Its energy comes from its store of fuel and oxygen. It carries tanks of liquid hydrogen. These are its store of chemical energy. When fuel burns, its store of energy is released.

The rocket is accelerating, so we can say that its kinetic energy is increasing. It is also rising upwards, so its gravitational potential energy is increasing. In Figure **6.6a**, you can see light coming from the burning fuel. You can also imagine that large amounts of thermal (heat) energy and sound energy are produced. This energy conversion is shown in Figure **6.6b**. We can also represent the conversion as an equation:

$$\text{chemical energy} \rightarrow \text{k.e.} + \text{g.p.e.} + \text{thermal energy} + \text{light energy} + \text{sound energy}$$

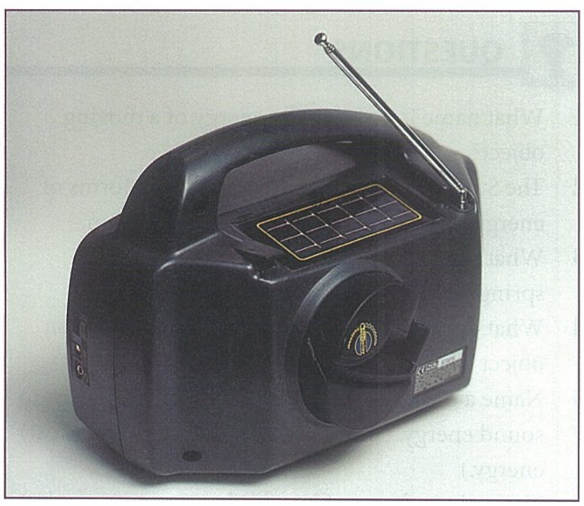

Figure 6.7 This clockwork radio is designed for use by people who do not have a ready supply of batteries or mains electricity. It operates from two alternative energy sources: a wound-up clockwork spring, and a solar cell. Since many users live in sunny parts of the world, a solar cell is a useful feature.

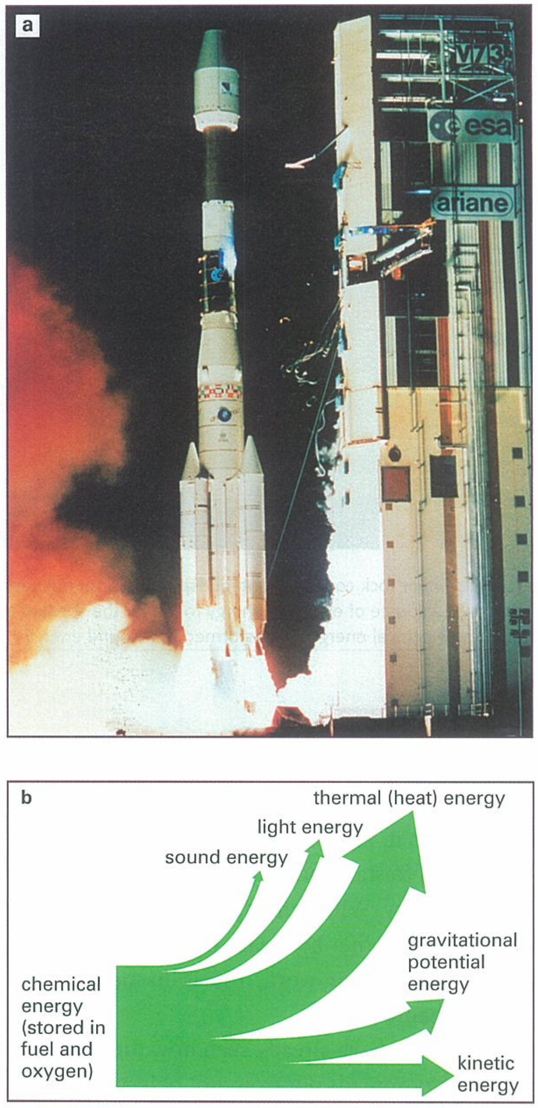

Figure 6.6 a This giant rocket uses rocket motors to lift it up into space. Each rocket motor burns about one tonne of fuel and oxygen every minute to provide the energy needed to move the rocket upwards. **b** This diagram represents the energy transformations going on as the rocket accelerates upwards. Chemical energy in the fuel and oxygen is transformed into five other forms of energy.

The clockwork radio (Figure **6.7**) is a famous invention. Where people do not have ready access to batteries or mains electricity, it allows them to listen to radio broadcasts with minimal running costs. The model shown in the photograph has an additional feature: a solar cell acts as an alternative energy source.

The wound-up spring of the clockwork mechanism is a store of elastic (strain) energy. The radio requires electrical energy to function. As the spring unwinds, it turns a generator. The elastic energy of the unwinding spring first becomes kinetic energy of the turning mechanism, and then electrical energy carried by the current to the radio. Finally, the energy is converted to sound energy. Along the way, energy is wasted as thermal (heat) energy. This is because no generator can convert all of the kinetic energy it is supplied with into electrical energy – some becomes thermal energy. Similarly, heat is produced by the electronic circuits of the radio, and by its loudspeaker. We can represent these conversions by an equation with several steps:

elastic energy → k.e.
→ electrical energy + thermal energy
→ sound energy + thermal energy

The solar cell converts light energy directly into electrical energy. Again, some energy is wasted as heat. The whole conversion then becomes:

light energy → electrical energy + thermal energy
→ sound energy + thermal energy

QUESTION

8 What energy conversions are going on in the following? In each case, write an equation to represent the conversion.

a Coal is burned to heat a room and to provide a supply of hot water.

b A student uses an electric lamp while she is doing her homework.

c A hairdryer is connected to the mains electricity supply. It blows hot air at the user's wet hair. It whirrs as it does so.

Activity 6.1 Energy conversions

Examine some devices that convert energy from one form to another. Can you decide what is going on?

6.3 Conservation of energy

When energy is transformed from one form to another, it is often the case that some of the energy ends up in a form that we do not want. The energy transformations in a light bulb were represented earlier in Figure **6.3**. The bulb produces light energy, which we do want, but also thermal (heat) energy, which we do not want. The rocket motor (see Figure **6.6**) transforms chemical energy into two forms that we do want (k.e. and g.p.e.) and three that we do not want (heat, light and sound).

Figure **6.8** shows an energy diagram for a car, driving along a flat road. Its source of energy is the petrol it burns, and the numbers show that the fuel supplies 80 kJ (kilojoules) every second. Some thermal energy escapes from the hot engine and in the exhaust gases. Some energy is wasted as heat produced by friction within the workings of the car. The rest is used in overcoming air resistance, another form of friction, so that the air is warmer after the car has passed through it.

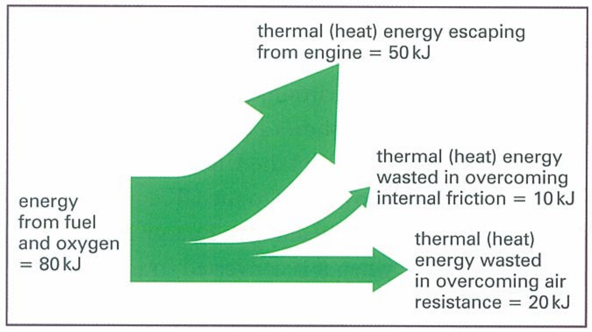

Figure 6.8 An energy diagram for a car, showing the energy converted by the car each second.

All of the energy supplied by the car's fuel ends up as thermal energy. If you add up the different amounts of thermal energy, you will see that they come to 80 kJ. This is an example of a very important idea, the **principle of conservation of energy**:

> In any energy conversion, the total amount of energy before and after the conversion is constant.

This tells us something very important about energy: it cannot be created or destroyed. The total amount of energy is constant. If we measure or calculate the amount of energy before a conversion, and again afterwards, we will always get the same result. If we find any difference, we must look for places where energy may be entering or escaping unnoticed.

Keeping an eye on the amounts of energy is rather like a form of book-keeping or accounting. Energy is like money: the amounts entering a system must equal the amounts leaving it, or stored within it.

QUESTION

9 A light bulb is supplied with 100 J of energy each second.

a How many joules of energy leave the bulb each second in the form of heat and light?

b If 10 J of energy leave the lamp each second in the form of light, how many joules leave each second in the form of heat?

