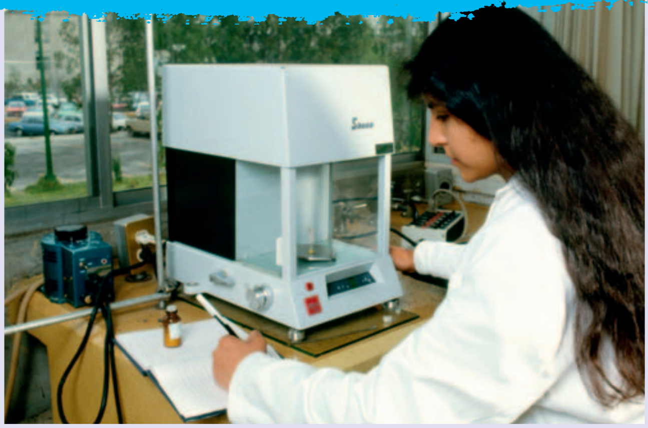
Chapter 1

Measurement



▲ **Figure 1.1**
What's the difference between mass and weight?

▲ **Figure 1.3**
Why does a block of iron sink but an iron ship floats?

Physics is a science that relies on accurate measurements. The scientific community throughout the world uses the same set of units, which are known as the SI (Système Internationale) units.

In this chapter we will look at the SI units, how the basic quantities of mass, length and time are defined and how they can be combined to form units for more complex quantities. Finally we will look at the concept of density, and investigate why things float.

▲ **Figure 1.2**
How did early clocks measure time?

▲ **Figure 1.4**
How does the balloon gain height?

1.1 SI units

SI units are based on the five basic quantities: length, mass, time, temperature and electric current. These are listed in Table 1.1.

Table 1.1
Basic SI uits.

Quantity	Unit	Symbol
Length	metre	m
Mass	kilogram	kg
Time	second	s
Thermodynamic temperature*	kelvin	K
Electric current	ampere	A

*Alternative unit is the degree celsius (°C). In this course we will only use this unit.

All other units are made up from these five basic units.

Sometimes the basic units are either too big or too small so we use prefixes to alter the size of the unit.

Table 1.2 shows some of the commonly used prefixes.

Table 1.2
Common prefixes.

Prefix	Symbol	Meaning
Mega	M	× 1 000 000
Kilo	k	× 1000
Milli	m	÷ 1000
Micro	μ	÷ 1 000 000

For example:

1 kilometre (1 km) = 1000 m

1 milliampère (1 mA) = 1/1000 A

1 microsecond (1 μs) = 1/1000 000 s

In the laboratory, when measuring length, the metre is often too large and the millimetre is too small, so we sometimes use the centimetre. So in addition to the common prefixes, you might also meet centi (c), which means ÷ 100.

DID YOU KNOW?

The prefix μ is the Greek letter mu, equivalent to our *m*.

DID YOU KNOW?

The metre was originally defined as a fraction of the Earth's circumference, but is now defined in terms of the distance travelled by light in a small fraction of a second.

The kilogram is defined as the mass of a standard kilogram held in a museum in Paris.

The second was originally defined as a fraction of the time it takes the Earth to orbit the sun. It is now defined in terms of the time period of a particular frequency radiation.

QUESTIONS

1.1 Write down the following in the basic units.
a) 32 km, b) 234 ms, c) 2400 mg,
d) 3500 μA, e) 3.5 Mm f) 6400 g

1.2 Write down the following using the most appropriate prefix.
a) 0.0048 m b) 3540 g c) 0.000 0032 s d) 8900 m

Errors and uncertainties

No quantity can ever be measured precisely. Whenever a measurement is made there is an **uncertainty**. For example, a hand-held stopwatch can measure to the nearest one-tenth of a second. An athlete is timed as completing a 100 m race in 10.1 s. This means that, assuming the timing is done perfectly, his actual time lay between 10.0 s and 10.2 s, an uncertainty of 0.1 s either way. This is often written as 10.1 ± 0.1 s. This might be improved by using an electronic timer, which could measure to the nearest $\frac{1}{100}$ of a second; this might give a result of 10.12 s. The uncertainty is now reduced to 0.01 s – but still not eliminated.

