2ND Edition

# Advanced PHYSICS for You

Sample material

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OXFORD

**Introduction** (for Students)

**Advanced Physics for You** is designed to help and support you during your advanced Physics course. No matter which exam course you are following, this book will help you to make the transition to A-level.

The book is carefully laid out so that each new idea is introduced and developed on a single page or on two facing pages. Words have been kept to a minimum and as straightforward as possible, with clear diagrams, and a cartoon character called 'Phiz'.
Pages with a red triangle in the top corner are the more difficult pages and can be left at first.

Each important fact or new formula is clearly printed in **heavy type** or is in a coloured box.
There is a summary of important facts at the end of each chapter, to help you with revision.

Worked examples are a very useful way of seeing how to tackle problems in Physics. In this book there are over 200 worked examples to help you to learn how to tackle each kind of problem.

At the back of the book there are extra sections giving you valuable advice on study skills, practical work, revision and examination techniques, as well as more help with mathematics.

Throughout the book there are 'Physics at Work' pages. These show you how the ideas that you learn in Physics are used in a wide range of interesting applications.

There is also a useful analysis of how the book covers the different examination syllabuses, with full details of which pages you need to study, on the web-site at :
www.oxfordsecondary.co.uk/advancedforyou

At the end of each chapter there are a number of questions for you to practise your Physics and so gain in confidence. They range from simple fill-in-a-missing-word sentences (useful for doing quick revision) to more difficult questions that will need more thought.

At the end of each main topic you will find a section of further questions, mostly taken from actual advanced level examination papers.
For all these questions, a 'Hints and Answers' section at the back of the book gives you helpful hints if you need them, as well as the answers.

We hope that reading this book will make Physics more interesting for you and easier to understand. Above all, we hope that it will help you to make good progress in your studies, and that you will enjoy using **Advanced Physics for You**.

**Keith Johnson**
**Simmone Hewett**
**Sue Holt**
**John Miller**

**Introduction** (for Teachers planning for September)

In considering the implementation of the new AS / A-level specifications for September there are a number of things for you to consider:

- **Coverage of the new Specification**
  A good text-book is a valuable backup and safety-net for your teaching, for students to use as a follow-up for homework and after any absences.
  For this revised edition the extensive new coverage is shown by:
  - An outline of the Contents, on the next page.
  - A short Summary of the specification coverage, see the inside of the back cover.
  - A detailed 'Map' of the coverage of your particular specification, as a free PDF, at: www.oxfordsecondary.co.uk/advancedforyou

- **Accessibility & Readability**
  If your students are going to use the book as a backup to your teaching, then they need to be able to study and understand independently.
  Accessibility, readability, layout and clarity of presentation are all vital here. Judge for yourself by looking at the sample pages we've included. And perhaps ask your students what they think?

- **Support for your students, across the full ability range**
  Your students will be supported not only by the clear layout and the hundreds of worked examples ...but also by the expanded support for Maths (now 15 pages), and sections on Practical work and Study Skills.
  All of the hundreds of questions have been analysed by Senior Examiners. They have selected a large number of past-paper questions that are appropriate for the new specifications, including Synoptic questions and questions on Practical work.
  The Hints & Answers section has also been expanded.

In updating and expanding the very successful first edition, we have taken great care to provide a quality text-book. One that is clearly written, strongly supportive, and with a slight touch of humour to present a friendly face of Physics.

We hope you will find it a useful and significant support to boost your teaching and enhance your results.

**Keith Johnson**
**Simmone Hewett**
**Sue Holt**
**John Miller**

On the following pages we have included all of Chapter 1, followed by samples from other parts of the book, so that you can see the range of support that we provide.

# Contents



Chapters marked * are usually not in AS, only in A-level.

For more details of which sections you need to study for your particular examination, see page 506, and download the relevant 'Specification Map' from www.oxfordsecondary.co.uk/advancedforyou

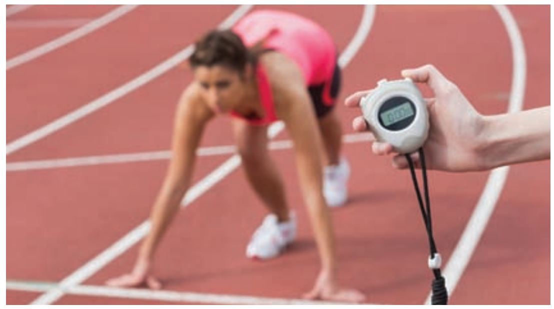
# 1 Basic Ideas

How fast does light travel? How much do you weigh?
What is the radius of the Earth?
What temperature does ice melt at?

We can find the answers to all of these questions by measurement. Speed, mass, length and temperature are all examples of ***physical quantities***.
Measurement of physical quantities is an essential part of Physics.

*Measuring temperature …*

In this chapter you will learn:
- the difference between 'base' and 'derived' units,
- how you can use units to check equations,
- how to use 'significant figures',
- how to deal with vectors.



*… and time …*

## Stating measurements

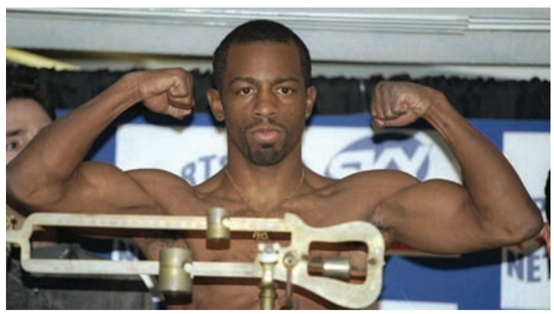
All measurement requires a system of units.
For example: How far is a distance of 12?

Without a unit this is a meaningless question. You must always give a measurement as ***a number multiplied by a unit***.

For example:

12 m means 12 multiplied by the length of one metre.
9 kg means 9 multiplied by the mass of one kilogram.

But what do we mean by one metre and one kilogram?
Metres and kilograms are two of the seven internationally agreed ***base units***.



*… and weight.*

## Base quantities and units

The Système International (SI) is a system of measurement that has been agreed internationally. It defines 7 base quantities and units, but you only need six of them at A-level.

The 7 base quantities and their units are listed in the table:

| **Base quantity** | | **Base unit** | |
|---|---|---|---|
| Name | Symbol | Name | Symbol |
| time | $t$ | second | s |
| length | $l$ | metre | m |
| mass | $m$ | kilogram | kg |
| temperature | $T$, $\theta$ | kelvin | K |
| electric current | $I$ | ampere | A |
| amount of substance | $n$ | mole | mol |
| luminous intensity *(Not used at A-level)* | | candela | cd |

Their definitions are based on specific physical measurements that can be reproduced, very accurately, in laboratories around the world.

The only exception is the kilogram. This is the mass of a particular metal cylinder, known as the prototype kilogram, which is kept in Paris.

## Derived units

Of course, we use far more physical quantities in Physics than just the 7 base ones. All other physical quantities are known as ***derived quantities***. Both the quantity and its unit are derived from a combination of base units, using a defining equation:

*Example 1*
***Velocity*** is defined by the equation:

$$\text{velocity} = \frac{\text{distance travelled in a given direction (m)}}{\text{time taken (s)}}$$

Both distance (ie. length) and time are base quantities. The unit of distance is the metre and the unit of time is the second. So, from the defining equation, the derived unit of velocity is **metres per second**, written **m/s** or **m $s^{-1}$**.

*Example 2*
***Acceleration*** is defined by the equation:

$$\text{acceleration} = \frac{\text{change in velocity (m s}^{-1}\text{)}}{\text{time taken (s)}}$$

Again, combining the units in the defining equation gives us the derived unit of acceleration.
This is **metres per second per second** or **metres per second squared**, written **m/$s^2$** or **m $s^{-2}$**.

What other units have you come across in addition to these base units and base unit combinations?
Newtons, watts, joules, volts and ohms are just a few that you may remember.
These are special names that are given to particular combinations of base units.


*Example 3*
***Force*** is defined by the equation:

force = mass (kg) × acceleration (m $s^{-2}$) (see page 55)

The derived unit of force is therefore:
**kilogram metres per second squared** or **kg m $s^{-2}$**.
This is given a special name: the **newton** (symbol **N**).

The table below lists some common derived quantities and units for you to refer to.

Some of the combinations are quite complicated. You can see why we give them special names!

| Physical quantity | Defined as | Unit | Special name |
|---|---|---|---|
| density | mass (kg) ÷ volume ($m^3$) | kg $m^{-3}$ | |
| momentum | mass (kg) × velocity (m $s^{-1}$) | kg m $s^{-1}$ | |
| force | mass (kg) × acceleration (m $s^{-2}$) | kg m $s^{-2}$ | newton (N) |
| pressure | force (kg m $s^{-2}$ or N) ÷ area ($m^2$) | kg $m^{-1}$ $s^{-2}$ (N $m^{-2}$) | pascal (Pa) |
| work (energy) | force (kg m $s^{-2}$ or N) × distance (m) | kg $m^2$ $s^{-2}$ (N m) | joule (J) |
| power | work (kg $m^2$ $s^{-2}$ or J) ÷ time (s) | kg $m^2$ $s^{-3}$ (J $s^{-1}$) | watt (W) |
| electrical charge | current (A) × time (s) | A s | coulomb (C) |
| potential difference | energy (kg $m^2$ $s^{-2}$ or J) ÷ charge (A s or C) | kg $m^2$ $A^{-1}$ $s^{-3}$ (J $C^{-1}$) | volt (V) |
| resistance | potential difference (kg $m^2$ $A^{-1}$ $s^{-3}$ or V) ÷ current (A) | kg $m^2$ $A^{-2}$ $s^{-3}$ (V $A^{-1}$) | ohm (Ω) |

## Homogeneity of equations

We have seen that all units are derived from base units using equations. This means that in any correct equation the base units of each part must be the ***same***. When this is true, the equation is said to be homogeneous. Homogeneous means 'composed of identical parts'.

*Example 4*
Show that the following equation is homogeneous: kinetic energy $= \frac{1}{2} \times$ mass $\times$ velocity$^2$

From the table on page 7:
Unit of kinetic energy = joule = kg m$^2$ s$^{-2}$
Unit of $\frac{1}{2}$ × mass × velocity$^2$ = kg × (m s$^{-1}$)$^2$ = kg m$^2$ s$^{-2}$ (Note: $\frac{1}{2}$ is a pure number and so has no unit.)

The units on each side are the same and so the equation is homogeneous.

This is a useful way of checking an equation. It can be particularly useful after you have rearranged an equation:

*Example 5*
Phiz is trying to calculate the power $P$ of a resistor when he is given its resistance $R$ and the current $I$ flowing through it.
He cannot remember if the formula is: $P = I^2 \times R$ or $P = I^2 \div R$.
By checking for homogeneity, we can work out which equation is correct:


Using the table on page 7: Units of $P$ = watts (W) = kg m$^2$ s$^{-3}$
Units of $I^2$ = A$^2$
Units of $R$ = ohms ($\Omega$) = kg m$^2$ A$^{-2}$ s$^{-3}$

***Multiplying*** together the units of $I^2$ and $R$ would give us the units of power. So the first equation is correct.

One word of warning. This method shows that an equation could be correct – but it doesn't prove that it is correct!

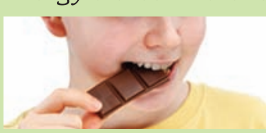
Can you see why not? Example 4 above is a good illustration. The equation for kinetic energy would still be homogeneous even if we had accidentally omitted the $\frac{1}{2}$.

## Prefixes

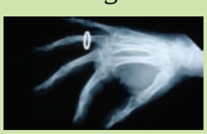
For very large or very small numbers, we can use standard prefixes with the base units.
The main prefixes that you need to know are shown in the table:

| Prefix | Symbol | Multiplier |
|---|---|---|
| tera | T | $10^{12}$ |
| giga | G | $10^{9}$ |
| mega | M | $10^{6}$ |
| kilo | k | $10^{3}$ |
| deci | d | $10^{-1}$ |
| centi | c | $10^{-2}$ |
| milli | m | $10^{-3}$ |
| micro | µ | $10^{-6}$ |
| nano | n | $10^{-9}$ |
| pico | p | $10^{-12}$ |
| femto | f | $10^{-15}$ |

*Example 6*
a) Energy stored in a chocolate bar = 1 000 000 J
= 1 × 10$^6$ J
= 1 megajoule
= 1 MJ



b) Wavelength of an X-ray = 0.000 000 001 m
= 1 × 10$^{-9}$ m
= 1 nanometre
= 1 nm



## The importance of significant figures

What is the difference between lengths of 5 m, 5.0 m and 5.00 m?

Writing 5.00 m implies that we have measured the length more precisely than if we write 5 m.

Writing 5.00 m tells us that the length is accurate to the nearest centimetre.
A figure of 5 m may have been rounded to the nearest metre.
The actual length could be anywhere between $4\frac{1}{2}$ m and $5\frac{1}{2}$ m.

The number 5.00 is given to three **significant figures** (or 3 **s.f.**).

To find the number of significant figures you must ***count up the total number of digits, starting at the first non-zero digit, reading from left to right***.
The table gives you some examples:

| 3 s.f. | 2 s.f. | 1 s.f. |
|---|---|---|
| 4.62 | 4.6 | 5 |
| 0.00501 | 0.0050 | 0.005 |
| $3.40 \times 10^8$ | $3.4 \times 10^8$ | $3 \times 10^8$ |
| 169 | $1.7 \times 10^2$ | $2 \times 10^2$ |

It shows you how a number in the first column (where it is given to 3 s.f.) would be rounded to 2 significant figures or 1 significant figure.

In the last example in the table, why did we change the number to 'standard form'?
Writing $1.7 \times 10^2$ instead of 170 makes it clear that we are giving the number to two significant figures, not three.
(If you need more help on standard form look at the ***Check Your Maths*** section on page 473.)

### Significant figures and calculations

How many significant figures should you give in your answers to calculations?
This depends on the precision of the numbers you use in the calculation. Your answer cannot be any more precise than the data you use. This means that you should round your answer to the same number of significant figures as those used in the calculation.

If some of the figures are given less precisely than others, then round up to the ***lowest*** number of significant figures.
Example 7 explains this.

Make sure you get into the habit of rounding all your answers to the correct number of significant figures. You may lose marks in an examination if you don't!

*Example 7*
The swimmer in the photograph covers a distance of 100.0 m in 68 s.
Calculate her average speed.

$$\text{speed} = \frac{\text{distance travelled}}{\text{time taken}} = \frac{100.0\text{ m}}{68\text{ s}} = 1.4705882\text{ m s}^{-1}$$

This is the answer according to your calculator.
How many significant figures should we round to?

The distance was given to 4 significant figures. But the time was given to only 2 significant figures. Our answer cannot be any more precise than this, so we need to round to 2 significant figures.

Our answer should be stated as: $1.5\text{ m s}^{-1}$ (2 s.f.)

## Vectors and scalars

Throwing the javelin requires a force. If you want to throw it a long distance, what two things are important about the force you use?


The javelin's path will depend on both the **size** and the **direction** of the force you apply.

Force is an example of a ***vector*** quantity.
**Vectors have both size (magnitude) and direction.**
Other examples of vectors include: velocity, acceleration and momentum. They each have a size and a direction.

Quantities that have size (magnitude) but ***no*** direction are called **scalars**. Examples of scalars include: temperature, mass, time, work and energy.

The table shows some of the more common vectors and scalars that you will use in your A-level Physics course:

| Scalars | Vectors |
|---|---|
| distance | displacement |
| speed | velocity |
| mass | weight |
| pressure | force |
| energy | momentum |
| temperature | acceleration |
| volume | electric current |
| density | torque |

Look back at the table of base quantities on page 6.
Are these vectors or scalars? Most of the base quantities are scalars.
Can you spot the odd one out?

## Representing vectors

Vectors can be represented in diagrams by arrows.

- **The length of the arrow represents the magnitude of the vector.**
- **The direction of the arrow represents the direction of the vector.**

Here are some examples:

**Force vectors**

A horizontal force of 20 N:

A vertical force of 10 N:

Using the same scale, how would you draw the vector for a force of 15 N at 20° to the horizontal?

**Velocity vectors**

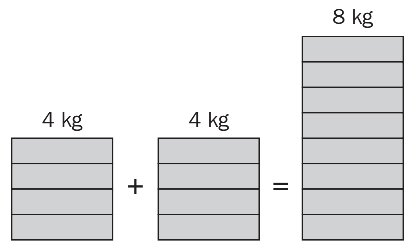
A velocity of 30 m $s^{-1}$ in a NE direction:


A velocity of 20 m $s^{-1}$ due west:

Using the same scale, how would you draw the vector for a velocity of 15 m $s^{-1}$ in a NW direction?

## Vector addition

What is 4 kg plus 4 kg? Adding two masses of 4 kg ***always*** gives the answer 8 kg. Mass is a scalar. You combine scalars using simple arithmetic.




*Scalars are simply added together.*

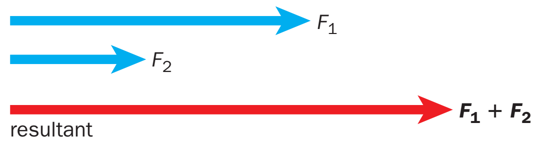
What about 4 N plus 4 N? Adding two forces of 4 N can give any answer between 8 N and 0 N.
Why do you think this is?
It's because force is a vector. When we combine vectors we also need to take account of their ***direction***.

Often in Physics we will come across situations where two or more vectors are acting together. The overall effect of these vectors is called the **resultant**. This is the single vector that would have the same effect.
To find the resultant we must use the directions of the 2 vectors:

### Vectors acting along the same straight line

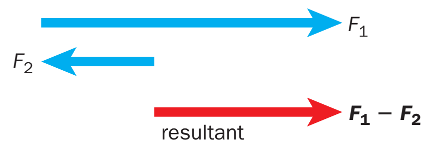
Two vectors acting in the ***same*** direction can simply be added together:

**Resultant** $= \boldsymbol{F_1} + \boldsymbol{F_2}$




If the vectors act in ***opposite*** directions, we need to take one direction as positive, and the other as negative, before adding them:

**Resultant** $= \boldsymbol{F_1} + (-\boldsymbol{F_2}) = \boldsymbol{F_1} - \boldsymbol{F_2}$




*Example 8*
Phiz is standing on a moving walkway in an airport.
The walkway is moving at a steady velocity of 1.50 m s$^{-1}$.

a) Phiz starts to walk forwards along the walkway at 2.00 m s$^{-1}$.
What is his resultant velocity?

Both velocity vectors are acting in the same direction.

Resultant velocity = 1.50 m s$^{-1}$ + 2.00 m s$^{-1}$
= 3.50 m s$^{-1}$ in the direction of the walkway.


b) Phiz then decides he is going the wrong way. He turns round and starts to run at 3.40 m s$^{-1}$ in the opposite direction to the motion of the walkway. What is his new resultant velocity?

The velocity vectors now act in opposite directions.
Taking motion in the direction of the walkway to be positive:

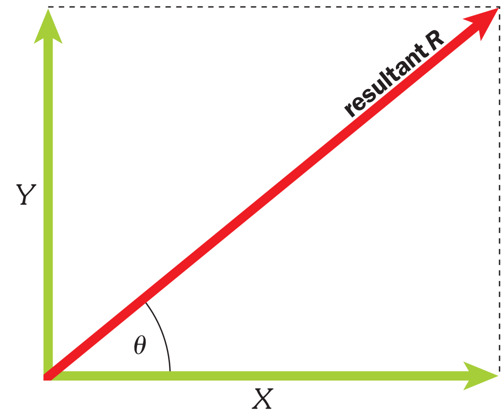
Resultant velocity = +1.50 m s$^{-1}$ − 3.40 m s$^{-1}$
= −1.90 m s$^{-1}$ (3 s.f.)

As this is negative, the resultant velocity acts in the opposite direction to the motion of the walkway. He moves to the left.

## Combining perpendicular vectors

To find the resultant of two vectors ($X$, $Y$) acting at 90° to each other, we draw the vectors as adjacent sides of a rectangle:

The resultant is the ***diagonal*** of the rectangle, as shown here:




The ***magnitude*** (size) of the resultant vector $R$ can be found using Pythagoras' theorem:

$$R^2 = X^2 + Y^2$$

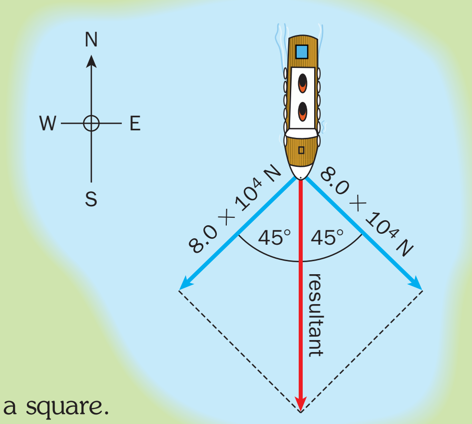
The ***direction*** of the resultant is given by the angle $\theta$:

$$\tan\theta = \frac{\text{opposite}}{\text{adjacent}} = \frac{Y}{X} \qquad \therefore\ \theta = \tan^{-1}\left(\frac{Y}{X}\right)$$

You can also find the resultant using an accurate scale drawing. The magnitude of the resultant can be found by measuring its length with a ruler. The direction can be measured with a protractor. For more on scale drawing, see page 14.

