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David Sang , Mike Follows , Sheila Tarpey
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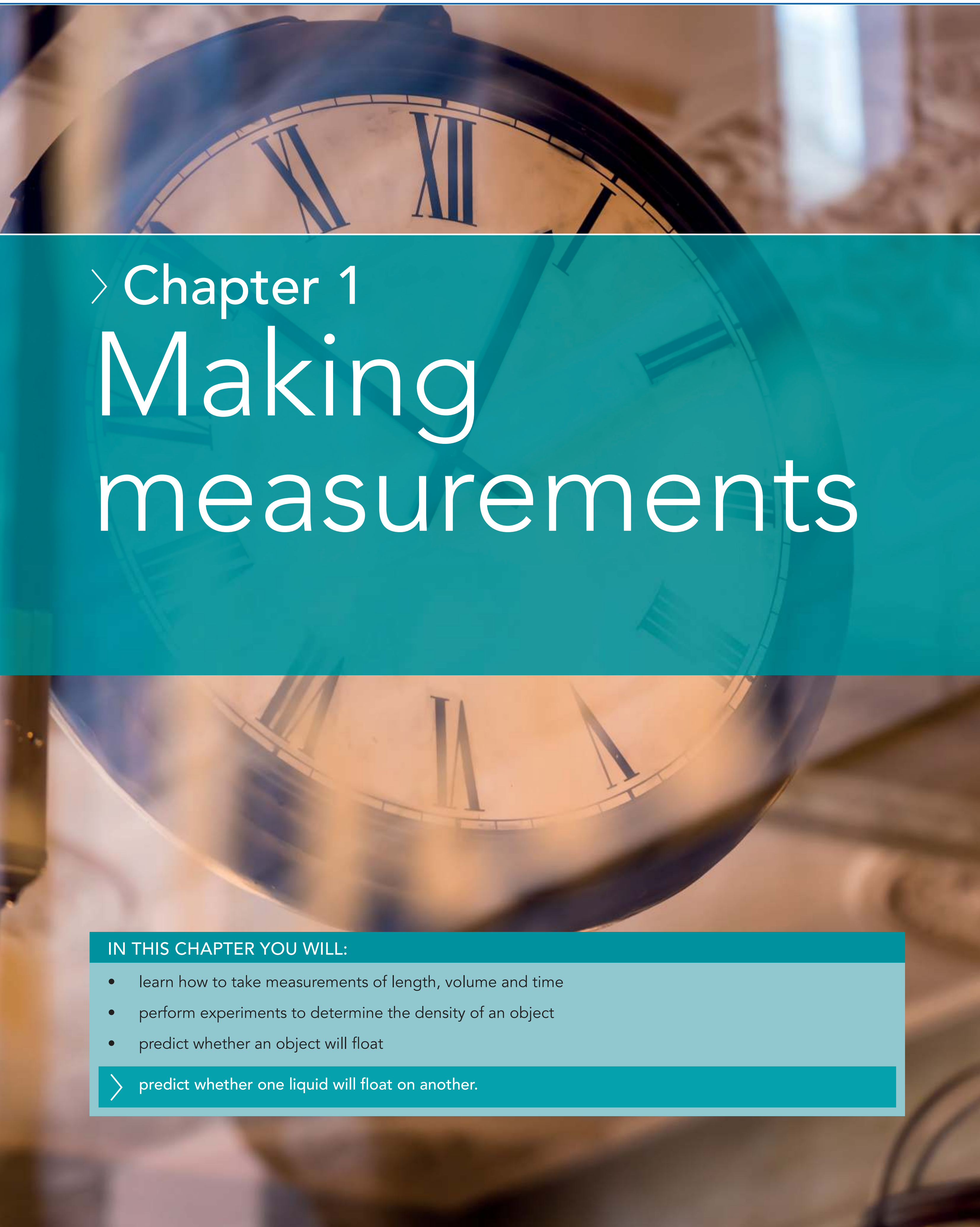

Chapter 1
Making measurements

IN THIS CHAPTER YOU WILL:

- learn how to take measurements of length, volume and time
- perform experiments to determine the density of an object
- predict whether an object will float
- predict whether one liquid will float on another.

