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 test-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
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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.
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.

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.

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.

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:

<table>
<thead>
<tr>
<th>Base quantity</th>
<th>Name</th>
<th>Symbol</th>
<th>Base unit</th>
<th>Name</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>length</td>
<td>metre</td>
<td>m</td>
<td>mass</td>
<td>kilogram</td>
<td>kg</td>
</tr>
<tr>
<td>mass</td>
<td>kilogram</td>
<td>kg</td>
<td>temperature</td>
<td>kelvin</td>
<td>K</td>
</tr>
<tr>
<td>temperature</td>
<td>kelvin</td>
<td>K</td>
<td>pressure</td>
<td>pascal</td>
<td>Pa</td>
</tr>
<tr>
<td>pressure</td>
<td>pascal</td>
<td>Pa</td>
<td>work (energy)</td>
<td>joule</td>
<td>J</td>
</tr>
<tr>
<td>work (energy)</td>
<td>joule</td>
<td>J</td>
<td>power</td>
<td>watt</td>
<td>W</td>
</tr>
<tr>
<td>power</td>
<td>watt</td>
<td>W</td>
<td>electrical charge</td>
<td>coulomb</td>
<td>C</td>
</tr>
<tr>
<td>electrical charge</td>
<td>coulomb</td>
<td>C</td>
<td>potential difference</td>
<td>volt</td>
<td>V</td>
</tr>
<tr>
<td>potential difference</td>
<td>volt</td>
<td>V</td>
<td>resistance</td>
<td>ohm</td>
<td>Ω</td>
</tr>
<tr>
<td>resistance</td>
<td>ohm</td>
<td>Ω</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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.

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

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 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{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\(^{-2}\).

Physical quantity Defined as                                                                 Unit         Special name
---                                                                                       ---           ---
density                                                                                   kg m\(^{-3}\)   
momentum                                                                                   kg m s\(^{-1}\)  
force                                                                                      kg m s\(^{-2}\)  newton (N)  
power                                                                                     kg m\(^2\) s\(^{-3}\) (N m s\(^{-1}\))  joule (J)  
work (energy)                                                                             kg m\(^2\) s\(^{-3}\) (N m)  watt (W)  
electrical charge                                                                          A s  coulomb (C)  
potential difference                                                                      kg m\(^2\) A\(^{-1}\) s\(^{-3}\) (V J C\(^{-1}\))  volt (V)  
resistance                                                                               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 = \( \frac{1}{2} \times \text{mass} \times \text{velocity}^2 \)

From the table on page 7:
Unit of kinetic energy = joule = \( \text{kg m}^2 \text{s}^{-2} \)
Unit of \( \frac{1}{2} \times \text{mass} \times \text{velocity}^2 \) = \( \text{kg} \times (\text{m s}^{-1})^2 = \text{kg m}^2 \text{s}^{-2} \) (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.

\[ P = I^2 R \]

By checking for homogeneity, we can work out which equation is correct:

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

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:

<table>
<thead>
<tr>
<th>Prefix</th>
<th>Symbol</th>
<th>Multiplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>tера</td>
<td>T</td>
<td>10(^{12})</td>
</tr>
<tr>
<td>гига</td>
<td>G</td>
<td>10(^9)</td>
</tr>
<tr>
<td>мега</td>
<td>M</td>
<td>10(^6)</td>
</tr>
<tr>
<td>кило</td>
<td>k</td>
<td>10(^3)</td>
</tr>
<tr>
<td>деки</td>
<td>d</td>
<td>10(^{-1})</td>
</tr>
<tr>
<td>центи</td>
<td>c</td>
<td>10(^{-2})</td>
</tr>
<tr>
<td>милли</td>
<td>m</td>
<td>10(^{-3})</td>
</tr>
<tr>
<td>микро</td>
<td>µ</td>
<td>10(^{-6})</td>
</tr>
<tr>
<td>нано</td>
<td>n</td>
<td>10(^{-9})</td>
</tr>
<tr>
<td>пико</td>
<td>p</td>
<td>10(^{-12})</td>
</tr>
<tr>
<td>фемто</td>
<td>f</td>
<td>10(^{-15})</td>
</tr>
</tbody>
</table>

The importance of significant figures

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

Writing 5.0 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 4.5 m and 5.5 m.