The precision of a measurement can be shown by how the figures are written. A length written as 100 m means that the length is measured to the nearest metre. However, if this is written as 100.0 m, it indicates that it is measured to the nearest tenth of a metre.

Errors are quite different from uncertainties: they arise from poorly adjusted instruments or poor use of apparatus. This is explained in Figure 1.5, showing that care must be taken to ensure that the eye is at right angles to the ruler. A reading taken from point A would give an answer of 11 mm, instead of the correct length, 12 mm.

What would a reading taken from point B give?

Standard form

Another method of showing the precision of a measurement is to use standard form. For example, the distance of the Sun from the Earth is 150 000 000 km. In standard form this is written as 1.50×10^8 km. This method of displaying readings has two advantages:

1 It is much easier to read either very small or large numbers. For example, the mass of an electron is 9.1×10^{-31} kg, that means 9.1 divided by 1 followed by 31 zeros. Try writing that out in full!

2 It also clearly shows the precision to which the reading is taken. Above the mass of the electron is shown to 2 significant figures, whereas a measurement of its mass taken to 5 significant figures is written as 9.1095×10^{-31} kg.

QUESTIONS

1.3 Write the following in standard form.
- a) 21 500 m
- b) 0.031 s
- c) 299 000 000 m

1.4 Write the following in full.
- a) 3.0×10^8 m/s
- b) 1.7×10^{-4} m
- c) 5.12×10^{-3} s

1.2 Measurement

Measurement of length

The basic SI unit of length is the metre, although kilometres (1000 m) are often used for long distances, and millimetres (0.001 m) are used for shorter distances. On some occasions the centimetre (0.01m) is also used. There are various instruments that can be used to measure length, the choice will be determined by the particular situation. In this course we shall only consider the use of rulers.

Figure 1.5 shows a ruler being used to measure the length of an electric cell.

When you use a ruler it is important that the eye is placed so that you are looking at right angles to the ruler. If the reading is taken from either position **A** or **B** an error is introduced. This type of error is called a **parallax error**.

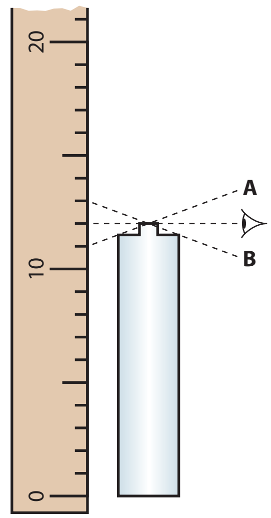
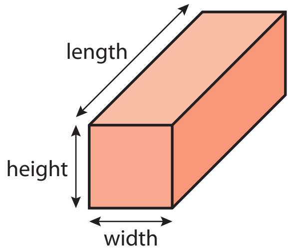
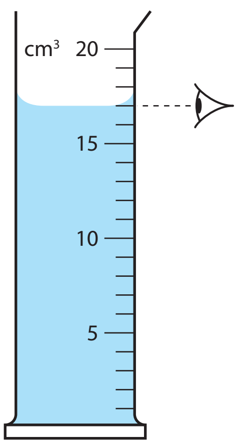


Figure 1.5



▲ **Figure 1.6**
Calculating volume.



▲ **Figure 1.7**
Reading from a measuring cylinder volume

Measurement of volume

The volume of an object is the space it takes up. Consider the box in Figure 1.6.

The volume of the box = width × height × length

The basic unit of length is the metre. If each of the sides is measured in metres, the unit of volume is metre × metre × metre or the metre cubed. The short form for this is m^3. If the unit used for measuring the dimensions of the box is the centimetre, then the unit for the volume is cm^3.

The volume of liquids can be found using a measuring cylinder as shown in Figure 1.7. When using a measuring cylinder, you will see that the water curves up to the glass at the edges. This is called a **meniscus**. The reading should always be taken from the bottom of the meniscus. The measuring cylinder should be placed on the bench and the eye should be kept level with the line of the liquid, to avoid parallax errors.