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GETTING STARTED

In pairs, either take the measurements or write down how you would do the following:

- measure the length, width and thickness of this book and work out its volume
- measure the thickness of a sheet of paper that makes up this book
- measure the length of a journey (for example, on a map) that is not straight.

Now discuss how you would work out the density of:

- a regular-shaped solid
- an irregular-shaped solid
- a liquid.

ARE WE CLEVERER THAN OUR ANCESTORS WERE?

People tend to dismiss people who lived in the past as less intelligent than we are. After all, they used parts of their bodies for measuring distances. A cubit was the length of the forearm from the tip of the middle finger to the elbow. However, the ancient Egyptians knew this varied between people. Therefore, in around 3000 BCE, they invented the royal cubit (Figure 1.1), marked out on a piece of granite and used this as a **standard** to produce cubit rods of equal length.

Figure 1.1: Cubit rod.

The Ancient Egyptians were experts at using very simple tools like the cubit rod. This enabled them to build their pyramids accurately. Eratosthenes, a brilliant scientist who lived in Egypt in about 300 BCE, showed the same care and attention to detail. This allowed him to work out that the Earth has a circumference of 40 000 km (Figure 1.2).

In contrast, there are many recent examples where incorrect measurements have led to problems. Although the Hubble Space Telescope had the most precisely shaped mirror ever made, the original images it produced were not as clear as expected. Tiny mistakes in measuring meant that it had the wrong shape and it took a lot of effort to account for these errors.

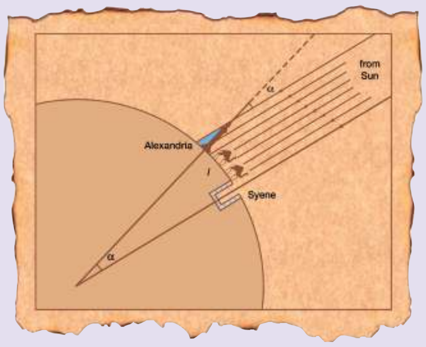

Figure 1.2: Eratosthenes used shadows and geometry to work out the circumference of the Earth.

Discussion questions

1 You cannot always depend on your eyes to judge lengths. Look at Figure 1.3 and decide which line is longer? Check by using a ruler.

Figure 1.3: Which line is longer?

2 Eratosthenes may have hired a man to pace the distance between Alexandria and Syene (present-day Aswan) to calculate the Earth's circumference. People have different stride lengths so some people take longer steps than others. Discuss the possible ways that anyone with any stride length could have measured the distance between these towns accurately.

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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 ruler (such as a metre ruler).

Measuring lengths with a ruler is a familiar task. But when you use a ruler, 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 1.4).

- The wire must be straight, and laid closely alongside the ruler. (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 ruler. They are probably 1 mm apart, but they may be quite wide. Line one end of the wire up against the zero on 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 ruler itself. How sure can you be that it is correctly **calibrated**? Are the marks at the ends of a metre ruler 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 ruler).

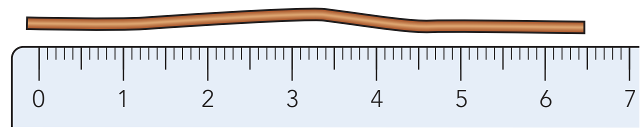

Figure 1.4: Simple measurements still require careful technique, for example, finding the length of a wire.

KEY WORDS

standard: is an absolute or primary reference or measurement

precise: when several readings are close together when measuring the same value

calibrated: should agree closely with a standard or agrees when a correction has been applied

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 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 ruler (Figure 1.5). Then divide by 500 to find the thickness of one sheet.

