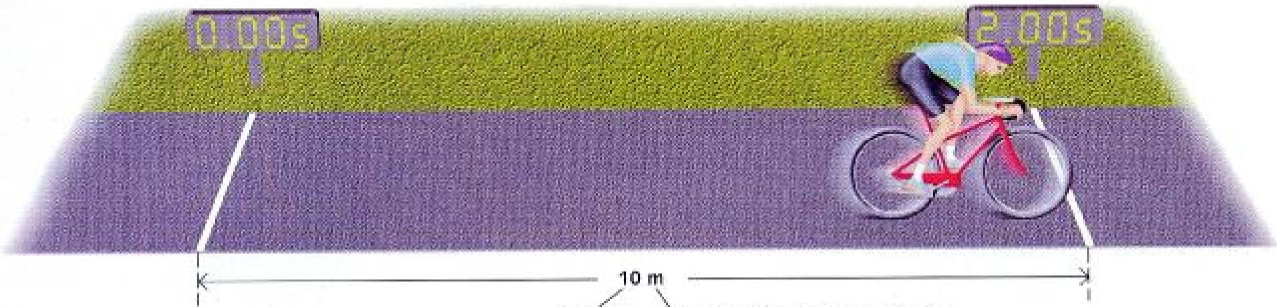
1.01 Numbers and units



When you make a measurement, you might get a result like the one above: a distance of 10 m. The complete measurement is called a **physical quantity**. It is made up of two parts: a number and a unit.

10 m really means $10 \times \text{m}$ (ten times metre), just as in algebra, $10x$ means $10 \times x$. (ten times x). You can treat the m just like a symbol in an algebraic equation. This is important when combining units.

Advanced units

5 m/s is a space-saving way of writing $5\frac{\text{m}}{\text{s}}$.

But $5\frac{\text{m}}{\text{s}}$ equals $5\text{ m}\frac{1}{\text{s}}$.

Also, $\frac{1}{\text{s}}$ can be written as s^{-1}.

So the speed can be written as 5 m s^{-1}.

This method of showing units is more common in advanced work.

Combining units

In the diagram above, the girl cycles 10 metres in 2 s. So she travels 5 metres every second. Her *speed* is 5 metres per second. To work out the speed, you divide the distance travelled by the time taken, like this:

$$\text{speed} = \frac{10\text{ m}}{2\text{ s}} \qquad \text{(s is the symbol for second)}$$

As m and s can be treated as algebraic symbols:

$$\text{speed} = \frac{10}{2} \cdot \frac{\text{m}}{\text{s}} = 5\frac{\text{m}}{\text{s}}$$

To save space, $5\frac{\text{m}}{\text{s}}$ is usually written as 5 m/s.

So m/s is the unit of speed.

Rights and wrongs

This equation is correct: $\text{speed} = \frac{10\text{ m}}{2\text{ s}} = 5\text{ m/s}$

This equation is incorrect: $\text{speed} = \frac{10}{2} = 5\text{ m/s}$

It is incorrect because the m and s have been left out. 10 divided by 2 equals 5, and not 5 m/s.

Strictly speaking, units should be included at *all* stages of a calculation, not just at the end. However, in this book, the 'incorrect' type of equation will sometimes be used so that you can follow the arithmetic without units which make the calculation look more complicated.

Bigger and smaller

You can make a unit bigger or smaller by putting an extra symbol, called a prefix, in front. (Below, W stands for watt, a unit of power.)

prefix	meaning		example
G (giga)	1 000 000 000	(10^9)	GW (gigawatt)
M (mega)	1 000 000	(10^6)	MW (megawatt)
k (kilo)	1000	(10^3)	km (kilometre)
d (deci)	$\frac{1}{10}$	(10^{-1})	dm (decimetre)
c (centi)	$\frac{1}{100}$	(10^{-2})	cm (centimetre)
m (milli)	$\frac{1}{1000}$	(10^{-3})	mm (millimetre)
μ (micro)	$\frac{1}{1\,000\,000}$	(10^{-6})	μW (microwatt)
n (nano)	$\frac{1}{1\,000\,000\,000}$	(10^{-9})	nm (nanometre)

Powers of 10

$1000 = 10 \times 10 \times 10 = 10^3$

$100 = 10 \times 10 = 10^2$

$0.1 = \frac{1}{10} = 10^{-1}$

$0.01 = \frac{1}{100} = \frac{1}{10^2} = 10^{-2}$

$0.001 = \frac{1}{1000} = \frac{1}{10^3} = 10^{-3}$

'milli' means 'thousandth', *not* 'millionth'

Scientific notation

An atlas says that the population of Iceland is this:

270 000

There are two problems with giving the number in this form. Writing lots of zeros isn't very convenient. Also, you don't know which zeros are accurate. Most are only there to show you that it is a six-figure number. These problems are avoided if the number is written using powers of ten:

$2.7 \times 10^5 \qquad (10^5 = 10 \times 10 \times 10 \times 10 \times 10 = 100\,000)$

'2.7×10^5' tells you that the figures 2 and 7 are important. The number is being given to *two significant figures*. If the population were known more accurately, to three significant figures, it might be written like this:

2.70×10^5

Numbers written using powers of ten are in **scientific notation** or **standard form**. The examples on the right are to one significant figure.

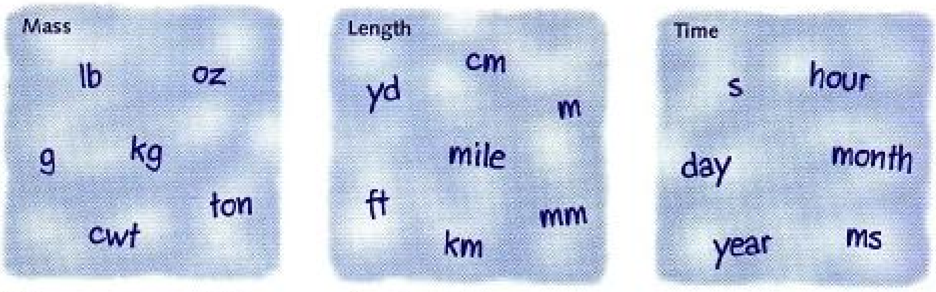
decimal	fraction	scientific notation
500		5×10^2
0.5	$\frac{5}{10}$	5×10^{-1}
0.05	$\frac{5}{100}$	5×10^{-2}
0.005	$\frac{5}{1000}$	5×10^{-3}

Q

1 How many grams are there in 1 kilogram?
2 How many millimetres are there in 1 metre?
3 How many microseconds are there in 1 second?
4 This equation is used to work out the area of a rectangle: area = length × width.
If a rectangle measures 3 m by 2 m, calculate its area, and include the units in your calculation.
5 Write down the following in km:
2000 m 200 m 2×10^4 m
6 Write down the following in s:
5000 ms 5×10^7 μs
7 Using scientific notation, write down the following to two significant figures:
1500 m 1 500 000 m 0.15 m 0.015 m

Related topics: SI units 1.02; speed 2.01

1.02 A system of units



There are many different units – including those above. But in scientific work, life is much easier if everyone uses a common system of units.

SI units

Most scientists use **SI units** (full name: Le Système International d'Unités). The basic SI units for measuring mass, time, and length are the kilogram, the second, and the metre. From these **base units** come a whole range of units for measuring volume, speed, force, energy, and other quantities.

Other SI base units include the ampere (for measuring electric current) and the kelvin (for measuring temperature).