The number 5.0 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:

<table>
<thead>
<tr>
<th>3 s.f.</th>
<th>2 s.f.</th>
<th>1 s.f.</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.62</td>
<td>4.6</td>
<td>5</td>
</tr>
<tr>
<td>0.00501</td>
<td>0.0050</td>
<td>0.005</td>
</tr>
<tr>
<td>3.40 \times 10^6</td>
<td>3.4 \times 10^6</td>
<td>3 \times 10^6</td>
</tr>
<tr>
<td>169</td>
<td>1.7 \times 10^2</td>
<td>2 \times 10^2</td>
</tr>
</tbody>
</table>

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. 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 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:

<table>
<thead>
<tr>
<th>Scalars</th>
<th>Vectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>distance</td>
<td>displacement</td>
</tr>
<tr>
<td>speed</td>
<td>velocity</td>
</tr>
<tr>
<td>mass</td>
<td>weight</td>
</tr>
<tr>
<td>pressure</td>
<td>force</td>
</tr>
<tr>
<td>energy</td>
<td>momentum</td>
</tr>
<tr>
<td>temperature</td>
<td>acceleration</td>
</tr>
<tr>
<td>volume</td>
<td>electric current</td>
</tr>
<tr>
<td>density</td>
<td>torque</td>
</tr>
</tbody>
</table>

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?

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.

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 = \( F_1 + F_2 \)

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

Resultant = \( F_1 + (-F_2) = F_1 - F_2 \)

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?
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 \( \theta \):

\[ \tan \theta = \frac{Y}{X} \quad \therefore \quad \theta = \tan^{-1} \left( \frac{Y}{X} \right) \]

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:

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

= \( \sqrt{128 \times 10^{10} N^2} \)

= \( 1.1 \times 10^5 N \) (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 m s\(^{-1}\). The river has a current of velocity 4.0 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:

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

Direction of resultant: \( \tan \theta = \frac{3.0}{4.0} \quad \therefore \quad \theta = \tan^{-1} \left( \frac{3.0}{4.0} \right) = 37° \)

So the resultant velocity is 5.0 m s\(^{-1}\) at 37° 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 m s\(^{-1}\) – 6 m s\(^{-1}\)

= 4 m s\(^{-1}\)

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

\[ \text{change in velocity} = \text{final velocity} - \text{initial velocity} \]

\[ = 10 \text{ m s}^{-1} \text{ up} - 6 \text{ m s}^{-1} \text{ down} \]

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:

\[ \text{change in velocity} = +10 \text{ m s}^{-1} - (-6 \text{ m s}^{-1}) \]

\[ = +16 \text{ m s}^{-1} \]

So the change in velocity is 16 m s\(^{-1}\) in an upward direction.

Can you see that subtracting 6 m s\(^{-1}\) downwards is the same as adding 6 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 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.

\[ \text{Change in velocity} = \text{new velocity} - \text{old velocity} \]

\[ = (-4.5 \text{ m s}^{-1}) - (+4.5 \text{ m s}^{-1}) \]

\[ = -9.0 \text{ m s}^{-1} \] (2 s.f.)

So the change in velocity is 9.0 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 \( \mathbf{R} \) 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 \( \mathbf{a}, \mathbf{b}, \mathbf{c} \) 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 \( \mathbf{P} \) and \( \mathbf{Q} \).

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 \( \mathbf{V} \) in this diagram:

We can resolve this vector into two components, \( V_x \) and \( V_y \), at right angles to each other:

- \( V_x \) acts at an angle \( \theta_1 \) to the original vector.
- \( V_y \) acts at an angle \( \theta_2 \) to the original vector: \( (\theta_1 + \theta_2 = 90°) \)

To find the size of \( V_x \) and \( V_y \) we need to use trigonometry:

\[
\cos \theta_1 = \frac{V_x}{V} \quad \text{Rearranging this gives: } V_x = V \cos \theta_1
\]

\[
\cos \theta_2 = \frac{V_y}{V} \quad \text{Rearranging this gives: } V_y = V \cos \theta_2
\]

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**: \( v_x = 10 \cos 30° = 8.7 \text{ m s}^{-1} \) (2 s.f.)