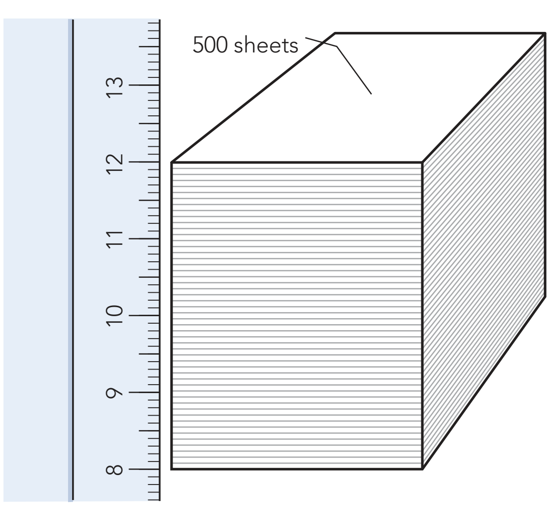

Figure 1.5: Making multiple measurements.

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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 ruler 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 cube or cuboid, such as a rectangular block, measure the length, width and height of the object and multiply the measurements 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 equation for the **volume**.

For liquids, measuring cylinders can be used as shown in Figure 1.6. (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**.) The meniscus is the curved upper surface of a liquid, caused by surface tension. It can curve up or down but the surface of water in a measuring cylinder curves downwards. Think carefully about the choice of cylinder. A 1 litre (or a 1 dm^3) 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.

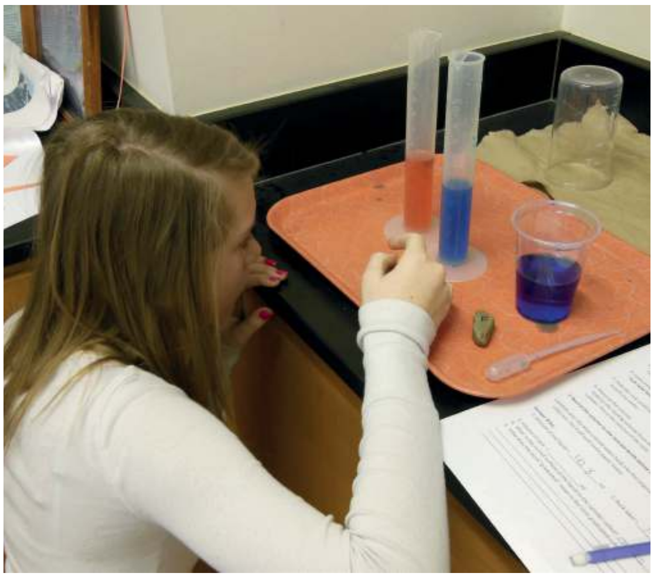

Figure 1.6: A student measuring the volume of a liquid. Her eyes are level with the scale so that she can accurately measure where the meniscus meets the scale.

Measuring volume by displacement

Most objects do not have a regular shape, so we cannot find their volumes simply by measuring the lengths of their sides. Here is how to find the volume of an irregularly shaped object. This technique is known as measuring volume by **displacement**.

- Select a measuring cylinder that is about 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, because the object pushes the water out of the way and the only way it can move is upwards. The increase in its volume is equal to the volume of the object.

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. Note that the litre and millilitre are not official SI units of volume, and so are not used in this book. One litre (1 l) is the same as 1 dm^3, and one millilitre (1 ml) is the same as 1 cm^3.

KEY WORDS

volume: the space occupied by an object

meniscus: curved upper surface of a liquid

displace: moving something to another place so water is moved out of the way (upwards) when an object is lowered into it

immerse: to cover something in a fluid (usually water) so that the object is submerged

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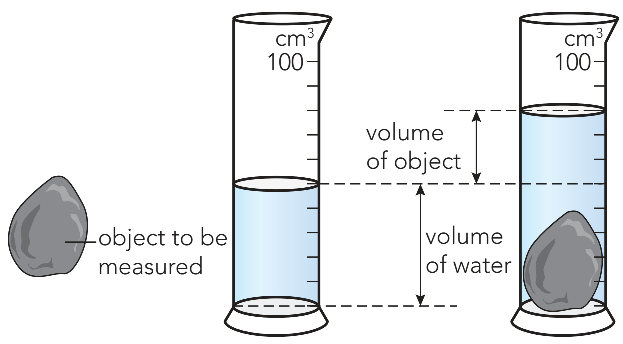

Figure 1.7: Measuring volume by displacement.