*Example 9*

Two tugs are pulling a ship into harbour. One tug pulls in a SE direction. The other pulls in a SW direction. Each tug pulls with a force of $8.0 \times 10^4$ N. What is the resultant force on the ship?




The two forces act at 90° to each other. Using Pythagoras' theorem:

$$\text{Magnitude of resultant} = \sqrt{(8.0 \times 10^4\ \text{N})^2 + (8.0 \times 10^4\ \text{N})^2}$$

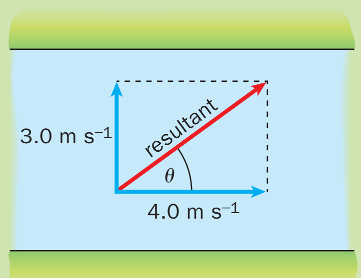
$$= \sqrt{1.28 \times 10^{10}\ \text{N}}$$

$$= \underline{1.1 \times 10^5\ \text{N}} \quad \text{(2 s.f.)}$$

Since both tugs pull with the same force, the vectors form adjacent sides of a square. The resultant is the diagonal of the square. So it acts at 45° to each vector. The resultant force must therefore act due south.

*Example 10*

A man tries to row directly across a river.
He rows at a velocity of $3.0\ \text{m s}^{-1}$.
The river has a current of velocity $4.0\ \text{m s}^{-1}$ parallel to the banks.
Calculate the resultant velocity of the boat.




The diagram shows the two velocity vectors.

We can find their resultant using Pythagoras' theorem:

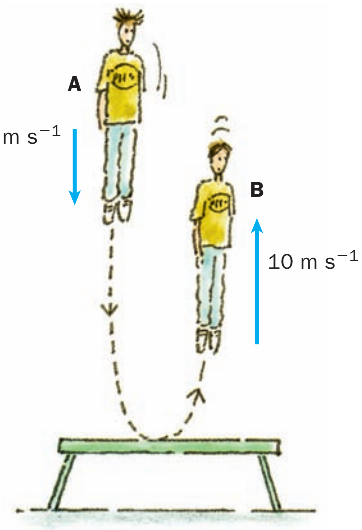
$$\text{Size of resultant} = \sqrt{(3.0\ \text{m s}^{-1})^2 + (4.0\ \text{m s}^{-1})^2} = \sqrt{25\ \text{m s}^{-1}} = 5.0\ \text{m s}^{-1}$$

$$\text{Direction of resultant: } \tan\theta = \frac{\text{opposite}}{\text{adjacent}} = \frac{3.0}{4.0} \qquad \therefore\ \theta = \tan^{-1}\left(\frac{3.0}{4.0}\right) = 37°$$

So the resultant velocity is $\underline{5.0\ \text{m s}^{-1}}$ at $\underline{37° \text{ to the bank}}$.

## Vector subtraction

The diagram shows the speed and direction of a trampolinist at two points during a bounce:




What is the trampolinist's change in **speed** from A to B?

Change in speed $= \text{new speed} - \text{old speed}$
$= 10 \text{ m s}^{-1} - 6 \text{ m s}^{-1}$
$= 4 \text{ m s}^{-1}$

What about his change in **velocity**?
To find the change in a vector quantity we use vector subtraction:

Change in velocity $= \text{new velocity} - \text{old velocity}$
$= 10 \text{ m s}^{-1}$ ***up*** $- 6 \text{ m s}^{-1}$ ***down***

Remember, with vectors we must take account of the direction. In this example let us take the upward direction to be positive, and the downward direction to be negative.

We can then rewrite our equation as:

Change in velocity $= +10 \text{ m s}^{-1} - (-6 \text{ m s}^{-1})$
$= +10 \text{ m s}^{-1} + 6 \text{ m s}^{-1}$
$= +16 \text{ m s}^{-1}$

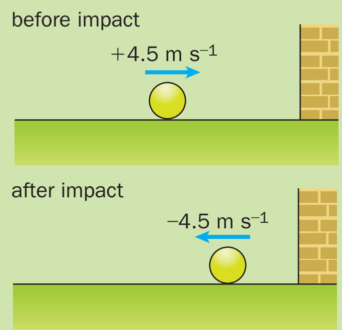
So the change in velocity is $16 \text{ m s}^{-1}$ in an ***up***ward direction.


Can you see that subtracting $6 \text{ m s}^{-1}$ downwards is the same as adding $6 \text{ m s}^{-1}$ acting upwards?
***Vector subtraction is the same as the addition of a vector of the same size acting in the opposite direction.***

*Example 11*
A boy kicks a ball against a wall with a horizontal velocity of $4.5 \text{ m s}^{-1}$.
The ball rebounds horizontally at the same speed.
What is the ball's change in velocity?


Although the speed is the same, the velocity has changed. Why?
Velocity is a vector, so a change in direction means a change in velocity.

Let us take motion towards the wall as positive, and motion away from the wall as negative.

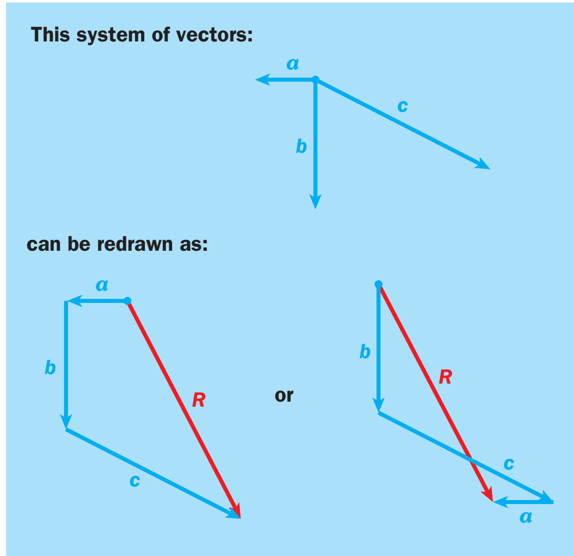



Change in velocity $= \text{new velocity} - \text{old velocity}$
$= (-4.5 \text{ m s}^{-1}) - (+4.5 \text{ m s}^{-1})$
$= -4.5 \text{ m s}^{-1} - 4.5 \text{ m s}^{-1}$
$= -9.0 \text{ m s}^{-1}$ (2 s.f.)

So the change in velocity is $9.0 \text{ m s}^{-1}$ in a direction away from the wall.

## Combining vectors using scale drawing

If more than one vector acts on an object we can find the **resultant vector** by drawing each vector consecutively head to tail. The resultant ***R*** will be a line joining the start to the final end point. This works for any number of vectors acting at a point.



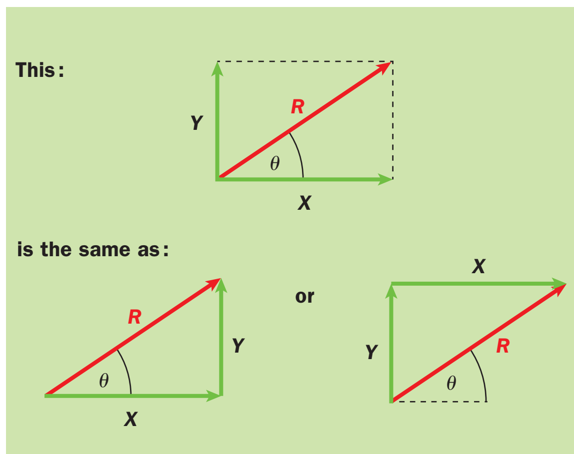

If each vector is drawn carefully to scale, using a protractor to ensure the correct angles, then the resultant can be found by taking measurements from the finished diagram.

Notice that it doesn't matter in which order you choose to redraw the vectors. You always end up with the same resultant. Two of the six possible arrangements for vectors ***a***, ***b***, ***c*** are shown here:
Try out the other combinations for yourself.

What if, after drawing each vector head to tail, you end up back where you started?
If this happens then the **resultant is zero**. This will be the case for a system of forces acting on an object **in equilibrium** (see pages 32 and 36).

### Vector triangles

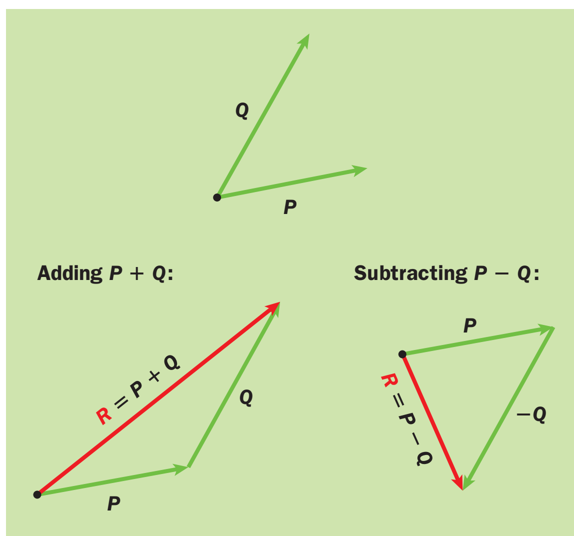
We can redraw the diagram on page 12 for two perpendicular vectors using the head-to-tail technique:
Can you see that this gives the same resultant?




Any two vectors can be combined in this way.
The resultant becomes the third side of a **vector triangle**.
This is also a useful technique where the vectors are not perpendicular to each other.

If the vectors' lengths and directions are drawn accurately to scale, the resultant can be found by measuring the length of the resultant on the diagram with a ruler.
The direction is measured with a protractor.

The method also works for **vector subtraction**.
Again the vectors are drawn head to tail, but the vector to be subtracted is drawn in the reverse direction.
The diagrams show the resultant of the addition and subtraction of two vectors ***P*** and ***Q***:



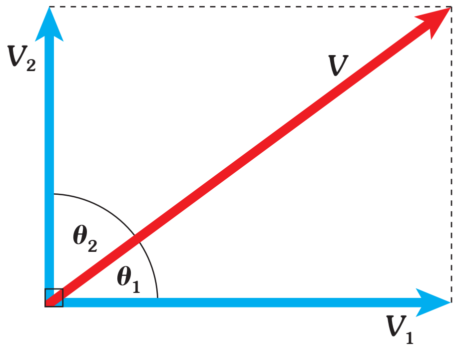

If you prefer a more mathematical solution, lengths and angles can be calculated using trigonometry. For a right-angled triangle, Pythagoras' theorem and sine, cosine or tangent will give you the magnitude and direction of the resultant (see also page 474).
Other triangles can be solved using the sine or cosine rule.

Although a mathematical solution does not require a scale diagram, you should always draw a sketch using the head-to-tail method to ensure you have your triangle the right way round.

## Resolving vectors

We have seen how to combine two vectors that are acting at 90°, to give a single resultant. Now let's look at the reverse process.

We can **resolve** a vector into two **components** acting at right angles to each other. The component of a vector tells you the effect of the vector in that direction.




So how do we calculate the 2 components?
Look at the vector $V$ in this diagram:

We can resolve this vector into two components, $V_1$ and $V_2$, at right angles to each other:

$V_1$ acts at an angle $\theta_1$ to the original vector.
$V_2$ acts at an angle $\theta_2$ to the original vector. ($\theta_1 + \theta_2 = 90°$)

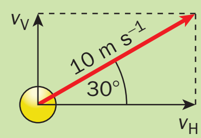
To find the size of $V_1$ and $V_2$ we need to use trigonometry:

$$\cos\theta_1 = \frac{adjacent}{hypotenuse} = \frac{V_1}{V}$$ Rearranging this gives: $\mathbf{V_1 = V\cos\theta_1}$

$$\cos\theta_2 = \frac{adjacent}{hypotenuse} = \frac{V_2}{V}$$ Rearranging this gives: $\mathbf{V_2 = V\cos\theta_2}$

So to find the component of a vector in any direction you need to ***multiply by the cosine of the angle between the vector and the component direction***.

*Example 12*
A tennis player hits a ball at 10 m s$^{-1}$ at an angle of 30° to the ground.
What are the initial horizontal and vertical components of velocity of the ball?

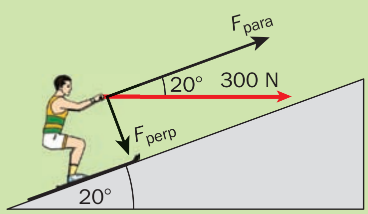



***Horizontal*** component: $v_H = 10\cos 30° = \underline{8.7 \text{ m s}^{-1}}$ (2 s.f.)

The angles in a right angle add up to 90°.
So the angle between the ball's path and the *vertical* = 90° − 30° = 60°

***Vertical*** component: $v_V = 10\cos 60° = \underline{5.0 \text{ m s}^{-1}}$ (2 s.f.)

*Example 13*
A water-skier is pulled up a ramp by the tension in the tow-rope. This is a force of 300 N acting horizontally. The ramp is angled at 20.0° to the horizontal.
What are the components of the force from the rope acting (a) parallel to and (b) perpendicular to the slope?



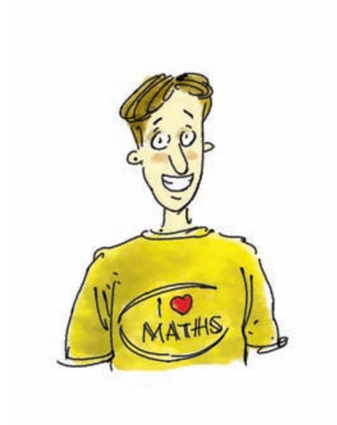

The angle between the rope and the parallel slope direction = 20°
So, the angle between the rope and the perpendicular direction = 90° − 20° = 70°

a) Component of force ***parallel*** to ramp $F_{para} = 300\text{ N} \times \cos 20° = \underline{282\text{ N}}$ (3 s.f.)

b) Component of force ***perpendicular*** to ramp $F_{perp} = 300\text{ N} \times \cos 70° = \underline{103\text{ N}}$ (3 s.f.)

## Combining non-perpendicular vectors by calculation

On the previous page you learnt how to resolve a vector into two perpendicular components. You can also use the same technique to combine multiple vectors without the need for scale drawings.

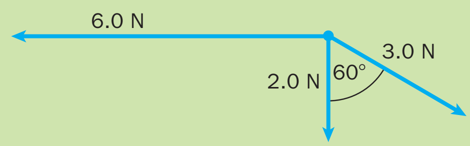



The trick is to first resolve each vector into its components. Often it's convenient to resolve horizontally and vertically (but you can use any convenient mutually perpendicular directions).

All the horizontal components can then be added together (taking account of their direction).
Similarly, all the vertical components can be added.
The resultant horizontal and vertical vectors can then be combined using Pythagoras' theorem.

See how this works in the following example:

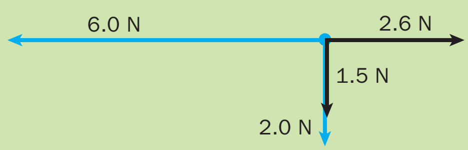
*Example 14*
Three forces act on a single point, as shown in the diagram:
Find the magnitude and direction of their resultant force.




Step 1: Resolve the 3.0 N force into its horizontal and vertical components:

Horizontal component $= 3.0 \times \cos 30° = 2.6$ N
Vertical component $= 3.0 \times \cos 60° = 1.5$ N

Step 2: Replace the 3.0 N force with its components in the diagram (shown in black):



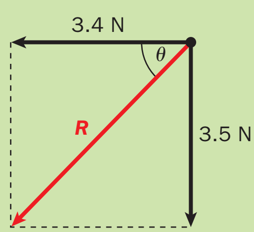

Step 3: Find the total force in the horizontal and vertical directions:

Total horizontal force $= 6.0 - 2.6 = 3.4$ N (to the left)
Total vertical force $= 2.0 + 1.5 = 3.5$ N (downwards)

Step 4: Finally, combine the total horizontal and vertical forces into a single resultant force:

Using Pythagoras' theorem:
Magnitude of resultant $R = \sqrt{3.4^2 + 3.5^2} = 4.9$ N (2 s.f.)

$$\tan\theta = \frac{\text{opposite}}{\text{adjacent}} = \frac{3.5}{3.4} \qquad \therefore \quad \theta = \tan^{-1}\left(\frac{3.5}{3.4}\right) = 46°$$




So the resultant force is 4.9 N acting at 46° below the original 6.0 N force.

## Summary

There are 6 base quantities that you need for A-level (time, length, mass, temperature, electric current, and amount of substance).
All other quantities are derived from these.

For an equation to be correct it must be homogeneous. This means that all the terms have the same units. But remember, a homogeneous equation may not be entirely right!

You should always give your numerical answers to the correct number of significant figures.

***Scalars*** have size (magnitude) only.

***Vectors*** have size (magnitude) and direction. Vectors can be represented by arrows.

When vectors are added together to find the resultant, we must take account of their direction.

For vectors acting along the same straight line we take one direction as positive and the other as negative.

To add two perpendicular vectors $X$ and $Y$ you can use Pythagoras' theorem: $R^2 = X^2 + Y^2$

A single vector can be resolved to find its effect in two perpendicular directions.
The component of a vector in any direction is found by multiplying the vector by the ***cosine*** of the angle between the vector and the required direction.

Subtracting a vector is the same as adding a vector of the same size, acting in the opposite direction.

## Questions

**1.** Can you complete the following sentences?
a) Measurements must be given as a number multiplied by a .......
b) Seconds, metres and kilograms are all ....... units. Units made up of combinations of base units are known as ....... units.
c) Vector quantities have both ....... and ....... Scalars have only .......
d) The single vector that has the same effect as two vectors acting together is called the .......
e) The effect of a vector in a given direction is called the ....... in that direction.
f) The ....... of a vector in any direction is found by mutiplying the ....... by the ....... of the angle between the vector and the required direction.

**2.** Rewrite each of the following quantities using a suitable prefix:
a) 2 000 000 000 J
b) 5900 g
c) 0.005 s
d) 345 000 N
e) 0.000 02 m

**3.** The drag force $F$ on a moving vehicle depends on its cross-sectional area $A$, its velocity $v$ and the density of the air, $\rho$.
a) What are the base units for each of these four variables?
b) By checking for homogeneity, work out which of these equations correctly links the variables:
i) $F = kA^2\rho v$
ii) $F = kA\rho^2 v$
iii) $F = kA\rho v^2$
(The constant $k$ has no units.)

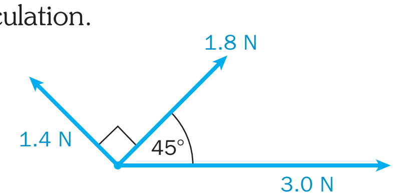
**4.** In a tug-of-war one team pulls to the left with a force of 600 N. The other team pulls to the right with a force of 475 N.
a) Draw a vector diagram to show these forces.
b) What is the magnitude and direction of the resultant force?

**5.** Two ropes are tied to a large boulder. One rope is pulled with a force of 400 N due east. The other rope is pulled with a force of 300 N due south.
a) Draw a vector diagram to show these forces.
b) What is the magnitude and direction of the resultant force on the boulder?

**6.** A javelin is thrown at 20 m s$^{-1}$ at an angle of 45° to the horizontal.
a) What is the vertical component of this velocity?
b) What is the horizontal component of this velocity?

**7.** A ball is kicked with a force of 120 N at 25° to the horizontal.
a) Calculate the horizontal component of the force.
b) Calculate the vertical component of the force.

**8.** Find the resultant of the following system of forces (not drawn to scale):
a) by scale drawing,
b) by calculation.




**Further questions on page 114.**

# 4 Describing Motion

We live in a world full of movement. Humans, animals and the many forms of transport we use are obvious examples of objects designed for movement. This chapter is about the Physics of motion.

In this chapter you will learn:
- how to describe motion in terms of distance, displacement, speed, velocity, acceleration and time,
- how to use equations that link these quantities,
- how to draw and interpret graphs representing motion.

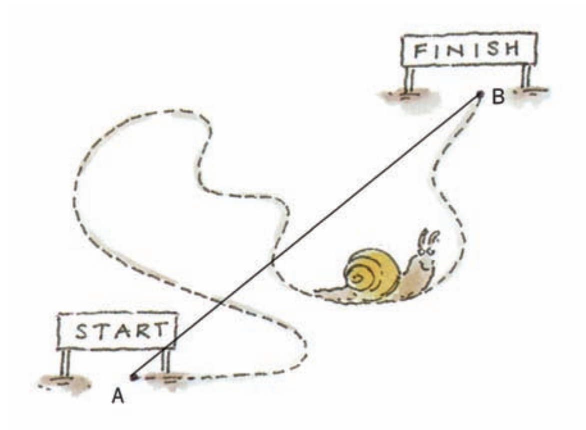
## Distance and displacement

Distance and displacement are both ways of measuring how far an object has moved. So what is the difference?