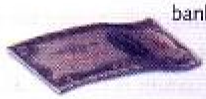
The mass of an object can be found using a **balance** like this. The balance really detects the gravitational pull on the object on the pan, but the scale is marked to show the mass.

Mass

Mass is a mysterious property. It affects how objects behave in two ways:

- All objects are attracted to the Earth. The greater the mass of an object, the stronger is the Earth's gravitational pull on it.
- All objects resist attempts to make them go faster, slower, or in a different direction. The greater the mass, the greater is the resistance to change in motion.

The SI base unit of mass is the **kilogram** (symbol **kg**). The standard kilogram is a block of platinum alloy kept at the Office of Weights and Measures in Paris. Other units based on the kilogram are shown below:

mass		comparison with base unit	scientific notation	approximate size
1 tonne (t)		1000 kg	10^3 kg	 medium-sized car
1 kilogram (kg)		**1 kg**		 bag of sugar
1 gram (g)	1 g	$\frac{1}{1000}$ kg	10^{-3} kg	 banknote
1 milligram (mg)	$\frac{1}{1000}$ g	$\frac{1}{1000000}$ kg	10^{-6} kg	 human hair

Note: the SI base unit of mass is the **kilogram**, not the gram

Time

The SI base unit of time is the **second** (symbol **s**). Here are some shorter units based on the second:

1 millisecond (ms) = $\frac{1}{1000}$ s = 10^{-3} s

1 microsecond (µs) = $\frac{1}{1\,000\,000}$ s = 10^{-6} s

1 nanosecond (ns) = $\frac{1}{1\,000\,000\,000}$ s = 10^{-9} s

To keep time, clocks and watches need something that beats at a steady rate. Some old clocks used the swings of a pendulum. Modern digital watches count the vibrations made by a tiny quartz crystal.

The second was originally defined as $\frac{1}{60 \times 60 \times 24}$ of a day, one day being the time it takes the Earth to rotate once. But the Earth's rotation is not quite constant. So, for accuracy, the second is now defined in terms of something that never changes: the frequency of an oscillation which can occur in the nucleus of a caesium atom.

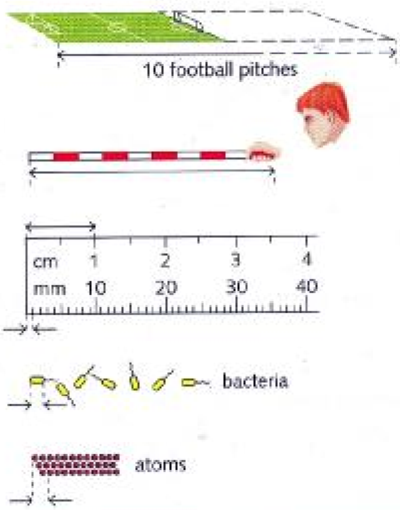
Length

The SI base unit of length is the **metre** (symbol **m**). At one time, the standard metre was the distance between two marks on a metal bar kept at the Office of Weights and Measures in Paris. A more accurate standard is now used, based on the speed of light, as on the right.

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

There are larger and smaller units of length based on the metre:

distance	comparison with base unit	scientific notation
1 kilometre (km)	1 000 m	10^3 m
1 metre (m)	**1 m**	
1 centimetre (cm)	$\frac{1}{100}$ m	10^{-2} m
1 millimetre (mm)	$\frac{1}{1\,000}$ m	10^{-3} m
1 micrometre (µm)	$\frac{1}{1\,000\,000}$ m	10^{-6} m
1 nanometre (nm)	$\frac{1}{1\,000\,000\,000}$ m	10^{-9} m



Q

1 What is the SI unit of length?
2 What is the SI unit of mass?
3 What is the SI unit of time?
4 What do the following symbols stand for?
g mg t µm ms
5 Write down the value of
a) 1564 mm in m **b)** 1750 g in kg
c) 26 t in kg **d)** 62 µs in s
e) 3.65×10^4 g in kg **f)** 6.16×10^{-7} mm in m
6 The 500 pages of a book have a mass of 2.50 kg. What is the mass of each page **a)** in kg **b)** in mg?
7 km µg µm t nm kg m
ms s mg ns µs g mm

Arrange the above units in three columns as below. The units in each column should be in order, with the largest at the top.

	mass	length	time
largest unit →			

1 In each of the following pairs, which quantity is the larger?

a) 2 km or 2500 m?
b) 2 m or 1500 mm?
c) 2 tonnes or 3000 kg?
d) 2 litres or 300 cm^3? [4]

2 Which of the following statements is/are correct?

A One milligram equals one million grams.
B One thousand milligrams equals one gram.
C One million milligrams equals one gram.
D One million milligrams equals one kilogram. [2]

3 The table shows the density of various substances.

substance	*density/ g/cm³*
copper	8.9
iron	7.9
kerosene	0.87
mercury	13.6
water	1.0

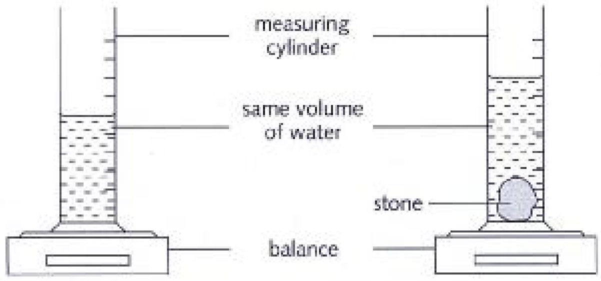
Consider the following statements:

A 1 cm^3 of mercury has a greater mass than 1 cm^3 of any other substance in this table – true or false?
B 1 cm^3 of water has a smaller mass than 1 cm^3 of any other substance in this table – true or false?
C 1 g of iron has a smaller volume than 1 g of copper – true or false?
D 1 g of mercury has a greater mass than 1 g of copper – true or false? [2]

4 Which block is made of the densest material? [1]

block	*mass/ g*	*length/ cm*	*breadth/ cm*	*height/ cm*
A	480	5	4	4
B	360	10	4	3
C	800	10	5	2
D	600	5	4	3

5 The mass of a measuring cylinder and its contents are measured before and after putting a stone in it.



Which of the following could you calculate using measurements taken from the apparatus above?

A the density of the liquid only
B the density of the stone only
C the densities of the liquid and the stone [2]

6 A plastic bag filled with air has a volume of 0.008 m^3. When air in the bag is squeezed into a rigid container, the mass of the container (with air) increases from 0.02 kg to 0.03 kg. Use the formula

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

to calculate the density of the air in the bag. [2]

Measurements and Units **Revision Checklist**

Photocopy the list of topics below and tick the boxes of the ones that are included in your examination syllabus. (Your teacher should be able to tell you which they are.) Use your list when you revise. The spread number in brackets tells you where to find more information.

- ❑ **1** How to use units. (1.01)
- ❑ **2** Making bigger or smaller units using prefixes. (1.01)
- ❑ **3** Writing numbers in scientific notation. (1.01)
- ❑ **4** SI units, including the metre, kilogram, and second. (1.02)
- ❑ **5** Units for measuring volume. (1.03)
- ❑ **6** How density is defined. (1.03)
- ❑ **7** Methods of measuring volume and density. (1.04)
- ❑ **8** The meaning of relative density. (1.04)

2.01 Speed, velocity, and acceleration

▲ *Thrust* supersonic car travelling faster than sound. For speed records, cars are timed over a measured distance (either one kilometre or one mile). The speed is worked out from the average of two runs – down the course and then back again – so that the effects of wind are cancelled out.