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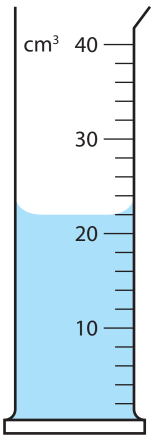
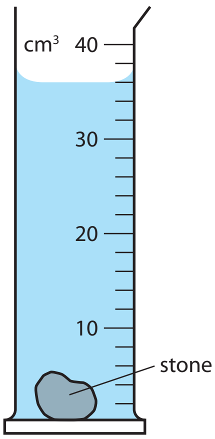
Measurement of the volume of an irregular object



▲ **Figure 1.8(a)**



▲ **Figure 1.8(b)**

First partly fill a measuring cylinder (Figure 1.8(a)). Record the volume of water.

Then gently slide the stone into the measuring cylinder (Figure 1.8(b)). Record the new volume.

The volume of the stone is the new volume minus the original volume of the water.

What is the volume of the stone in this example?

(Note that each division on the scale is 2 cm^3.)

Measurement of time

A stopwatch or stop clock may be used to measure time. The choice of which to use will depend on availability and the precision that is needed.

A stop clock, generally, will measure to the nearest second. If greater precision is needed, a stopwatch must be used. A hand-held stopwatch can be used to measure to the nearest one-tenth of a second. Even though a digital stopwatch may record to $\frac{1}{100}$ of a second, the uncertainty in the human reaction time is much more than this, consequently the hundredths are meaningless. To measure to this level of precision, the stopwatch must be started and stopped electronically.

QUESTIONS

Figure 1.9(a)

Figure 1.9(b)

Figure 1.9(c)

1.5 What are the readings on the stop clock and stopwatches in Figures 1.9(a) to 1.9(c)? Give your answer to show the uncertainty in the reading.

The simple pendulum

Clocks must have a device that repeats at a regular interval. Early clocks used a pendulum.

A simple pendulum consists of a light string, clamped at the top and with a mass attached at the bottom. The mass is called a bob.

The time it takes for the pendulum to make one complete swing or oscillation is called its **period**. The period of a simple pendulum depends only on the length of the pendulum.

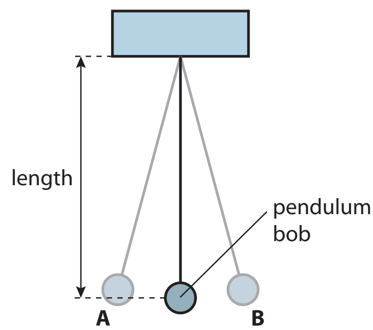


Figure 1.10
One complete oscillation is from **A** to **B** and back to **A** once more.

The period of a pendulum of length 25 mm is about 1s. To measure the time for a single oscillation with any reasonable degree of accuracy is impossible. Remember the uncertainty in the reading with a hand-held stopwatch is 0.1 s, giving at best a 10% uncertainty.

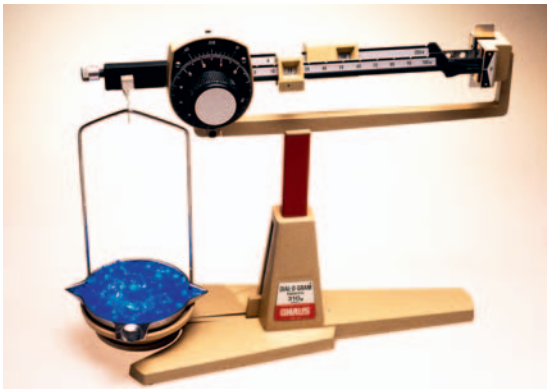
To find the period accurately we time at least 10 oscillations and then divide the reading by the number of swings. This reduces the uncertainty in the time for one oscillation by a factor of 10, from 0.1 s to 0.01 s.

Measurement of mass

Mass is one of the basic SI quantities. The basic unit of mass is the kilogram (kg). As with all units, multiples and submultiples may be used, so that small masses may be measured in grams, milligrams or even micrograms. Larger masses can be measured in megagrams, although for historical reasons one megagram is usually referred to as one tonne (t).