Distance is a scalar. Displacement is a ***vector*** quantity (see page 10). Displacement is the distance moved in a particular direction.

The snail in the picture moves from A to B along an irregular path: The ***distance*** travelled is the total length of the dashed line.

But what is the snail's ***displacement***?
The magnitude of the displacement is the length of the straight line AB. The direction of the displacement is along this line.




## Speed and velocity

The speed of an object tells you the distance moved per second, or the ***rate of change of*** distance:

$$\textbf{average speed} = \frac{\textbf{distance travelled (m)}}{\textbf{time taken (s)}}$$

Speed is a scalar quantity, but velocity is a vector.
Velocity measures the rate of change of ***displacement***:

$$\textbf{average velocity} = \frac{\textbf{displacement (m)}}{\textbf{time taken (s)}}$$

Both speed and velocity are measured in **metres per second**, written **m/s** or **m s$^{-1}$**. With velocity you also need to state the direction.

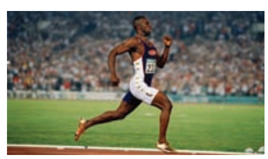
Using these equations you can find the ***average*** speed and the ***average*** velocity for a car journey.
A speedometer shows the actual or ***instantaneous*** speed of the car. This varies throughout the journey as you accelerate and decelerate.

So how can we find the instantaneous speed or velocity at any point? The answer is to find the distance moved, or the displacement, over a very small time interval. The smaller the time interval, the closer we get to an instantaneous value (see also page 40).

*Military jet*
*450 m s$^{-1}$*

*Racing car*
*60 m s$^{-1}$*

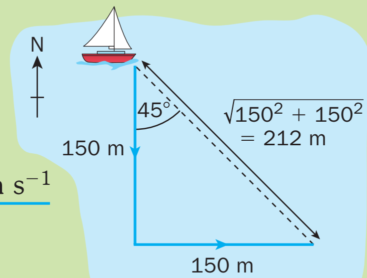
*Cheetah*
*27 m s$^{-1}$*



*Sprinter*
*10 m s$^{-1}$*

*Tortoise*
*0.060 m s$^{-1}$*

*Example 1*
The boat in the diagram sails 150 m due south and then 150 m due east.
This takes a total time of 45 s.
Calculate (a) the boat's average speed, and (b) the boat's average velocity.




a) average speed $= \dfrac{\text{distance travelled}}{\text{time taken}} = \dfrac{150\text{ m} + 150\text{ m}}{45\text{ s}} = \dfrac{300\text{ m}}{45\text{ s}} = \underline{6.7\text{ m s}^{-1}}$

b) average velocity $= \dfrac{\text{displacement}}{\text{time taken}} = \dfrac{212\text{ m}}{45\text{ s}} = \underline{4.7\text{ m s}^{-1}}$ in a $\underline{\text{SE direction}}$

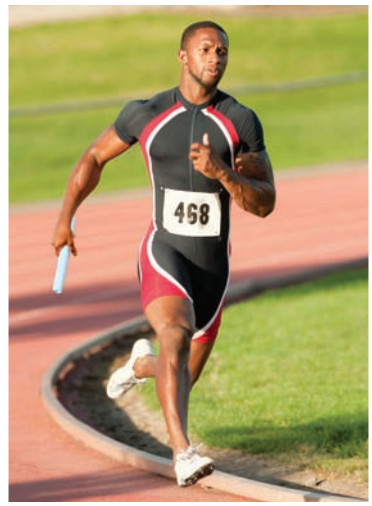
## Acceleration

Acceleration is the rate of change of velocity:

$$\textbf{acceleration} = \frac{\textbf{change in velocity}\ (\text{m s}^{-1})}{\textbf{time taken}\ (\text{s})}$$

Acceleration is measured in metres per second per second, or metres per second squared, written **m/s²** or **m s⁻²**.
It is a vector quantity, acting in a particular direction.

The change in velocity may be a change in ***speed***, or ***direction***, or both.
If an object is slowing down, its change in velocity is negative.
This gives a negative acceleration or 'deceleration'.




*The runner is going round the curve at a constant speed.*
*So how can he also be accelerating? His velocity is changing because his direction is changing.*

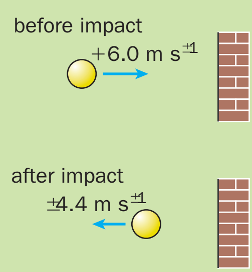
## Indicating direction

It is important to state the direction of vectors such as displacement, velocity and acceleration. In most motion problems you will be dealing with motion in a straight line (***linear motion***).
In this case you can use + and − signs to indicate direction.
For example, with horizontal motion, if you take motion to the ***right*** as ***positive***, then:

| | |
|---|---|
| −3 m | means a displacement of 3 m to the left |
| $+8\text{ m s}^{-1}$ | means a velocity of $8\text{ m s}^{-1}$ to the right |
| $-4\text{ m s}^{-2}$ | means an acceleration of $4\text{ m s}^{-2}$ to the left (***or*** a deceleration of an object moving towards the right) |

The sign convention you choose is entirely up to you.
In one question it may be easier to take *up* as positive whereas in another you might use *down* as positive. It doesn't matter as long as you keep to the ***same*** convention for the entire calculation.

*Example 2*
A ball hits a wall horizontally at $6.0\text{ m s}^{-1}$. It rebounds horizontally at $4.4\text{ m s}^{-1}$.
The ball is in contact with the wall for 0.040 s. What is the acceleration of the ball?




Taking motion ***towards*** the wall as positive:

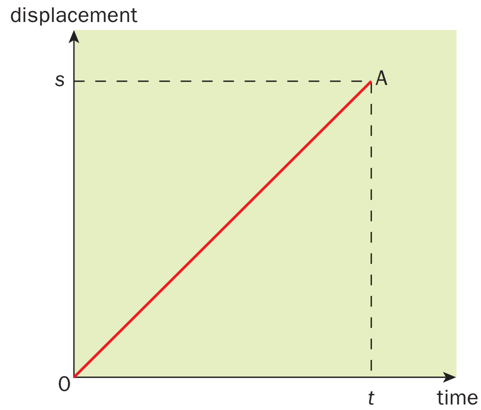
$$\begin{aligned}\text{change in velocity} &= \text{new velocity} - \text{old velocity}\\ &= (-4.4\text{ m s}^{-1}) - (+6.0\text{ m s}^{-1})\\ &= -10.4\text{ m s}^{-1}\end{aligned}$$

$$\text{acceleration} = \frac{\text{change in velocity}}{\text{time taken}} = \frac{-10.4\text{ m s}^{-1}}{0.040\text{ s}} = \underline{-260\text{ m s}^{-2}}$$

Negative, therefore in a direction ***away from*** the wall.

## Displacement–time graphs

The diagram shows a graph of displacement against time, for a car:




What type of motion does this straight line represent?
The displacement increases by equal amounts in equal times. So the object is moving at **constant velocity**.

You can calculate the velocity from the graph:

$$\text{Velocity from 0 to A} = \frac{\text{displacement}}{\text{time taken}}$$

$$= \text{gradient of line 0A}$$

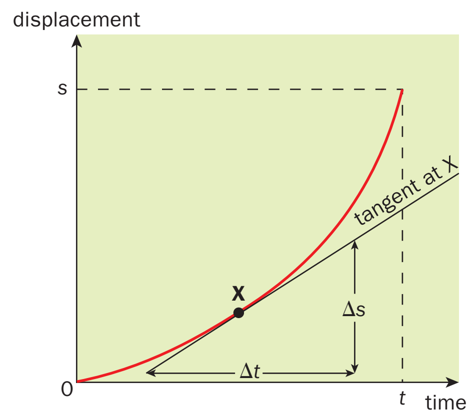
***The steeper the gradient, the greater the velocity.***

Velocity is a vector so the graph also needs to indicate its direction. Positive gradients (sloping upwards) indicate velocity in one direction. Negative gradients (sloping downwards) indicate velocity in the opposite direction.

*The gradient of a displacement–time graph gives us the velocity.*

How would you draw a displacement–time graph for a stationary object? If the velocity is zero, the gradient of the graph must also be zero. So your graph would be a horizontal line.

This second graph is a curve. How is the velocity changing here? The gradient of the graph is gradually increasing. This shows that the velocity is increasing. So the object is **accelerating**.



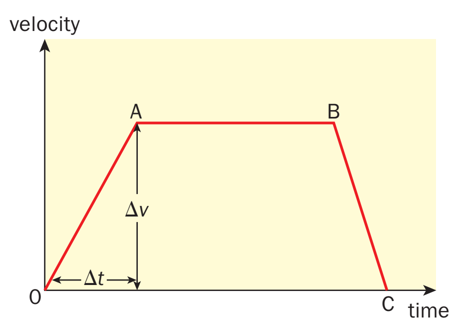

We could find the *average* velocity for this motion by dividing the total displacement $s$ by the time taken $t$ $(= s/t)$.

But how do we find the actual (instantaneous) velocity at any point? The instantaneous velocity is given by the gradient at that point. This is found by drawing a tangent to the curve and calculating its gradient $(= \Delta s/\Delta t$; see the labels on the graph; see page 476).

What would the gradient of a *distance*–time graph represent? In this case the gradient would give the scalar quantity, *speed*.

## Velocity–time graphs

This graph shows the motion of a car travelling in a straight line:




It starts at rest, speeds up from 0 to A, travels at constant velocity (from A to B), and then slows down to a stop (B to C).

What does the gradient tell us this time?

$$\text{Gradient of line 0A} = \frac{\text{change in velocity}}{\text{time taken}} = \text{acceleration}$$

***The steeper the line, the greater the acceleration.***

A positive gradient indicates acceleration. A negative gradient (eg. BC) indicates a negative acceleration (deceleration).

Straight lines indicate that the acceleration is constant or uniform.

If the graph is curved, the acceleration at any point is given by the gradient of the tangent at that point.

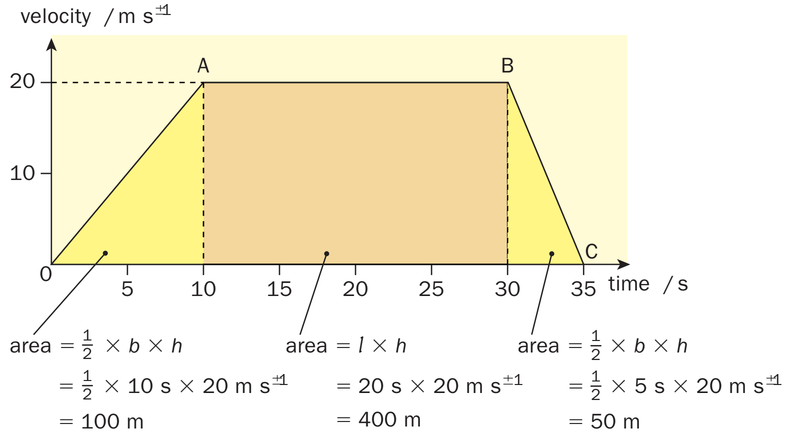
*The gradient of a velocity–time graph gives us the acceleration.*

The **area** under a velocity–time graph also gives us information. First let's calculate the displacement of the car during its motion.

From 0 to A:
displacement = average velocity × time taken
= $(\frac{1}{2} \times 20\ \text{m s}^{-1}) \times 10\ \text{s}$
= 100 m

From A to B:
displacement = average velocity × time taken
= $20\ \text{m s}^{-1} \times 20\ \text{s}$
= 400 m

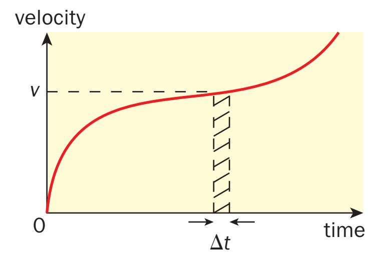
From B to C:
displacement = average velocity × time taken
= $(\frac{1}{2} \times 20\ \text{m s}^{-1}) \times 5\ \text{s}$
= 50 m




Compare these values with the areas under the velocity–time graph. (They are marked on the diagram.) What do you notice?
In each case ***the area under the graph gives the displacement***.

This also works for non-linear velocity–time graphs:

Area of shaded strip = $v \times \Delta t$ = average velocity × time interval
= displacement in this interval



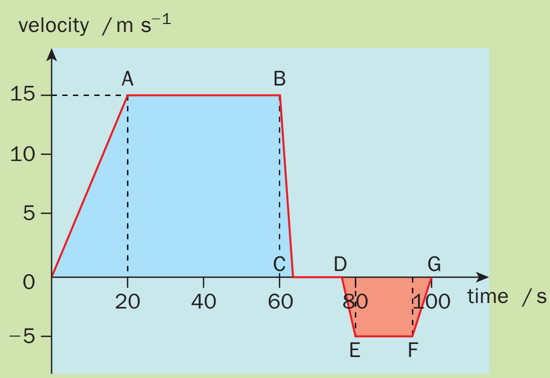

Adding up the total area under the curve would give us the total displacement during the motion.

What does the area under a *speed*–time graph represent?
This gives us the *distance* moved.

*Example 3*
The velocity–time graph represents the motion of a stockcar starting a race, crashing into another car and then reversing.

a) Describe the motion of the car during each labelled section.
b) What is the maximum velocity of the car?
c) At which point does the car crash?
d) Does the car reverse all the way back to the start point?


a) 0 to A: The car accelerates.
A to B: The car is moving at constant velocity.
B to C: The car rapidly decelerates to a standstill.
C to D: The car is not moving.
D to E: The velocity is increasing again but the values are negative. Why? The car is starting to reverse.
E to F: The car is now reversing at constant velocity.
F to G: The car decelerates and stops.




b) From the graph, maximum velocity = $15\ \text{m s}^{-1}$.

c) The car crashes at point B. This causes the rapid deceleration.

d) The area under the positive part of the velocity–time graph (shaded blue) gives the forward displacement of the car.
The negative area (shaded red) gives the distance that the car reversed.
As the red area is smaller than the blue area, we can see that the car did not reverse all the way back to the start point.

## Equations of motion

These are 4 equations that you can use whenever an object moves with **constant, uniform acceleration** in a straight line.
The equations are written in terms of the 5 symbols in the box:

They are derived from our basic definitions of acceleration and velocity.
Check your syllabus to see if you need to learn these derivations, or whether you only need to know how to use the equations to solve problems.

| | | |
|---|---|---|
| $s$ | = | **displacement** (m) |
| $u$ | = | **initial velocity** (m $s^{-1}$) |
| $v$ | = | **final velocity** (m $s^{-1}$) |
| $a$ | = | **constant acceleration** (m $s^{-2}$) |
| $t$ | = | **time interval** (s) |

**Derivations**

From page 39, acceleration $= \dfrac{\text{change in velocity}}{\text{time taken}} = \dfrac{\text{final velocity} - \text{initial velocity}}{\text{time taken}}$

Writing this in symbols: $a = \dfrac{v - u}{t}$

So $at = v - u$ which we can rearrange to give $\boldsymbol{v = u + at}$ . . . . . (1)

From page 38, average velocity $= \dfrac{\text{displacement}}{\text{time taken}}$

If the acceleration is constant, the average velocity during the motion will be halfway between $u$ and $v$. This is equal to $\frac{1}{2}(u + v)$.
Writing our equation for velocity in symbols:

$\frac{1}{2}(u + v) = \dfrac{s}{t}$ which we can rearrange to give $\boldsymbol{s = \frac{1}{2}(u + v)\,t}$ . . . . . (2)

Using equation (1) to replace $v$ in equation (2):

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

$\therefore\ s = \frac{1}{2}(2u + at)\,t$ which we can multiply out to give $\boldsymbol{s = ut + \frac{1}{2}at^2}$ . . . . . (3)

From equation (1), $t = \dfrac{v - u}{a}$

Using this to replace $t$ in equation (2):

$s = \frac{1}{2}(u + v)\dfrac{(v - u)}{a}$

$\therefore\ 2as = (u + v)(v - u)$

$\therefore\ 2as = v^2 - u^2$ which we can rearrange to give $\boldsymbol{v^2 = u^2 + 2as}$ . . . . . (4)

Note:

- You can use these equations only if the acceleration is ***constant***.
- Notice that each equation contains only 4 of our five '$suvat$' variables.
  So if we know any 3 of the variables we can use these equations to find the other two.

*Example 4*

A cheetah starts from rest and accelerates at 2.0 m $s^{-2}$ due east for 10 s.
Calculate a) the cheetah's final velocity,
b) the distance the cheetah covers in this 10 s.

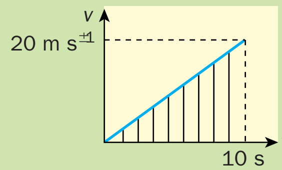
First, list what you know:
$s = ?$
$u = 0$ ( = 'from rest')
$v = ?$
$a = 2.0\ \text{m s}^{-2}$
$t = 10\ \text{s}$

a) Using equation (1): $\boldsymbol{v = u + at}$

$v = 0 + (2.0\ \text{m s}^{-2} \times 10\ \text{s}) = \underline{20\ \text{m s}^{-1}\ \text{due east}}$

b) Using equation (2): $\boldsymbol{s = \frac{1}{2}(u + v)\,t}$

$s = \frac{1}{2}(0 + 20\ \text{m s}^{-1}) \times 10\ \text{s} = \underline{100\ \text{m}\ \text{due east}}$




Or you could find the displacement by plotting a velocity–time graph for this motion. The magnitude of the displacement is equal to the area under the graph. Check this for yourself.

*Example 5*

An athlete accelerates out of her blocks at 5.0 m $s^{-2}$.
a) How long does it take her to run the first 10 m?
b) What is her velocity at this point?

First, list what you know:
$s = 10\ \text{m}$
$u = 0$
$v = ?$
$a = 5.0\ \text{m s}^{-2}$
$t = ?$

a) Using equation (3): $\boldsymbol{s = ut + \frac{1}{2}at^2}$

$\therefore 10\ \text{m} = 0 + (\frac{1}{2} \times 5.0\ \text{m s}^{-2} \times t^2)$ So $t^2 = \dfrac{10\ \text{m}}{2.5\ \text{m s}^{-2}} = 4.0\ \text{s}^2$ $\therefore t = \underline{2.0\ \text{s}}$

b) Using equation (1): $\boldsymbol{v = u + at}$

$v = 0 + (5.0\ \text{m s}^{-2} \times 2.0\ \text{s}) = \underline{10\ \text{m s}^{-1}}$ (2 s.f.)

*Example 6*

A bicycle's brakes can produce a deceleration of 2.5 m $s^{-2}$.
How far will the bicycle travel before stopping, if it is moving at 10 m $s^{-1}$ when the brakes are applied?

First, list what you know:
$s = ?$
$u = 10\ \text{m s}^{-1}$
$v = 0$
$a = -2.5\ \text{m s}^{-2}$ (negative for *deceleration*)

Using equation (4): $\boldsymbol{v^2 = u^2 + 2as}$

$0 = (10\ \text{m s}^{-1})^2 + (2 \times -2.5\ \text{m s}^{-2} \times s)$

$0 = 100\ \text{m}^2\ \text{s}^{-2} - (5.0\ \text{m s}^{-2} \times s)$ So $s = \dfrac{100\ \text{m}^2\ \text{s}^{-2}}{5.0\ \text{m s}^{-2}} = \underline{20\ \text{m}}$ (2 s.f.)

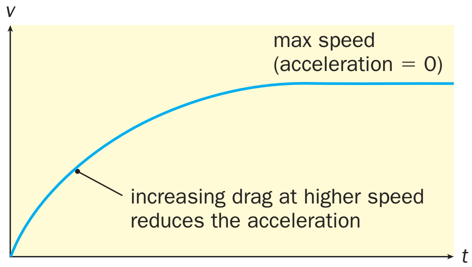
## Physics at work: Speed and stopping distance

### Fast cars

In 2014, the Hennessey Venom became the world's fastest production road car, reaching 270.49 mph on the Space Shuttle landing strip in Florida. This beat the previous record holder, the Bugatti Veyron, by just 0.63 mph!

*The Hennessey Venom.*

So what limits the top speed of a car? On page 45 you saw how a falling object will accelerate until it reaches its maximum speed, or terminal velocity. This is due to the increase in the drag force as the object speeds up. Exactly the same effect limits the speed of a car. Even with the accelerator pressed to the floor, there is a maximum driving force available from the engine. This will accelerate the car rapidly at first but as the speed increases the drag force on it will also increase. Eventually the drag force becomes large enough to balance the motive force and so it is no longer possible to accelerate. The graph shows the shape of the velocity–time graph for a car reaching its maximum speed:




*Thrust SSC.*

*Bloodhound SSC.*

So the key to high speed is minimising drag by using streamlined shapes, as well as maximising engine power. This has been taken to extremes in vehicles such as Thrust SSC. SSC stands for 'supersonic car'! Thrust SSC holds the official land speed record for a wheeled vehicle, achieving an incredible 763.035 mph using a mix of car and aircraft technology. Thrust's driver, Andy Green, is now involved in designing Bloodhound SSC, a rocket-powered car being designed to break the 1000 mph barrier!