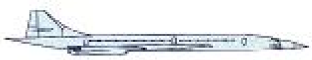
Travel times

time taken to travel 1 kilometre (1000 m)

runner 150 s

Grand Prix car 10 s

jet car 3 s



Concorde 1.5 s

Space Shuttle 0.1 s

Speed

If a car travels between two points on a road, its average speed can be calculated like this:

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

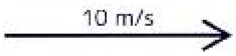
If distance is measured in metres (m) and time in seconds (s), speed is measured in metres per second (m/s). For example: if a car moves 90 m in 3 s, its average speed is 30 m/s.

On most journeys, the speed of a car varies, so the actual speed at any moment is usually different from the average speed. To find an actual speed, you need to discover how far the car moves in the shortest time you can measure. For example, if a car moves 0.20 metres in 0.01 s:

$$\text{speed} = \frac{0.20\ \text{m}}{0.01\ \text{s}} = 20\ \text{m/s}$$

Velocity

Velocity means the speed of something *and* its direction of travel. For example, a cyclist might have a velocity of 10 m/s due east. On paper, this velocity can be shown using an arrow:



For motion in a straight line you can use a + or - to indicate direction. For example:

+10 m/s (velocity of 10 m/s *to the right*)
-10 m/s (velocity of 10 m/s *to the left*)

Note: +10 m/s may be written without the +, just as 10 m/s.

Quantities, such as velocity, which have a direction as well as a magnitude (size) are called **vectors**.

Acceleration

Something is accelerating if its velocity is *changing*. Acceleration is calculated like this:

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

For example, the car on the right increases its velocity from zero to 12 m/s in 4 s. So:

$$\text{average acceleration} = \frac{12\text{ m/s}}{4\text{ s}} = 3\text{ m/s}^2$$

Note that acceleration is measured in metres per second^2 (m/s^2).

Acceleration is a vector. It can be shown using an arrow (usually double-headed). Alternatively, a + or - sign can be used to indicate whether the velocity is increasing or decreasing. For example:

+3 m/s^2 (velocity *increasing* by 3 m/s every second)
-3 m/s^2 (velocity *decreasing* by 3 m/s every second)

A *negative* acceleration is called a **deceleration** or a **retardation**.
A *uniform* acceleration means a constant (steady) acceleration.

time	velocity
0 s	0 m/s
1 s	3 m/s
2 s	6 m/s
3 s	9 m/s
4 s	12 m/s

The velocity of this car is increasing by 3 m/s every second. The car has a steady acceleration of 3 m/s^2.

Solving a problem

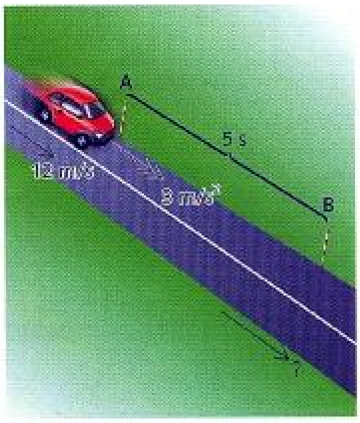
Example The car on the right passes post A with a velocity of 12 m/s. If it has a steady acceleration of 3 m/s^2, what is its velocity 5 s later, as it passes B?

The car is gaining 3 m/s of velocity every second. So in 5 s, it gains an extra 15 m/s on top of its original 12 m/s. Therefore its final velocity is 27 m/s. Note that the result is worked out like this:

final velocity = original velocity + extra velocity

So: final velocity = original velocity + (acceleration × time)

The above equation also works for retardation. If a car has a retardation of 3 m/s^2, you treat this as an acceleration of -3 m/s^2.

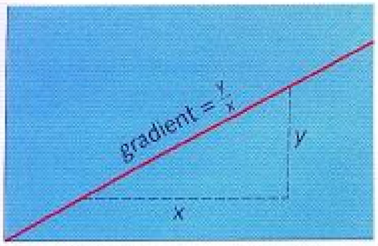


Q

1. A car travels 600 m in 30 s. What is its average speed? Why is its actual speed usually different from its average speed?
2. How is velocity different from speed?
3. A car has a steady speed of 8 m/s.
   a) How far does the car travel in 8 s?
   b) How long does the car take to travel 160 m?
4. Calculate the average speed of each thing in the chart of travel times on the opposite page.
5. A car has an acceleration of +2 m/s^2. What does this tell you about the velocity of the car? What is meant by an acceleration of -2 m/s^2?
6. A car takes 8 s to increase its velocity from 10 m/s to 30 m/s. What is its average acceration?
7. A motor cycle, travelling at 20 m/s, takes 5 s to stop. What is its average retardation?
8. An aircraft on its take-off run has a steady acceleration of 3 m/s^2.
   a) What velocity does the aircraft gain in 4 s?
   b) If the aircraft passes one post on the runway at a velocity of 20 m/s, what is its velocity 8 s later?
9. A truck travelling at 25 m/s puts its brakes on for 4 s. This produces a retardation of 2 m/s^2. What does the truck's velocity drop to?

Related topics: units **1.01**; equations of motion **2.03**; vectors **2.11**

2.02 Motion graphs



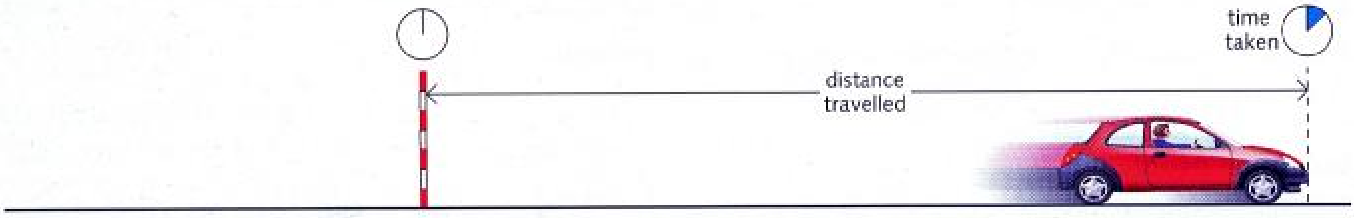
On a straight line graph like this, the gradient has the same value wherever you measure *y* and *x*.

Distance–time graphs

Graphs can be useful when studying motion. Below, a car is travelling along a straight road, away from a marker post. The car's distance from the post is measured every second. The charts and graphs show four different examples of what the car's motion might be.

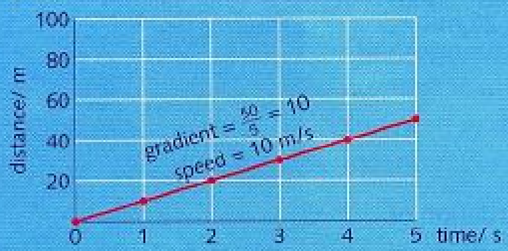
On a graph, the line's rise on the vertical scale divided by its rise on the horizontal scale is called the **gradient**, as shown on the left. With a distance–time graph, the gradient tells you how much extra distance is travelled every second. So:

> On a distance–time graph, the gradient of the line is numerically equal to the speed.



