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Excerpt
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1 Making measurements

In this chapter, you will find out:

- how to make measurements of length, volume and time
- how to increase the precision of measurements of length and time
- how to determine the densities of solids and liquids.

How measurement improves

Galileo Galilei did a lot to revolutionise how we think of the world around us, and in particular how we make measurements. For example, he observed a lamp swinging. 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 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). Units of weight were 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.

Today, there are international agreements on the basic units of measurement. For example, the metre is defined as 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** 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. In fact, if you use a 'satnav' device to find your way around, you rely on ultra-precise time measurements. A 'satnav' detects radio signals from satellites orbiting the Earth, and works 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 0033 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 'satnav' device must measure the time at which the signal arrives to this degree of accuracy.

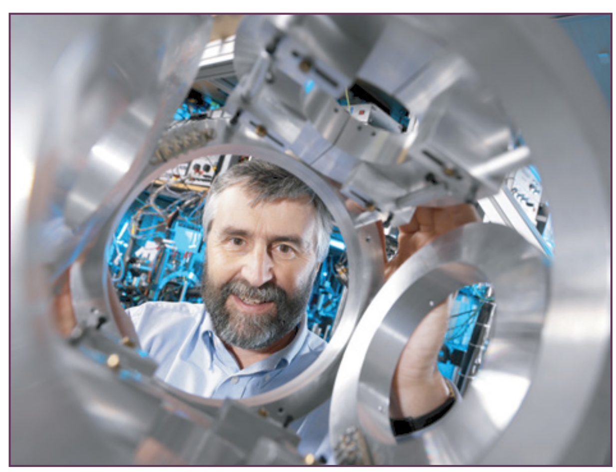


Figure 1.1 Professor Patrick Gill of the National Physical Laboratory is devising an atomic clock that will be 1000 times more accurate than previous types.

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 **1.2**).

- 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 the same approach when measuring something very

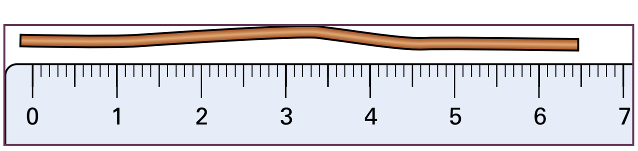


Figure 1.2 Simple measurements – for example, finding the length of a wire – still require careful technique.

thin, such as a sheet of paper. Take a stack of 500 sheets and measure its thickness with a rule (Figure **1.3**). 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 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.

Measuring volume by displacement

Most objects do not have a regular shape, so we cannot find their volumes simply by measuring the lengths

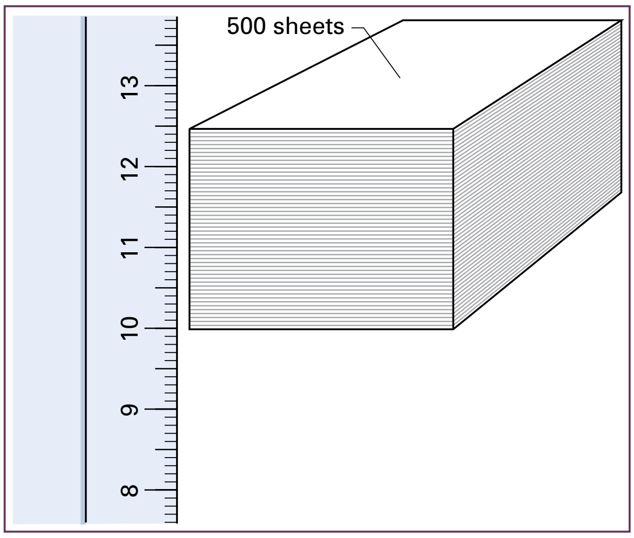


Figure 1.3 Making multiple measurements.

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 **1.4**), 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.

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.