Energy efficiency

Energy is expensive, and we do not want to waste it. Using more energy than necessary increases the damage we do to the environment, so it is important to avoid waste. Figure **6.9** shows a diagram that represents energy flows in the whole of the UK in one typical year. Most of the energy flowing in to the UK comes from fuels, particularly coal, oil and gas. Energy is wasted in two general ways: when it is converted (transformed)

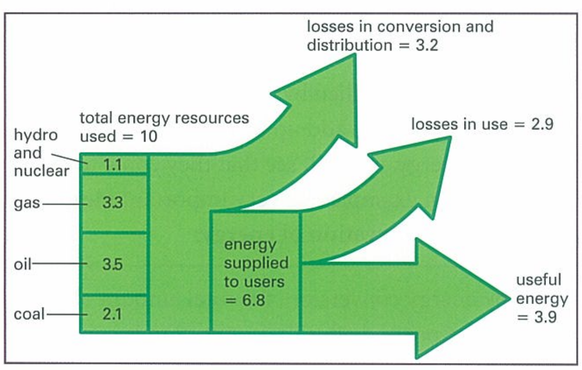

Figure 6.9 A diagram showing energy flows in the UK in a typical year, 2000. (All numbers are $\times 10^{18}$ J.) A large proportion of the energy supplied by fuels is wasted in conversion processes and in its final use. Some of this waste is inevitable, but better insulation and more efficient machines could reduce the waste and environmental damage, and save money.

into electricity, and when it is used (for example, in light bulbs).

Most wasted energy ends up as thermal (heat) energy. There are two main reasons for this:

- When fuels are burned (perhaps to generate electricity, or to drive a car), heat is produced as an intermediate step. Hot things readily lose energy to their surroundings, even if they are well insulated. Also, engines and boilers have to lose heat as part of the way they operate: power stations produce warm cooling water; and cars produce hot exhaust gases.
- Friction is very often a problem when things are moving. Lubrication can help to reduce friction, and a streamlined design can reduce air resistance. But it is impossible to eliminate friction entirely from machines with moving parts. Friction generates heat.

Another common form of wasted energy is sound. Noisy machinery, loud car engines and so on are all wasting energy. However, loud noises do not contain very much energy, so there is little to be gained (in terms of energy) by reducing noise. Waste energy in the form of heat and sound is sometimes referred to as low-grade energy.

Making better use of energy

It is important to make good use of the energy resources available to us. This is because energy is expensive, supplies are often limited, and our use of energy can damage the environment. So we must use resources efficiently. Here is what we mean by **efficiency**:

> The efficiency of an energy conversion is the fraction of the energy that ends up in the desired form.

Figure **6.10** shows one way to make more efficient use of electricity. It shows two types of light bulb and the energy they use each second. One is a filament lamp, and the other is an energy-efficient lamp. We use light bulbs to provide us with light. The diagrams show that each of the two bulbs produces the same amount of light energy. However, the energy-efficient lamp requires a much smaller input of electrical energy because it wastes much less energy as heat.

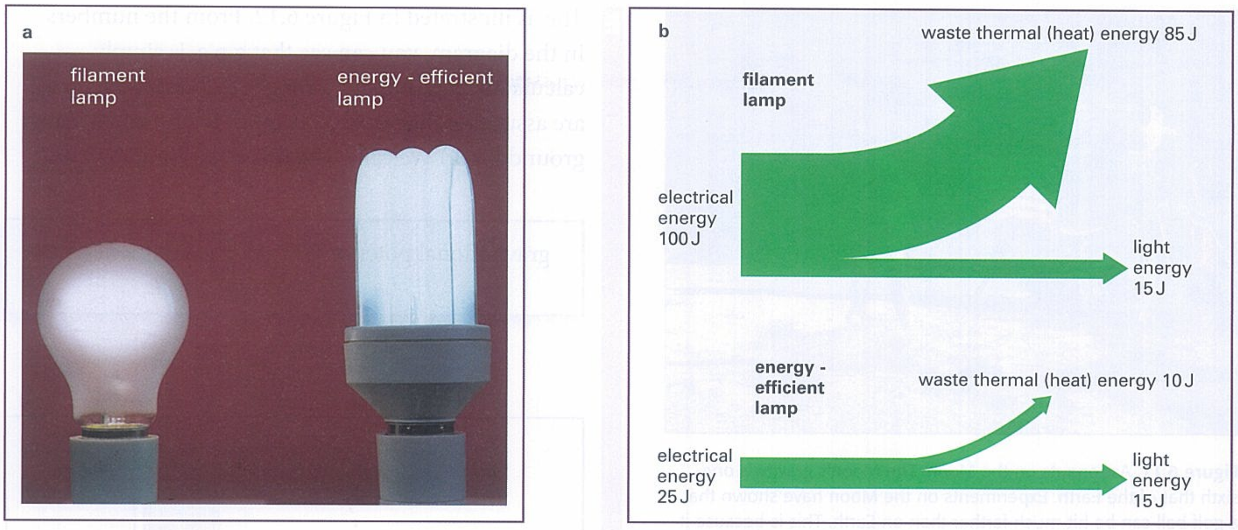

Figure 6.10 **a** Each of these two light bulbs provides the same amount of light. **b** The energy-efficient lamp (on the right) wastes much less energy as heat.

Device	Typical efficiency
electric heater	100%
large electric motor	90%
washing machine motor	70%
gas-fired power station	50%
diesel engine	40%
car petrol engine	30%
steam locomotive	10%

Table 6.2 Energy efficiencies. Most devices are less than 100% efficient because they produce waste heat. An electric heater is 100% efficient because all of the electrical energy supplied is transformed to heat. There is no problem about waste here!

Table 6.2 shows the typical efficiencies for some important devices. You can see that even the most modern gas-fired power station is only 50% efficient. Half of the energy it is supplied with is wasted.

QUESTIONS

10 a What is the most common form of waste energy?

b Name another form in which energy is often wasted.

11 Why is it important not to waste energy? Give three reasons.

E

Calculating efficiency

You can see from Table 6.2 that efficiency is often given as a percentage. We can calculate the percentage efficiency of an energy change as follows:

$$\text{efficiency} = \frac{\text{useful energy output}}{\text{energy input}} \times 100\%$$

When the filament lamp shown in Figure 6.10 is supplied with 100 J of electrical energy, it produces 15 J of useful light energy. Its efficiency is thus

$$\text{efficiency of filament lamp} = \frac{15}{100} \times 100\% = 15\%$$

QUESTIONS

12 Calculate the efficiency of the energy-efficient lamp shown in Figure 6.10.

13 A coal-fired power station produces 100 MJ of electrical energy when it is supplied with 400 MJ of energy from its fuel. Calculate its efficiency.

14 A lamp is 10% efficient. How much electrical energy must be supplied to the lamp each second if it produces 20 J of light energy per second?

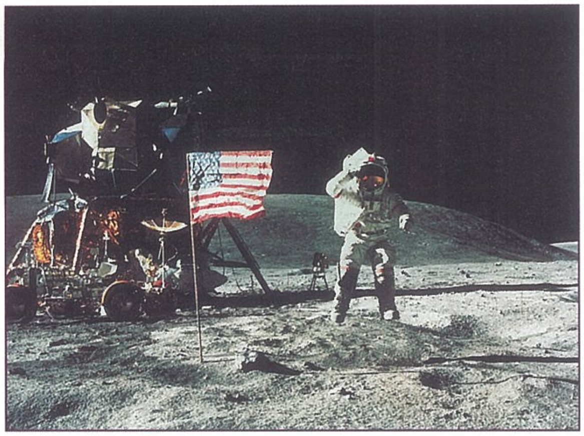

Figure 6.11 Astronauts on the Moon. The Moon's gravity is one-sixth that of the Earth. Experiments on the Moon have shown that a golf ball can be hit much farther than on Earth. This is because it travels a much greater distance horizontally before gravity pulls it back to the ground.

6.4 Energy calculations

Energy is not simply an idea, it is also a quantity that we can calculate.

Gravitational potential energy

Mountaineering on the Moon should be easy (see Figure **6.11**). The Moon's gravity is much weaker than the Earth's, because the Moon's mass is only one-eightieth of the Earth's. This means that the weight of an astronaut on the Moon is a fraction of his or her weight on the Earth. In principle, it is possible to jump six times as high on the Moon. Unfortunately, because an astronaut has to carry an oxygen supply and wear a cumbersome suit, this is not possible.

Earlier, we saw that an object's gravitational potential energy (g.p.e.) depends on its height above the ground. The higher it is, the greater its g.p.e. If you lift an object upwards, you provide the force needed to increase its g.p.e. The heavier the object, the greater the force needed to lift it, and hence the greater its g.p.e.

This suggests that an object's **gravitational potential energy** depends on two factors:

- the object's weight mg – the greater its weight, the greater its g.p.e.
- the object's height h above ground level – the greater its height, the greater its g.p.e.

This is illustrated in Figure **6.12**. From the numbers in the diagram, you can see that g.p.e. is simply calculated by multiplying weight by height. (Here, we are assuming that an object's g.p.e. is zero when it is at ground level.) We can write this as an equation:

$$\text{gravitational potential energy} = \text{weight} \times \text{height}$$
$$\text{g.p.e.} = mg \times h$$

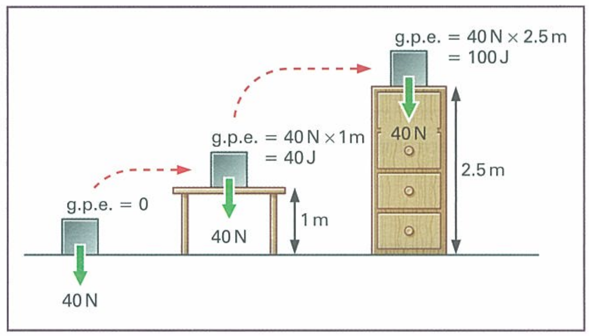

Figure 6.12 The gravitational potential energy of an object increases as it is lifted higher. The greater its weight, the greater its g.p.e.