A Car travelling at **steady speed**

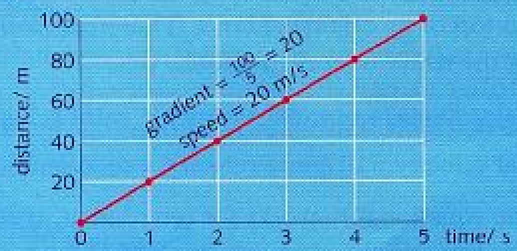
time/ s	0	1	2	3	4	5
distance/ m	0	10	20	30	40	50



The line rises 10 m on the distance scale for every 1 s on the time scale.

B Car travelling at **higher steady speed**

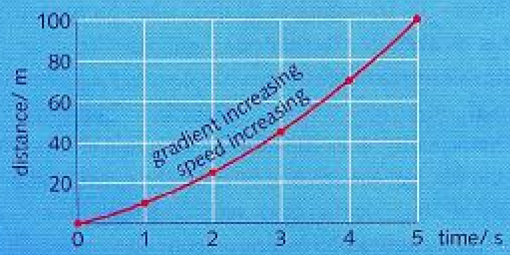
time/ s	0	1	2	3	4	5
distance/ m	0	20	40	60	80	100



The line is steeper than before. It rises 20 m on the distance scale for every 1 s on the time scale.

C Car **accelerating**

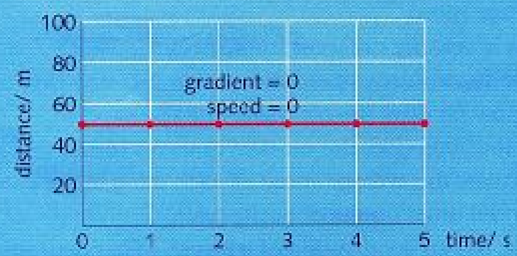
time/ s	0	1	2	3	4	5
distance/ m	0	10	25	45	70	100



The speed rises. So the car travels further each second than the one before, and the line curves upwards.

D Car **stopped**

time/ s	0	1	2	3	4	5
distance/ m	50	50	50	50	50	50



The car is parked 50 m from the post, so this distance stays the same.

Speed–time graphs

Each speed–time graph below is for a car travelling along a straight road. The gradient tells you how much extra speed is gained every second. So:

> On a speed–time graph, the gradient of the line is numerically equal to the acceleration.

In graph E, the car travels at a steady 15 m/s for 5 s, so the distance travelled is 75 m. The area of the shaded rectangle, calculated using the scale numbers, is also 75. This principle works for more complicated graph lines as well. In graph F, the area of the shaded triangle, $^1/_2 \times$ base $\times$ height, equals 50. So the distance travelled is 50 metres.

> On a speed–time graph, the area under the line is numerically equal to the distance travelled.

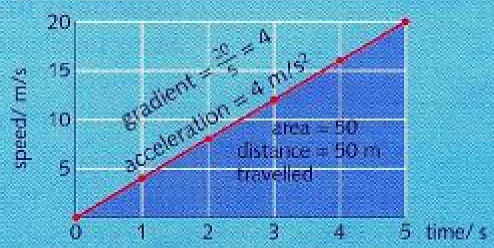
E Car travelling at **steady speed**

time/ s	0	1	2	3	4	5
speed/ m/s	15	15	15	15	15	15

The speed stays the same, so the line stays at same level.

F Car with **steady acceleration**

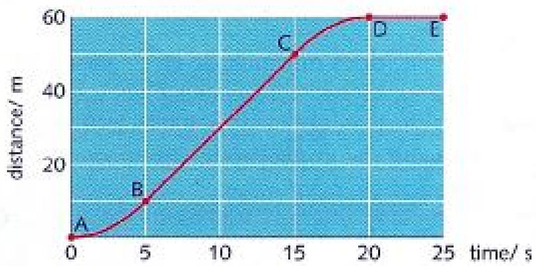
time/ s	0	1	2	3	4	5
speed/ m/s	0	4	8	12	16	20



As car gains speed, the line rises 4 m/s on speed scale for every 1 s on time scale.

Q

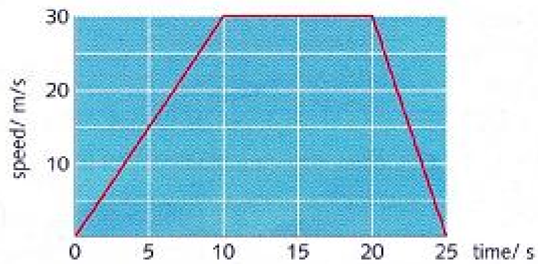
1



The distance–time graph above is for a motor cycle travelling along a straight road.

a) What is the motor cycle doing between points D and E on the graph?
b) Between which points is it accelerating?
c) Between which points is its speed steady?
d) What is this steady speed?
e) What is the distance travelled between A and D?
f) What is the average speed between A and D?

2



The speed–time graph above is for another motor cycle travelling along the same road.

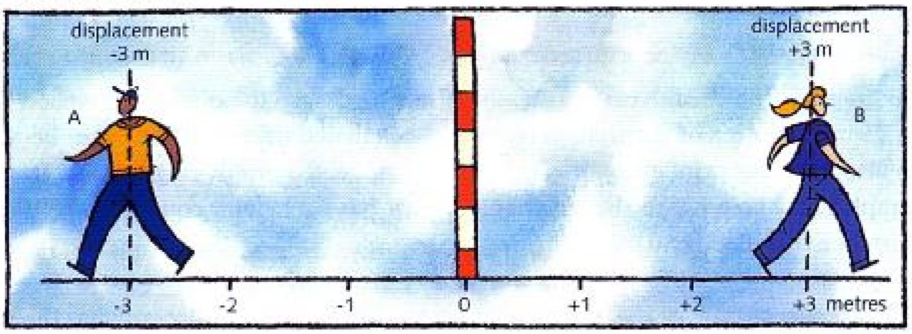
a) What is the motor cycle's maximum speed?
b) What is the acceleration during the first 10 s?
c) What is its deceleration during the last 5 s?
d) What distance is travelled during the first 10 s?
e) What is the total distance travelled?
f) What is the time taken for the whole journey?
g) What is the average speed for the whole journey?

Related Topics: speed, velocity, and acceleration **2.01**; braking distance **4.04**

2.03 Equations of motion

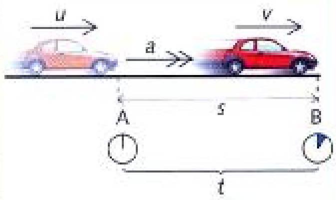
A displacement vector
(a vector is any quantity which has direction as well as size).

Displacement



Distance moved in a particular direction is called **displacement**. It is a vector. In simple cases, the vector direction can be shown using a + or a - . Above, for example, one person has a displacement of -3 m from the post; the other has a displacement of +3 m (often written without the + sign).

Equations linking *s*, *u*, *v*, *a*, and *t*



s = displacement (m)

u = initial velocity (m/s)

v = final velocity (m/s)

a = acceleration (m/s^2)

t = time (s)

Be careful not to confuse s, the displacement in metres, with s, the symbol for second.

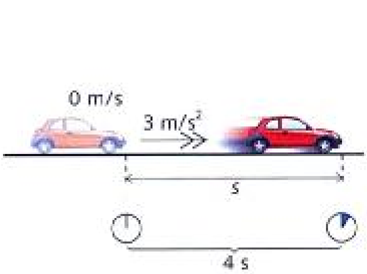
Many problems involving moving objects can be solved using just four equations. They apply if the motion is in a straight line and the acceleration is uniform (steady).