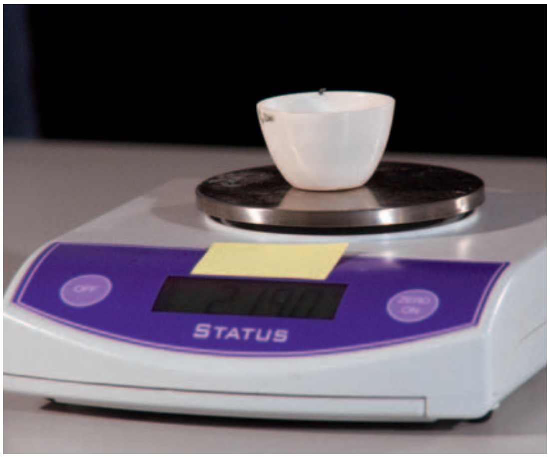
Mass is measured using a balance. The photographs in Figure 1.11 (see page 6) show various types of balances.

▲ **Figure 1.11(a)**
Beam balance.



▲ **Figure 1.11(b)**
Triple beam balance.

▲ **Figure 1.11(c)**
Lever arm balance.



▲ **Figure 1.11(d)**
Top pan balance.

In everyday life we often use the term *weight* when we mean *mass*, and for this reason it is easy to confuse the terms.

Mass is the amount of matter in an object, and it does not change with position.

Weight is the gravitational pull on the object. This means that the same object will have a greater weight on the Earth's surface than on the Moon's surface, because the Earth has a greater gravitational field than the Moon. The object will have no weight (be weightless) when in outer space where there is no gravity! We will explore this in more detail in Chapter 3.

Measuring masses of liquids

The mass of a sample of liquid cannot be measured directly. The liquid must be held in a container of some form. To measure the mass of a liquid, first measure the mass of the empty container, pour the liquid into the container, and then measure the mass again. The mass of the liquid is equal to the difference between the two readings.

WORKED EXAMPLE

An empty jug has a mass of 490 g. When it is filled with water its mass is 840 g.
Calculate the mass of water in the jug.

Mass of water = mass of jug and water − mass of empty jug
= 840 − 490 g
= **350 g**

QUESTIONS

1.6 A beaker plus liquid has a mass of 695 g. The beaker has a mass of 110 g. What is the mass of liquid?

1.7 Convert the following:
a) 43 kg to grams
b) 475 g to kilograms
c) 2.46 g to milligrams
d) 387 kg to tonnes
e) 236 μg to grams

Density

We might say that 'lead is heavier than wood', but this is technically incorrect. A kilogram of lead has the same mass as a kilogram of wood, and therefore the same weight! The difference is that the plastic has a much larger volume than the lead.

To compare materials we must look at equal volumes of material. We define **density** as the mass of 1 cm^3 or 1 m^3.

Density is defined as the mass per unit volume.

Density is a property of a material rather than a particular object. A given material always has the same density no matter what its size or shape.

To calculate density of an object we must measure both the mass and the volume of the object and then use the formula:

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

Units

The basic unit of mass is the kilogram (kg), and the basic unit of volume is the metre cubed (m^3). The unit of density is formed by dividing kg by m^3, giving kg/m^3 or kgm^{-3}. Alternatively, if the mass is measured in grams and the volume in centimetres cubed, the unit will be g/cm^3 or gcm^{-3}.

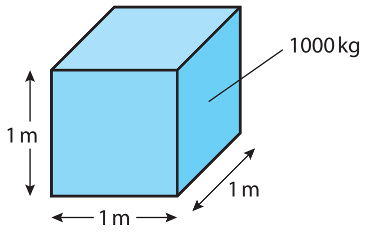
WORKED EXAMPLES

An aluminium cylinder has a volume of 250 cm^3 and a mass of 675 g.
Calculate the density of aluminium.

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

$$= \frac{675}{250}\ \text{g/cm}^3$$

$$= \mathbf{2.7\ g/cm^3}$$



▲ **Figure 1.12**
Cube of water.