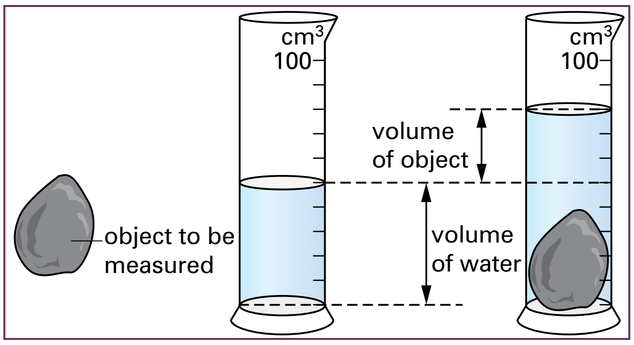


Figure 1.4 Measuring volume by displacement.

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.

Study tip

Remember that the unit is as important as the numerical value of a quantity. Take care when reading and writing units. For example, if you write mm instead of cm, your answer will be wrong by a factor of ten.

Activity 1.1
Measuring lengths and volumes

Skills

AO3.1 Demonstrate knowledge of how to safely use techniques, apparatus and materials (including following a sequence of instructions where appropriate)
AO3.3 Make and record observations, measurements and estimates
AO3.4 Interpret and evaluate experimental observations and data
AO3.5 Evaluate methods and suggest possible improvements

Practise measuring lengths and volumes. As you do so, evaluate the method you are using.

1. Measure the length of a toy block.
2. Place ten blocks side-by-side in a row. Measure the length of the row and calculate the average length of one block.
3. Write a comment about these two methods for finding the length of a block. Which is better, and why?
4. Repeat steps **1** and **2** to find the average diameter of a ball-bearing and the average thickness of the wire.
5. Evaluate the methods you have used.
6. Measure the three sides of a rectangular block and calculate its volume.
7. Measure the volume of the same block by displacement. Is one method better than the other? Give a reason for your answer.
8. Look at the pebble and compare it with the block. Is it bigger or smaller? Estimate its volume.
9. Measure the volume of the pebble by displacement. How good was your estimate?

Questions

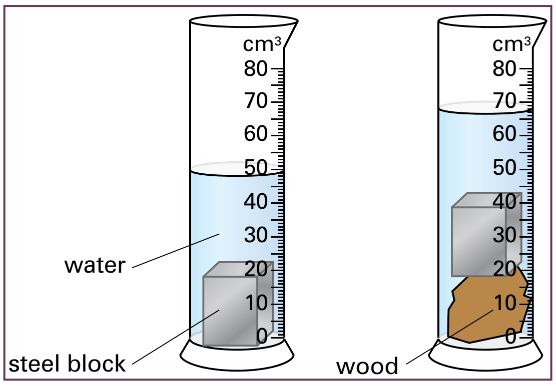
1.1 A rectangular block of wood has dimensions 240 mm × 20.5 cm × 0.040 m. Calculate its volume in cm^3.

1.2 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).

1.3 The volume of a piece of wood (which floats in water) can be measured as shown. Write a brief paragraph to describe the procedure. State the volume of the wood.



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 calipers

The calipers 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 calipers so that the jaws touch lightly but firmly on the sides of the object being measured.

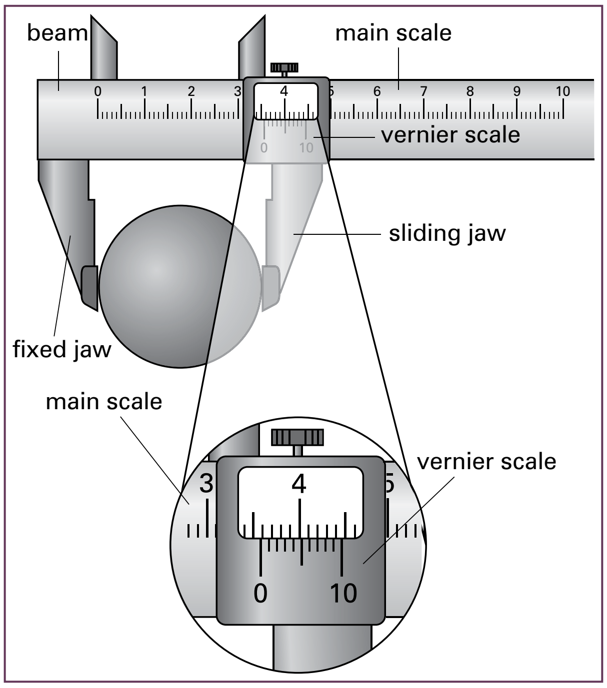


Figure 1.5 Using vernier calipers.