Worked example 1

An athlete of mass 50 kg runs up a hill. The foot of the hill is 400 m above sea-level. The summit is 1200 m above sea-level. By how much does the athlete's g.p.e. increase? (Acceleration due to gravity $g = 10\,\text{m/s}^2$.)

Step 1: Assume that g.p.e. is zero at the foot of the hill. Calculate the increase in height.

$$h = 1200\,\text{m} - 400\,\text{m} = 800\,\text{m}$$

Step 2: Write down the equation for g.p.e., substitute values and solve.

$$\begin{aligned}\text{g.p.e.} &= \text{weight} \times \text{height}\\ &= mg \times h\\ &= 50\,\text{kg} \times 10\,\text{m/s}^2 \times 800\,\text{m}\\ &= 400\,000\,\text{J}\\ &= 400\,\text{kJ}\end{aligned}$$

So the athlete's g.p.e. increases by 400 kJ.

A note on height

We have to be careful when measuring or calculating the change in an object's height.

First, we have to consider the **vertical** height through which it moves. A train may travel 1 km up a long and gentle slope, but its vertical height may only increase by 10 m. A satellite may travel around the Earth in a circular orbit. It stays at a constant distance from the centre of the Earth, and so its height does not change. Its g.p.e. is constant.

Second, it is the change in height of the object's centre of gravity that we must consider. This is illustrated by the high-jumper shown in Figure **6.13**. As he jumps, he must try to increase his g.p.e. enough to get over the bar. In fact, by curving his body, he passes over the bar but his centre of gravity may pass under it.

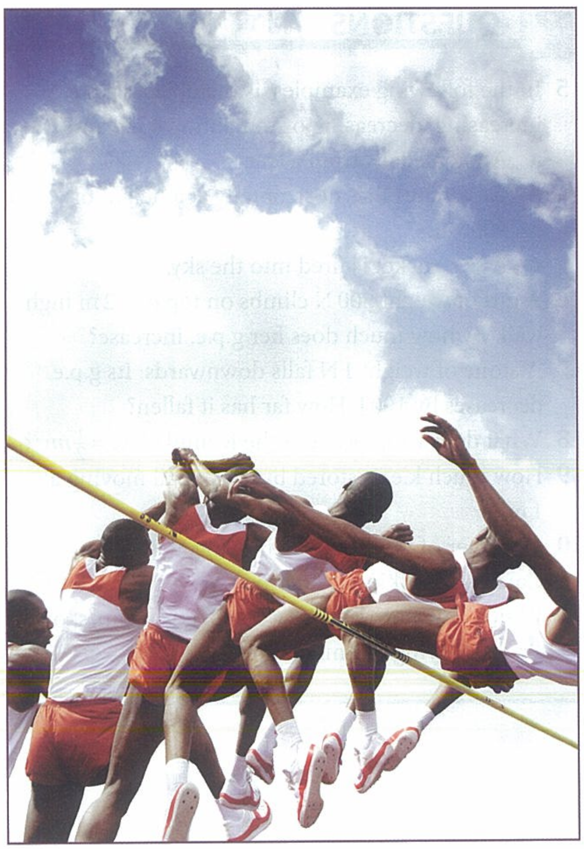

Figure 6.13 This high-jumper adopts a curved posture to get over the bar. He cannot increase his g.p.e. enough to get his whole body above the level of the bar. His centre of gravity may even pass under the bar, so that at no time is his body entirely above the bar.

Kinetic energy

It takes energy to make things move. You transfer energy to a ball when you throw it or hit it. A car uses energy from its fuel to get it moving. Elastic energy stored in a stretched piece of rubber is needed to fire a pellet from a catapult. So a moving object is a store of energy. This energy is known as kinetic energy (k.e.).

We often make use of an object's kinetic energy. To do this, we must slow it down. For example, moving air turns a wind turbine. This slows down the air, reducing its k.e. The energy extracted can be used to turn a generator to produce electricity.

This suggests that the **kinetic energy** of an object depends on two factors:

- the object's mass m – the greater the mass, the greater its k.e.
- the object's speed v – the greater the speed, the greater its k.e.

These are combined in a formula for k.e.:

$$\text{kinetic energy} = \frac{1}{2} \times \text{mass} \times \text{speed}^2$$
$$\text{k.e.} = \frac{1}{2}mv^2$$

Worked example **2** shows how to use the formula to calculate the k.e. of a moving object. Note also that kinetic energy (like all forms of energy) is a scalar quantity, despite the fact that it involves v. It is best to think of v here as **speed** rather than velocity.

Worked example 2

A van of mass 2000 kg is travelling at 10 m/s. Calculate its kinetic energy. If its speed increases to 20 m/s, by how much does its kinetic energy increase?

Step 1: Calculate the van's k.e. at 10 m/s.

$$\begin{aligned}\text{k.e.} &= \frac{1}{2}mv^2\\ &= \frac{1}{2} \times 2000\,\text{kg} \times (10\,\text{m/s})^2\\ &= 100\,000\,\text{J}\\ &= 100\,\text{kJ}\end{aligned}$$

E

Step 2: Calculate the van's k.e. at 20 m/s.

$$\text{k.e.} = \tfrac{1}{2}mv^2$$
$$= \tfrac{1}{2} \times 2000\,\text{kg} \times (20\,\text{m/s})^2$$
$$= 400\,000\,\text{J}$$
$$= 400\,\text{kJ}$$

Step 3: Calculate the change in the van's k.e.

$$\text{change in k.e.} = 400\,\text{kJ} - 100\,\text{kJ}$$
$$= 300\,\text{kJ}$$

So the van's k.e. increases by 300 kJ when it speeds up from 10 m/s to 20 m/s.

Comments on Worked example 2

It is worth looking at Worked example 2 in detail, since it illustrates several important points.

When calculating k.e. using $\frac{1}{2}mv^2$, take care! Only the speed is squared. Using a calculator, start by squaring the speed. Then multiply by the mass, and finally divide by 2.

When the van's speed doubles from 10 m/s to 20 m/s, its k.e. increases from 100 kJ to 400 kJ. In other words, when its speed increases by a factor of 2, its k.e. increases by a factor of 4. This is because k.e. depends on speed squared. If the speed trebled (increased by a factor of 3), the k.e. would increase by a factor of 9 (see Figure **6.14**).

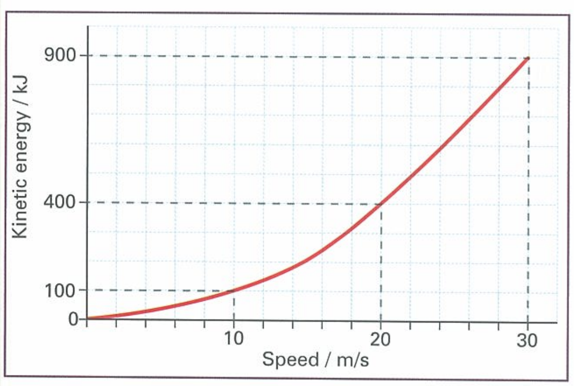

Figure 6.14 The faster the van travels, the greater its kinetic energy – see Worked example **2**. Double the speed means four times the kinetic energy, because k.e. depends on speed². The graph shows that k.e. increases more and more rapidly as the van's speed increases.

E

When the van starts moving from rest and speeds up to 10 m/s, its k.e. increases from 0 to 100 kJ. When its speed increases by the same amount again, from 10 m/s to 20 m/s, its k.e. increases by 300 kJ, three times as much. It takes a lot more energy to increase your speed when you are already moving quickly. That is why a car's fuel consumption starts to increase rapidly when the driver tries to accelerate in the fast lane of a motorway.

Activity 6.2 Running downhill

When a toy car runs downhill, g.p.e. changes to k.e. Can you test this idea?

QUESTIONS

15 In the following examples, is the object's g.p.e. increasing, decreasing or remaining constant?
- **a** An apple falls from a tree.
- **b** An aircraft flies horizontally at a height of 9000 m.
- **c** A sky-rocket is fired into the sky.

16 A girl of weight 500 N climbs on top of a 2 m high wall. By how much does her g.p.e. increase?

17 A stone of weight 1 N falls downwards. Its g.p.e. decreases by 100 J. How far has it fallen?

18 What does v represent in the formula k.e. $= \frac{1}{2}mv^2$?

19 How much k.e. is stored by a 1 kg ball moving at 1 m/s?

20 A runner of mass 80 kg is moving at 8 m/s. Calculate her kinetic energy.

21 Which has more k.e., a 2 g bee flying at 1 m/s, or a 1 g wasp flying at 2 m/s?

Summary

Energy can be converted from one form to another.