Quantity	Units
length	metre (m) 1 decimetre (dm) = 0.1 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

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

Questions

1 The volume of a piece of wood which floats in water can be measured as shown in Figure 1.8.
   a Write a paragraph to describe the procedure.
   b State the volume of the wood.

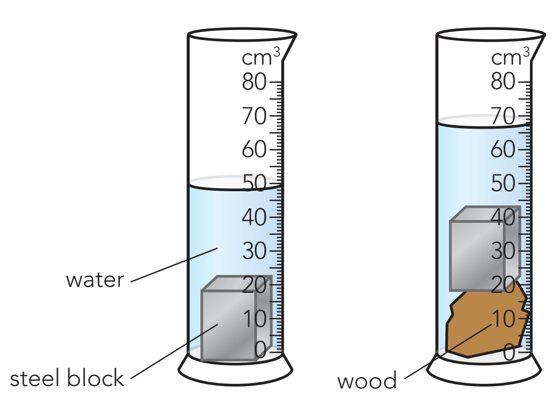

Figure 1.8: Measuring the volume of an object that floats.

2 A stack of paper contains 500 sheets of paper. The stack has dimensions of 0.297 m × 21.0 cm × 50.0 mm.
   a What is the thickness of one sheet of paper?
   b What is the volume of the stack of paper in cm^3?

1.2 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.

The mass of an object is the quantity (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. You will learn 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 shown, in words and as an equation.

Density is the mass per unit volume for a substance.

KEY EQUATION

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

$$\rho = \frac{m}{V}$$

KEY WORDS

mass: the quantity of matter a body is composed of; mass causes the object to resist changes in its motion and causes it to have a gravitational attraction for other objects

density: the ratio of mass to volume for a substance

weight: the downward force of gravity that acts on an object because of its mass

The symbol for density is ρ, the Greek letter rho. 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.

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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	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.

Values of density

Some values of density are shown in Table 1.3. Gases have much lower densities than solids or liquids.

An object that is less dense than water will float. Ice is less dense than water which explains why icebergs float in the sea, rather than sinking to the bottom. Only about one tenth of an iceberg is above the water surface. If any part of an object is above the water surface, then it is less dense than water.

	Material	Density / kg/m^3
Gases	air	1.29
	hydrogen	0.09
	helium	0.18
	carbon dioxide	1.98
Liquids	water	1000
	alcohol (ethanol)	790
	mercury	13 600
Solids	ice	920
	wood	400–1200
	polyethene	910–970
	glass	2500–4200
	steel	7500–8100
	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.

Many materials have a range of densities. Some types of wood, for example, are less dense than water and will float. Other types of wood (such as mahogany) are more dense and will sink. The density depends on the nature of the wood (its 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 kg/dm^3 or 1.0 g/cm^3.

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 1.1

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 ρ = ?

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

$$\rho = \frac{m}{V}$$

$$= \frac{190\ \text{g}}{240\ \text{cm}^3}$$

$$= 0.79\ \text{g/cm}^3$$

Answer

Density of ethanol = 0.79 g/cm^3

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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 Section 1.1). Find its mass using a balance. Then calculate the density.

Questions

3 A brick is shown in Figure 1.9. It has a mass of 2.8 kg.

Figure 1.9: A brick labelled with its dimensions.

   a Give the dimensions of the brick in metres.
   b Calculate the volume of the brick.
   c Calculate the density of the brick.