Five symbols are used in the equations. The diagram on the left shows what they mean. The car has an acceleration a. It passes the first marker (A) with a velocity u, its *initial velocity*. Time t later, it passes the second marker (B) with velocity v, its *final velocity*. It then has a displacement s.

These are the equations. Each one links four out of the five quantities:

$v = u + at$	(does not include s)
$s = ut + \frac{1}{2}at^2$	(does not include v)
$s = \frac{1}{2}(u + v)t$	(does not include a)
$v^2 = u^2 + 2as$	(does not include t)

If values of three of the quantities s, u, v, a, and t are known, you can calculate the value of a fourth by using the appropriate equation.



Example A car accelerates from rest at 3 m/s^2 along a straight road. How far has the car travelled after 4 s?

In this case:
s is the quantity to be found
u is zero because the car starts at rest
a is 3 m/s^2
t is 4 s

So, choosing the equation which includes s, u, a, and t, but not v, and omitting some of the units for simplicity:

$$s = ut + \tfrac{1}{2}at^2 = (0 \times 4) + (\tfrac{1}{2} \times 3 \times 4^2) = 24\,\text{m}$$

So: distance travelled = 24 m

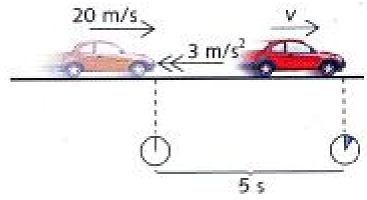
Negatives and positives

u, v, a, and s are vectors, so you must allow for their direction when substituting numbers in the equations. The equations assume that all four vectors are in the same direction (for example, to the right), so if any are in the opposite direction you count them as negative (-).

These mean the same thing.

A deceleration is a negative acceleration. Mathematically, it is the same as an acceleration in the opposite direction.

Example The car on the right is travelling at 20 m/s along a straight road. The driver puts the brakes on for 5 s. If this causes a deceleration of 3 m/s², what is the car's final velocity?



The car's deceleration has been shown as an acceleration to the left.

In this case: u is 20 m/s (positive, because it is to the right)
v is the quantity to be found
a is -3 m/s² (negative, because it is to the left)
t is 5 s

So, choosing the equation which includes u, v, a, and t, but not s, and omitting some of the units for simplicity:

$$v = u + at = 20 + (-3 \times 5) = 20 - 15 = 5\ \text{m/s}$$

So: final velocity = 5 m/s (to the right, because it is positive)

Explaining the equations

$v = u + at$

at, acceleration x time, is the gain in speed. So this equation is, in effect, telling you that:

final speed = initial speed + gain in speed

$s = \frac{1}{2}(u + v)t$

$\frac{1}{2}(u + v)$ is the average speed. So this equation is, in effect, telling you that:

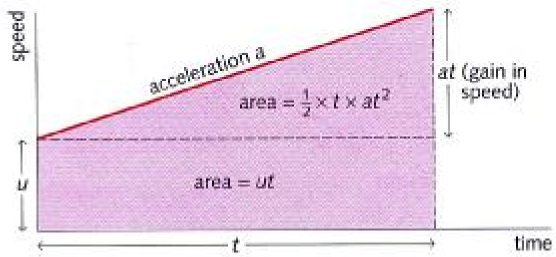
distance travelled = average speed x time taken

$v^2 = u^2 + 2as$

This equation can be found by combining the two equations above, and eliminating t from them.

$s = ut + \frac{1}{2}at^2$

This equation can be found by working out the area under a speed–time graph for an object accelerating from one speed to another. The area gives the distance travelled and, therefore, the displacement.



Q

Use the equations of motion to solve the following. In each case, assume that the motion is in a straight line and that the acceleration is uniform (steady).

1 A motor cycle travelling at 10 m/s accelerates at 4 m/s² for 8 s.
  a) What is its final velocity?
  b) How far does it travel during the 8 s?

2 A car accelerates from 8 m/s to 20 m/s in 10 s.
  a) What is its acceleration?
  b) How far does it travel during the 10 s?

3 A train is travelling at 40 m/s when its brakes are applied. This produces a deceleration of 2 m/s².
  a) How long does the train take to come to rest? (Hint: if the train comes to rest, what does this tell you about its final speed?)
  b) How far does the train travel before stopping?

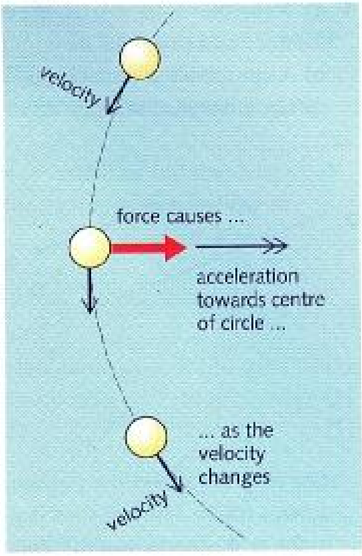
4 An aircraft accelerates at 2.5 m/s². Its take-off speed is 60 m/s.
  a) What length of runway does it need to take off?
  b) How long does it take to reach its take-off speed?

Related topics: speed, velocity, and acceleration **2.01**; motion graphs **2.02**; acceleration of free fall **2.05 – 2.06**; vectors **2.11**

Inward acceleration

Motion in a circle is one example of a force producing acceleration.

When something is moving in a circle, the inward centripetal force produces an inward acceleration as on the right. It may be difficult to imagine a ball accelerating towards the centre of a circle without getting any closer to it, but the ball is constantly moving inwards from the position it would have had if it travelled in a straight line.

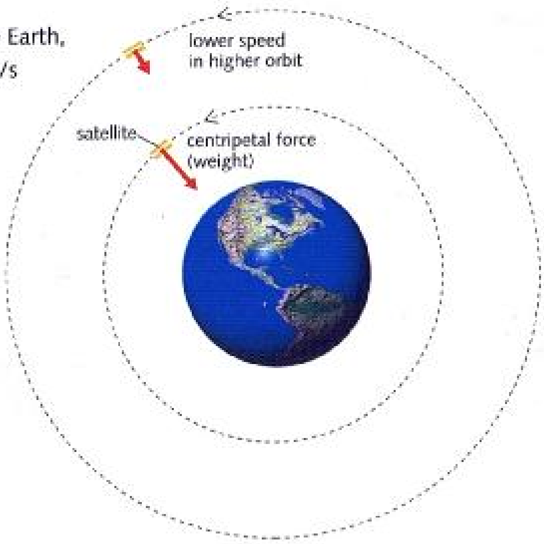


Satellites in orbit

Gravitational pull provides the centripetal force needed to make a satellite move in a circle around the Earth. When a satellite is put into a circular orbit, its speed is carefully chosen so that its weight supplies exactly the right amount of centripetal force required.

The mass of a satellite does not affect the speed required for a particular orbit. If the mass is doubled, twice as much centripetal force is needed, but that is supplied by the doubled gravitational pull of the Earth.

For a satellite orbiting close to the Earth, an orbital speed of about 8000 m/s (29 000 km per hour) is needed. The further out the orbit, the lower the gravitational pull, and the less speed is required.



The time for one orbit is called the **period** (T). It is linked to the satellite's speed (v) and radius (r) of its orbit by the equation: $T = 2\pi r/v$. So, the greater the radius of the orbit, and the slower the speed, the longer the period.

Calculating...