In any energy conversion, the total amount of energy before the conversion is equal to the total amount after the conversion. This is the principle of conservation of energy.

Energy can be transferred from place to place, or from one object to another, by a variety of means.

In energy conversions, some energy often appears in forms that are not wanted, particularly as waste heat.

Energy efficiency indicates the fraction of the input energy that ends up in a useful form.

E

Gravitational potential energy g.p.e. = $mg \times h$.

Kinetic energy k.e. = $\frac{1}{2}mv^2$.

End-of-chapter questions

6.1 What name is given to:

a the energy of a moving object? [1]

b the energy stored in a fuel? [1]

c the energy stored in a hot object? [1]

6.2 What are the energy conversions in the following? Write an equation for each.

a A glow-worm is an insect that glows in the dark. Chemicals in its body react together to produce light and heat. [2]

b An electric motor is used to start a computer's disk drive spinning round. [2]

c A wind turbine spins and generates electricity. [2]

d Friction in a car's brakes slows it down. [2]

6.3 A light bulb is supplied with 100 J of electrical energy each second. It produces 7 J of light energy and 93 J of thermal (heat) energy. Explain how this shows that energy is conserved. [3]

6.4 The girl on the skate ramp (Figure 6.15) roller-skates down one side of the slope and up the opposite side. She cannot quite reach the top of the slope, level with her starting position.

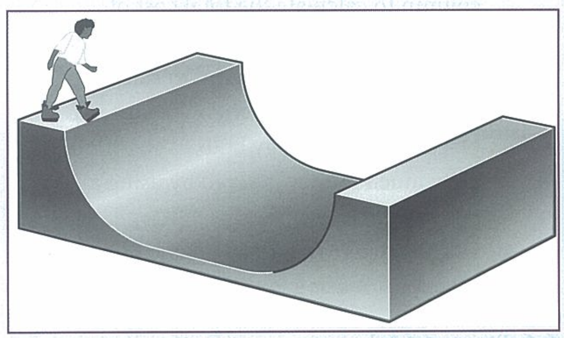

Figure 6.15 For Question **6.4**.

a What energy conversion is taking place as the girl moves downwards? [2]

b What energy conversion is taking place as the girl moves back upwards? [2]

c Explain why the girl cannot reach the top of the slope. [2]

d Suggest how the girl could reach the top of the slope. [2]

E

6.5 Low-energy light bulbs are designed to save energy, but do they also save money? An individual low-energy bulb is more expensive than the filament bulb it replaces. However, it lasts for much longer, typically 10 000 hours. Table **6.3** shows typical costs in pence (p).

	Low-energy bulb	Filament bulbs
cost of one bulb	400 p	50 p
number of bulbs required for 10 000 hours	1	10
cost of electricity for 1 hour	0.2 p	1.0 p
total cost of electricity for 10 000 hours	……	……
total cost of bulbs and electricity	……	……

Table 6.3 For Question **6.5**.

a Copy the table and complete the second column to calculate the total cost of using a low-energy bulb for 10 000 hours. [2]

b Complete the third column to calculate the cost of using filament bulbs instead of a single low-energy bulb. [2]

c How much money is saved by using a low-energy bulb? [2]

d Suggest **two** reasons that people might have for not using low-energy bulbs. [2]

6.6 Figure **6.16** shows a power station that burns rubbish to generate electricity. It also supplies hot water to nearby offices and shops.

a What **two** useful energy forms are produced? [2]

b What waste energy is produced? [1]

c Is this an efficient use of energy? Explain your answer using information from the diagram. [2]

E

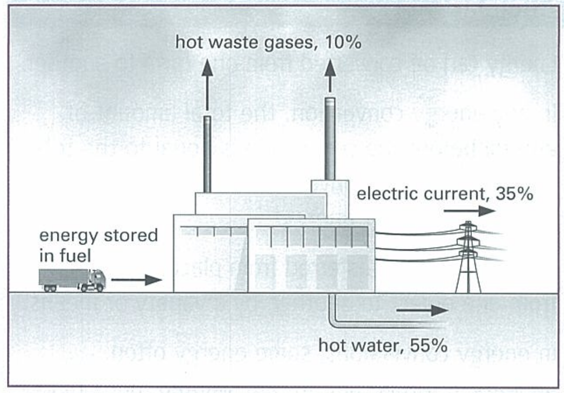

Figure 6.16 For Question **6.6**.

6.7 Figure **6.17** shows an idea for a perpetual motion machine. The car runs on electricity. As it moves along, the air moving past the car turns the generator on the roof. This generates the electricity needed to power the car.

Figure 6.17 For Question **6.7**.

a Explain the energy transformations that are going on here. [2]

b Explain why this idea will not work in practice. [2]

6.8 An astronaut on the Moon has a mass (including his spacesuit and equipment) of 180 kg. The acceleration due to gravity on the Moon's surface is 1.6 m/s^2.

a Calculate the astronaut's weight on the Moon. [3]

The astronaut climbs 100 m to the top of a crater.

b By how much does his gravitational potential energy (g.p.e.) change? [3]

c Does his g.p.e. increase or decrease? [1]

7 Energy resources

Core Identifying and describing energy resources

E Extension Understanding the Sun's energy source

7.1 The energy we use

Here on Earth, we rely on the Sun for most of the energy we use. The Sun is a fairly average star, 150 million kilometres away. The heat and light we receive from it have taken about eight minutes to travel through empty space to get here. Plants absorb this energy in the process of photosynthesis, and animals are kept warm by it.

The Earth is at a convenient distance from the Sun for living organisms. The Sun's rays are strong enough, but not too strong. The Earth's average temperature is about 15 °C, which is suitable for life. If we were closer to the Sun, we might be intolerably hot like Venus, where the average surface temperature is over 400 °C. Further out, things are colder. Saturn is roughly ten times as far from the Sun, so the Sun in the sky looks one-tenth of the diameter that we see it, and its radiation has only one-hundredth of the intensity. Saturn's surface temperature is about −180 °C.

Most of the energy we use comes from the Sun, but only a very little is used directly from the Sun. On a cold but sunny morning, you might sit in the sunshine to warm your body. Your house might be designed to collect warmth from the Sun's rays, perhaps by having larger windows on the sunny side. However, most of the energy we use comes only indirectly from the Sun. It must be converted into a more useful form, such as electricity (Figure 7.1).

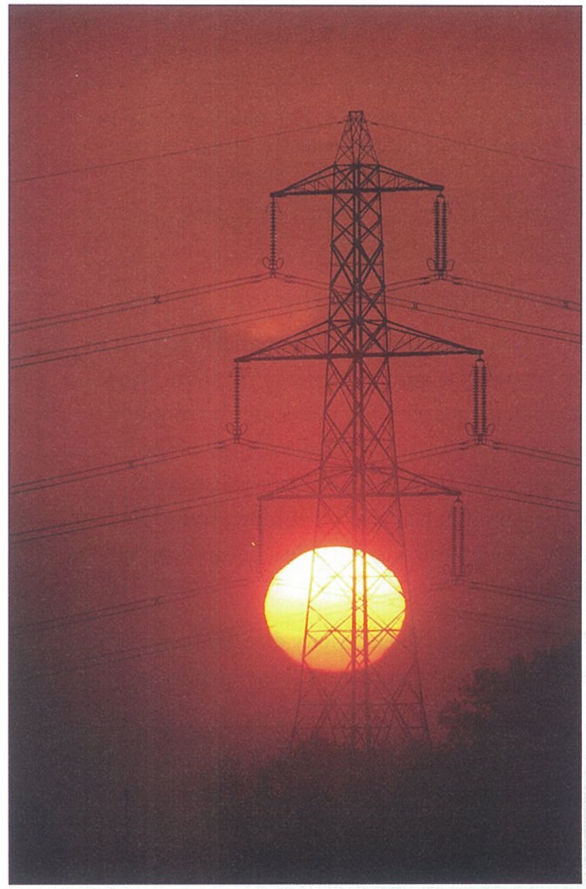

Figure 7.1 We use energy from the Sun in many different ways – for example, for producing electricity.

Figure 7.2 is a chart showing the different fuels that contribute to the world's energy supplies. This chart reflects patterns of energy consumption in the early years of the 21st century. Many people today live in industrialised countries and consume large amounts of energy, particularly from fossil fuels (coal, oil and gas). People living in less-developed countries consume far less energy – mostly they use biomass fuels, particularly wood. A thousand years ago, the chart would have looked very different. Fossil fuel consumption was much less important then. Most people relied on burning wood to supply their energy requirements. We will now look at these groups of fuels in turn.

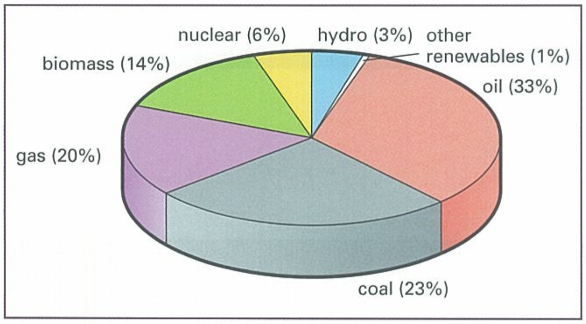

Figure 7.2 World energy use, by fuel. This chart shows the contributions made by different fuels to energy consumption by people in 2006, across the world. Three-quarters of all energy is from fossil fuels.