- 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

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**).

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

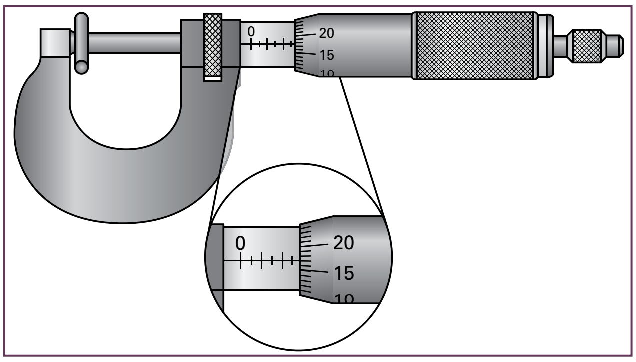


Figure 1.6 Using a micrometer screw gauge.

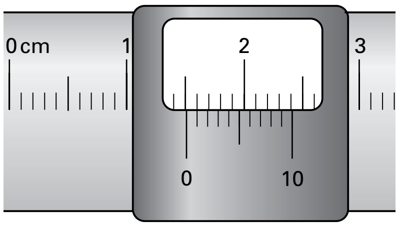
For the example in Figure **1.6**:

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

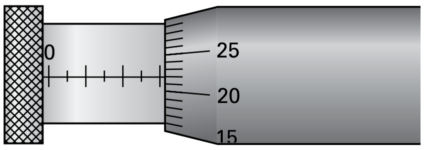
Question

1.4 State the measurements shown in the diagrams on the scale of:

a the vernier calipers



b the micrometer screw gauge.



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 shown, in words and as an equation.

Key definition

density – the ratio of mass to volume for a substance.

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

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

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**. A useful value to remember is the density of water (Table **1.3**):

density of water = 1000 kg/m^3

Study tip

It is important to be able to recall equations such as density = mass/volume. You may recall this in words, or in symbols ($\rho = M/V$). An alternative is to recall the units of density, such as kg/m^3. This should remind you that density is a mass divided by a volume.

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.

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.

	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
	polythene	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.

- 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 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 $D = ?$

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

Figure **1.7** 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.

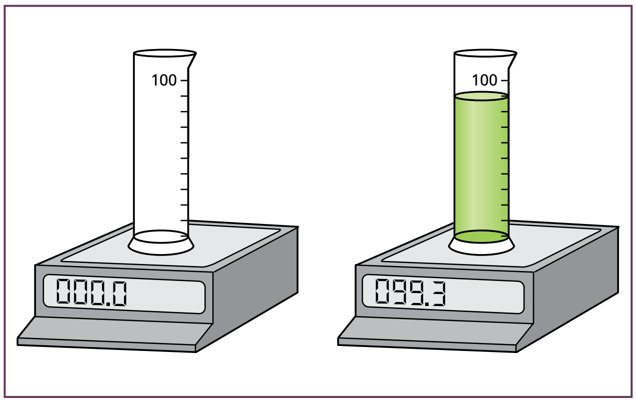


Figure 1.7 Measuring the density of a liquid.

Activity 1.2
Measuring density

Skills

AO3.1 Demonstrate knowledge of how to safely use techniques, apparatus and materials (including following a sequence of instructions where appropriate)

AO3.3 Make and record observations, measurements and estimates

AO3.4 Interpret and evaluate experimental observations and data

In this experiment, you are going to make measurements to determine the densities of some different materials. Use blocks that have a regular shape.

1. Start by comparing two blocks of different materials by hand, as shown. Can you tell which is the more dense? Can you put them all in order, from least dense to most dense? (This will be relatively easy if the blocks are all the same size, but you will still be able to make a judgement for blocks of different sizes.)
2. Use a balance to find the mass of each block.
3. Use a rule to measure the dimensions of the block. (If they are cubes, you should check that the sides are truly equal.)
4. Calculate the volume and density for each block. For repeated calculations like this, it helps to record your results and calculations in a table like the one shown. Alternatively, if you have access to a computer with a spreadsheet program, devise a spreadsheet that will perform the calculations for you.
5. Compare the results of your measurements with your earlier judgements. Did you put the materials in the correct order?