4 A box full of 35 matches has a mass of 6.77 g. The box itself has a mass of 3.37 g.
   a What is the mass of one match in grams?
   b What is the volume (in cm^3) of each match. A match has dimensions of 42 mm × 2.3 mm × 2.3 mm?
   c What is the density of the matches?
   d How do you know if these matches will float?

5 The Earth has a mass of 6×10^{24} kg and a radius of about 6400 km. What is the density of the Earth (in kg/m^3)? The volume of a sphere is given by the equation $V = \frac{4}{3}\pi r^3$, where r is the radius.

6 40 drawing pins (thumb tacks) like those shown in Figure 1.10 have a mass of 17.55 g. What is the volume (in mm^3) of one pin when they are made of metal with a density of 8.7 g/cm^3?

Figure 1.10: A pair of drawing pins (thumb tacks).

7 A young girl from the Kayan people in northern Thailand wears a neck ring made of brass (Figure 1.11). It looks as if there are 21 individual rings but the ring is actually one continuous length of brass fashioned (bent) into a coil. The height of the brass coil is 12 cm and its average circumference is 40 cm. Neck rings are usually only removed to be replaced with a bigger one as the girl grows. However, we can estimate the mass of this neck ring without removing it.

Figure 1.11: A Kayan girl wearing a neck ring.

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a What looks like 21 individual rings around the girl's neck is actually 21 turns of a coil of brass. Each turn has a circumference of 40 cm. Calculate (in cm) the total length of brass used to make the girl's neck ring.

b The coil has a height of 12 cm and the coil has 21 turns. Calculate the radius of the brass in cm.

c If the brass coil is unwound from the girl's neck and straightened out, it would be a long, thin, cylinder. Calculate the volume of this cylinder in cm^3. The volume of a cylinder is given by the equation $V = \pi r^2 h$, where r = radius and h = height.

d Calculate the mass of brass used to make the neck ring and express your answer in kg. The density of brass = 8.73 g/cm^3.

Finding the density of a liquid

Figure 1.12 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.

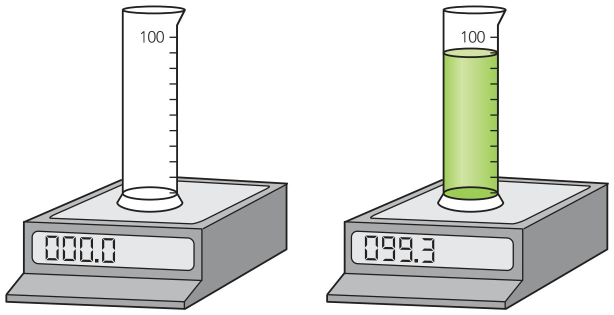

Figure 1.12: Measuring the mass of a liquid.

When liquids with different densities are poured into the same container, they will arrange themselves so that the liquid with the lowest density will be at the top and the ones with the highest density will be at the bottom. This is because the denser liquids displace the less dense liquids. This is easier to see when each liquid is given a different colour. In Figure 1.13, the green liquid is less dense than the red liquid and so on.

When a distinct layer forms in a mixed solution, the liquids are said to be immiscible, which means they do not mix. This is why oil floats on water. However, not all liquids stay separated so you would be disappointed if you tried this at home with squash and water, for example.

When liquids mix, it is usually because one liquid dissolves in the other. For example, orange squash is a concentrated syrup that is diluted by dissolving it in water.

Figure 1.13: Liquid density towers.

Apart from making colourful liquid density towers, do variations in the density of liquids have practical consequence? In Chapter 11, you will learn about convection currents in fluids (liquids and gases), which are driven by differences in density. These convection currents include the thermohaline circulation in the oceans. Colder and saltier water sinks, displacing (pushing up) warmer and less salty water.

ACTIVITY 1.1

Finding the density of a regularly shaped solid

In pairs, create a worksheet on the computer for finding the density of a regularly shaped solid object (for example, a rectangular block) using a ruler and a mass balance. Your worksheet should include:

- a method for measuring the mass and working out the volume
- the equation for calculating density
- a table to record the data.