Energy direct from the Sun

In hot, sunny countries, **solar panels** are used to collect thermal (heat) and light energy from the Sun. The Sun's rays fall on a large solar panel, on the roof of a house, for example. This absorbs the energy of the rays, and water inside the panel heats up. This provides hot water for washing. It can also be pumped round the house, through radiators, to provide a cheap form of central heating.

We can also make electricity directly from sunlight (Figure 7.3). The Sun's rays shine on a large array of

Figure 7.3 This array of solar cells provide electricity for a water pump in a Kenyan village.

solar cells (also known as a **photocells**). The energy of the rays is absorbed, and electricity is produced. As this technology becomes cheaper, it is finding more and more uses. It is useful in remote locations – for example, for running a refrigerator that stores medicines in central Africa, or for powering roadside emergency phones in desert regions such as the Australian outback. Solar cells have also been used extensively for powering spacecraft. Ideally, a solar cell is connected to a rechargeable battery, which stores the energy collected, so that it can be available during the hours of darkness.

Wind and wave power

Wind and waves are also caused by the effects of the Sun. The Sun heats some parts of the atmosphere more than others. Heated air expands and starts to move around – this is a convection current (see Chapter 11). This is the origin of winds. Most of the energy of winds is given up to the sea as waves are formed by friction between wind and water. There are many technologies for extracting energy from the wind. Windmills for grinding and pumping are traditional, and modern wind turbines can generate electricity (see Figure 7.4).

Figure 7.4 These giant turbines are part of a wind farm at Xinjiang in China. They produce as much electricity as a medium-sized coal-fired power station.

Wave technology is trickier. The up-and-down motion of waves must be used to spin a turbine, which then turns a generator. This is tricky to achieve, and rough seas are a hazardous place to work. On calm days, the system produces no power.

QUESTIONS

1 Explain why wind and wave power could not be relied on to provide a country's entire electricity supply.

2 A photovoltaic cell produces electricity when the Sun shines. What energy conversion is going on here?

3 When a wave travels across the sea, the water moves up and down. What two forms of energy does a wave have?

Biomass fuels

For many people in the world, wood is the most important fuel. It warms their homes and provides the heat necessary for cooking their food. Wood is made by trees and shrubs. It stores energy that the plant has captured from sunlight in the process of photosynthesis. When we burn wood, we are releasing energy that came from the Sun in the recent past, perhaps ten or a hundred years ago.

Wood is just one example of a **biomass fuel**. Others include animal dung and biogas, generated by rotting vegetable matter. These can be very important fuels in societies where most people live by farming. As you can see from Figure 7.2, biomass fuels account for about one-seventh of all energy consumption in the world. This figure can only be a rough estimate, because no-one keeps track of all the wood consumed as fuel. However, we can say that this segment of the chart represents the energy consumption of about three-quarters of the world's population. The remaining one-quarter (who live in developed, industrial nations) consume roughly six times as much.

Fossil fuels

Oil, coal and gas are all examples of **fossil fuels**. These are usually hydrocarbons (compounds of hydrogen and carbon). When they are burned, they combine with oxygen from the air. In this process, the carbon becomes carbon dioxide. The hydrogen becomes 'hydrogen oxide', which we usually call water. Energy is released.

We can write this as an equation:

hydrocarbon + oxygen
→ carbon dioxide + water + energy

Hence, we can think of a fossil fuel as a store of energy. They store energy as chemical energy. Where has this energy come from?

Fossil fuels (Figure 7.5) are the remains of organisms (plants and animals) that lived in the past. Many of the Earth's coal reserves, for example, formed from trees that lived in the Carboniferous era, between 286 and 360 million years ago. ('Carboniferous' means 'coal-producing'.) These trees captured sunlight by photosynthesis, they grew and eventually they died. Their trunks fell into the swampy ground, but they did not rot completely, because there was insufficient oxygen.

Figure 7.5 Coal is a fossil fuel. A fossil is any living material that has been preserved for a long time. Usually, its chemical composition changes during the process. Coal sometimes, as here, shows evidence of the plant material from which it formed. Sometimes you can see fossilised creatures that lived in the swamps of the Carboniferous era. These creatures died along with the trees that eventually became coal.

As material built up on top of these ancient trees, the pressure on them increased. Eventually, millions of years of compression turned them into underground reserves of coal (see Figure 7.5). Today, when we burn coal, the light that we see and the warmth that we feel have their origins in the sunlight trapped by trees hundreds of millions of years ago.

Oil and gas are usually found together. They are formed in a similar way to coal, but from the remains of tiny shrimp-like creatures called microplankton that lived in the oceans. The oilfields of the Persian Gulf, North Africa and the Gulf of Mexico, which contain half of the world's known oil reserves, all formed in the Cretaceous era, 75 to 120 million years ago.

QUESTIONS

4 **a** Name **three** fossil fuels.
  b Name **three** non-fossil fuels.
5 What energy conversion is happening when charcoal is used as the fuel for a barbecue?

Nuclear fuels

Nuclear power was developed in the second half of the 20th century. It is a very demanding technology, which requires very strict controls, because of the serious damage that can be caused by an accident.

The fuel for a nuclear power station (Figure 7.6) is usually uranium, sometimes plutonium. These are radioactive materials. Inside a nuclear reactor, their radioactive decay is speeded up so that the energy they store is released much more quickly. This is the process of **nuclear fission**.

Uranium is a very concentrated store of energy in the form of nuclear energy. A typical nuclear power station will receive about one truckload of new fuel each week. Coal is less concentrated. A similar coal-fired power station is likely to need a whole trainload of coal every hour. A wind farm capable of generating electricity at the same rate would cover a large area of ground – perhaps 20 square kilometres.

Figure 7.6 This nuclear power station generates electricity. Its fuel is uranium. As the fuel is used up, highly radioactive waste products are produced. These have to be dealt with very carefully to avoid harm to the surroundings. Here, checks are being carried out to ensure that the level of radioactive materials near the power station is safe.

In some countries that have few other resources for generating electricity, nuclear power provides a lot of energy. In France, for example, nuclear power stations generate three-quarters of the country's electricity. Excess production is exported to neighbouring countries, including Spain, Switzerland and the UK.

Nuclear fuel is a relatively cheap, concentrated energy resource. However, nuclear power has proved to be expensive because of the initial cost of building the power stations, and the costs of disposing of the radioactive spent fuel and decommissioning the stations at the end of their working lives.

Water power

One of the smallest contributions to the chart in Figure 7.2 is water or **hydro-power**. For centuries, people have used the kinetic energy of moving water to turn water-wheels, which then drive machinery of all sorts – for example, to grind corn and other crops, pump water and weave textiles. Today, water power's biggest contribution is in the form of hydro-electricity (see Figure 7.7). Water stored behind a dam is released to turn turbines, which make generators spin. This is a very safe, clean and reliable way of producing electricity, but it is not without its problems. A new reservoir floods land that might otherwise have been used for hunting or farming. People may be made homeless, and wildlife habitats destroyed.

Figure 7.7 The giant Itaipú Dam on the Paraná river generates electricity for Brazil and Paraguay.

Most hydro-power comes ultimately from the Sun. The Sun's rays cause water to evaporate from the oceans and land surface. This water vapour in the atmosphere eventually forms clouds at high altitudes. Rain falls on high ground, and can then be trapped behind a dam. This is the familiar **water cycle**. Without energy from the Sun, there would be no water cycle and much less hydro-power.

A small amount of hydro-power does not depend on the Sun's energy. Instead, it is generated from the tides. The Moon and the Sun both contribute to the oceans' tides. Their gravitational pull causes the level of the ocean's surface to rise and fall every twelve-and-a-bit hours. At high tide, water can be trapped behind a dam. Later, at lower tides, it can be released to drive turbines and generators. Because this depends on gravity, and not the Sun's heat and light, we can rely on tidal power even at night and when the Sun is not shining.

Geothermal energy

The interior of the Earth is hot. This would be a useful source of energy – if we could get at it! People do make use of this **geothermal energy** where hot rocks are found at a shallow depth below the Earth's surface. (These rocks are hot because of the presence of radioactive substances inside the Earth.) To make use of this energy, water is pumped down into the rocks, where it boils. High-pressure steam returns to the surface, where it can be used to generate electricity.

Suitable hot underground rocks are usually found in places where there are active volcanoes. Iceland, for example, has several geothermal power stations. These also supply hot water to heat nearby homes and buildings.