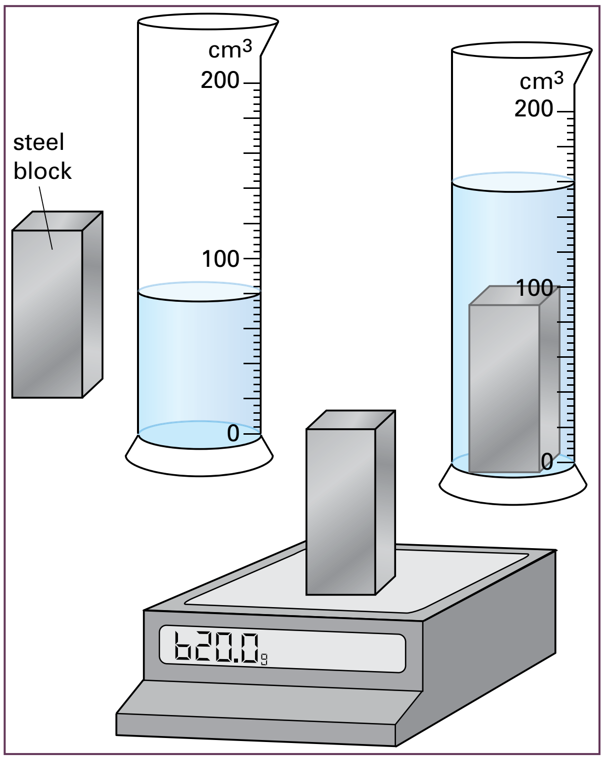
Material	Mass / g	Length / cm	Width / cm	Height / cm	Volume / cm^3	Density / g / cm^3
cheddar cheese	20.7	2.4	2.5	3.0	18.0	1.15

Questions

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

1.6 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.

1.7 A student measures the density of a piece of steel. She uses the method of displacement to find its volume. Her measurements are shown in the diagram. Calculate the volume of the steel and its density.



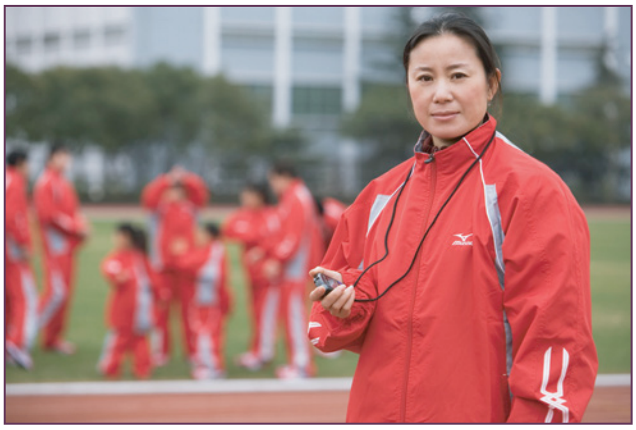


Figure 1.8 The female athletics coach uses a stopwatch to time a sprinter, who can then learn whether she has improved.

1.4 Measuring time

The athletics coach in Figure **1.8** 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.

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. You may come across two types of timing device:

- An *analogue* clock 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.
- A *digital* clock is one that gives a direct reading of the time in numerals. For example, a digital stopwatch might show a time of 23.45 s.

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**.

Measuring short intervals of time

Figure **1.9** shows a typical lab pendulum. A weight, called a '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 swing of a pendulum (from left to right and back again) is called its **period**. A single

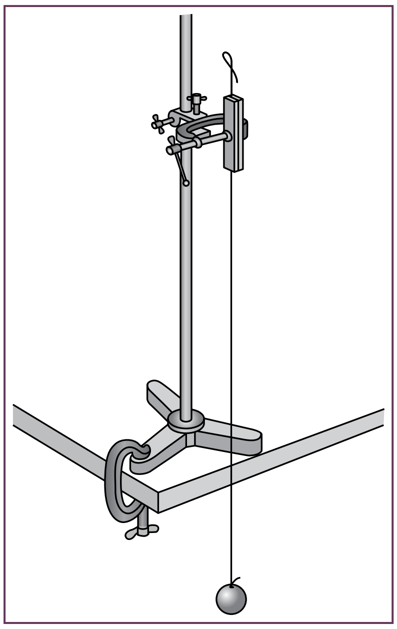


Figure 1.9 A simple pendulum.