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

**Vertical component**: \( v_y = 10 \cos 60° = 5.0 \text{ m s}^{-1} \) (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° 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°

- **Component of force parallel to ramp** \( F_{\text{para}} = 300 \text{ N} \times \cos 20° \approx \underline{282 \text{ N}} \) (3 s.f.)
- **Component of force perpendicular to ramp** \( F_{\text{perp}} = 300 \text{ N} \times \cos 70° \approx \underline{103 \text{ N}} \) (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.

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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^\circ = 2.6 N
Vertical component = 3.0 \times \cos 60^\circ = 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.)

\[
\tan \theta = \frac{3.5}{3.4} \quad \therefore \quad \theta = \tan^{-1} \left( \frac{3.5}{3.4} \right) = 46^\circ
\]

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.

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.
   c) Vector quantities have both ....... and ........
   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 multiplying 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) 0.000 002 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) \( F = k A^2 \rho v \)
      ii) \( F = k A^2 \rho v^2 \)
      iii) \( F = k A v^2 \rho \)
      (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:

\[
\text{average speed} = \frac{\text{distance travelled (m)}}{\text{time taken (s)}}
\]

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

\[
\text{average velocity} = \frac{\text{displacement (m)}}{\text{time taken (s)}}
\]

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.

<table>
<thead>
<tr>
<th>Car</th>
<th>Speed (m/s)</th>
<th>Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Military jet</td>
<td>400</td>
<td>400 + 400 (\hat{x})</td>
</tr>
<tr>
<td>Racing car</td>
<td>60</td>
<td>60 + 60 (\hat{x})</td>
</tr>
<tr>
<td>Cheetah</td>
<td>27</td>
<td>27 + 27 (\hat{x})</td>
</tr>
<tr>
<td>Sprinter</td>
<td>10</td>
<td>10 + 10 (\hat{x})</td>
</tr>
<tr>
<td>Tortoise</td>
<td>0.060</td>
<td>0.060 (\hat{x})</td>
</tr>
</tbody>
</table>

A speedometer shows the actual or 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).

The change in velocity may be a change in direction or speed or both.

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

## Acceleration

Acceleration is the rate of change of velocity:

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

Acceleration is measured in metres per second per second, or metres per second squared, written m/s\(^{2}\) or m s\(^{-2}\). It is a vector quantity, acting in a particular direction.

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;

(b) the boat’s average velocity.

**Solution**

\[
\text{a) average speed} = \frac{\text{distance travelled}}{\text{time taken}} = \frac{300 \text{ m}}{45 \text{ s}} = 6.7 \text{ m s}^{-1}
\]

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

## 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/s means a displacement of 3 m to the right
- -8 m/s means a velocity of 8 m s\(^{-1}\) to the left
- -4 m/s\(^{2}\) means an acceleration of 4 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.

Example 2

A ball hits a wall horizontally at 6.0 m s\(^{-1}\). It rebounds horizontally at 4.4 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:

\[
\text{change in velocity} = \text{new velocity} - \text{old velocity} = (-4.4 \text{ m s}^{-1}) - (+6.0 \text{ m s}^{-1}) = -10.4 \text{ m s}^{-1}
\]

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

Negative, therefore in a direction away from the wall.

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.
**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:

Velocity from 0 to A = displacement / time taken = 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.

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?

Gradient of line 0A = change in velocity / time taken = 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 the tangent at that point.