...centripetal acceleration

There is an equation for calculating centripetal acceleration. If an object moves at speed v in a circle of radius r:

centripetal acceleration $= \frac{v^2}{r}$

Note: if the object moves *faster* in a circle of *smaller* radius, its centripetal acceleration *increases*.

...and centripetal force

Force = mass x acceleration. So, if the object moving in a circle has a mass m:

centripetal force required $= \frac{mv^2}{r}$

Q

1 A piece of clay is stuck to the edge of a potter's wheel. Draw a diagram to show the path of the clay if it comes unstuck while the wheel is rotating.

2 A car travels round a bend in the road. What supplies the centripetal force needed?

3 In question 2, how does the centripetal force change if the car

a) has less mass

b) travels at a slower speed

c) travels round a tighter curve?

4 A satellite is in a circular orbit around the Earth.

a) Draw a diagram to show any forces on the satellite. On your diagram, show the direction of the satellite's acceleration.

b) If the satellite had more mass, how would this affect the speed required for the orbit?

c) If the satellite had a higher orbit, how would this affect the speed required?

d) If the satellite had a higher orbit, how would this affect the centripetal force required?

Related topics: velocity **2.01**, Newton's 1st law **2.07**; force, mass, and acceleration **2.08**; gravitational force **2.09**; orbits of satellites **12.04**

Photocopy the list of topics below and tick the boxes of the ones that are included in your examination syllabus. (Your teacher should be able to tell you which they are.) Use your list when you revise. The spread number in brackets tells you where to find more information.

- ❑ **1** Measuring speed. (2.01)
- ❑ **2** The difference between speed and velocity. (2.01)
- ❑ **3** How acceleration is defined. (2.01)
- ❑ **4** The meaning of retardation. (2.01)
- ❑ **5** Representing motion using distance-time and speed-time graphs. (2.02)
- ❑ **6** Calculating
  - speed from a distance-time graph.
  - acceleration from a speed-time graph.
  - distance travelled from a speed-time graph. (2.02)
- ❑ **7** The equations linking s, u, v, a, and t, and how to use them. (2.03)
- ❑ **8** Recording the motion of a trolley using ticker-tape, and calculating an acceleration from the data collected. (2.04)
- ❑ **9** The acceleration of free fall, g. (2.05)
- ❑ **10** Measuring g. (2.05)
- ❑ **11** Carrying out calculations on the motion of an object in free fall using the s, u, v, a, and t, equations. (2.06)
- ❑ **12** The motion of an object that is falling while travelling sideways. (2.06)
- ❑ **13** Measuring force. (2.07)
- ❑ **14** How an object moves if the forces on it are balanced: Newton's first law of motion. (2.07)
- ❑ **15** Terminal velocity. (2.07)
- ❑ **16** The meaning of resultant force. (2.08)
- ❑ **17** The link between force, mass, and acceleration: Newton's second law of motion. (2.08)
- ❑ **18** Defining the SI unit of force: the newton. (2.08)
- ❑ **19** The properties of gravitational force. (2.09)
- ❑ **20** The difference between weight and mass. (2.09)
- ❑ **21** Defining gravitational field strength. (2.09)
- ❑ **22** Why the weight of an object can vary but, under normal circumstances, the mass does not change. (2.09)
- ❑ **23** Two meanings of g. (2.09)
- ❑ **24** How all forces exist in pairs: Newton's third law of motion. (2.10)
- ❑ **25** How rockets and jets produce a force. (2.10)
- ❑ **26** The difference between vectors and scalars. (2.11)
- ❑ **27** Adding vectors using the parallelogram rule. (2.11)
- ❑ **28** Resolving a vector into two components. (2.11)
- ❑ **29** Defining momentum. (2.12)
- ❑ **30** The link between force and momentum. (2.12)
- ❑ **31** The meaning of impulse. (2.12)
- ❑ **32** The law of conservation of momentum. (2.13)
- ❑ **33** Applying the law of conservation of momentum to objects which are springing apart or colliding. (2.13)
- ❑ **34** The meaning of centripetal force. (2.14)
- ❑ **35** The factors on which centripetal force depends. (2.14)
- ❑ **36** Why an object moving in a circle has an inward acceleration. (2.14)
- ❑ **37** The conditions required for a satellite to move in a circular orbit around the Earth. (2.14)

14.02 Experimental procedures (1) – preparing

This spread should help you plan an experimental procedure. The handwritten notes show part of one student's commentary on her procedure.

Presenting the problem

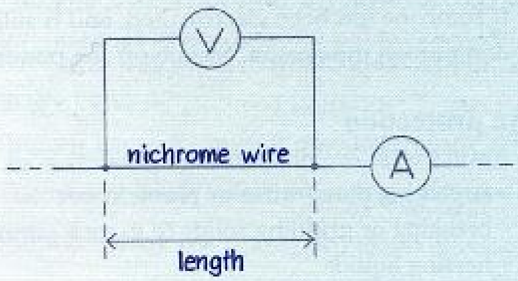
Start by describing the problem you are going to investigate, and the main features of the method you will use to tackle it.

I am going to investigate how the resistance of nichrome wire depends on its length.

I know that resistance can be calculated with this equation:

$$\text{resistance (in } \Omega) = \frac{\text{voltage (in V)}}{\text{current (in A)}}$$

So to find the resistance of a length of nichrome wire, I need to put the wire in a circuit, then measure the voltage across it and the current through it. I will do this for different lengths of nichrome.



I think I can predict how the resistance will vary with length. If the length of wire is doubled, the current (flow of electrons) has to be pushed between twice as many atoms. So I would expect the resistance to double as well.

Making a prediction

You may have an idea of what you expect to happen in your enquiry. This prediction is called your **hypothesis**. You should write it down. It may not be right! It is just an idea. The aim of your procedure is to test it.

In my experiment, three of the key variables are:

length of nichrome wire – to be measured with a ruler marked in mm

voltage – to be measured with a voltmeter

current – to be measured with an ammeter

I shall start with 50cm of thin nichrome wire, put a voltage of 6V across it, and measure the current through it. From the voltmeter and ammeter readings, I can calculate the resistance.

I will take more sets of readings, shortening the wire by 5cm each time until it is only 10cm long.

For convenience, I will probably keep the voltage fixed at 6V throughout the experiment.

Dealing with variables

Quantities like length, current, and voltage are called **variables**. They can *change* from one situation to another.

Key variables These are the variables that can affect what happens in an experiment. You must decide what they are. For example, in the nichrome wire experiment, length is one of the key variables because changing the length of wire changes the resistance.

You must also decide how to measure the variables, and over what range. For example, in planning the nichrome wire experiment, you would have to:

- decide what the highest voltage and current values should be (safety must be considered here)
- decide what lengths of wire to use.

Controlling variables Some variables don't have to be measured, but they do need to be controlled. For example, in the nichrome wire experiment, you might want to keep the wire at a steady temperature, in case the temperature affects the resistance.

Some variables can be difficult to control. In your experiment, you may want to use the same thickness of nichrome wire each time, but this depends on how accurately the wire was manufactured. You must take factors like this into account when deciding how reliable your results are.

A fair test When doing an experiment, you should change just one variable at a time and find out how it affects one other. If lots of variables change at once, it will not be a fair test. For example, if you want to find out how the length of a wire affects its resistance, it wouldn't be fair to compare a long, thick wire with short, thin one.