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.

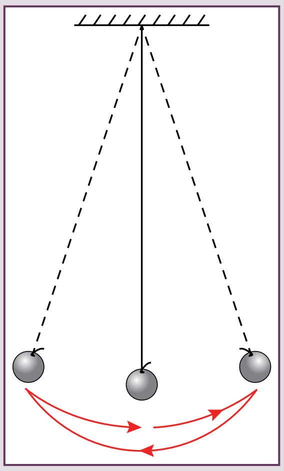
Study tip

Remember that 'one complete swing' of a pendulum is from one side to the other and back again. When using a stopwatch, it may be easier to start timing when the pendulum passes through the midpoint of its swing. Then one complete swing is to one side, to the other side, and back to the midpoint.

Activity 1.3
The period of a pendulum

Skills

AO3.1 Demonstrate knowledge of how to safely use techniques, apparatus and materials (including following a sequence of instructions where appropriate)
AO3.2 Plan experiments and investigations
AO3.3 Make and record observations, measurements and estimates
AO3.4 Interpret and evaluate experimental observations and data



In this experiment, you will measure the time for one complete swing of the pendulum. You will need a stopwatch to time the swings. You may have a watch or mobile phone that can act as a digital stopwatch. One complete swing of a pendulum is from the centre to the right, to the left, and back to the centre. The time for this is the period of the pendulum.

1 Set the pendulum swinging. It is easier to start and stop the watch when the pendulum passes through the middle of its swing, that is, when the string is vertical. Measure the time for a single complete swing. Repeat this ten times. How much do your values vary? Now calculate the average.
2 Time a sequence of 20 complete swings and find the average time for one swing.
3 Repeat step **2**. Do your answers differ by much?
4 A student has noticed that, if the pendulum is shorter, it swings more quickly. She has an idea and says: 'If we halve the length of the string, the period of the pendulum will also be halved'. Test this idea.
5 Devise a means of testing Galileo's idea, mentioned at the start of this chapter, that the period of a pendulum does not depend on the size of its swing.

Questions

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

1.9 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. Suggest some possible experimental reasons for this.

Summary

You should know:
- how to measure length, volume, mass and time
- how to measure small quantities
- S that special instruments are available to measure with greater precision
- all about density.

End-of-chapter questions

1 The table shows four quantities that you may have to measure in physics. Copy the table and complete it by listing one or more measuring instruments for each of these quantities.

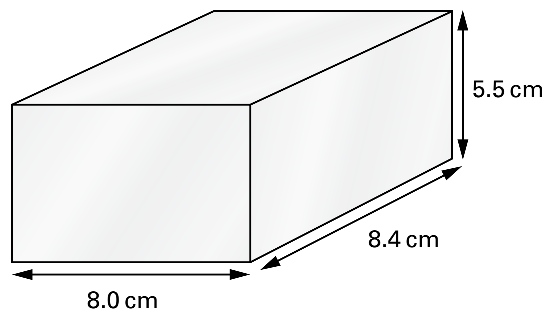
Mass	Length	Volume	Time

2 To find the density of a substance, we need to measure the mass and volume of a sample of the substance.
  a Write the equation that links these three quantities.
  b The units of density depend on the units we use when measuring mass and volume. Copy and complete the table to show the correct units for density.

Unit of mass	Unit of volume	Unit of density
kg	m^3	
g	cm^3	

S 3 a Name **two** instruments that are used for measuring small lengths, such as the thickness of a wire.
  b A tap is dripping. The drops fall at regular intervals of time. Describe how you would find an accurate value for the time between drops.