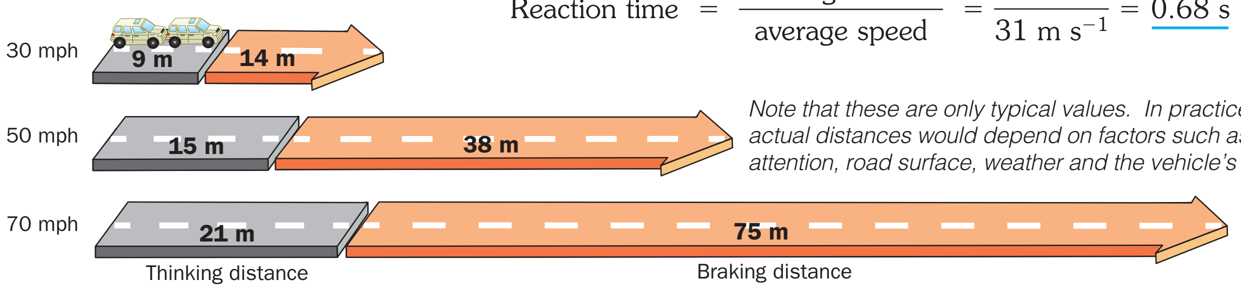
### Stopping distances

When you learn to drive you need to learn the Highway Code to pass your Driving Theory Test.
The Highway Code includes a table of typical stopping distances for cars travelling at different speeds.
A section of this is shown below. Notice that the total stopping distance is made up of two parts.
The ***thinking distance*** is the distance travelled before the driver reacts and starts to brake.
You move a surprising distance after spotting a hazard before you even press the brake pedal.
The ***braking distance*** is the distance travelled while decelerating to a stop once you've pressed the brake.
What deceleration and reaction time do these figures assume? We can find out using our equations of motion.
Using the 70 mph (31 m s$^{-1}$) figures:

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

$$0 = (31\text{ m s}^{-1})^2 + (2 \times a \times 75\text{ m}) \quad \text{So} \quad a = -\frac{(31\text{ m s}^{-1})^2}{(2 \times 75\text{ m})} = \underline{-6.4\text{ m s}^{-2}} \text{ (negative as it is a deceleration)}$$

$$\text{Reaction time} = \frac{\text{thinking distance}}{\text{average speed}} = \frac{21\text{ m}}{31\text{ m s}^{-1}} = \underline{0.68\text{ s}}$$




*Note that these are only typical values. In practice the actual distances would depend on factors such as your attention, road surface, weather and the vehicle's condition.*

## Physics at work: Car safety

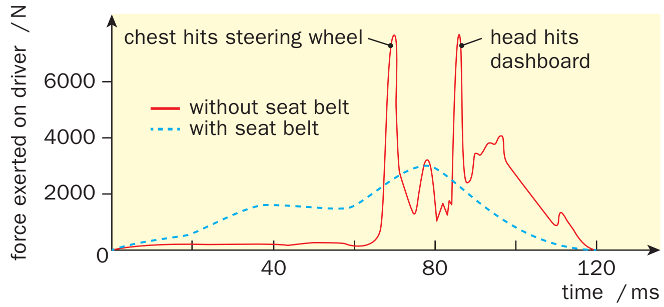
### Seat belts and crumple zones

Seat belts save lives! In a collision with a stationary object, the front of your car stops almost instantly. But what about the passengers?

Unfortunately they will obey Newton's first law and continue moving forwards at constant velocity until a force changes their motion. Without a seat belt, this force will be provided by an impact with the steering wheel or windscreen. This can cause you serious injury, even at low speeds.
A seat belt allows you to decelerate in a more controlled way, reducing the forces on your body. In an accident it is designed to stretch about 25 cm.
This allows the restraining force to act over a longer time.

Newton's second law ($F = \Delta(m\,v)/\Delta t$, see page 55) tells us that the longer the time $\Delta t$ taken to reduce a passenger's momentum $\Delta(m\,v)$, the smaller the force $F$ needed to stop them.

Look at the graph. It compares the forces acting on a driver involved in a collision with, and without, a seat belt:




Newton's second law also explains why modern cars are designed with **crumple zones**.
The passenger cell is designed as a rigid cage to maximise passenger protection by transmitting forces away around the roof and floor of the car.
But crumple zones are deliberately built into the car's bodywork.
By crumpling, the car takes a longer time to come to rest.
Again this means a lower rate of change of momentum and a smaller force acting on the passengers.
So, although cars suffer significant damage in even a minor collision, you are far more likely to walk away from an accident.

*Sections of a car are designed to crumple in an accident.*

### Airbags

Airbags are designed to provide a cushion between your upper body and the steering wheel or dashboard. This can reduce the pressure exerted on you by more than 80% in a collision.

Without an airbag, your head would hit the steering wheel about 80 milliseconds after an impact. To be of any use, the crash must be detected and the airbag inflated in less than 50 ms!
So the bag is inflated explosively. This could be dangerous if it inflated accidentally under normal driving conditions.

*Crash detection, inflation and deflation of the airbag (to allow the driver to see again) must all take place in less time than it takes you to blink!*

So what triggers the airbag? Why does it inflate during a collision and not whenever you brake hard?

In a collision you are brought to rest very rapidly, say in 0.10 s. Even at low speeds this produces high deceleration. For example, at 20 mph (9 m s$^{-1}$):

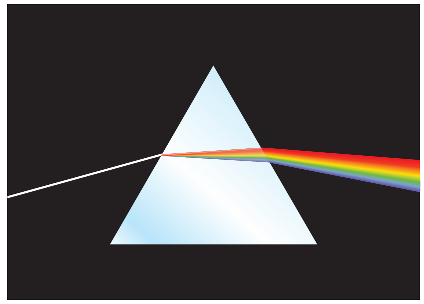
$$\text{acceleration} = \frac{\Delta v}{t} = \frac{0 - 9\ \text{m s}^{-1}}{0.10\ \text{s}} = -90\ \text{m s}^{-2} = -9.2\ g \quad (\text{where } g = \text{acceleration due to gravity})$$

This means that your seat belt must be able to exert a force over 9 times your body weight without snapping!

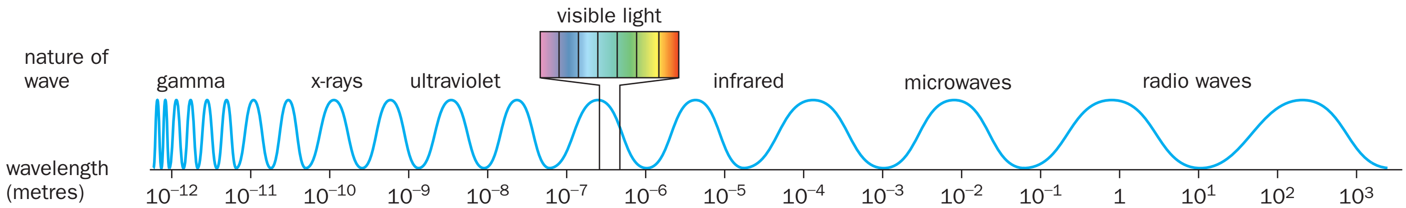
Compare this with the deceleration during an emergency stop, even at high speed.
On page 49 we used data from the Highway Code to calculate the typical deceleration of a car from 70 mph.
The answer of 6.4 m s$^{-2}$ (0.65 $g$) is 14 times smaller than the deceleration in even a low-speed collision.
An acceleration sensor can easily detect the difference between the two, and only activate the airbag in a collision.

## Electromagnetic waves

Do you recognise this well-known experiment?
White light is a mixture of several colours and can be split by a prism to show a spectrum. Light travels as a transverse wave and each colour of light has a different wavelength. Red light has the longest wavelength, violet the shortest.



The visible spectrum is a tiny part of a much wider spectrum, with wavelengths that range from $10^{-15}$ m to more than 1 km.




## The regions of the electromagnetic spectrum

The diagram above shows how the spectrum is labelled, but there are no sudden boundaries between the different regions.

### Gamma radiation and X-rays

Gamma radiation is emitted by radioactive nuclei (see page 360).
X-rays are produced when high-speed electrons decelerate quickly. High-energy X-rays have shorter wavelengths than low-energy gamma rays. They are given different names only because of the way that they are produced.

### Ultraviolet (UV)

Why is the arc welder in the photograph wearing eye protection?
Electric arcs, such as sparks and lightning, produce ultraviolet. It is also given out by our Sun. Small amounts of UV are good for us, producing vitamin D in our skin. Large amounts of high-energy UV can damage living tissue.

Luckily for us the Ozone Layer, high in the Earth's atmosphere, absorbs UV rays with wavelengths less than 300 nm ($3 \times 10^{-7}$ m). But its recent thinning increases the risk of skin cancer.

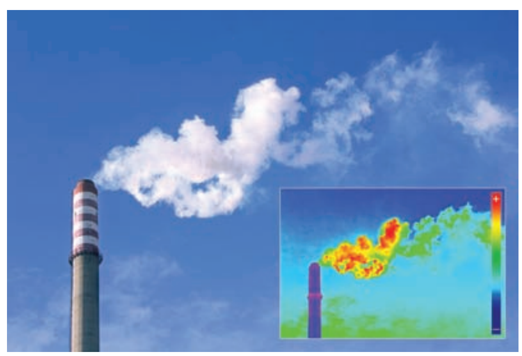
*Welders must protect themselves against UV.*

### Visible light

Human eyes can detect wavelengths from 400 nm (violet light) to 700 nm (red light). Other animals have eyes that are sensitive to different ranges. Bees, for example, can see ultraviolet radiation.

### Infrared (IR)

Every object that has a temperature above absolute zero gives out infrared waves. Rescue workers can use infrared viewers to search for survivors trapped below collapsed buildings.
IR was the first invisible part of the spectrum to be discovered (by the astronomer William Herschel in 1800).



*Photographs taken with visible light and IR.*

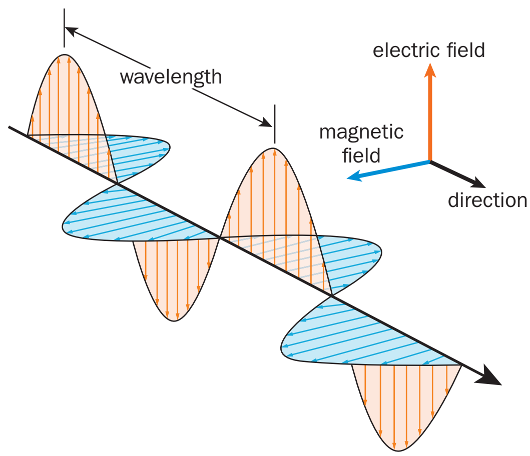
### Radio waves

Radio waves range in wavelength from millimetres to tens of kilometres. Microwaves are the shortest of the radio waves and they are used for mobile phone and satellite communication. Longer wavelengths are used for radio transmissions.

## The nature of electromagnetic radiation

All electromagnetic waves can travel through a vacuum at $3.00 \times 10^8$ m s$^{-1}$. This value is called the 'speed of light'. But what are electromagnetic waves?

Electromagnetic waves consist of electric and magnetic fields. Can you see that the fields oscillate in phase, and are at 90° to each other and to the direction of travel of the wave? Each field vibrates at the wave frequency.




Who discovered these ideas?
By the early 19th century it was known that an electric current always produces a magnetic field. Michael Faraday then showed that changing a magnetic field produces an electric current.

In 1862 James Clerk Maxwell saw the connection:
If a changing magnetic field produces a changing electric field, the electric field must create a changing magnetic field.
The two oscillating fields are linked!

Maxwell predicted that an oscillating electric charge should radiate an electromagnetic wave. He also derived an equation for the speed $\boldsymbol{c}$ of the wave in free space, using the magnetic field constant $\boldsymbol{\mu_o}$ and the electric field constant $\boldsymbol{\varepsilon_o}$:

$$\boldsymbol{c = \frac{1}{\sqrt{\mu_o \varepsilon_o}}}$$

Maxwell's calculation for the value of $c$:

$\boldsymbol{\mu_o}$ is the permeability of free space (see page 260)

$\boldsymbol{\varepsilon_o}$ is the permittivity of free space (see page 290)

$$c = \frac{1}{\sqrt{4\pi \times 10^{-7} \times 8.85 \times 10^{-12}}}$$

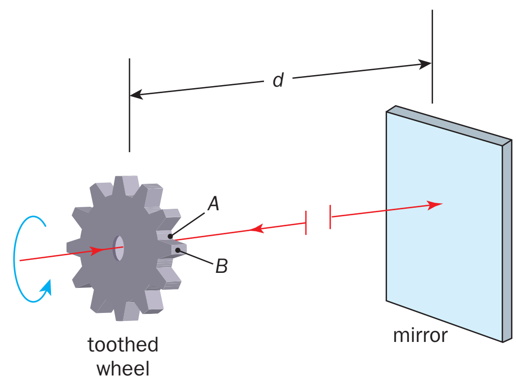
$$c = 3.00 \times 10^8 \text{ m s}^{-1}$$

Using the constants in this equation gives the speed of light!
Maxwell had shown that light waves are electromagnetic waves.
He thought that light was just one part of a wider spectrum.
In 1887, Heinrich Hertz proved that Maxwell's ideas were correct when he discovered radio waves (see page 167).

## Measuring the speed of light

Galileo had tried to measure the speed of light in 1638.
Can you suggest why he did not succeed?

The first successful direct measurement of the speed of light was achieved by Fizeau in 1849. His apparatus consisted of a rotating toothed wheel with $N$ teeth and a mirror.




A beam of light passes through a gap A between two teeth. It travels to the distant mirror and is reflected back towards the wheel. The wheel spins, going faster and faster.
If light leaving through one gap returns to the wheel as the next tooth B takes the place of the gap, the light is cut off.

We now know the time $t$ for the light to travel to the mirror and back, a distance $2d$.
The wheel spins $f$ times per second and in time $t$ it makes $\frac{1}{2N}$ of a turn while a cog replaces a gap. So $t = \frac{1}{2Nf}$.
This method gave Fizeau a value for $c$ of 313 000 km s$^{-1}$.

Fizeau's calculation for the value of $c$:

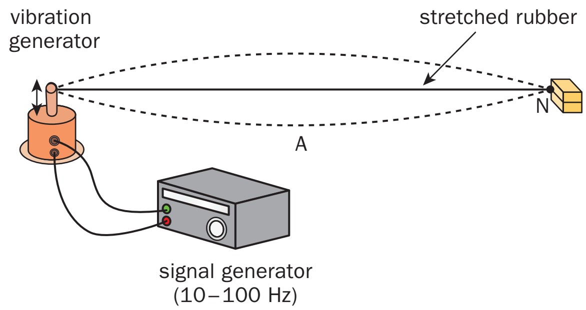
The wheel had 720 teeth.
The frequency $f$ was 12.6 Hz.
Distance $2d$ was 17.26 km = $1.726 \times 10^4$ m.

$$\text{Speed} = \frac{\text{distance}}{\text{time}}, \quad \text{so} \quad c = \frac{2d}{1/(2Nf)} = 2d \times 2Nf$$

$$c = 1.726 \times 10^4 \text{ m} \times 2 \times 720 \times 12.6 \text{ Hz}$$
$$= 3.13 \times 10^8 \text{ m s}^{-1}$$

## Standing waves and resonance

You can trap waves on a string by attaching a vibration generator to a long cord, fastened firmly at the other end:

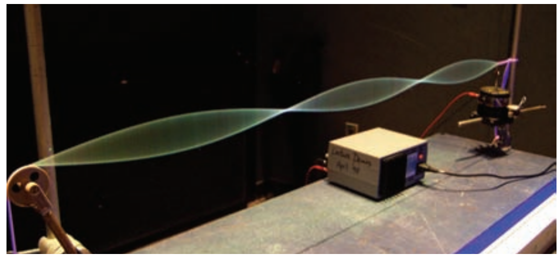



The vibrator sends waves along the cord. The waves reflect back from the fixed end, and superpose with the incident waves from the vibration generator, to form a standing wave.

The output of the signal generator can be varied so that the generator forces the cord to vibrate at different frequencies. At certain frequencies, the string vibrates with a large amplitude. These are the ***resonant*** frequencies of the system.

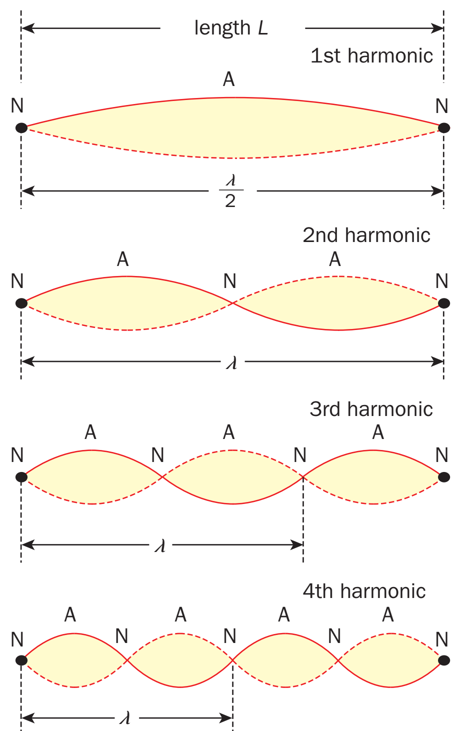
Resonance occurs when the frequency that is driving the system (from the vibration generator) matches a natural frequency of the system (see also page 110).

The photograph shows what you might see. At a node the cord does not move at all, and you can see the string quite distinctly. At the anti-nodes the string vibrates with a maximum amplitude, and so it appears as a blur.



### Stationary waves in string instruments

The guitar and violin are just two types of string instrument. When one of the strings is plucked or bowed in the middle, transverse waves travel along the string in opposite directions. At the ends of the string the waves are reflected back and a stationary wave, with nodes **N** and anti-nodes **A**, is set up.




The string can only vibrate with certain frequencies. These are the resonant frequencies of the string; we call them ***harmonics***. Why are only certain frequencies allowed?

This is because you must have a whole number of stationary wave loops fitting into the length of the string.

The simplest way the string can vibrate is with just one loop.
The wavelength is twice the length $L$ of the string.
Can the stationary wave have a longer wavelength than this?
No, one loop produces a sound of the lowest possible frequency.
This is the ***fundamental frequency*** or ***first harmonic***, $f_1$.

In the second diagram, the string vibrates with two loops.
The wavelength is now equal to the length of the string.
This is half as long as it was for one loop.
The frequency $f_2$ of this ***second harmonic*** must be twice the frequency of the fundamental frequency.

The third harmonic is at three times the fundamental frequency, because the wavelength is $\frac{1}{3}$ of its value for one loop.
Can you predict the pattern for the rest of the harmonics?

| Number of loops | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Wavelength | $2L$ | $\frac{2L}{2}$ | $\frac{2L}{3}$ | $\frac{2L}{4}$ | $\frac{2L}{5}$ |
| Frequency | $f_1$ | $f_2 = 2 \times f_1$ | $f_3 = 3 \times f_1$ | $f_4 = 4 \times f_1$ | $f_5 = 5 \times f_1$ |

How could you increase the fundamental frequency of a string? You could press down on the string with your finger to shorten its length. Or you could tighten the string, to increase its tension.

## The first harmonic of a stretched string

Have you noticed that guitar strings have different thicknesses? Each string has a different ***mass per unit length***, $\mu$.

If you tighten any of the strings, increasing its ***tension***, $T$, why does the frequency of the note from the wire increase?

When you strum the guitar string, waves move in both directions along the string and superpose to give a stationary wave. Both the tension ***and*** the mass per unit length affect the ***speed*** $c$ of these waves on the string.

In fact:

$$\textbf{speed, } c\ (\mathrm{m\ s^{-1}}) = \sqrt{\frac{\textbf{tension, } T\ (\mathrm{N})}{\textbf{mass per unit length, } \mu\ (\mathrm{kg\ m^{-1}})}} \quad \text{or} \quad c = \sqrt{\frac{T}{\mu}}$$

From the previous page we know that when the string vibrates in its first harmonic mode, the wavelength $\lambda$ of the stationary wave is twice the length $L$ of the string.

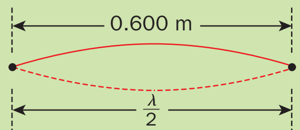
For any wave $c = f\lambda$ (page 125) and so the first harmonic frequency $f_1$ is given by:

$$f_1 = \frac{c}{\lambda} \quad \text{or} \quad f_1 = \frac{1}{2L}\sqrt{\frac{T}{\mu}}$$

*Example 3*

A guitar string has a mass per unit length of $7.95 \times 10^{-4}$ kg m$^{-1}$
The string is 0.600 m long and is under a tension of 78.5 N.
What value is the first harmonic frequency of the guitar string?