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:

\[
\text{displacement} = \text{average velocity} \times \text{time taken} = \left(\frac{1}{2} \times 20 \text{ m/s}^2\right) \times 10 \text{ s} = 100 \text{ m}
\]

From A to B:

\[
\text{displacement} = \text{average velocity} \times \text{time taken} = 20 \text{ m/s} \times 20 \text{ s} = 400 \text{ m}
\]

From B to C:

\[
\text{displacement} = \text{average velocity} \times \text{time taken} = \left(\frac{1}{2} \times 20 \text{ m/s}^2\right) \times 5 \text{ s} = 50 \text{ m}
\]

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 = \(\text{velocity} \times \text{time interval}\) = 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?

\[\begin{align*}
\text{a) 0 to A:} & \quad \text{The car accelerates.} \\
& \quad \text{A to B:} \quad \text{The car is moving at constant velocity.} \\
& \quad \text{B to C:} \quad \text{The car rapidly decelerates to a standstill.} \\
& \quad \text{C to D:} \quad \text{The car is not moving.} \\
& \quad \text{D to E:} \quad \text{The velocity is increasing again but the values are negative. Why? The car is starting to reverse.} \\
& \quad \text{E to F:} \quad \text{The car is now reversing at constant velocity.} \\
& \quad \text{F to G:} \quad \text{The car decelerates and stops.}
\end{align*}\]

b) From the graph, maximum velocity = 15 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:

\[ s = \text{displacement (m)} \]
\[ u = \text{initial velocity (m s}^{-1}) \]
\[ v = \text{final velocity (m s}^{-1}) \]
\[ a = \text{constant acceleration (m s}^{-2}) \]
\[ t = \text{time interval (s)} \]

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.

Derivations

From page 39, acceleration is the \[ \text{change in velocity} \over \text{time taken} = \text{final velocity} - \text{initial velocity} \]

Writing this in symbols: \[ a = {v - u \over t} \]

So \[ at = v - u \] which we can rearrange to give \[ v = u + at \] . . . (1)

From page 38, average velocity is \[ \text{displacement} \over \text{time taken} \]

If the acceleration is constant, the average velocity during the motion will be halfway between \( a \) and \( u \). This is equal to \[ {1 \over 2} (u + v) \].

Writing our equation for velocity in symbols:

\[ s = {1 \over 2} (u + v) t \]

which we can rearrange to give \[ s = {1 \over 2} (u + v) t \] . . . (2)

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

\[ s = {1 \over 2} (u + u + at) t \]

\[ . \]

\[ s = {1 \over 2} (2u + at) t \]

which we can multiply out to give \[ s = ut + {1 \over 2} at^2 \] . . . (3)

From equation (1), \[ t = {v - u \over a} \]

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

\[ s = {1 \over a} (u + u) \left( {v - u} \over a \right) \]

\[ . \]

\[ 2as = (u + u) (v - u) \]

\[ . \]

\[ 2as = v^2 - u^2 \]

which we can rearrange to give \[ v^2 = u^2 + 2as \] . . . (4)

Note:

- You can use these equations only if the acceleration is \textit{constant}.
- Notice that each equation contains only 4 of our five \( 'u', 'v', 'a', 't' \) 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 \( 2.0 \text{ m s}^{-2} \) due east for \( 10 \text{ s} \).

Calculate a) the cheetah’s final velocity, b) the distance the cheetah covers in this \( 10 \text{ s} \).

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):

\[ v = u + at \]

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

b) Using equation (2):\[ s = {1 \over 2} (u + v) t \]

\[ s = {1 \over 2} (0 + 20 \text{ m s}^{-1}) \times 10 \text{ s} = 100 \text{ m} \] 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 \( 5.0 \text{ m s}^{-2} \).

a) How long does it take her to run the first \( 10 \text{ m} \)?

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):

\[ s = ut + {1 \over 2} at^2 \]

\[ . \]

\[ 10 \text{ m} = 0 + {1 \over 2} (2.0 \text{ m s}^{-2}) \times t^2 \]

\[ . \]

\[ So \ t^2 = 10 \text{ m} \times 2.5 \text{ m s}^{-2} = 4.0 \text{ s}^2 \]

\[ . \]

\[ ∴ t = 2 \text{ s} \]

b) Using equation (1):

\[ v = u + at \]

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

Example 6

A bicycle’s brakes can produce a deceleration of \( 2.5 \text{ m s}^{-2} \).