4 An ice cube has the following dimensions.

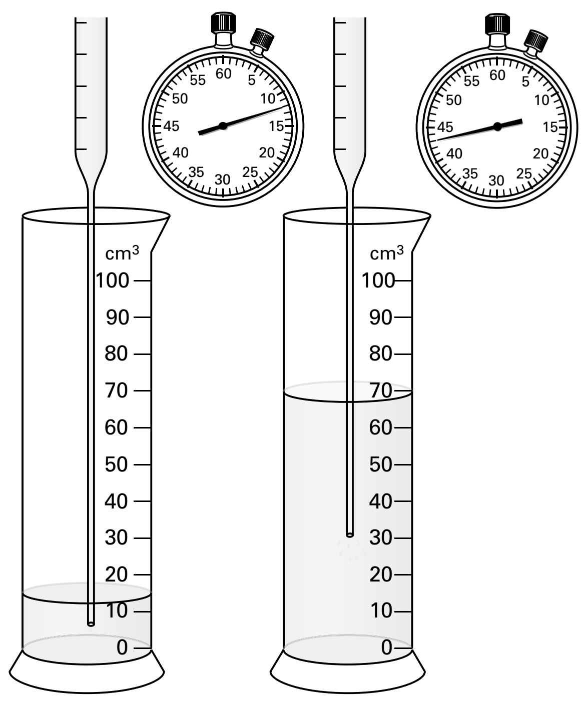


Its mass is 340 g. Calculate:

a its volume [3]

b its density. [3]

5 A student is collecting water as it runs into a measuring cylinder. She uses a clock to measure the time interval between measurements. The level of the water in the cylinder is shown 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]

6 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, calculate the density of the liquid. [5]

7 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]

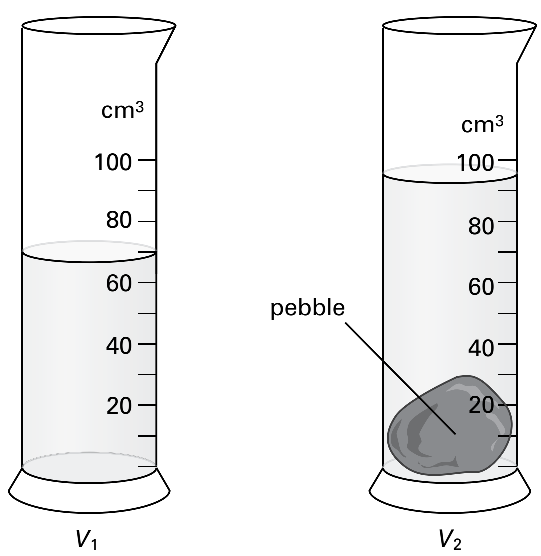
b Calculate the mass of the air. State the equation you are using. [3]

S **8** 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]

9 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. The diagram shows her displacement results for sample A.



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]

The table shows the student's readings for samples B and C.

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

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

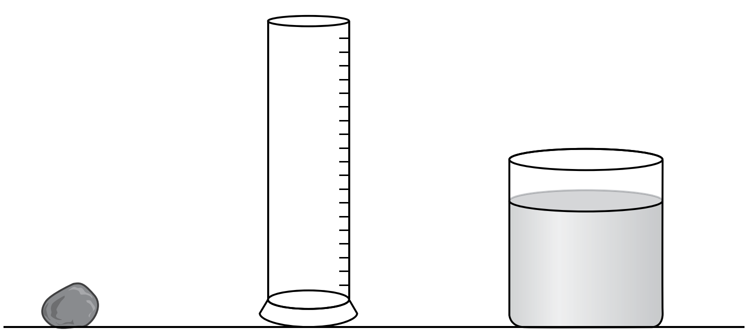
10 A flask with a tap has a volume of 200 cm^3.
When full of air, the flask has a mass of 30.98 g.
The flask is connected to a vacuum pump, the air is pumped out and then the tap is closed.
The flask now has a mass of 30.72 g.
Calculate:

a the mass of the air in the flask before connecting to the vacuum pump, in g [2]

b the density of the air in the flask. [4]

[Cambridge IGCSE® Physics 0625/23, Question 5, October/November, 2011]

11 The volume of a stone is to be found using the equipment illustrated.



The following five steps are intended to describe how the volume of the stone is found.
Copy and complete the sentences by adding appropriate words.

a Pour some .... into the measuring cylinder. [1]

b Take the reading of the .... from the scale on the measuring cylinder. [1]

c Carefully put .... into the measuring cylinder. [1]

d Take the new reading of the .... from the scale on the measuring cylinder. [1]

e Calculate the volume of the stone by .... [2]

[Cambridge IGCSE® Physics 0625/22, Question 1, May/June, 2011]