You could include an optional task to work out the density of a liquid.

After your allotted time, another pair is going to test a copy of your worksheet (perhaps by doing the experiment). They are going to add any steps that are missing or make suggestions to make your worksheet clearer. When you get your worksheet returned, edit and save a new version of it.

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CONTINUED

Finding the density of an irregularly shaped solid

Before you start, make a copy of your previous worksheet and save it under a new name. Some of what you included in the previous worksheet can be kept and some will need to be edited.

In pairs, create a worksheet for finding the density of an irregularly shaped solid object using a mass balance, a measuring cylinder, some thread, a pair of scissors and a eureka can (if you have access to one). Your method explaining how to measure the mass and how to calculate the density should be the same. However, you should:

- explain how to measure volume by displacement
- say something about choosing a suitably sized measuring cylinder
- change your previous table

You could include an optional task to work out the density of an irregularly shaped solid object that is less dense than water. Finding its mass and calculating the density is straightforward. The challenging part is explaining how to work out the volume of an object that floats.

Design a flowchart or decision-tree (optional)

Design a flowchart or decision-tree for use by anyone who wants to work out the density of any liquid or any solid object. Ensure that your flowchart includes enough information so that someone could take the measurements. Ask your partner or someone else who has completed the first two parts to check and correct your flowchart.

REFLECTION

Write down one thing that you did really well in this activity.

Write down one thing that you will try to do better next time. How will you do this?

1.3 Measuring time

The athletics coach in Figure 1.14 is using his 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 1.14: An athletics coach uses a stopwatch to time a hurdler, who can then learn whether she has improved.

ACTIVITY 1.2

How dense can you be?

In groups of three, write a method showing how you could work out your own density, or that of a friend or of a younger sibling. Alternatively, plan out your strategy and be prepared to share it with the class. There are at least two methods: a dry method and a wet method. Discuss one or both of them.

You will need to include:

- a method that is detailed enough for someone to follow (this should include advice about how a measurement should be taken)
- any calculations
- possible sources of uncertainty in the measurements
- what you expect your answer to be.

If you actually carried out the experiment, comment on how close your measurement was to what you expected.

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In the laboratory, you might need to record the temperature of a container of water every minute, or find out how long an electric current is flowing. For measurements like these, stopclocks and stopwatches can be used. You may come across two types of timing device.

An **analogue** clock (Figure 1.15) is like a traditional clock whose hands move round the clock's face. You find the time by looking at where the hands are pointing on the scale. It can be used to measure time intervals to no better than the nearest second.

Figure 1.15: An analogue clock.

A **digital** clock (Figure 1.16) or stopwatch is one that gives a direct reading of the time in numerals. For example, a digital clock might show a time of 9.58 s. A digital clock records time to a precision of at least one hundredth of a second. You would never see an analogue watch recording times in the Olympic Games.

Figure 1.16: A digital clock started when the gun fired and stopped 9.58 s later when Usain Bolt crossed the finishing line to win the 100 m at the 2009 World Championships in world record time.

KEY WORDS

analogue: display has hands (or a needle) and is often not very precise

digital: display shows numbers and is often precise

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.

You will learn more about how to use electronic timing instruments in Chapter 2.

Measuring short intervals of time

Figure 1.17 shows a typical lab pendulum. A mass, called a **plumb bob**, hangs on the end of a string. The string is clamped tightly at the top between two wooden jaws. If you pull the bob gently to one side and release it, the pendulum will swing from side to side.

The time for one **oscillation** of a pendulum (when it swings 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 oscillations (perhaps 20 or 50), and calculate the average time per oscillation. 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 oscillations.

KEY WORDS

plumb bob: a mass (usually lead) hanging from a string to define a vertical line

oscillation: a repetitive motion or vibration

period: the time for one complete oscillation or wave; the time it takes an object to return to its original position

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