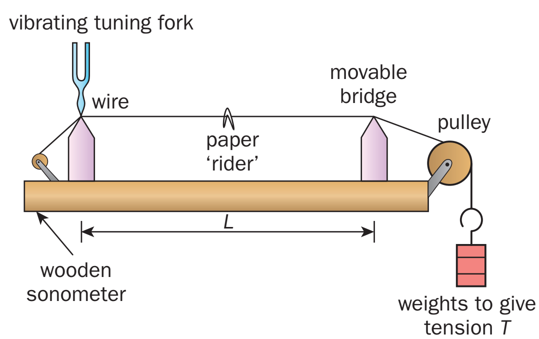
$$f_1 = \frac{c}{\lambda} = \frac{1}{2L}\sqrt{\frac{T}{\mu}} = \frac{1}{2 \times 0.600\ \mathrm{m}}\sqrt{\frac{78.5\ \mathrm{N}}{7.95 \times 10^{-4}\ \mathrm{kg\ m^{-1}}}} = \underline{262\ \mathrm{Hz}}\ (3\ \mathrm{s.f.})$$




*The string vibrating in its first harmonic, $f_1$.*

## Using a sonometer

The factors that affect the first harmonic frequency of a string can be investigated using a ***sonometer***, as shown:



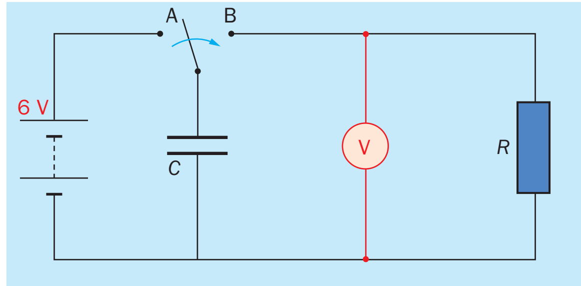

One experiment is to see how the length $L$ of the wire affects the frequency of the note it produces. You can adjust the length by altering the position of the moveable bridge.
Or you can investigate how the tension $T$ in the wire affects the frequency, by adjusting the weights.

How do you measure the frequency of the sound from the wire? This is done by adjusting the wire until the sound it produces matches that of the tuning fork.

Unless you have a keen ear for music, you may find it difficult to match the sounds! The paper ‘rider’ will help.
If the tuning fork is placed as shown, it forces the wire to vibrate. When the paper rider vibrates vigorously, the wire is resonating. So then the frequency of the wire equals the frequency of the fork.

## Discharging a capacitor

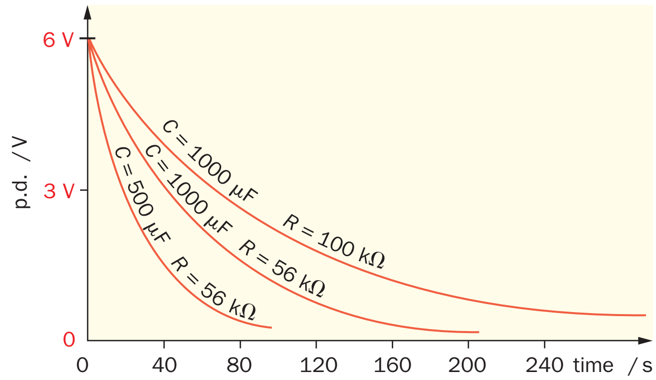
What factors affect the ***time*** taken for a capacitor to discharge? You can investigate this using the apparatus shown:




The capacitor charges up when the switch is in position A. You can then move the switch to position B and discharge the capacitor through the resistor.

The voltmeter records the p.d. across the capacitor. Can you see that this is also the p.d. across the resistor? Why will the voltmeter read 6 V at the start of the discharge?

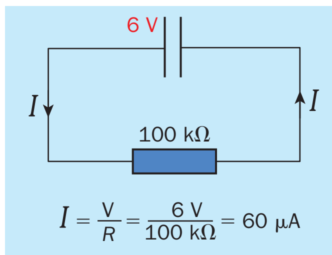
You can record the p.d. every 10 s as the capacitor discharges. The graph shows the results that you would get using different values for the capacitance $C$ and the resistance $R$:

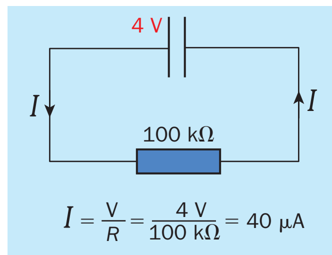



Why does the discharge take longer as $C$ and $R$ increase? The larger the resistance, the more it resists the flow of charge. The charge moves more slowly around the circuit.

The greater the capacitance, the greater the charge stored. It takes longer for the charge to flow off the capacitor plates.

Why does the p.d. fall more and more slowly with time? Look at the circuit diagrams:
Notice that the smaller the p.d., the smaller the current: in other words, the smaller the rate of flow of charge.
As the p.d. falls, the charge flows off the plates more slowly and the time for the p.d. to drop takes longer and longer.




### The time constant

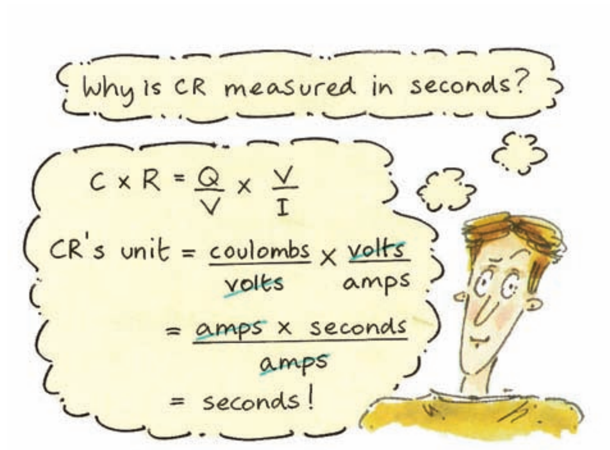
The **time constant** $\tau$ gives us information about the time it takes for a capacitor to discharge:

| **Time constant, $\tau$** | = | **capacitance, $C$** | × | **resistance, $R$** |
|---|---|---|---|---|
| (seconds) | | (farads) | | (ohms) |

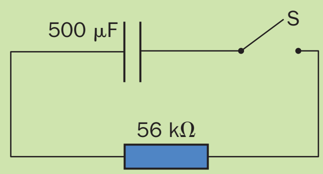
In fact, the time constant $\tau$ is the time it takes for the p.d. to fall to $\mathbf{1/e}$ of its original value $V_0$.
(**e** is one of those special mathematical numbers, rather like $\pi$).
The value of e is 2.72 (3 s.f.) and so $\mathbf{1/e}$ equals **0.37** (2 s.f.).

After a time $CR$, the p.d. $V$ across the capacitor equals $0.37 \times V_0$. $V$ is now 37% (very roughly $^1/_3$) of its original value.

After a time $5CR$, the p.d. will have fallen to about 0.7% of $V_0$ and we can consider the capacitor to be effectively discharged.




*Example 5*
What is the time constant for the circuit shown?




**Time constant,** $\boldsymbol{\tau}$ = **capacitance, $C$** × **resistance, $R$**

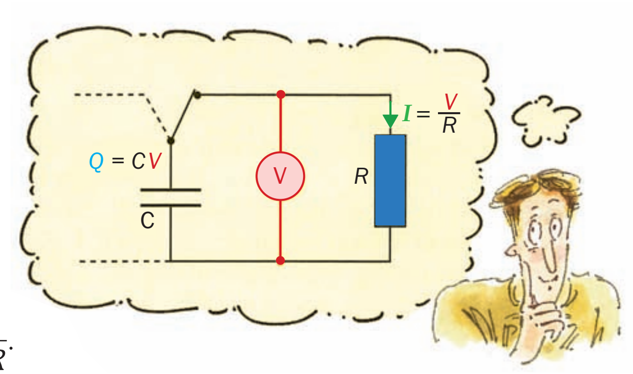
$= 500 \times 10^{-6}\ \text{F} \times 56 \times 10^{3}\ \Omega$

$\tau$ = 28 seconds

## Exponential discharge

How does the charge on the capacitor plates vary as it discharges?

The diagram shows our discharge circuit again:




At this instant, the charge on the capacitor is $\boldsymbol{Q}$, the discharge current is $\boldsymbol{I}$ and the p.d. across the resistor and the capacitor is $\boldsymbol{V}$.

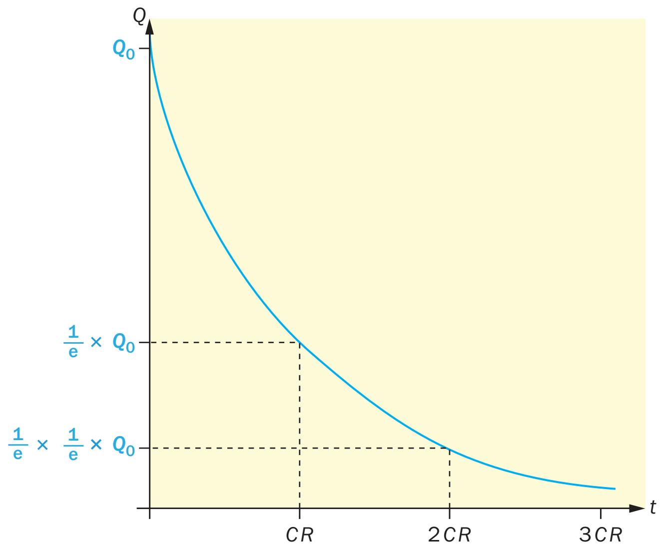
In a short time $\Delta t$, a small charge $\Delta Q$ flows off the capacitor plates. From page 228 we know that: $\Delta Q = I\Delta t$

But for the resistor, $I = \frac{V}{R}$, and for the capacitor, $V = \frac{Q}{C}$, so $I = \frac{Q}{CR}$.

Substituting for $I$ in the equation for $\Delta Q$: $\Delta Q = \frac{Q}{CR}\ \Delta t$ or $$\boldsymbol{\frac{\Delta Q}{\Delta t} = -\frac{Q}{CR}}$$

(The minus sign tells us that $Q$ decreases as time passes.)

This equation tells us that the rate of flow of charge off the capacitor plates, $\Delta Q/\Delta t$, depends on the time constant $CR$ and on the charge $Q$ on the capacitor plates. As time passes, $Q$ falls and the capacitor discharges more and more slowly.




Let's look in detail at the graph of charge $Q$ against time $t$:
After a time $CR$, the charge has fallen to $\mathbf{1/e}$ (about $1/3$) of $Q_0$.

After a further time $CR$, the charge has again fallen by $\mathbf{1/e}$.
Now the charge is $1/e \times 1/e$ (roughly $1/9$) of its original value.

A further $CR$ seconds and the charge is $1/e \times 1/e \times 1/e$ of $Q_0$.

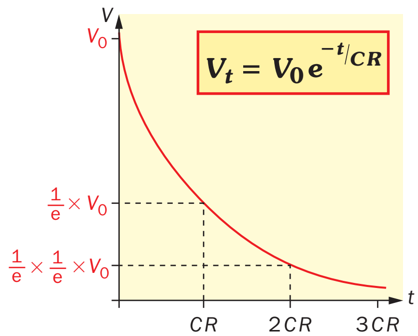
The charge continues to fall by $\mathbf{1/e}$ every $CR$ seconds.
We say that the charge falls ***exponentially with time***, and

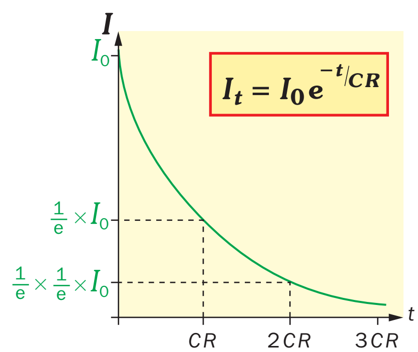
$$\boldsymbol{Q_t = Q_0\, e^{-t/CR}}$$

$Q_0$ is the initial charge
$Q_t$ is the charge after time $t$
$CR$ is the time constant

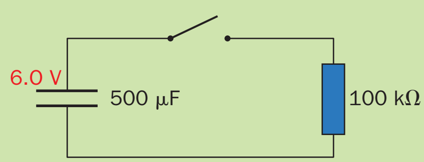
$Q = CV$, and so $V$ is proportional to $Q$.
∴ The p.d. $\boldsymbol{V}$ must also fall exponentially.

$V = IR$, and so $I$ is proportional to $V$.
∴ The current $\boldsymbol{I}$ must fall exponentially.




*Example 6*
In the circuit shown, the capacitor is charged to 6.0 V.
The switch is now closed. Calculate:
a) the time constant,
b) the p.d. across the capacitor after 20 s,
c) the charge on the capacitor after 20 s.



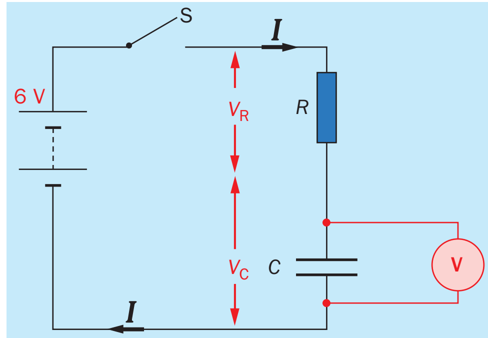

a) $\boldsymbol{\tau = C \times R}$
$= 500 \times 10^{-6}\ \text{F} \times 100 \times 10^{3}\ \Omega$
∴ $\tau$ = <u>50 s</u> (2 s.f.)

b) $\boldsymbol{V_t = V_0\, e^{-t/CR}}$
$= 6.0 \times e^{-20\ \text{s}/50\ \text{s}}$
$= 6.0 \times e^{-0.4}$
∴ $V_t$ = <u>4.0 V</u> (2 s.f.)

c) $\boldsymbol{Q_t = C\, V_t}$
$= 500 \times 10^{-6}\ \text{F} \times 4.0\ \text{V}$
∴ $Q_t$ = <u>$2.0 \times 10^{-3}$ C</u> (2 s.f.)

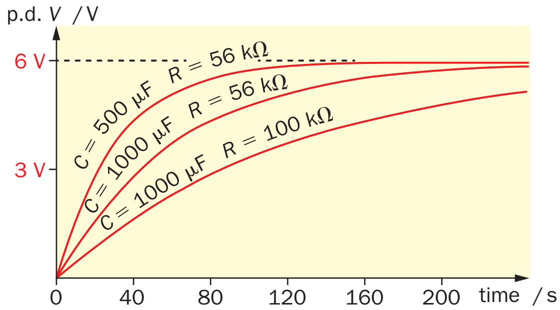
## Charging a capacitor: Exponential growth

What factors affect the time taken for a capacitor to charge up?
You can investigate this using the apparatus shown:




Here we are using a 6 V supply.
The voltmeter is recording the p.d. across the capacitor.
Is this also the p.d. across the resistor?
No, because the capacitor and resistor ***share*** the supply p.d.

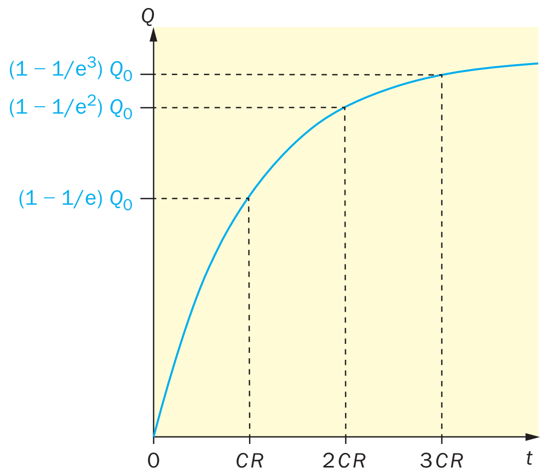
When the switch S is closed, the capacitor starts to charge up, and you can record the p.d. across the capacitor every 10 s.
The graph shows the results that you would get using different values for the capacitance $C$ and resistance $R$:




Notice that, as the capacitor charges, the p.d. increases ever more slowly, eventually reaching the supply p.d. of 6.0 V.
Can you see that charging takes longer as $C$ and $R$ increase?
The time constant $\tau$ affects the charging process.

Since the charge on the capacitor is proportional to the p.d. across its plates, the graph of charge $Q$ against time must be the same shape as the graph of p.d. against time.

Let's look in more detail at the graph of charge against time:
Note that the charge on the fully charged capacitor is $\boldsymbol{Q_0}$.




After a time $CR$, the charge has risen to $(1 - {}^1/e)$ of $Q_0$.
This is about 2/3 of the final charge $Q_0$.

After time $2 \times CR$, the charge has risen to $(1 - ({}^1/e \times {}^1/e))$ or $(1 - {}^1/e^2)$ of $Q_0$. This is about 8/9 of $Q_0$.
Can you see a pattern?

We say the charge ***increases exponentially*** with time, and:

$$Q_t = Q_0\,(1 - e^{-t/CR})$$

$Q_0$ is the final charge
$Q_t$ is the charge after time $t$
$CR$ is the time constant

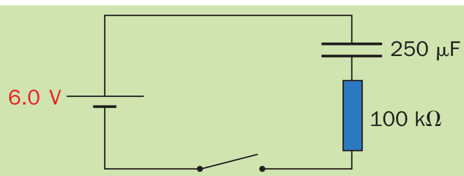
We can write a similar equation for the p.d. across the capacitor as it charges up, but what about the current?

$$V_t = V_0\,(1 - e^{-t/CR})$$

Look at the circuit diagram again.
$V_C$ is the p.d. across the capacitor, $V_R$ the p.d. across the resistor.
Can you see that $V_C + V_R$ must ***always*** equal the supply voltage?
So as $V_C$ rises exponentially, $V_R$ must fall exponentially.
The current is proportional to the p.d. $V_R$ across the resistor, so the charging current ***falls*** exponentially as the capacitor charges.

$$I_t = I_0\, e^{-t/CR}$$

*Example 7*
The switch is closed in the circuit shown. Calculate:
a) the time constant,
b) the p.d across the capacitor after 40 s,
c) the charging current after 40 s.




a) $\tau = C \times R$

$= 250 \times 10^{-6}\text{F} \times 100 \times 10^3\ \Omega$

$\tau = \underline{25\text{ s}}$ (2 s.f.)

b) $V_t = V_0\,(1 - e^{-t/CR})$

$= 6.0 \times (1 - e^{-40/25\text{ s}})$

$= 6.0 \times (1 - e^{-1.6})$

$V_t = \underline{4.8\text{ V}}$ (2 s.f.)

c) The p.d. across $R$ = 6.0V − 4.8V = 1.2V

Using $V = I \times R$ = 1.2 V:

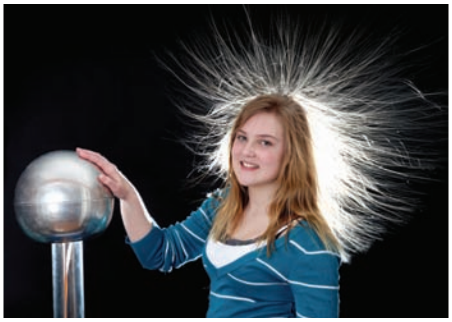
$1.2\text{ V} = I \times 100 \times 10^3\ \Omega$

$I = \underline{1.2 \times 10^{-5}\text{ A}}$ (2 s.f.)

## Physics at work: Capacitors

**The capacitance of charged spheres**

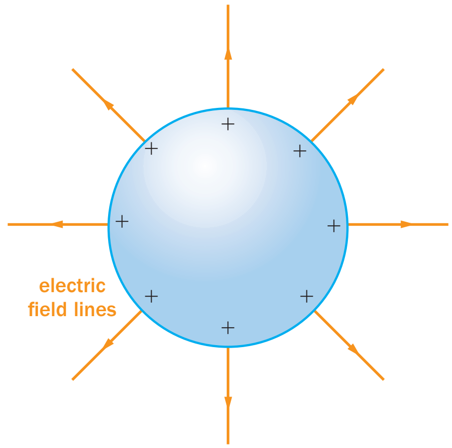
Have you seen this 'experiment' being carried out?



The student stands on a block of polystyrene and touches the dome of the Van de Graaff generator. When the Van de Graaff is switched on, the dome and the student become charged. Her hair demonstrates that like charges repel!

You need to take care when using a Van de Graaff generator. As the dome becomes highly charged, an electric field is created at its surface. The electric field strength can be so large that the insulation of the air breaks down, and sparks pass from the dome to any nearby object that is connected to Earth (see page 294). You may get an unexpected electric shock!

The dome of the Van de Graaff is storing electric charge. It is acting as a capacitor. Can we calculate its capacitance ***C***?




The diagram shows an isolated sphere of radius $r_s$, in a vacuum: The dome of the Van de Graaff is (almost) a sphere.

The charge on the sphere is $+Q$. From page 296 we know that the electric potential $V$ at the surface of the sphere is:

$$V = \frac{kQ}{r_s}, \text{ where } k = \frac{1}{4\pi\varepsilon_0}$$

For any capacitor $C = \frac{Q}{V}$, and so: $C = Q \div \frac{Q}{4\pi\varepsilon_0 r_s}$

$$C = \not{Q} \times \frac{4\pi\varepsilon_0 r_s}{\not{Q}}, \qquad \therefore \quad \boldsymbol{C = 4\pi\varepsilon_0 r_s}$$

*Example 8*

Treating the Earth as an isolated sphere, what is its capacitance? The radius of the Earth is $6.4 \times 10^6$ m.