QUESTIONS

6 Name **three** energy resources for which the original energy source is not radiation from the Sun.

7 What energy conversion happens when a nuclear power station uses uranium fuel to produce electricity?

Renewables and non-renewables

Figure 7.2 on page 70 shows that most of the energy supplies we use are fossil fuels – coal, oil and gas. There are limited reserves of these, so that, if we continue to use them, they will one day run out. They are described as **non-renewables**. Once used, they are gone for ever.

Other sources of energy, such as wind, solar and biomass, are described as **renewables**. This is because, when we use them, they will soon be replaced. The wind will blow again, the Sun will shine again – and, after harvesting a biomass crop, we can grow another.

Ideally, we should develop an 'energy economy' based on renewables. Then we would not have to worry about supplies that will run out. We would also avoid the problems of global warming and climate change.

Comparing energy sources

We use fossil fuels a lot because they represent concentrated sources of energy. A modern gas-fired power station might occupy the space of a football ground and supply a town of 100 000 people. To replace it with a wind farm might require 50 or more wind turbines spread over an area of several square kilometres – the wind is a dilute source of energy.

This illustrates some of the ideas that we use when comparing different energy sources. If you look back through this chapter, you will find many comments about different energy sources. Each has its advantages and disadvantages. We need to think about the following factors:

- **Cost.** We should separate initial costs from running costs. A solar cell is expensive to buy but there are no costs for fuels – sunlight is free!
- **Reliability.** Is the energy supply constantly available? The wind is variable, so wind power is unreliable. Wars and trade disputes can interrupt fuel supplies.
- **Scale.** As discussed above, a fossil-fuel power station can be compact and still supply a large population. It would take several square metres of solar panels to supply a small household.
- **Environmental impact.** The use of fossil fuels leads to climate change. A hydro-electric dam may flood useful farmland. Every energy source has some effect on the environment.

Activity 7.1 Renewables versus non-renewables

Explain why some energy resources are described as 'renewables'.

Why should we make more use of renewables, and what are their problems?

Activity 7.2 Future energy

Make a plan for a world that does not rely on fossil fuels for most of its energy.

QUESTION

8 Explain whether the following energy sources are renewable or non-renewable:

a uranium-fuelled nuclear power

b wave power.

7.2 Fuel for the Sun

The Sun releases vast amounts of energy, but it is not burning fuel in the same way as we have seen for fossil fuels. The Sun consists largely of hydrogen, but there is no oxygen to burn this gas. Instead, energy is released in the Sun by the process of **nuclear fusion**. In fusion, two energetic hydrogen atoms collide and fuse (join up) to form an atom of helium.

Nuclear fusion requires very high temperatures and pressures. The temperature inside the Sun is close to 15 million degrees. The pressure is also very high, so that hydrogen atoms are forced very close together, allowing them to fuse.

Scientists and engineers would like to be able to make fusion happen in a similar way here on Earth. Experimental reactors have been built, but it is very tricky to create the necessary conditions for fusion to happen in a controlled way. Perhaps, one day, fusion will prove a safe, clean way of producing a reliable electricity supply.

Summary

Most of our energy comes, directly or indirectly, from the Sun.

Useful energy resources include heat and light from the Sun, biomass and fossil fuels, water, wind, nuclear fuels and geothermal energy.

These energy resources are often used to produce electricity or other useful forms of energy.

A renewable energy resource is replaced after it has been used. When a non-renewable resource is used, it is gone forever.

The Sun releases energy by the fusion of hydrogen to form helium.

End-of-chapter questions

7.1 Explain how the following energy resources rely on energy from the Sun:

a biomass fuel, such as wood [2]

b electricity from a hydro-electric power station. [3]

7.2 Electricity supplied by solar cells is expensive. This is because, although sunlight is free, the cells themselves are expensive to produce.

a Explain why solar cells are a suitable choice for powering a spacecraft but are less likely to be used for providing domestic electricity to consumers in a city such as London, Dubai or Hong Kong. [3]

b Suggest **one** other situation in which solar cells would be a good choice, and justify your suggestion. [2]

c Why are solar cells often used in conjunction with a battery? [2]

7.3 In a hydro-electric power station, water is stored behind a dam. It flows down past a turbine, so that the turbine spins. This causes a generator to turn and produce electricity.

a What form of energy is stored by the water when it is behind the dam? [1]

b What form of energy does the spinning turbine have? [1]

c Write down the **two** energy transformations that occur in a hydro-electric power station. [2]

E

7.4 Fission and fusion are two nuclear processes that release energy.

a **i** Which is used in a nuclear power station? [1]

ii What is the fuel used for this? [1]

b **i** Which is the Sun's energy source? [1]

ii What element is the fuel? [1]

iii What element is produced? [1]

8 Work and power

Core Understanding the ideas of work and power
E Extension Calculating work and power

8.1 Doing work

Figure 8.1 shows one way of lifting a heavy object. Pulling on the rope raises the heavy box. As you pull, the force on the box moves upwards.

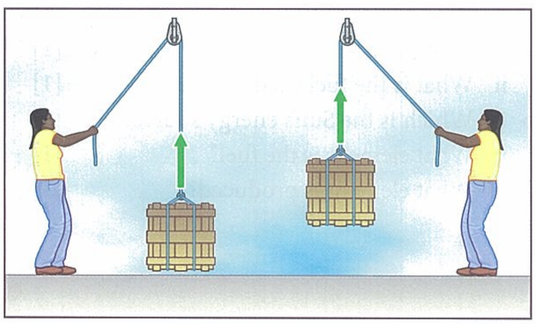

Figure 8.1 Lifting an object requires an upward force, pulling against gravity. As the box rises upwards, the force also moves upwards. Energy is being transferred by the force to the box.

To lift an object, you need a store of energy (as chemical energy, in your muscles). You give the object more gravitational potential energy (g.p.e.). The force is your means of transferring energy from you to the object. The name given to this type of energy transfer by a force is **doing work**.

The more work that a force does, the more energy it transfers. The amount of **work done** is simply the amount of energy transferred:

$$\text{work done} = \text{energy transferred}$$

Three further examples of forces doing work are shown in Figure 8.2.

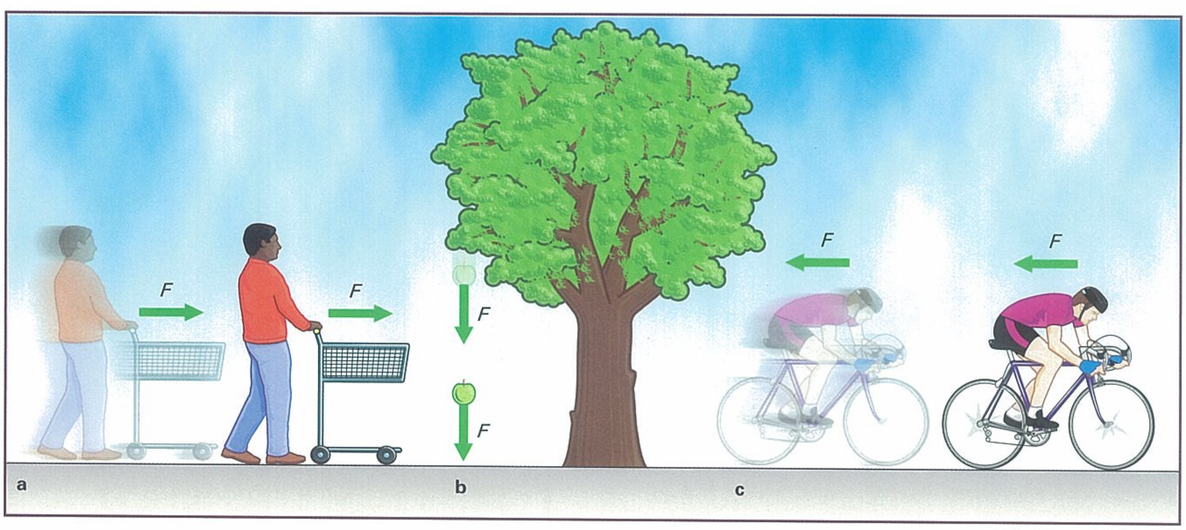

Figure 8.2 Three examples of forces doing work. In each case, the force moves as it transfers energy.

- Pushing a shopping trolley to start it moving. The pushing force does work. It transfers energy to the trolley, and the trolley's kinetic energy (k.e.) increases.
- An apple falling from a tree. Gravity pulls the apple downwards. Gravity does work, and the apple's k.e. increases.
- Braking to stop a bicycle. The brakes produce a backward force of friction, which slows down the bicycle. The friction does work, and reduces the bicycle's k.e. Energy is transferred to the brakes, which get hot.

How much work?

Think about lifting a heavy object, as shown in Figure **8.1**. A heavy object needs a big force to lift it. The heavier the object is, and the higher it is lifted, the more its g.p.e. increases. This suggests that the amount of energy transferred by a force depends on two things:

- the size of the force – the greater the force, the more work it does
- the distance moved in the direction of the force – the further it moves, the more work it does.

So a big force moving through a big distance does more work than a small force moving through a small distance.