There are two more variables I need to control:

temperature – I know from reference books that the resistance of nichrome changes with temperature. So I will use a large beaker of cold water to keep the temperature of the nichrome steady.

diameter (thickness) of nichrome wire – this could affect the resistance. To make sure that I have the same diameter all the time, I will use lengths of wire taken from the same reel, and check each piece with a gauge before using it.

Final preparations

Decide what equipment you need, how you will arrange it, and how you will use it.

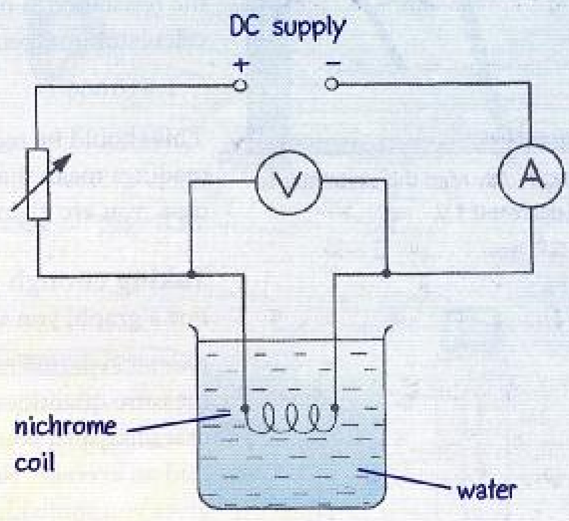
To help your planning, you may need to carry out a trial run of the experiment. Before you do this, make sure that all your procedures are safe.

Prepare tables for your readings *before* you start your experiments. Look at the next spread on **getting the evidence** before doing this.

Equipment needed:
voltmeter (0–6V), ammeter (0–3A), 50cm of 0.28mm diameter nichrome wire, ...

nichrome: length / cm	voltage / V	current / A	resistance / Ω
50			
45			
40			
35			
30			
25			
20			

I will set up this circuit:



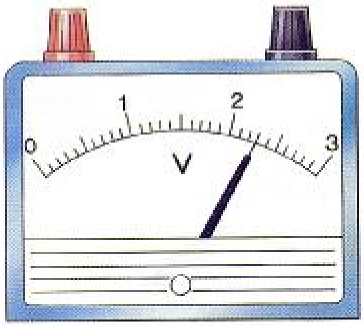
I am not sure how big the maximum current will be, so I will do a trial run of the experiment first. I will start with an ammeter that can measure several amperes, but may be able to change to a more sensitive meter for the main experiment.

Safety:
I must make sure that the power supply is switched off before I remove the nichrome wire to change its length.

14.03 Experimental procedures (2) – getting the evidence

voltage / V
2.3
2.1

Remember to include a unit in the heading at the top of each column.



You can only read this voltmeter to the nearest 0.1 V.

This spread should help you take and record measurements correctly.

Units

When you write down a measurement, remember to include the unit. For example:

voltage = 2.3 V

If you just write down '2.3', you may not be able to remember whether this was supposed to be a voltage of 2.3 V or 2.3 mV.

When writing measurements in a table, you don't need to put the unit after each number. But be sure to include the unit in the heading at the top of each column. You can see an example on the left.

Uncertainties

No measurement is exact. There is always some **uncertainty** about it. For example, you may only be able to read a voltmeter to the nearest 0.1 V.

Say that you measure a voltage of 2.3 V and a current of 1.2 A. To work out the resistance in ohms (Ω), you divide the voltage by the current on a calculator and get...

1.916 666 7

This should be recorded as 1.9 Ω. Uncertainties in your voltage and current readings mean that you cannot justify including any more figures. In this case, you are giving the result to two **significant figures**.

Taking enough readings

For a graph, you should have at least five sets of readings.

Not all experiments give you readings for a graph. Sometimes, you have to measure quantities that don't change – the diameter of a wire for example. In cases like this, you should repeat the measurement at least three times and find an average. Repeating a measurement helps you spot mistakes. It also gives you some idea of the uncertainty. Look at this example.

The diameter of a wire was measured four times:

1.41 mm   1.34 mm   1.19 mm   1.30 mm

You can work out the average like this:

$$\text{average} = \frac{(1.41 + 1.34 + 1.19 + 1.30)}{4} = 1.31\text{ mm}$$

The original four numbers ranged from less than 1.2 to more than 1.4. So, the last figure, 1, in the average of 1.31, is completely uncertain. Therefore, you should write down the average diameter as 1.3 mm.

Reading scales

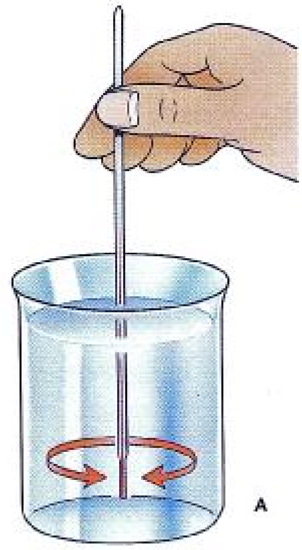
On many instruments, you have to judge the position of a pointer or level on a scale and work out the measurement from that. Here are some ways of making sure that you take the correct reading:

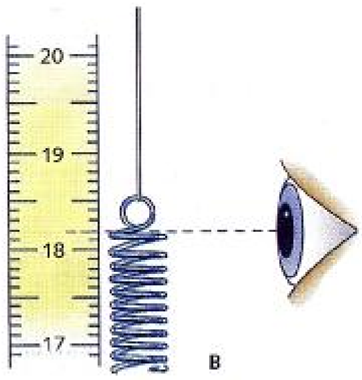
A **Using a glass thermometer** to measure the temperature of a liquid: keep the liquid well stirred, give the thermometer time to reach the temperature, and keep the bulb of the thermometer in the liquid while you take the reading.

B **Using a ruler**: be sure that the scale is right alongside the point you are trying to measure.

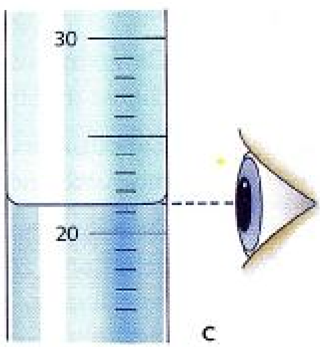
C **Measuring a liquid level** on a scale: look at the level of the liquid's flat surface, not its curved meniscus.

D **Reading a meter**: look at the pointer and scale 'square on'. (The pointer may have a flat end like that shown here, so that you can look at it edge on.)

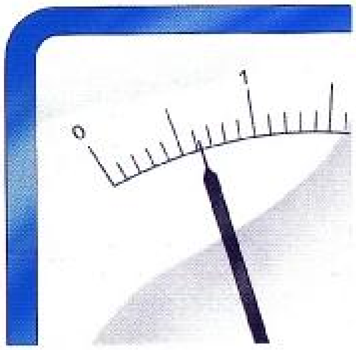

A



B

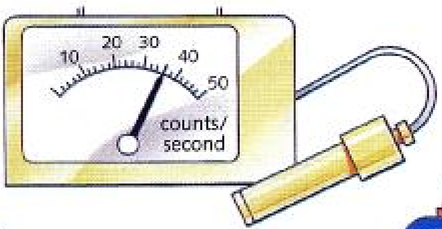


C

D


Can you read the instruments below correctly? The answers are on page 333.