(From page 290, the value of $\varepsilon_0$ is $8.85 \times 10^{-12}$ F m$^{-1}$.)

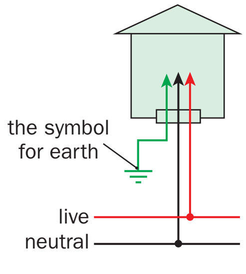
$\boldsymbol{C = 4\pi\varepsilon_0 r_s}$

$\boldsymbol{C} = 4\pi \times 8.85 \times 10^{-12}$ F m$^{-1}$ $\times$ $6.4 \times 10^6$ m $= 7.1 \times 10^{-4}$ F, or 710 μF (2 s.f.)

## Physics at work: Earthing

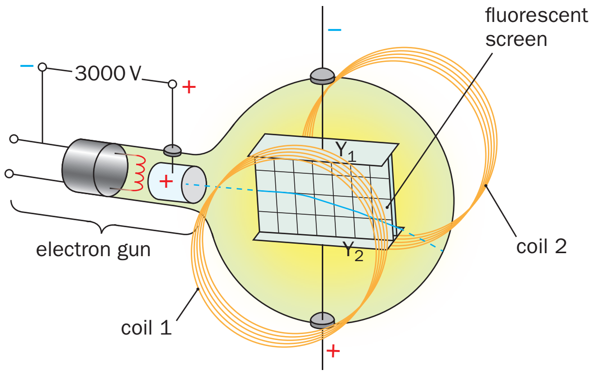
When a charged capacitor is connected to an uncharged capacitor (as in Example 3), electrons flow between the capacitors until the p.d. across both capacitors is the same. The capacitors share the charge, but not equally.

If the uncharged capacitor has a much larger capacitance than the charged capacitor, the charged capacitor loses almost all of its charge to the uncharged capacitor, and it is effectively discharged. Example 8 above shows that the Earth has a large capacitance. So when a charged conductor is connected to the Earth, it is (effectively) discharged.




The Earth has such a large capacitance that any loss or gain of charge causes a very small change in its potential. Therefore, we can treat the Earth as a convenient zero of electrical potential energy, as we saw in Chapter 21.

## Thomson's measurement of $\frac{Q}{m}$ for electron



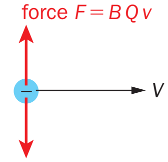

In 1897 J J Thomson found a way to measure the ratio of charge $Q$ to mass $m$ for the electron.

The diagram shows an electron beam moving through a vacuum tube called an **electron deflection tube**.

The beam can be deflected in 2 ways:

- by an ***electric*** field between the plates $Y_1$ and $Y_2$,
- by a ***magnetic*** field produced by the 2 coils carrying a current.

An electric field between $Y_1$ and $Y_2$ can push electrons ***downwards*** by a constant force $QE$ (see page 292), as shown in the diagram:




*Balanced forces on the moving electron.*

The value of the electric field $E$ is found by measuring the p.d. $V$ between the plates $Y_1$ and $Y_2$ and the separation $d$ between those plates, as we know that $E = \frac{V}{d}$ (see page 293).

A current in coils 1 and 2 provides a magnetic field $B$ across the electron deflection tube at right angles to the electric field. The coils are connected in series so they have the same current. The magnetic field gives an ***upwards*** force $BQv$ on the electron beam (see page 264).

The current through the coils is adjusted until the beam of electrons is a horizontal line. At this point the upward magnetic force balances the downward electric force. The current is noted.

The electron deflection tube is removed, and the magnetic field $B$ midway between the two coils is measured using a sensor such as a Hall probe (see page 257) while the coils carry the same current as before.


### Combining the electric and magnetic forces

We don't know the electron velocity $v$, so we need to eliminate it from our calculations. The kinetic energy gained by the electron from the electron gun is $QV_{gun}$ (see page 321).

so $\frac{1}{2} m v^2 = Q V_{gun}$ $\therefore$ $v^2 = \frac{2QV_{gun}}{m}$

But $BQv = QE$ $\therefore$ $v = \frac{E}{B}$ and so $v^2 = \frac{E^2}{B^2}$

$\therefore$ $\frac{2QV_{gun}}{m} = \frac{E^2}{B^2}$ and dividing both sides by $2V_{gun}$

$$\frac{Q}{m} = \frac{E^2}{2V_{gun}B^2}$$

*Example 2*

In this experiment, the electrons are accelerated by a p.d. of 2900 V. The same p.d. $V_{gun}$ is applied across the plates $Y_1$ and $Y_2$, which are 10 cm apart. The magnetic field $B$ needed to balance the forces on the electron beam is $9.1 \times 10^{-4}$ tesla.

Calculate the value of $\frac{Q}{m}$ given by this experiment.

$E = \frac{V_{gun}}{d} = \frac{2900\ \text{V}}{0.10\ \text{m}} = 29\,000\ \text{V m}^{-1}$ (or $29\,000\ \text{N C}^{-1}$). Note that you must use $d$ in metres!

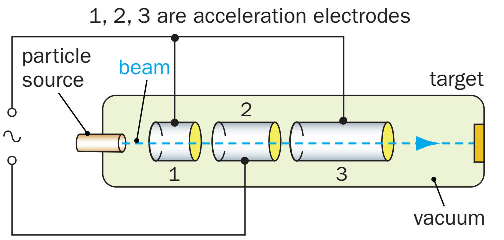
$\frac{Q}{m} = \frac{E^2}{2V_{gun}B^2} = \frac{(29\,000\ \text{V m}^{-1})^2}{2 \times 2900\ \text{V} \times (9.1 \times 10^{-4}\ \text{T})^2} = \underline{1.8 \times 10^{11}\ \text{C kg}^{-1}}$ (2 s.f.)

## Physics at work: Particle accelerators

Particle physicists can create new particles by colliding other particles together. To do this, the colliding particles need to be given large amounts of energy by an **accelerator.** Accelerators use electric fields to accelerate particles such as protons to energies much greater than the 2000 eV of the electron gun on page 321.

**Linear accelerator or 'linac'**

This accelerates particles in a straight line:
The cylindrical electrodes are connected to an alternating supply so that they are alternately positive and negative. The frequency of the p.d. is set so that as the particles emerge from each electrode they are accelerated across the next gap.
Why do the electrodes get progressively longer? To keep in step with the alternating p.d., the particles must take the same time to travel through each electrode. As the particles get faster the tubes must get longer. The accelerator may be 3 km long!
A linear accelerator can accelerate electrons to about 50 GeV.



*A linear accelerator.*

**Cyclotron**

A cyclotron consists of two semicircular metal 'dees' separated by a small gap. When a charged particle enters the cyclotron, a perpendicular magnetic field makes it move along a circular path at a steady speed. Each time the particle reaches the gap between the dees, an alternating p.d. accelerates it across.

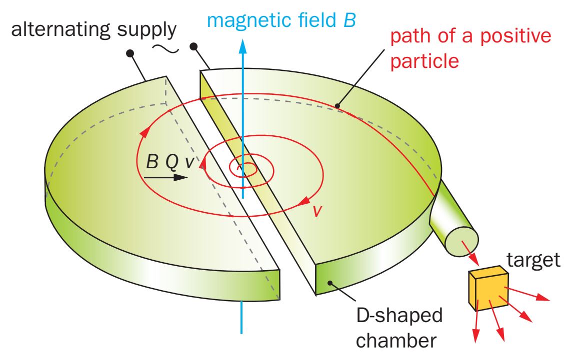
The force on a moving charged particle in a magnetic field is given by $\boldsymbol{F = B\,Q\,v}$ (see page 264). Since this provides the centripetal force ($\boldsymbol{F = m\,v^2/r}$, see page 80), we can write:

$$\frac{m\,v^2}{r} = BQv \qquad \therefore \quad v = \frac{BQr}{m}$$

This shows that the velocity is proportional to the radius, so as the particles get faster they spiral outwards. The time spent in each dee stays the same (see the coloured box):

So the alternating p.d. must reverse every $\frac{\pi m}{BQ}$ seconds.

Cyclotrons are used to accelerate heavy particles such as protons and α-particles. These can reach energies of about 25 MeV.




How long does a particle take to travel along its semicircular path within each dee?

$$\text{time} = \frac{\text{distance}}{\text{speed}} = \frac{\pi r}{BQr/m} = \frac{\pi m}{BQ}$$

This is independent of the speed and radius. See also page 265.

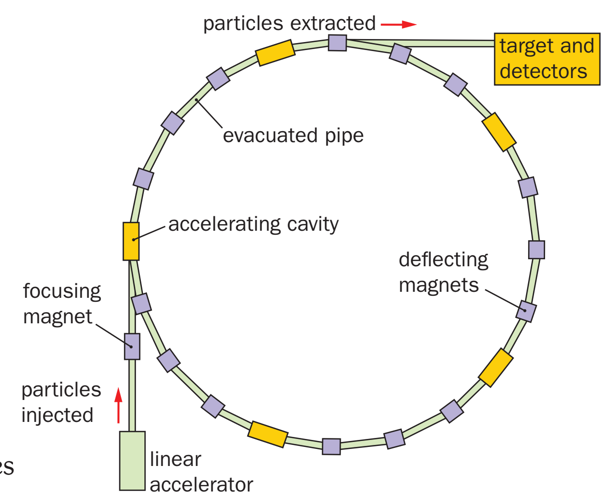
**Synchrotron**

In modern accelerators, particles travel at speeds close to the speed of light. At these very high speeds, Einstein's theory of **special relativity** (see Chapter 28) is needed to explain the way in which particles move. As particles approach the speed of light, a constant force does not produce a constant acceleration – you cannot use $E_k = \frac{1}{2}m\,v^2$ in special relativity!

Synchrotrons contain electromagnets which keep the particles moving in a circle. Regions of electric field at various points around the loop give the particles extra energy, in 'pushes' synchronised with the arrival of pulses of particles.

As the particles gain energy, the magnetic field is increased to keep them moving in a circle of constant radius.

Synchrotrons can accelerate particles such as protons to energies of more than 1000 GeV.



*A synchrotron.*

# 27 Particle Physics

What is everything made of? What holds everything together? Particle physicists are continuing to search for answers to these questions. This chapter introduces you to some of the key ideas.

In this chapter you will learn:
- what the building blocks of all matter are,
- what antimatter is and how it is created,
- about the fundamental forces that hold everything in the Universe together.

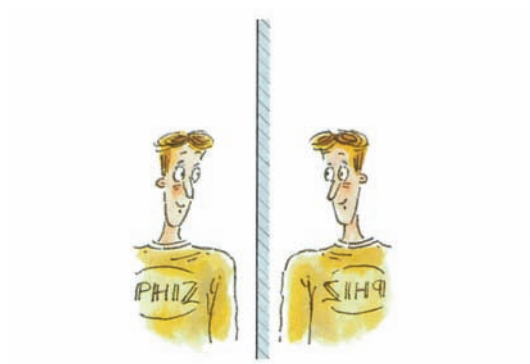
*Paul Dirac predicted the existence of antimatter in 1928.*

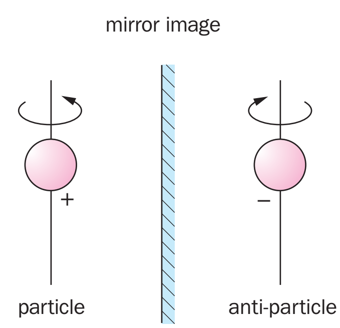
## Matter and antimatter

Antimatter is not just science fiction! Every particle has an equivalent antiparticle – for example, antiprotons and antineutrons. These are real particles.

Antimatter is a bit like a mirror image. A particle and its antiparticle have the same mass. They carry equal but opposite charge and they spin in opposite directions.

Some antiparticles have special names and symbols, but most are represented by a bar over the particle symbol. For example, $\overline{p}$ ('p–bar') represents an antiproton.




The existence of antimatter was predicted mathematically by British physicist Paul Dirac in 1928. Dirac's equation links the complex theories of special relativity and quantum mechanics. The equation describes both negative electrons and an equivalent ***positive*** particle. These **anti-electrons** or **positrons** ($e^+$ or $\beta^+$) were discovered experimentally by Carl Anderson in 1932.

Antiprotons and antineutrons were first observed in accelerator experiments in the mid-1950s. Since then antiparticles have been observed or detected for all known particles.
Many antiparticles occur naturally. They are created by high-energy collisions of cosmic rays with the molecules in our atmosphere. Positrons are also created in $\beta^+$-decay (page 366). This reaction is routinely used in hospitals for medical imaging by positron emission tomography (PET) (see page 432).

Can antiparticles join together to make anti-atoms and real antimatter? In theory, yes. In 1995, scientists at the European Laboratory for Particle Physics (CERN) created their first atoms of antihydrogen by joining positrons with antiprotons.
Only 9 atoms were made in total. They lasted just $10^{-10}$ s!

| | | | | |
|---|---|---|---|---|
| antiproton | + | positron | ➠ | antihydrogen |
| $\overline{p}$ | + | $e^+$ | ➠ | $\overline{H}$ |

By 2011, several hundred antihydrogen atoms could be made and stored, but only for around 17 minutes.
At current production rates it would take us 100 billion years to produce just 1 g of antihydrogen!

## Annihilation

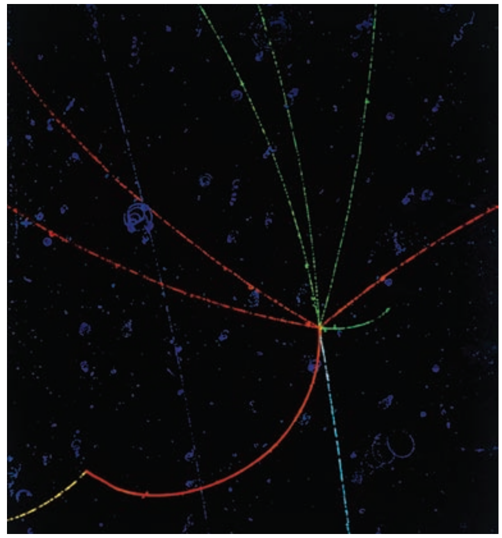
Why does antimatter not last long? As soon as an antiparticle meets its particle, the two destroy each other. Their mass is converted to energy. This is called **annihilation**.

For example, when an electron and a positron collide, they annihilate, producing two γ-ray photons of energy:

$$ {}^{0}_{-1}e^{-} + {}^{0}_{+1}e^{+} \rightarrow 2\ {}^{0}_{0}\gamma $$

Why are two photons produced? One photon could conserve charge and mass/energy. But ***momentum*** must also be conserved, and for that to happen, two photons are needed.
If an electron and positron with the same speed collide head-on, the total momentum before the collision is zero.
For zero momentum after the collision, we must have two identical photons moving in opposite directions.

When sufficient energy is available, annihilation can produce short-lived particles. The energy is converted back into ***matter***. This is how new particles are created in accelerator experiments.



*An antiproton (blue) collides with a proton in the bubble chamber liquid. The annihilation creates 4 positive (red) and 4 negative (green) particles.*

*Example 1*
An electron and positron with negligible kinetic energy annihilate and produce two identical γ-ray photons.
Calculate a) the energy released and b) the frequency of the γ-photons.
Rest mass of an electron $= 9.11 \times 10^{-31}$ kg   $h = 6.63 \times 10^{-34}$ J s   $c = 3.00 \times 10^{8}$ m s$^{-1}$

(a) Using Einstein's equation (see page 375),
$\boldsymbol{E = mc^2} = (2 \times 9.11 \times 10^{-31}\text{ kg}) \times (3.00 \times 10^{8}\text{ m s}^{-1})^2 = \underline{1.64 \times 10^{-13}\text{ J}}$

(b) Using Planck's equation $\boldsymbol{E = hf}$ (see page 328),
Energy of each photon $= \frac{1}{2} \times 1.64 \times 10^{-13}$ J $\therefore\ f = \dfrac{E}{h} = \dfrac{\frac{1}{2} \times 1.64 \times 10^{-13}\text{ J}}{6.63 \times 10^{-34}\text{ J s}} = \underline{1.24 \times 10^{20}\text{ Hz}}$

## Pair production

Pair production is the opposite of annihilation. High-energy photons can vanish, creating particle–antiparticle pairs in their place.
For example, a γ-ray can produce an electron–positron pair:

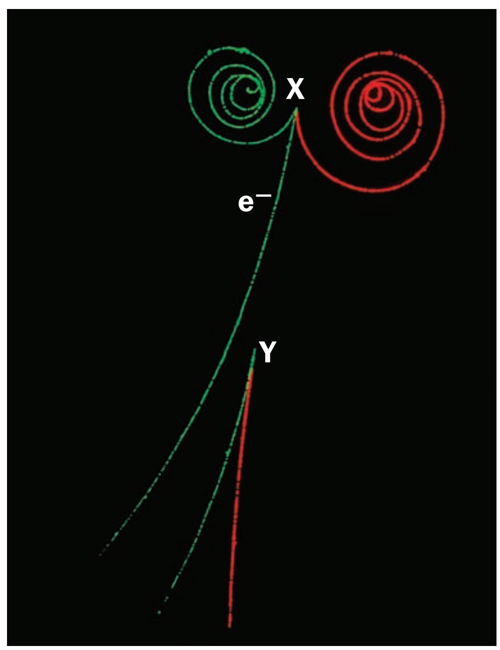
$$ {}^{0}_{0}\gamma \rightarrow {}^{0}_{-1}e^{-} + {}^{0}_{+1}e^{+} $$

A third particle such as an atomic nucleus or electron is often involved indirectly. This recoils, carrying away some of the photon energy.

The photograph shows the creation of electron–positron pairs at X and Y in a bubble chamber (see page 359). The tracks are curved due to a magnetic field. They are shown in green (electrons) and red (positrons). Notice that the γ-ray photons leave no tracks as they are uncharged.

In event X, a third particle is involved. (This is an electron ejected from the bubble chamber liquid during the interaction.)

Why are the tracks at X more curved than at Y?
In event X the ejected electron carries off some of the energy.
This leaves less energy for the electron–positron pair.
The lower the energy (and speed) of the particles produced, the more they are deflected in the magnetic field. This is why their paths curve more.



# 29 Astrophysics

Astronomers have made huge strides in observing the Universe. Today we use all ranges of the electromagnetic spectrum to give us insights into the processes in distant stars and galaxies.

In this chapter you will learn:

- how reflecting and refracting telescopes are used,
- how stars are classified, and how they change,
- how Doppler shift and cosmological red-shift are used.

## Observing the sky

### Naked-eye astronomy

Early astronomers observed the sky with the naked eye. They saw that the fixed stars appeared to rotate around the Earth, taking a little less than a day to do this. They also saw things which did not move with the stars: the Sun, the Moon and the planets Mercury, Venus, Mars, Jupiter and Saturn.
They saw other mysteries: comets which appeared from nowhere, and cloudy blurs called nebulas which moved with the stars.

*Halley's comet was seen just before the Norman Invasion in 1066.*

### The Solar System

The use of telescopes gave us a much better understanding of the Solar System. We now know that the Sun is a star, the Moon is a planetary satellite and the Earth is one of the family of planets, dwarf planets and asteroids orbiting the Sun.
The orbits are all in the same direction because they all condensed from the same rotating cloud of interstellar dust and gas.

Comets are icy, dusty masses from outer parts of the Solar System. If disturbed by the gravity of a nearby star, they may fall inwards towards the Sun and flash past in long elliptical orbits with their tails of evaporated ice streaming away from the Sun.

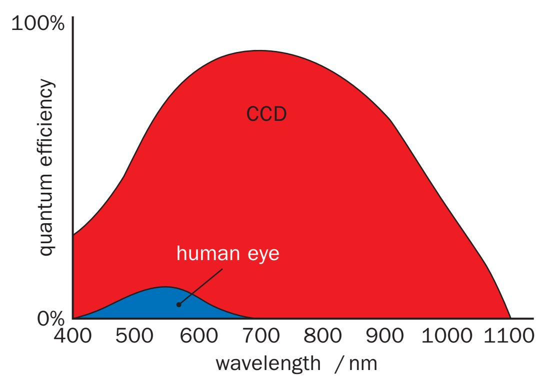
Nebulas were a mystery until well into the 20th century, when Edwin Hubble showed that many are distant galaxies like our Milky Way. Other nebulas are clouds of gas and dust.

### The eye and CCDs

In telescopes the image may be observed directly with the eye. But modern telescopes use the detectors found in digital cameras: CCDs.

A CCD (charge-coupled device) is a silicon chip divided into many tiny, sensitive areas (pixels). Photons hitting the chip liberate electrons and the charge on each pixel creates the image.