Words in physics

You will by now understand that 'work' is a word that has a specialised meaning in physics, different from its meaning in everyday life. When physicists think about the idea of 'work', they think about forces moving.

If you are sitting thinking about your homework, no forces are moving and you are doing no work. It is only when you start to write that you are doing work in the physics sense. To make the ink flow from your pen, you must push against the force of friction, and then you really are working.

Many words have specialised meanings in science.

In earlier chapters, we used these words:

force mass weight velocity moment energy

Each has a carefully defined meaning in physics. This is important because physicists have to agree on the terms they are using. However, if you look these words up in a dictionary, you will find that they have a range of everyday meanings, as well as their specialised scientific meaning. This is not a problem, provided you know whether you are using a particular word in its scientific sense or in a more everyday sense. (Some physicists get very upset if they hear shopkeepers talking about weights in kilograms, for example, but no-one will understand you if you ask for 10 newtons of oranges!)

QUESTIONS

1 Which requires more work, lifting a 10 kg sack of coal or lifting a 15 kg bag of feathers?

2 Which force does work when a ball rolls down a slope?

8.2 Calculating work done

When a force does work, it transfers energy to the object it is acting on. The amount of energy transferred is equal to the amount of work done. We can write this as a simple equation:

$$\Delta W = \Delta E$$

In this equation, we use the symbol Δ (Greek letter delta) to mean 'amount of' or 'change in'. So

ΔW = amount of work done

ΔE = change in energy

How can we calculate the work done by a force? Above, we saw that the work done depends on two things:

- the size of the force F
- the distance d moved by the force.

We can write:

work done = force × distance moved by the force

$$\Delta W = F \times d$$

We use the symbol ΔW to represent the amount of work done. Since this is the same as the amount of energy transferred, it is measured in joules (J), the unit of energy.

Joules and newtons

The equation for the work done by a force ($\Delta W = F \times d$) shows us the relationship between joules and newtons. If we replace each quantity in the equation by its SI unit, we get

$$1\,\text{J} = 1\,\text{N} \times 1\,\text{m} \qquad \text{or} \qquad 1\,\text{J} = 1\,\text{N}\,\text{m}$$

So a joule is a newton-metre. More formally the **joule** (J) is defined as follows:

> One joule (1 J) is the energy transferred (or the work done) by a force of one newton (1 N) when it moves through a distance of one metre (1 m).

Worked example 1

A crane lifts a crate upwards through a height of 20 m. The lifting force provided by the crane is 5 kN (see Figure 8.3). How much work is done by the force? How much energy is transferred to the crate?

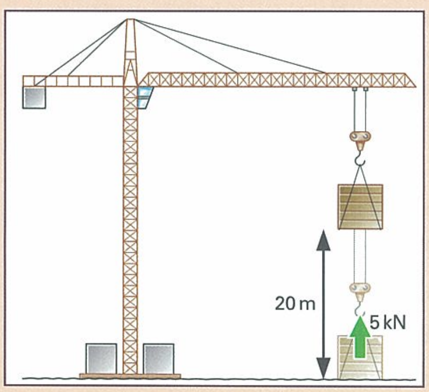

Figure 8.3 A crane provides the upward force needed to lift a crate. The force transfers energy from the crane to the crate. The crate's g.p.e. increases.

Step 1: Write down what you know, and what you want to know.

$F = 5\,\text{kN} = 5000\,\text{N}$

$d = 20\,\text{m}$

$\Delta W = ?$

Step 2: Write down the equation for work done, substitute values and solve.

$$\Delta W = F \times d$$
$$= 5000\,\text{N} \times 20\,\text{m}$$
$$= 100\,000\,\text{J}$$

So the work done by the force is 100 000 J, or 100 kJ.

Since work done = energy transferred, this is also the answer to the second part of the question: 100 kJ of energy is transferred to the crate.

Work done and *mgh*

Worked example **1** in which the crane lifts the crate illustrates an important idea. The force provided by the crane to lift the crate must equal the crate's weight *mg*. It lifts the crate through a height *h*. Then the work it does is force × distance, or $mg \times h$. Hence the gain in g.p.e. of the crate is *mgh*. This explains where the equation for g.p.e. comes from.

In Figure **8.4**, the child slides down the slope. Gravity pulls her downwards, and makes her speed up. To calculate the work done by gravity, we need to know the vertical distance *h*, because this is the distance moved **in the direction of the force**. If we calculated the work done as weight × distance moved down the slope, we would get an answer that was too large. So we have:

work done = force × distance moved in the direction of the force

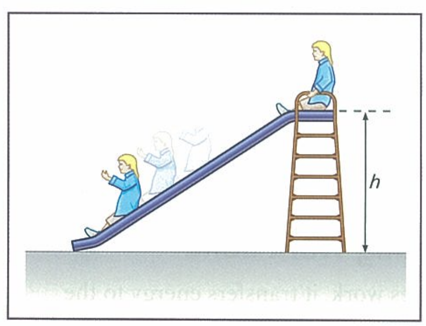

Figure 8.4 It is important to use the correct distance when calculating work done by a force. Gravity makes the child slide down the slope. However, to calculate the energy transferred by gravity, we must use the vertical height moved.

Forces doing no work

If you sit still on a chair (Figure **8.5a**), there are two forces acting on you. These are your weight (*mg*), acting downwards, and the upward contact force *C* of the chair, which stops you from falling through the bottom of the chair.

Neither of these forces is doing any work to you. The reason is that neither of the forces is moving, so they do not move through any distance *d*. Hence, from $\Delta W = F \times d$, the amount of work done by each force is zero. When you sit still on a chair, your energy does not increase or decrease as a result of the forces acting on you.

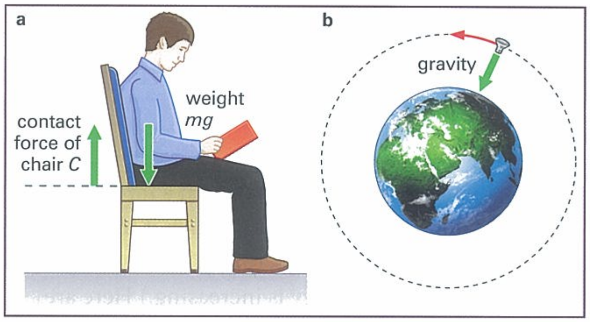

Figure 8.5 **a** When you sit still in a chair, there are two forces acting on you. Neither transfers energy to you. **b** The spacecraft stays at a constant distance from the Earth. Gravity keeps it in its orbit without transferring any energy to it.

Figure **8.5b** shows another example of a force that is doing no work. A spacecraft is travelling around the Earth in a circular orbit. The Earth's gravity pulls on the spacecraft to keep it in its orbit. The force is directed towards the centre of the Earth. However, since the spacecraft's orbit is circular, it does not get any closer to the centre of the Earth. There is no movement in the direction of the force, and so gravity does no work. The spacecraft continues at a steady speed (its k.e. is constant) and at a constant height above the Earth's surface (its g.p.e. is constant). Of course, although the force is doing no work, this does not mean that it is not having an effect. Without the force, the spacecraft would escape from the Earth and disappear into the depths of space.

Worked example 2

A girl can provide a pushing force of only 200 N. To move a box weighing 400 N onto a platform, she uses a plank as a ramp (Figure **8.6**). How much work does she do in raising the box? How much g.p.e. does the box gain?

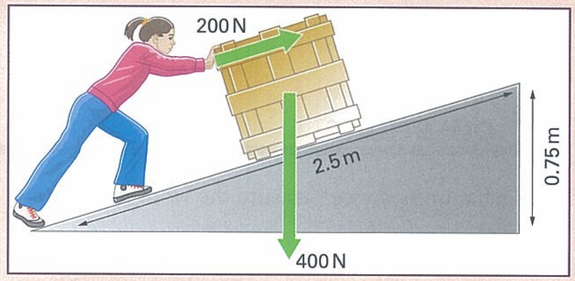

Figure 8.6 A ramp can allow you to lift a heavy load, but you do more work than if you could raise it unaided. From the diagram, you can see that the box is raised 0.75 m vertically, but the girl has to push it 2.5 m along the slope.

Step 1: Write down what you know, and what you want to know.

pushing force along the slope $F = 200$ N
distance moved along slope $d = 2.5$ m
weight of box downwards $mg = 400$ N
vertical distance moved $h = 0.75$ m
work done along the slope $\Delta W = ?$
work done against gravity $\Delta W' = ?$

Step 2: Calculate the work done by the pushing force along the slope, ΔW.

$$\Delta W = \text{pushing force along slope} \times \text{distance moved along slope}$$
$$= F \times d$$
$$= 200\,\text{N} \times 2.5\,\text{m}$$
$$= 500\,\text{J}$$

Step 3: Calculate the gain in g.p.e. of the box. This is the same as the work done against gravity, $\Delta W'$.

$$\Delta W' = \text{weight of box} \times \text{vertical distance moved}$$
$$= mg \times h$$
$$= 400\,\text{N} \times 0.75\,\text{m}$$
$$= 300\,\text{J}$$

So the girl does 500 J of work, but only 300 J is transferred to the box. The remaining 200 J is the work done against friction as the box is pushed along the slope.