A closer look at units

Water has a density of 1000 kg/m^3.
Consider the cube of water of side 1 m shown in Figure 1.12. Its mass will be 1000 kg.

The volume of the cube is $1\text{ m} \times 1\text{ m} \times 1\text{ m} = 1\text{m}^3$

$1\text{ kg} = 1000\text{ g}$

Therefore the mass of the cube is $1000 \times 1000\text{ g} = 1\,000\,000\text{ g}$

$1\text{ m} = 100\text{ cm}$

Therefore the volume of the cube $= 100\text{ cm} \times 100\text{ cm} \times 100\text{ cm}$
$= 1\,000\,000\text{ cm}^3$

$$\text{The density of the cube} = \frac{\text{mass}}{\text{volume}} = \frac{1\,000\,000}{1\,000\,000}\text{ g/cm}^3 = 1\text{ g/cm}^3$$

So we see that a density of 1000 kg/m^3 = 1 g/cm^3.

QUESTIONS

1.8 Calculate the density of a steel door of mass 585 kg and dimensions $2.0\text{ m} \times 0.75\text{ m} \times 0.050\text{ m}$.

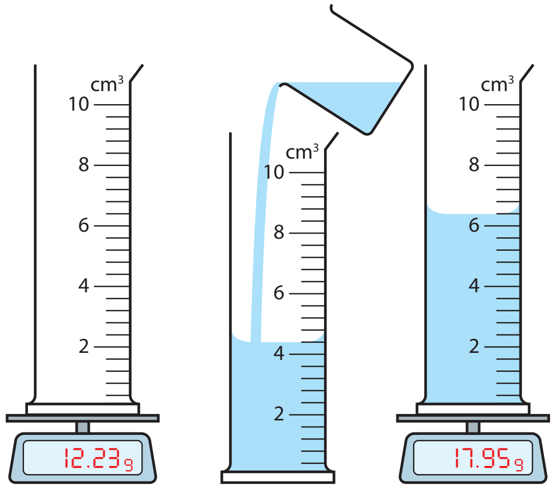
1.9 Calculate the volume of a gold ring of mass 84 g. Density of gold = 19.3 g/cm^3.

1.10 Calculate the mass of a cube of ice of side 2.0 cm. Density of ice = 0.92 g/cm^3.

Measurement of density

To find the density of a material, you must measure both the volume and the mass of the material. The techniques used are the same as those met earlier in this chapter.

Figure 1.13 show the stages of measuring the density of cooking oil.



▶ **Figure 1.13**
Measuring the density of cooking oil.

$$\text{Mass of the measuring cylinder} = 12.23\text{ g}$$
$$\text{Mass of measuring cylinder and oil} = 17.95\text{ g}$$
$$\text{Volume of oil} = 6.4\text{ cm}^3$$
$$\text{Mass of oil} = 17.95 - 12.23\text{ g} = 5.72\text{ g}$$
$$\text{Density of oil} = \frac{5.72}{6.4}\text{ g/cm}^3 = 0.92\text{ g/cm}^3$$

The answer is given to two significant figures as the least accurate measurement (the volume) is only given to two significant figures.

Hint

Even though the problem is quite simple, each stage of the calculation is clearly shown. This is good practice, which you should follow. It will help you to avoid mistakes.

Floating and sinking

Why do some objects float and others sink when placed in different liquids? If you look at Table 1.3, you will see that the substances that are less dense than water (cork, wood, wax, ice) will float in water. You will also observe that a helium-filled balloon, or a balloon filled with hot air will float in air. The general rule is that an object will float in a fluid if it is less dense than the fluid.

Table 1.3
Densities.

Material	Density (kg/m^3)
Aluminium	2700
Copper	8940
Gold	19 300
Lead	11300
Platinum	21 450
Glass	2800
Perspex	1200
Cork	240
Wood	500–700
Wax	430
Water	1000
Brine	1200
Ice	920
Petrol	730
Air	1.26
Helium	0.22

Figure 1.14
A steel boat floats because the average density of the steel and the air it contains is less than the density of water.

Figure 1.15
Hot air is less dense than cool air, so the hot air balloon floats in air.