Look at the graph of quantum efficiency:



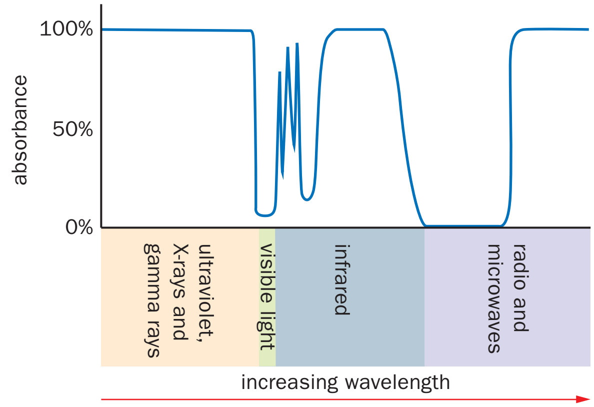

It shows the percentage of incoming photons that can be detected by a CCD and by the eye. The eye is very good, but a CCD is more sensitive and it can detect a much wider range of wavelengths. CCDs are now made for each part of the electromagnetic spectrum.

### The atmosphere and the electromagnetic spectrum

Look at the diagram:

It shows the ***absorbance*** of different parts of the electromagnetic spectrum by the Earth's atmosphere.

Can you see which parts get through to the Earth's surface? The diagram shows that visible light, microwaves and some radio waves are transmitted by the atmosphere, together with some infrared and very small amounts of ultraviolet. Telescopes on Earth observe these regions of the electromagnetic spectrum.




*Regions of the electromagnetic spectrum*

### Telescopes and observatories

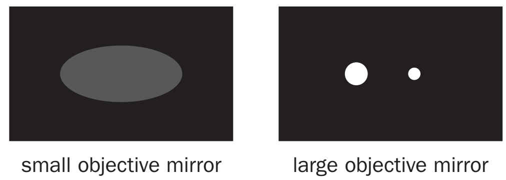
As you saw on page 150, astronomical telescopes are usually reflectors, and the best reflectors have large objective mirrors. There are ***two*** reasons why large mirrors are used:

**1. Brighter images**

A larger objective mirror has a larger area, so it will collect more light and the images will be less faint.

**2. Better resolution**

When you look through a telescope, the objective mirror or lens is the hole you are looking through. As you saw on page 168, light passing through a bigger hole spreads out much less.




*View of the same region of the sky with two telescopes at the same angular magnification.*

*Example 1*

The 10 m diameter Keck reflecting telescope observes infrared radiation of wavelength 2.4 μm. What is the smallest angle $\theta$ that the telescope can resolve at this wavelength?

Rayleigh's criterion (on page 170) states that $\sin\theta \geq \frac{\lambda}{b}$, where $b$ = diameter of the objective mirror.

$\lambda = 2.4\ \mu m = 2.4 \times 10^{-6}$ m and $b$ = 10 m

$$\sin\theta \geq \frac{2.4 \times 10^{-6}\ \text{m}}{10\ \text{m}} = 2.4 \times 10^{-7} \qquad \therefore\ \theta \geq 0.000\,014° = \underline{0.050\ \text{seconds of arc}}\ \ (2\ \text{s.f.})$$

(This is the angle subtended at your eye by a £1 coin placed about 100 km away!)

***Radio telescopes*** are also reflectors, but the wavelengths that they detect are nearly half a million times bigger. This means that they need to be huge to be able to resolve even as well as the naked eye. A bigger reflector also increases the collecting power of the radio telescope, allowing astronomers to study very faint radio sources.

### Where should observatories be sited?

Modern optical observatories on Earth are placed where the sky is clear and where there is little air pollution. Most are on high mountains, such as the Chilean Andes or Mauna Kea in Hawaii.

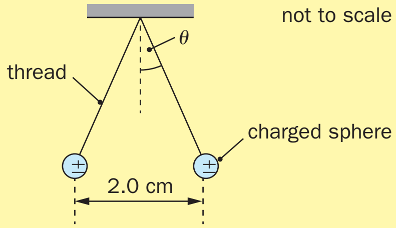
Putting observatories into Earth orbit is very expensive, but it avoids problems caused by the atmosphere. Besides detecting visible and infrared light without any atmospheric distortion, these orbiting telescopes detect other regions of the electromagnetic spectrum.

Orbiting telescopes which can 'see' ultraviolet, X-rays and gamma rays have led to much of our current knowledge of the Universe. These telescopes use specially designed CCD detectors which respond to these high-energy electromagnetic photons.

*The Compton gamma-ray telescope.*

**33.** a) Describe the similarities and the differences between the gravitational field of a point mass and the electric field of a point charge. [3]

b) The diagram shows two identical negatively charged conducting spheres.

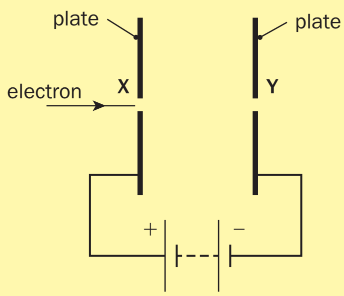



The spheres are tiny and each is suspended from a nylon thread. Each sphere has mass $6.0 \times 10^{-5}$ kg and charge $-4.0 \times 10^{-9}$C. The separation of the centres of the spheres is 2.0 cm.

i) Explain why the spheres are separated as shown. [2]

ii) Calculate the angle $\theta$ made by each thread with the vertical. [4]

c) This diagram shows two parallel vertical metal plates connected to a battery.




The plates are placed in a vacuum and have a separation of 1.2 cm. The uniform electric field strength between the plates is $1500\,\mathrm{V\,m^{-1}}$. An electron travels through holes X and Y in the plates. The electron has a horizontal velocity of $5.0 \times 10^6\,\mathrm{m\,s^{-1}}$ when it enters hole X.

i) Draw 5 lines on a copy of the diagram to show the electric field between the plates. [2]

ii) Calculate the final speed of the electron as it leaves hole Y. [3] (OCR)

**34.** a) i) Draw a labelled diagram of the apparatus you could use to find the relationship between the resistance and length of a metal wire. [3]

ii) Sketch a graph to show the relationship you would expect to find. [1]

iii) Describe how you would use your graph to find the resistivity of the metal. You should describe the additional measurement you need to make and how you would use it. [3]

b) A metal wire has resistance $R$ and is a cylinder of length $l$ and uniform cross-sectional area $A$. The wire is now stretched to 3 times its original length while keeping the volume constant. Show that the resistance of the wire increases to $9R$. [3] (W)

**35.** a) Define the e.m.f. of a cell. [2]

b) A student carries out an experiment to determine the e.m.f. and internal resistance of a cell. The p.d. across the cell is measured when it is supplying various currents. The following readings are obtained. Plot these results on a grid (p.d. on the $y$-axis and current on the $x$-axis) and draw a line through your points. [3]

| Current /A | 0.20 | 0.42 | 0.66 | 0.96 | 1.20 |
|---|---|---|---|---|---|
| p.d. /V | 1.31 | 1.13 | 0.93 | 0.68 | 0.48 |

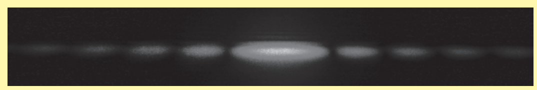
c) Use your graph to determine:

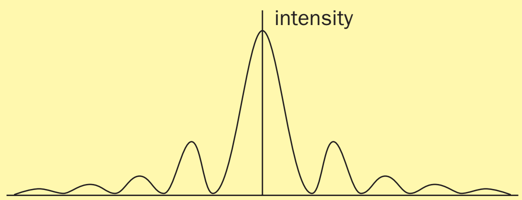
i) the e.m.f. of the cell, [1]

ii) the internal resistance of the cell. [2]

d) The cell is then connected to a torch bulb of resistance $6.0\,\Omega$ for 20 minutes. Calculate the charge that flows through the bulb in this time. Assume the e.m.f. remains constant. [4] (W)

**36.** A student obtains the following diffraction pattern on a wall by shining a red laser beam through a single narrow slit. The corresponding graph of intensity against position is shown below.

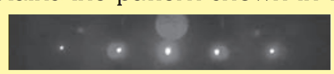




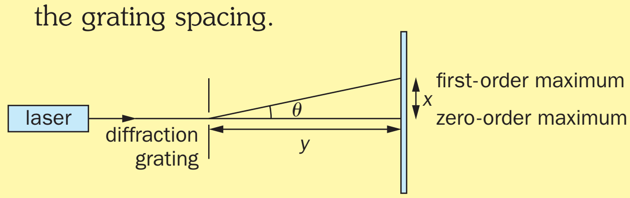

a) Explain how the diffraction pattern is created. [3]

b) Explain how the pattern would differ if green laser light were used instead of red laser light. [3]

c) A student replaces the single slit with a diffraction grating and obtains the pattern shown in the photograph.

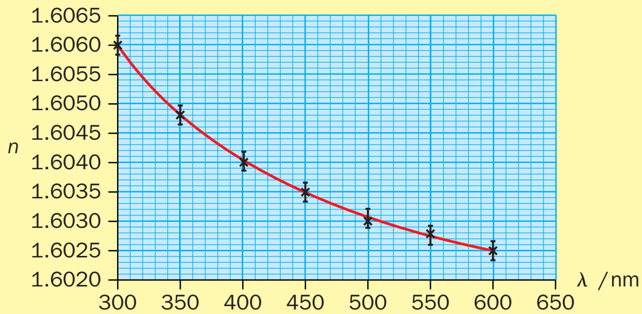


The photograph shows the zero-order maximum and the first and second orders on either side. The student takes measurements to determine the grating spacing.




The student measures $x$, the distance between the zero-order maximum and the first-order maximum, and $y$, the distance between the slit and the screen. $x$ = 23 cm $y$ = 1.5 m
Number of lines per millimetre = 300
Calculate the wavelength of light from the laser. [3] (Edex)

**37.** The graph shows how the refractive index $n$ of a type of glass varies with the wavelength of light $\lambda$ passing through the glass. The data for plotting the graph were determined by experiment.




a) A student says that it resembles that of the decay of radioactive atomic nuclei with time and that it shows half-life behaviour. Comment on whether the student is correct. [1]

b) The dispersion $D$ of glass is defined as the rate of change of its refractive index with wavelength. At a particular wavelength $D = \Delta n / \Delta\lambda$. Determine $D$ at a wavelength 400 nm. State an appropriate unit for your answer. [3]

c) It is suggested that the relationship between $n$ and $\lambda$ is of the form $n = a + b/\lambda^2$ where $a$ and $b$ are constants.

| λ /nm | 300 | 350 | 400 | 450 | 500 | 550 | 600 |
|---|---|---|---|---|---|---|---|
| $n$ | 1.6060 | 1.6048 | 1.6040 | 1.6035 | 1.6030 | 1.6028 | 1.6025 |

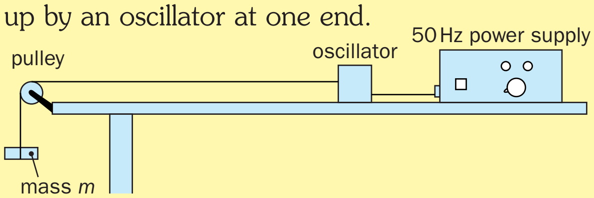
Plot a graph of $n$ against $1/\lambda^2$. [3]

d) Use your graph to determine $a$. [1]

e) State the significance of $a$. [1]

f) Another suggestion for the relationship between $n$ and $\lambda$ is that $n = c\lambda^d$ where $c$ and $d$ are constants. Explain how $d$ can be determined graphically. Do not attempt to carry out this analysis. [3] (AQA)

**38.** A wire is held under tension. A standing wave is set up by an oscillator at one end.



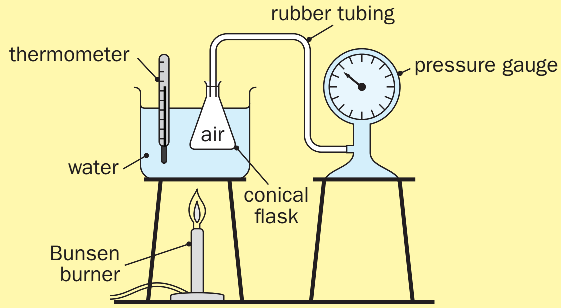

a) The wire is oscillated at a constant frequency. Measurements are taken to determine the wavelength for different values of the mass $m$. The following data are obtained. Draw a straight-line graph to test the relationship $\lambda^2 = km$. [4]

| $m$ /kg | 0.100 | 0.150 | 0.200 | 0.250 | 0.300 | 0.350 |
|---|---|---|---|---|---|---|
| λ /m | 0.641 | 0.776 | 0.905 | 1.012 | 1.103 | 1.196 |

b) Use your graph to find a value for $k$. [2]

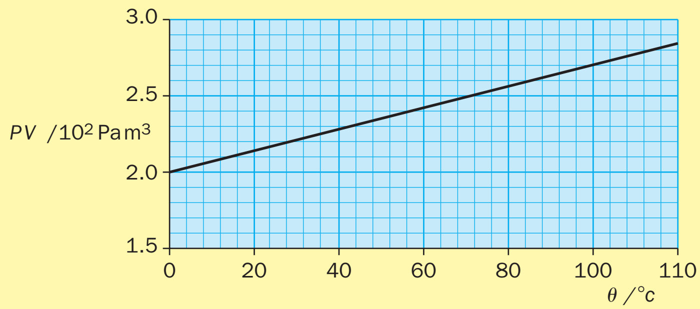
c) It is suggested that $k = g/f^2\mu$ where $g = 9.81\,\text{N kg}^{-1}$, frequency $f = 50.0\,\text{Hz}$ and $\mu$ = the mass per unit length of the wire. Use your value for the gradient to calculate a value for $\mu$. [3] (Edex)

**39.** The apparatus shown in the diagram is used to investigate the variation of the product $PV$ with temperature in the range 20 °C to 100 °C. The pressure exerted by the air is $P$ and the volume of air inside the flask is $V$.




a) Describe how this apparatus can be set up and used to ensure accurate results. [4]

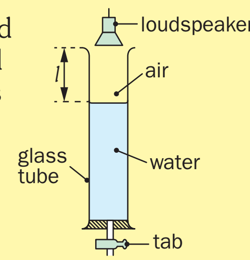
b) An investigation similar to that shown gives measurements of the pressure $P$, volume $V$ and temperature $\theta$ in degrees Celsius of a fixed mass of gas. The results are used to plot the graph of $PV$ against $\theta$.




i) Explain, in terms of motion of particles, why the graph does not go through the origin. [2]

ii) The mass of a gas particle is $4.7 \times 10^{-26}$ kg. Use the graph to calculate
1 the mass of the gas,
2 the internal energy of the gas at a temperature of 100 °C. [4] (OCR)

**40.** A small loudspeaker emitting sound of constant frequency is positioned a short distance above a long glass tube containing water. When water is allowed to run slowly out of the tube, the intensity of the sound heard increases whenever the length $l$ takes certain values.




a) Explain these observations by reference to the physical principles involved. [4]

b) With the loudspeaker emitting sound of frequency 480 Hz, the effect described in (a) is noticed first when $l$ = 168 mm. It next occurs when $l$ = 523 mm. Use both values of $l$ to calculate

i) the wavelength of the sound waves in the air column,

ii) the speed of these sound waves. [4] (AQA)

# Study Skills

**Making progress in Physics**

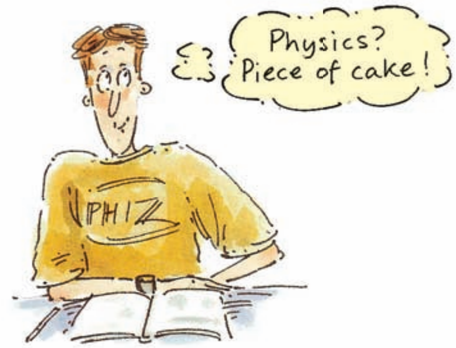
Are you finding the Advanced Physics course quite hard?
Do you sometimes have difficulty with homework?
Or do you just feel that you want to do better?

This section has some ideas that should help you.
Of course they will require effort from you, but as they begin to help you, you will start to gain confidence and satisfaction.


**Understanding work**

It is most important that you try to understand the work which is being covered in class ***at that time***, or later ***the same day***.
This is because:

- Much of the new work in Advanced Physics builds on the basic ideas that have been learned earlier in the course.
  If you don't understand the basic ideas really well then you will find it much harder to understand the new work.
- It is very difficult, when you are revising work, to remember facts which you don't really understand.
- You can prepare a list of questions to ask your teacher in the next lesson to help improve your understanding.




**In class**

- Try to concentrate as much as you can, and try to join in class discussions and group work. Research suggests that talking about your ideas helps you to understand Physics.
- Be brave enough to ask your teacher if you are not sure of anything! Either in class, or afterwards if you prefer.
  Your teacher will be able to explain an idea in several different ways in order to help you understand it.

**Other ways to make progress**

- It is really helpful if you can spend just 10 minutes at the end of the day reading notes from the lesson to remind yourself of work covered. It helps your brain to consolidate ideas.
  The more often that you read and think about new ideas, the more likely you are to remember and understand them.
- Talk to your friends about the key knowledge learned during the lesson. You can try formal questions or just discuss the ideas until you can explain them clearly to each other.
- Finding out about everyday applications of the Physics which you are learning will help you to understand it.
  It is a good idea to ask your teacher about applications as they explain new ideas to you. Reading books, watching TV or internet videos about Physics is also helpful.

## Homework

Some people say that students do not learn Physics in lessons, but away from lessons, when they are doing homework.

Although you are introduced to new ideas in class, you are unlikely to learn and understand them fully without thinking about the ideas and ***using*** them.  This is why work at home is so important.

### Organising yourself for homework

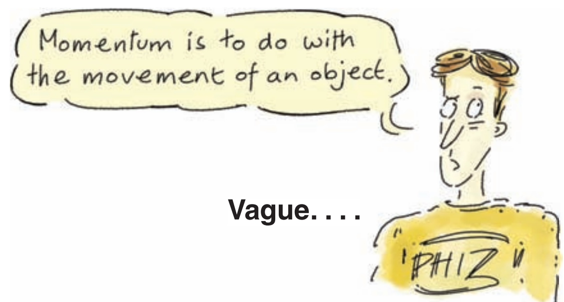
Sometimes you may find it difficult to organise your time so that you complete your homework.  There are a lot of distractions! Here are some ideas to help:


- ***Make a routine!*** Plan your time so that you always do your Physics at the same times each week – in the same free periods or on the same evenings when you have no other activities.
- ***Do homework early!*** This is so that you can get help with difficulties, from either friends, family or your teacher.
- ***Take breaks!*** People concentrate better in short bursts, so after about 30 minutes of work it is best to have a short break.
- ***Deal with distractions!***
  There are lots of other people and other activities which can draw you away from Physics homework.  You need to be strong-willed and avoid these distractions while you work.
  Ensure everybody knows you are busy and not to disturb you.
  Tell friends when you will and when you won't be available.
  Turn off your phone and keep it off while you work.
  Give yourself deadlines and reward yourself when you meet them.

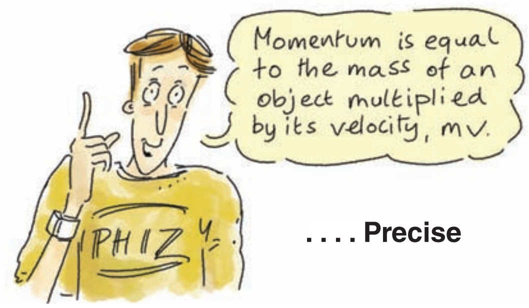

### Making progress from your homework

You will put many hours of effort into your homework during your Physics course.  Here are some ideas on how to get the most out of the effort that you make.

1. Look up anything you are not sure about, especially definitions. Doing this will help your understanding of Physics, and may also help you to revise work you did earlier in the course.
2. Read your answer after you have written it.  Is it clear? Does it answer the ***exact*** question asked? Will the person reading it understand what you have written?
3. Download a Mark Scheme and an Examiner's Report from the exam board to check examination questions. These let you judge your own answers and show you where you will score marks and where you might have missed some.
4. Aim to get a lot of detail into your explanations with a small number of words.  This is quite a skill – it takes time to improve.
5. Use precise Physics ideas in your answers rather than everyday language.  So, for example, instead of using the 'size' of an object, be clearer – is it mass, volume, diameter or length?
6. Read your teacher's feedback after your work has been marked. This should give you a clear idea about how to improve, and help to make sure that you don't make the same mistakes again.