E

Activity 8.1 Doing work

Push a load up a slope so that you do work. Where does your energy go?

QUESTIONS

3 In what units do we measure the work done by a force?

4 A fast-moving car has 0.5 MJ of kinetic energy. The driver brakes and the car comes to a halt. How much work is done by the force provided by the brakes?

5 a How much work is done by a force of 1 N moving through 1 m?

b How much work is done by a force of 5 N moving through 2 m?

6 Which does more work, a force of 500 N moving through 10 m or a force of 100 N moving through 40 m?

7 A steel ball of weight 50 N hangs at a height of 5 m above the ground, on the end of a chain 2 m in length. How much work is done on the ball by gravity, and by the tension in the chain?

8.3 Power

Exercising in the gym (Figure 8.7) can put great demands on your muscles. Speeding up the treadmill means that you have to work harder to keep up. Equally, your trainer might ask you to find out how many times you can lift a set of weights in one minute. These exercises are a test of how powerful you are. The faster you work, the greater your power.

In physics, the word **power** is often used with a special meaning. It means the rate at which you do work (that is, how fast you work). The more work you do, and the shorter the time in which you do it, the greater your power.

Power is the rate at which energy is transferred, or the rate at which work is done.

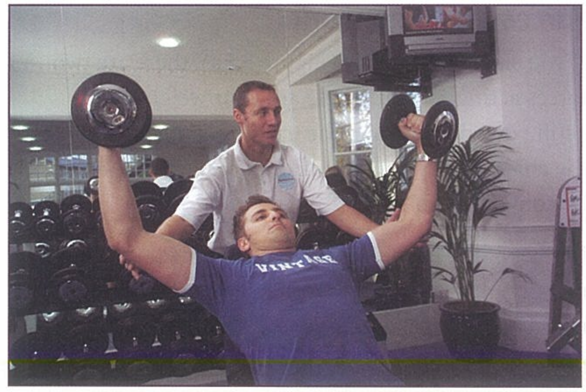

Figure 8.7 It is hard work down at the gym. It is easier to lift small loads, and to lift them slowly. The greater the load you lift and the faster you lift it, the greater the power required. It is the same with running on a treadmill. The faster you have to run, the greater the rate at which you do work.

Fast working

Power tells you about the rate at which a force does work – in other words, the rate at which it transfers energy. When you lift an object up, you are giving it energy. (Its potential energy is increasing.) Here are two ways you can increase your power:

- lift a heavier object in the same time
- lift the object more quickly.

It is not just people who do work. Machines also do work, and we can talk about their power in the same way.

- A crane does work when it lifts a load. The bigger the load and the faster it lifts the load, the greater is the power of the crane.
- A locomotive pulling a train of coaches or wagons does work. The greater the force with which it pulls and the greater the speed at which it pulls, the greater is the power of the locomotive.

QUESTION

8 Your neighbour is lifting bricks and placing them on top of a wall. He lifts them slowly, one at a time. State **two** ways in which he could increase his power (the rate at which he is transferring energy to the bricks).

E

8.4 Calculating power

We can write these ideas about power as an equation:

$$\text{power} = \frac{\text{work done}}{\text{time taken}} \qquad P = \frac{\Delta W}{t}$$

Since work done = energy transferred, we can also write a similar equation:

$$\text{power} = \frac{\text{energy transferred}}{\text{time taken}} \qquad P = \frac{\Delta E}{t}$$

Units of power

Power is measured in watts (W). One watt (1 W) is the power when one joule (1 J) of work is done in one second (1 s). So one watt is one joule per second:

1 W = 1 J/s
1 000 W = 1 kW (kilowatt)
1 000 000 W = 1 MW (megawatt)

Take care not to confuse (italic) *W* for work done (or energy transferred) with (upright) W for watts. In books, the first of these is shown in *italic* type (as here), but you cannot tell the difference when they are written.

Worked example 3

A car of mass 800 kg accelerates from rest to a speed of 25 m/s in 10 s. What is its power?

Step 1: Calculate the work done. This is the increase in the car's kinetic energy.

$$\text{k.e.} = \frac{1}{2}mv^2$$
$$= \frac{1}{2} \times 800\,\text{kg} \times (25\,\text{m/s})^2$$
$$= 250\,000\,\text{J}$$

Step 2: Calculate the power.

$$\text{power} = \frac{\text{work done}}{\text{time taken}}$$
$$= \frac{\Delta W}{t}$$
$$= \frac{250\,000\,\text{J}}{10\,\text{s}}$$
$$= 25\,000\,\text{W}$$
$$= 25\,\text{kW}$$

E

So the energy is being transferred to the car (from its engine) at a rate of 25 kW, or 25 kJ per second.

Car engines are not very efficient. In this example, the car's engine may transfer energy at the rate of 100 kW or so, although most of this is wasted as thermal (heat) energy.

Power in general

We can apply the idea of power to any transfer of energy. For example, electric light bulbs transfer energy supplied to them by electricity. They produce light and heat. Most light bulbs are labelled with their power rating – for example, 40 W, 60 W, 100 W – to tell the user about the rate at which it transfers energy.

There is more about electrical power in Chapter **19**.

QUESTIONS

9 **a** How many watts are there in a kilowatt?
b How many watts are there in a megawatt?

10 It is estimated that the human brain has a power requirement of 40 W. How many joules is that per second?

11 A light bulb transfers 1000 J of energy in 10 s. What is its power?

12 An electric motor transfers 100 J in 8 s. If it then transfers the same amount of energy in 6 s, has its power increased or decreased?

Activity 8.2 Measuring your power

It is hard work running up a flight of stairs. Time yourself and calculate your power.

Summary

When a force moves, it transfers energy. We say that it does work.

The greater the force and the greater the distance it moves, the more work is done.

E

Work done = energy transferred.

Work done = force × distance moved by the force

$$\Delta W = F \times d$$

The distance moved is measured in the direction of the force.

Power is the rate at which energy is transferred, or the rate at which work is done.

The greater the amount of work done and the shorter the time in which it is done, the greater the power.

E

$$\text{Power} = \frac{\text{work done}}{\text{time taken}} \qquad P = \frac{\Delta W}{t}$$

$$\text{Power} = \frac{\text{energy transferred}}{\text{time taken}} \qquad P = \frac{\Delta E}{t}$$

End-of-chapter questions

8.1 Omar and Ahmed are lifting weights in the gym. Each lifts a weight of 200 N. Omar lifts the weight to a height of 2.0 m, whereas Ahmed lifts it to a height of 2.1 m. Who does more work in lifting the weight? Explain how you know. [2]

8.2 Millie and Lily are identical twins who enjoy swimming. Their arms and legs provide the force needed to move them through the water. Millie can swim 25 m in 50 s. Lily can swim 100 m in 250 s.

a Calculate the swimming speed of each twin. [2]

b Which twin has the greater power when swimming? Explain how you can tell. [2]

E **8.3** Jim is pulling a load along a ramp, as shown in Figure 8.8. The diagram shows the force with which he pulls and the weight of the load.

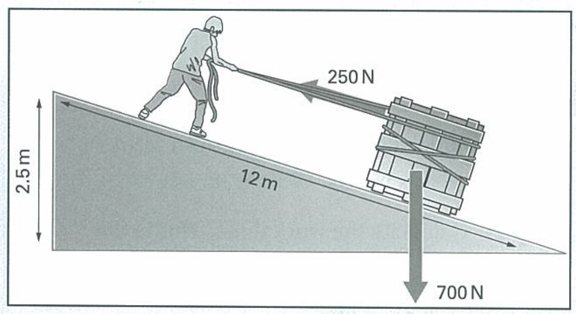

Figure 8.8 Pulling a load up a ramp – for Question **8.3**.

a Calculate the work done by Jim's pulling force. [3]

b What is the gain in potential energy of the load? [3]

E

8.4 Two girls are estimating each other's power. One runs up some steps, and the other times her. Here are their results:

height of one step = 20 cm
number of steps = 36
mass of runner = 45 kg
time taken = 4.2 s

a Calculate the runner's weight. (Acceleration due to gravity $g = 10\,\text{m/s}^2$.) [2]

b Calculate the increase in the girl's gravitational potential energy as she runs up the steps. [3]

c Calculate her power. Give your answer in kilowatts (kW). [4]

E

8.5 A car of mass 750 kg accelerates away from traffic lights. At the end of the first 100 m it has reached a speed of 12 m/s. During this time, its engine provides an average forward force of 780 N, and the average force of friction on the car is 240 N.

a Calculate the work done on the car by the force of its engine. [3]

b Calculate the work done on the car by the force of friction. [3]

c Using k.e. $= \frac{1}{2}mv^2$, calculate the increase in the car's kinetic energy at the end of the first 100 m. [2]

d Explain whether your answers are consistent with the principle of conservation of energy. [3]