QUESTIONS

(Use the values of density in Table 1.3.)

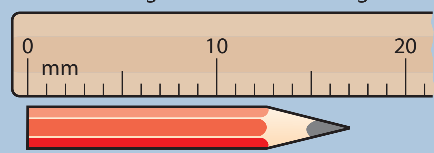
1.11 Calculate the density of a piece of wood measuring 30 cm × 20 cm × 5 cm and of mass 2.25 kg.
Give your answer a) in $g cm^{-3}$ and b) in $kg m^{-3}$.

1.12 A sheet of copper is used to make the roof a building. The copper sheet has dimensions 4.0 m × 3.2 m × 0.80 cm. Calculate the mass of the copper sheet.

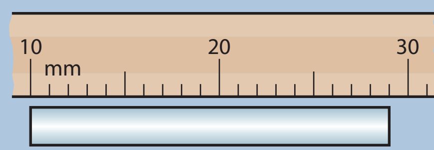
1.13 Calculate the volume of 78 g of brine.

1.14 What are the lengths of the following items?

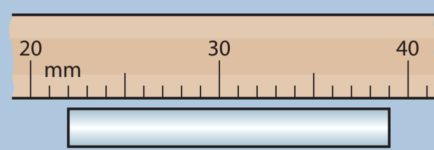
a)



b)

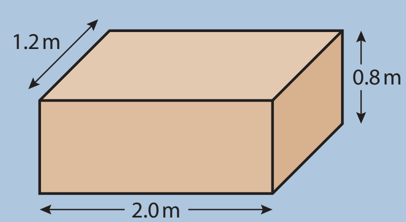


c)



1.15 A student measures the length of a room five times. The readings are 4.85 m, 4.78 m, 4.90 m, 4.83 m and 4.79 m. What is the average reading? Explain the advantage of taking the reading more than once and taking an average.

1.16 Calculate the volume of the box.

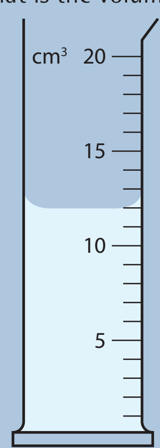


a) Calculate your answer in (i) m^3 and (ii) in cm^3 (remember that all the dimensions must be converted to cm).

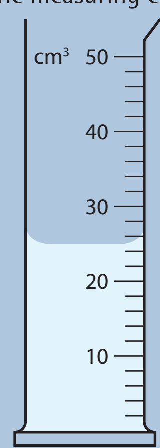
b) Use your answer to find the number of cm^3 in a m^3.

1.17 What is the volume of liquid in the measuring cylinders?

a)



b)



1.18 In an experiment a student makes the following measurements.

Mass of empty measuring cylinder = 134 g

Mass of measuring cylinder plus ethanol = 186 g

Calculate the mass of the ethanol.

1.19 List the stages needed to find the density of a stone.
A stone has a density of 2.70 g/cm^3, and a mass of 62.1 g.
Calculate the volume of the stone.

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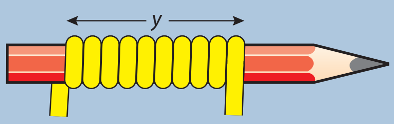
1.20 A student needs to measure the diameter of a wire. She wraps the wire round a pencil, as shown in the diagram.



She measures the distance, *y*, as 12 mm.

a) Calculate the diameter of the wire.

b) Suggest one source of error in the measurement and state how it could be minimised.

Summary

Now that you have completed this chapter, you should be able to:

- use and recall the SI units of length, mass and time
- recognise prefixes to alter the size of units
- recognise that all units are made up from five basic units
- understand that there is always an uncertainty when taking a measurement
- understand the use of standard form
- use rulers and measuring cylinders to measure length and volume
- use a stopwatch to measure time
- measure mass of solids and liquids using a balance
- understand the meaning of density
- recall and use the equation density $= \frac{\text{mass}}{\text{volume}}$
- measure the density of regular solids and liquids
- recognise that objects will float in fluids if they have lower density than the fluid

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- measure the volume of an irregular object
- measure the time period of a pendulum.