**Vague. . . .**




**. . . . Precise**

# Doing Your Practical Work

Practical work is an important aspect of AS and A-level Physics. During your course you will complete a set of practical activities designed to develop your skills and increase your understanding of measurement and analysis.
Your abilities will be assessed in two different ways:

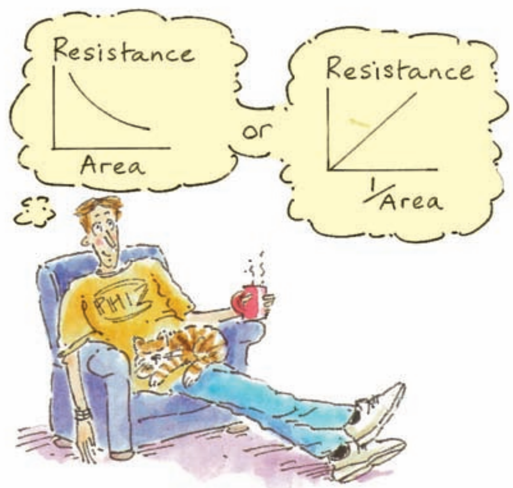
- Using ***examination questions*** which will test your understanding of the experimental process.
  These will account for 15% of your final A-level grade!
- Through ***Common Practical Assessment Criteria*** which will assess how well you carry out experiments. Your teacher will decide whether you have ***passed*** based on the evidence you collect and keep in your practical portfolio.
  This result will not count towards your final A-level grade.


**Developing your practical skills**

There are 4 different aspects you need to develop during your course: **Planning**, **Implementing**, **Analysis** and **Evaluation**. The following sections will help you to understand the skills needed to succeed in practical work and exams.

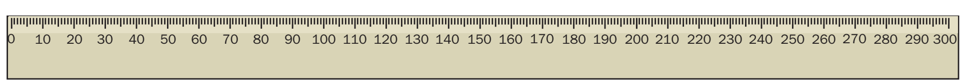
## Planning

Your Exam Board will have a set of investigations you will need to carry out during the course, and your teacher may also include some extra ones to help you develop your skills. Before carrying out each practical, you need to develop a plan. Research from textbooks or the internet can help you with the experimental design.




Your plan should describe how you intend to investigate the relationships between variables. Key parts of the plan include:

- Selecting the **independent variable** (the one you will change) and the **dependent variable** (the one you will measure).
  For example, in a resistivity experiment you may change the diameter of the wire while measuring the effect on the resistance.
- Identifying **control variables**. These are any other variables which could affect the outcome of the experiment.
  In the resistivity experiment, you would need to control the length of the wire and its temperature.
- The apparatus you will use, including the ***detailed specification*** of any measuring instruments.




*A ruler with a range of 0–300 mm and a resolution of 1 mm.*

- A thorough ***practical method***, explaining all of the steps you will take during your experiment. Numbered steps are best.
- A description explaining how you will process any data.
- You may also need a ***risk assessment*** to ensure hazards are identified and managed.

## Implementing

While carrying out your experiment you will need to:

- make sure you work safely,
- set up and use the apparatus correctly and skilfully,
- check for sources of error in your technique and take action to reduce them (see below),
- use the measuring instruments carefully, aiming for accurate and precise results,
- record all measurements in a column to the same number of decimal places, which should match the resolution of the measuring instrument used,
- repeat your readings when necessary and check any readings which don't fit with the others (***anomalous*** results),
- be flexible and adapt your plan if necessary.

should be written as 1.0 to agree with other two

no units shown

should be 1.00

| Diameter (mm) | Cross-sectional area | Resistance (Ω) |
|---|---|---|
| 1 | 1 | 1.2 |
| 0.5 | 0.25 | 4.9 |
| 0.3 | 0.09 | 13.0 |

three readings isn't enough

readings should be repeated

the current and voltage readings should have been noted too

### Showing the uncertainty in your measurements

Every measuring instrument has limitations, and there will always be an uncertainty in any readings taken using it.
For example, a reading of 1.0 V means that the voltage is between 0.95 V and 1.05 V but we cannot be certain of the exact value.
You need to take this uncertainty into account when recording measurements by using an appropriate number of significant figures.

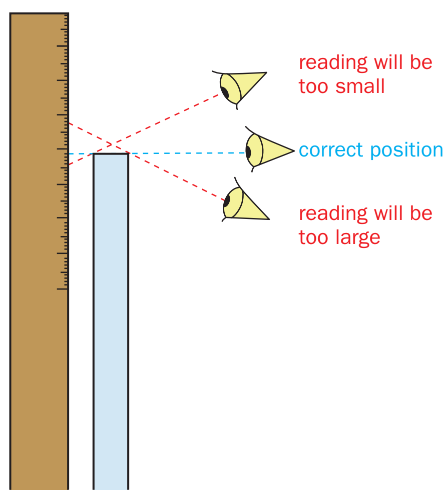
If you measured some wire as being 110 cm long to the nearest centimetre, how should this be recorded in metres?
You should write it as 1.10 m.
If you write it as 1.1 m, then this suggests you could only measure to the nearest 10 cm. If you record it as 1.100 m, it implies that you measured to the nearest millimetre. Both are misleading.

### Systematic errors

These are errors in the experimental method or equipment, when readings are consistently too big or consistently too small.

For example, if your newton-meter reads 0.2 N with no weight on it, then your measurements of force will always be 0.2 N too large.
Remember to check for these **zero errors** before using any equipment.
In addition, some instruments, such as balances, can be ***calibrated*** by checking them against known standards.

By reducing systematic errors the data becomes ***more accurate***, so it reflects the true value more closely.



*Parallax error*

### Random errors

These are errors which mean that the readings are sometimes too big and sometimes too small. For example, when timing a pendulum, there is an error in your timing because of your reactions. Some of the measurements will be below the true value and some will be above it.

The effect of random errors can be reduced by taking repeat readings; the mean value will be ***more precise*** than individual measurements.

### Measurement error

Systematic errors and random errors combine to cause a measured value to be different from the true value. Always check your equipment and refine your technique to keep measurement uncertainty to a minimum.

# Check Your Maths

Do you find Maths difficult?
Do you find it hard to remember?
If so, these pages can help you with some of the Maths that you need in your Physics lessons.


### Symbols used in Maths

Here are some of the symbols you may meet in Physics:

| | | | |
|---|---|---|---|
| $\propto$ | is proportional to | $=$ | is equal to |
| $\sim$ | about the same size as | $\approx$ | is approximately equal to |
| $>$ | is greater than | $<$ | is less than |
| $>>$ | is much greater than | $<<$ | is much less than |
| $\geqslant$ | greater or equal to | $\pm$ | plus or minus |
| $\Delta x$ | a change in $x$ | $\delta x$ | a small change in $x$ |
| $x^{\frac{1}{2}}$ | the square root of $x$ | $\sqrt{x}$ | the square root of $x$ |
| $\bar{x}$ | mean of the values of $x$ | $\Sigma x$ | sum of all the values of $x$ |
| $\therefore$ | therefore | $\Rightarrow$ | implies that |

### Significant figures

There is more detailed explanation of significant figures on page 9, but here are some reminders:

- To find the number of significant figures (**s.f.**), count the number of digits starting from the ***first non-zero*** number on the left. Include zeros, once you have started counting. For example:

  2.7 (2 s.f.) 271 (3 s.f.) 271.0 (4 s.f.)
  1.200 (4 s.f.) 0.0120 (3 s.f.) 0.00012 (2 s.f.)

- In a calculation, give the answer to the ***lowest*** number of s.f. of ***any*** of the numbers used to calculate the answer.
  Eg. $56.21 \times 3.1 = 174.251$ but the answer should be written as just: 170 (2 s.f.) because 3.1 is only 2 s.f.
  A better way of writing this answer would be $1.7 \times 10^2$ (2 s.f.).


### Vectors

For work on vectors please see pages 10–16.

### Prefixes

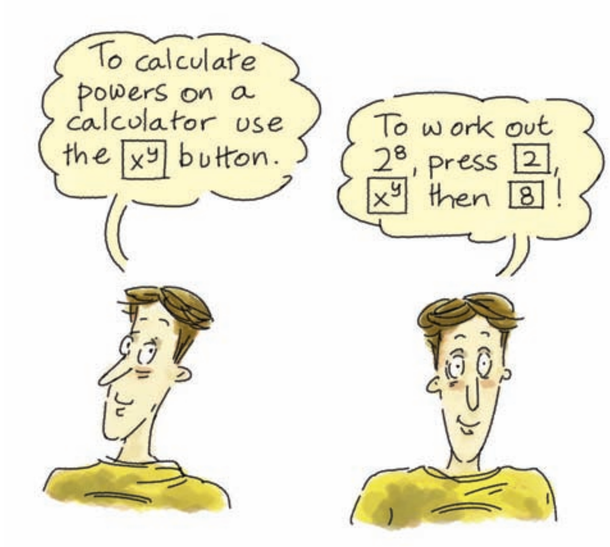
For prefixes (like milli, kilo, mega, etc.) see page 8.

## Powers

The power of a number is the small figure perched on the shoulder of the number. This is the 'index' (plural: 'indices'). It tells us how many times the number is multiplied by ***itself***.

For example: $2^3 = 2 \times 2 \times 2$ and $5^4 = 5 \times 5 \times 5 \times 5$

Any number to the power 1 is itself, so $5^1 = 5$.
Any number to the power 0 is equal to 1, so $2^0 = 1$ and $7^0 = 1$.




**Rules for powers**

| | |
|---|---|
| $y^a \times y^b = y^{a+b}$ | eg. $10^2 \times 10^3 = 10^{2+3} = 10^5$ |
| $y^a \,/\, y^b = y^{a-b}$ | eg. $10^3 \,/\, 10^2 = 10^{3-2} = 10^1$ |
| $(y^a)^b = y^{a \times b}$ | eg. $(2^4)^3 = 2^4 \times 2^4 \times 2^4 = 2^{12}$ |

**Negative Powers**
If a number has a negative power, like $10^{-1}$, what does this mean?
This is equal to $^1/$(10 to the positive power).

For example: $10^{-1} = {}^1/_{10^1} = {}^1/_{10} = 0.1$

$10^{-2} = {}^1/_{10^2} = {}^1/_{100} = 0.01$


**Standard Form**

Many quantities used in Physics are very small or very large.
Eg. mass of the Earth is 6 000 000 000 000 000 000 000 000 kg.
The diameter of an atom is about 0.000 000 000 1 metres.

Can you see the problem with using such large numbers?
It is very easy to make mistakes by missing one of the noughts off!

If we use ***Standard Form*** it helps us to avoid this.
This is when a number is written as a number between 1 and 10 and then ***multiplied by a power of 10***.

For example: $1280 = 1.28 \times 1000 = 1.28 \times 10^3$

$0.0128 = 1.28 \times 0.01 = 1.28 \times 10^{-2}$

So the mass of the Earth = $6 \times 10^{24}$ kg
The diameter of an atom = $1 \times 10^{-10}$ m

*The index tells you how many decimal places to move. Some examples:*

$2.1 \times 10^6 = 2\,100\,000$

$0.21 \times 10^7 = 2\,100\,000$

$4 \times 10^{-3} = 0.004$

$4.1 \times 10^{-4} = 0.00041$

**Using Standard Form on a calculator**

It is important to put Standard Form into your calculator correctly!

The **EXP** button on your calculator means "×10 to the power of".

So what would you press to put $1.28 \times 10^3$ into your calculator?

You would press [1] [·] [2] [8] then [EXP] then [3]

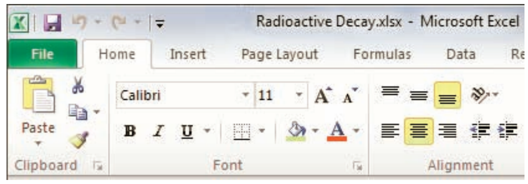
Notice that there is no need to put in the ×10 bit, because this is taken care of by the EXP button.

If you saw [2 03] on your calculator, would this mean $2^3$?

No, it would mean $2 \times 10^3 = 2000$.
Remember that the EXP button means: "×10 to the power of".


*Find the EXP button on your calculator.*

## Using Spreadsheets




Spreadsheets are really useful tools for understanding some areas of Physics. The on-line resources for this book have several example spreadsheets, showing just how useful they can be in:

- modelling behaviour,
- analysis of data,
- simulations.

The on-line resources are at: www.oxfordsecondary.co.uk/advancedforyou

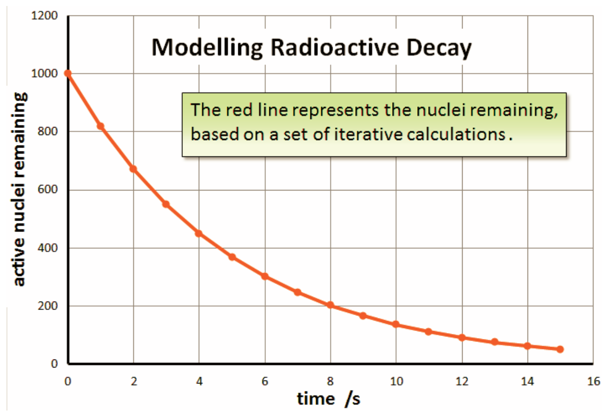

## Modelling behaviour

In some situations you need to model the behaviour of a system involving **rates of change**, where the rate of change is proportional to the 'amount' of something remaining.
This is expressed in the general equation:

$$\frac{\Delta x}{\Delta t} = -k\,x$$

where $x$ is the amount remaining, and
$k$ is the fraction of $x$ which will decay per second.

The two most important examples of this behaviour are radioactive decay (see page 368) and the decay of charge on a capacitor discharging through a resistor (see page 307).




For **radioactive decay** we have the relationship:

$$A = \frac{\Delta N}{\Delta t} = -\lambda\,N$$

where $A$ is the activity (the rate of decay),
$N$ is the number of active nuclei remaining, and
$\lambda$ is the decay constant (the fraction which decays each second).

For a **capacitor discharge** we have the relationship:

$$\frac{\Delta Q}{\Delta t} = -\frac{1}{C\,R}Q$$

where $Q$ is the charge remaining on the capacitor,
$C$ is the capacitance and $R$ is the resistance.

Using the initial charge, the capacitance and resistance, we can calculate the amount of charge $\Delta Q$ that will leave the capacitor in the first second. From this we know the charge remaining after one second. The example in the box shows the principle:

We can then use this new value for charge to calculate the charge leaving in the ***next*** second and thus the charge remaining after two seconds, and so on. Repeating this calculation 15 times to find the charge remaining after 15 seconds would be very time-consuming.

The relationship can be modelled more effectively by performing a series of repetitive (or iterative) calculations using a **spreadsheet**.

The spreadsheet approach also has the advantage of allowing you to change the ***initial conditions*** of a model quickly, and letting the spreadsheet instantly perform the new series of calculations and produce a new graph.

On-line at www.oxfordsecondary.co.uk/advancedforyou
you can find spreadsheets illustrating how this is achieved for **radioactive decay** and for **capacitor discharge**.

For example, consider a capacitor discharging in a circuit with a time constant of 5.0 s.
Suppose at time $t = 0$ the charge on the capacitor is 1000 μC.

What charge flows off the capacitor in the first second? Using the formula in the main text:

$$\Delta Q = \frac{1}{C\,R} \times Q \times \Delta t$$

$$\Delta Q = \frac{1}{5.0\ \text{s}} \times 1000\ \mu\text{C} \times 1\ \text{s} = 200\ \mu\text{C}$$

So after 1 second the charge remaining on the capacitor is: 1000 μC − 200 μC = 800 μC

We can then use this value to calculate the charge leaving in the next second, and so on.

This repetition or ***iteration*** is what the spreadsheet does for you.

## Analysis of data

Spreadsheets are also very useful for the processing and analysis of large sets of data.

For example, think about an experiment to find out how the diameter of a wire affects the resistance.
You might collect 30 different measurements of current and potential difference and need to calculate resistances from them. You would then need to find mean resistance and plot a graph comparing resistance to cross-sectional area.

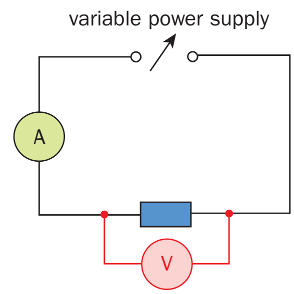
A suitably designed spreadsheet can be used to collect this data, perform the repetitive calculations and plot the required graphs.

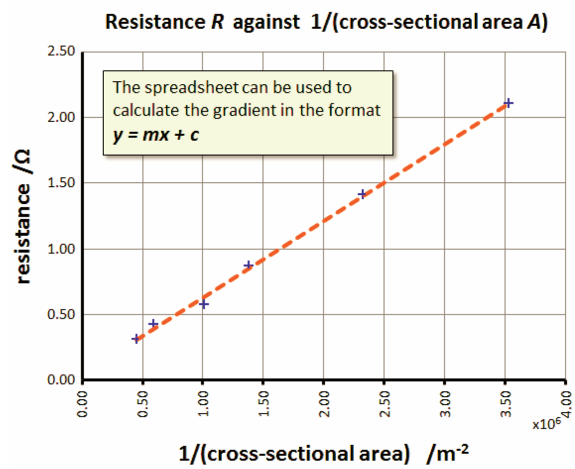
An example spreadsheet called **Resistivity Analysis** is provided on-line at: www.oxfordsecondary.co.uk/advancedforyou

In it the data is processed using a simple formula ($R = V/I$).
The spreadsheet is then used to calculate the mean resistance, cross-sectional area ($A$) and $1/A$ for wires of different diameters.

The spreadsheet plots a graph of $R$ against $A$ and shows that there is a clear relationship between them.
Then a second graph of $R$ plotted against $1/A$ shows that $R$ is inversely proportional to $A$.

The spreadsheet has also been used to determine the gradient of the line, and finally the resistivity.




## Simulations

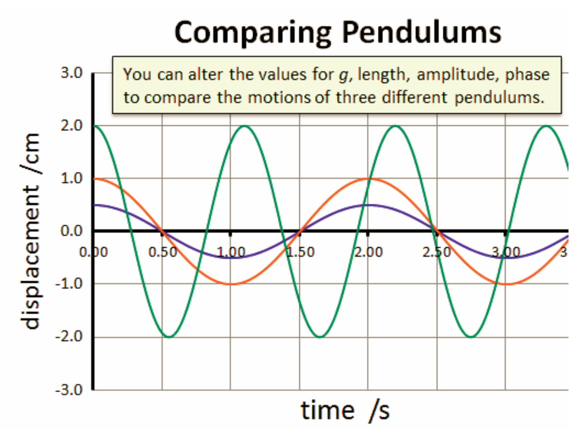
Sometimes it can be difficult to understand how changes to a system can alter its behaviour. Spreadsheets can help in this area too, by performing simple simulations based on the relevant equations.

Three examples are provided on-line, for you to look at:

- The behaviour of three pendulums is simulated in the file called **SHM Pendulums**.
  Altering the properties of these pendulums within the spreadsheet allows you to compare pendulums of different lengths or in different gravitational fields:

- Another example of a simulation spreadsheet is called **SHM Masses**.
  The behaviour of 3 mass–spring systems is modelled for easy comparison. You can alter the mass and the spring constant for each system, to investigate what happens.

- The superposition of two waves is shown in the file called **Superposition Model**.
  Here the frequency, amplitude and phase of the two source waves can be altered and the results are shown on the graph.




We suggest that you download each of these spreadsheets from:
**www.oxfordsecondary.co.uk/advancedforyou**
and 'play' with them by altering the parameters.

Look at how each spreadsheet is constructed, by reading the explanations that we have provided on each one.

Learning how to use spreadsheets effectively can take some time.
Download and use the on-line worksheet **Projectile Motion** to construct your own spreadsheet to investigate launching projectiles.

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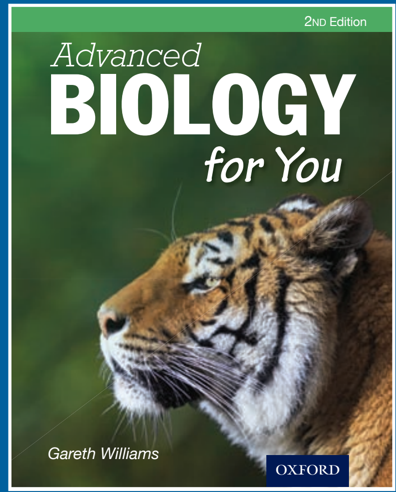


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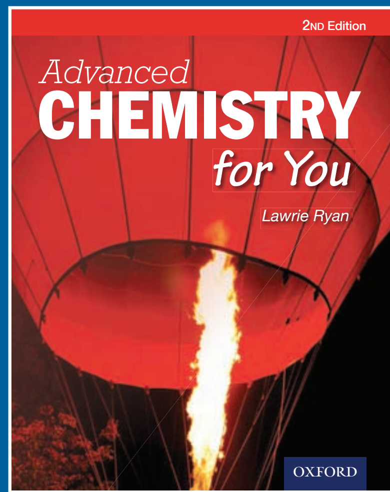


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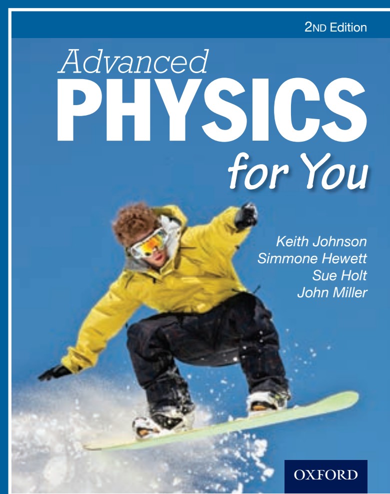


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