1


2


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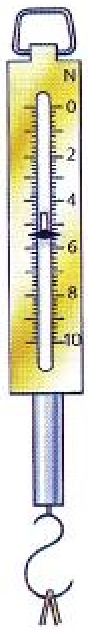
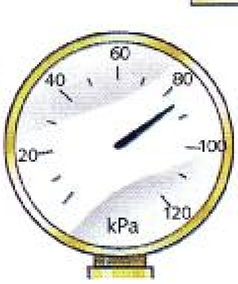
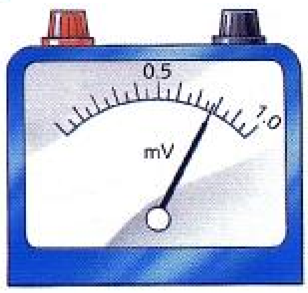


4


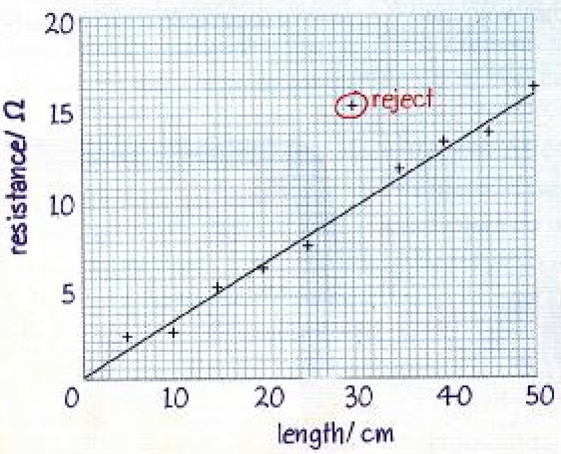


5

14.04 Experimental procedures (3) – handling the evidence

I have used my voltage and current readings to calculate the resistance of each length of nichrome wire. Now I shall use these values to plot a graph of resistance against length.

Length is the independent variable (the one I chose to change), so it goes along the bottom axis. Resistance goes up the side.



The points on my graph are a little scattered, but I think that the line of best fit is a straight line.

This line ought to go through the origin. If the wire has zero length, there is no metal to resist the current, so the resistance should also be zero.

I have rejected one point on my graph. In my table, the current reading for that point seems far too low. I probably misread the ammeter.

As the graph is a straight line through the origin, the resistance of the nichrome wire is in direct proportion to its length. This agrees with my original hypothesis that doubling the length of wire ought to make it twice as difficult to push electrons through.

This page should help you to analyse your data and draw conclusions from it. The handwritten notes show part of one student's commentary on her enquiry.

Drawing a graph

A graph can help you see trends in your data.

Choosing axes Decide which variable to put along the bottom axis. Usually, it is the one you chose to vary by set amounts – the length of nichrome wire, for example. This is the **independent variable.** The resistance would be the **dependent variable** because its value depends on the length you chose. It goes up the side axis.

Choosing scales Check your highest readings, then choose the largest scales you can for your axes.

Labelling axes Along each axis, write in what is being measured and the units being used.

Drawing the best line Because of uncertainties, the points on a graph will be uneven. So don't join up the points! Instead, draw the straight line or smooth curve that goes closest to most of them. This is called a **line of best fit**. Before you draw it:

- Decide whether the line should go through the origin.
- Decide whether any readings should be rejected. Some may be so far out that they are probably due to mistakes rather than uncertainties. See if you can find out why they occurred.

From the way points scatter about a line of best fit, you can see how reliable your readings are. But for this, you need plenty of points.

Trends and conclusions

From the shape of your graph, you can draw conclusions about the data.

The simplest form of graph is a straight line through the origin. A graph of resistance against length of wire might be like this. If so, it means that if the length doubles, the resistance doubles... and so on. in this case, resistance and length are in **direct proportion**.

If you think that your graph supports your original prediction, then say so and explain your reasons.

14.05 Experimental procedures (4) – evaluating the evidence

This page should help you decide how reliable your conclusions are, and how your procedure could be improved or extended.

The points on the graph are uneven. But as they zig-zag at random, I am fairly sure that, without uncertainties, they would lie on a straight line.

There are several reasons why the points may have been so scattered...

To get a more reliable graph, I need to find a more accurate method of measuring resistance...

To extend my enquiry, I could find out how the resistance of the nichrome wire depends on the diameter...

Reliability

In reaching your conclusions, remember that there are uncertainties in your measurements, and variables that you may not have allowed for. So your results can never *prove* your original prediction. You must decide how far they *support* it.

If you think that your results are unreliable in any way, see if you can explain why.

You may have some results which do not agree with the others and look like mistakes. These are called **anomalous results**. Try to explain what caused them.

Suggesting improvements

Having completed your procedure, suggest ways of improving it so that your conclusions are more reliable.

Looking further

Suggest some further work which might produce extra evidence or take your procedure further.

Writing your report

The student's commentary was designed to help you understand the different stages of an procedure. It includes far more detail than you would normally put in a report. When producing your own report, these are the things you *should* include:

Planning 1

- A description of what the procedure is about.
- A prediction of what you think will happen, and why.
- A list of key variables, and a description of how you will measure or control each one.
- A list of the equipment needed.
- Diagrams showing how the equipment will be set up.
- A description of what you plan to do.

Getting evidence 2

- A description of what you did, including comments about any difficulties and how you overcame them.
- Tables showing all measurements, including units.

Analysing and concluding 3

- Graphs and charts.
- Calculations based on your data.
- A conclusion, including details of:
  - what you found out.
  - whether your findings matched your prediction.

Evaluating 4

- Comments about:
  - how reliable you think your results were
  - any anomalous results, and their possible causes
  - how your procedure could be improved
  - further work that could be done.

14.07 Key experimental skills checklist

Planning

In planning an experimental procedure, you should be able to:

- **a** turn an idea into a form that can be investigated. ☐
- **b** carry out trial runs if necessary. ☐
- **c** make predictions, where appropriate. ☐
- **d** decide what the key factors (e.g. key variables) are. ☐
- **e** plan how to vary or control the key variables. ☐
- **f** decide on the range and number of measurements needed. ☐
- **g** decide how much evidence you will need, and recognize which variables may be difficult to control. ☐
- **h** select equipment, and plan how to use it – safely. ☐

Getting evidence

In getting your evidence, you should be able to:

- **a** use the equipment safely, and with skill. ☐
- **b** make accurate measurements. ☐
- **c** make enough measurements to produce reliable evidence. ☐
- **d** consider what uncertainties there are. ☐
- **e** repeat measurements as necessary. ☐
- **f** record measurements clearly. ☐

Analysing and concluding

In analysing your evidence and reaching conclusions, you should be able to:

- **a** present data clearly. ☐
- **b** present data in the form of a graph using a line of best fit. ☐
- **c** identify trends or patterns in your data. ☐
- **d** use a graph to identify how variables are related. ☐
- **e** present numerical results to an appropriate level of accuracy. ☐
- **f** check that your conclusions match the evidence. ☐
- **g** explain whether or not your results match your original prediction. ☐
- **h** explain your conclusions, if you can, using your knowledge of physics. ☐

Evaluating

In evaluating your procedure, you should be able to:

- **a** decide whether you have enough evidence to reach a firm conclusion. ☐
- **b** decide whether any results should be rejected, and if so, why. ☐
- **c** decide, from the uncertainties, how reliable your results are. ☐
- **d** suggest improvements to the methods you have used. ☐
- **e** suggest further work that could produce extra evidence or take your procedure further. ☐