How far will the bicycle travel before stopping, if it is moving at \( 10 \text{ m s}^{-1} \) when the brakes are applied?

First, list what you know:

- \[ s = 9 \]
- \[ u = 10 \text{ m s}^{-1} \]
- \[ v = 0 \]
- \[ a = -2.5 \text{ m s}^{-2} \] (negative for deceleration)

Using equation (4):

\[ s^2 = u^2 + 2as \]

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

\[ 0 = 100 \text{ m}^2 \text{ s}^{-2} - (5.0 \text{ m s}^{-2} \times s) \]

\[ So \ s = 100 \text{ m}^2 \text{ s}^{-2} \times 5.0 \text{ m s}^{-2} = 20 \text{ m} \] (2 s.f.)
### 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!

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. The velocity–time graph for a car reaching its maximum speed:

- As the car accelerates, its speed increases. However, as it continues to speed up, 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 further.

The graph shows the shape of the velocity–time graph for a car reaching its maximum speed:

\[
\begin{align*}
\text{max speed (acceleration = 0)} & \quad \text{increasing drag at high speed reduces the acceleration}
\end{align*}
\]

So the key to high speed is minimising drag by using streamlined shapes, as well as maximising engine power.

**Bloodhound SSC**, a rocket-powered car being designed to break the 1000 mph barrier, 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 while decelerating to a stop once you’ve pressed the brake.
- The **braking distance** is the distance travelled while decelerating to a stop before you’ve pressed the brake.

**Thinking distance**

At 70 mph

\[
\begin{align*}
\text{time} & = 2.2 \text{ s} \\
\text{reaction time} & = 0.7 \text{ s} \\
\text{thinking distance} & = 21 \text{ m} \\
\text{average speed} & = 31 \text{ m/s} \\
\text{braking distance} & = 75 \text{ m}
\end{align*}
\]

**Reaction time**

- At 70 mph, it takes 0.7 seconds to press the brake pedal.
- So the thinking distance is the distance travelled while decelerating to a stop once you’ve pressed the brake.

### Physics at work: Speed and stopping distance

**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 while decelerating to a stop once you’ve pressed the brake.
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**Thinking distance**

At 70 mph

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\text{time} & = 2.2 \text{ s} \\
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\text{braking distance} & = 75 \text{ m}
\end{align*}
\]

**Reaction time**

- At 70 mph, it takes 0.7 seconds to press the brake pedal.
- So the thinking distance is the distance travelled while decelerating to a stop once you’ve pressed the brake.

**Braking distance**

- At 70 mph, the braking distance is 75 m.
- The braking distance is the distance travelled while decelerating to a stop before you’ve pressed the brake.

### 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.

**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.

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\(^{-2}\)):

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

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 6.8 m s\(^{-2}\) (6.65 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 10⁻⁷ m to more than 1 km.

The nature of electromagnetic radiation

All electromagnetic waves can travel through a vacuum at 3.00 × 10⁸ 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 c of the wave in free space, using the magnetic field constant μ₀ and the electric field constant ε₀:

\[ c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \]

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.

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.

Ultra violet (UV)

Why is the arc welder in the photograph wearing eye protection?

Electric arcs, such as sparks and lightning, produce ultraviolet. Why is the arc welder in the photograph wearing eye protection?

Ultraviolet (UV)

Welders must protect themselves against UV.

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).

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.

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.

Photographs taken with visible light and IR.

Welders must protect themselves against UV.

Measuring the speed of light

The wheel had 720 teeth. The frequency f was 12.6 Hz. Distance 2d was 17.26 km = 1.726 × 10⁶ m.

\[ \text{Speed} = \frac{\text{distance}}{\text{time}} \]

\[ c = \frac{2d}{1/(2Nf)} = 2d \times 2Nf \]

\[ c = 1.726 \times 10^6 \text{ m} \times 2 \times 720 \times 12.6 \text{ Hz} = 3.13 \times 10^8 \text{ m s}^{-1} \]

Fizeau’s calculation for the value of c:

\[ c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \]

Maxwell’s calculation for the value of c:

\[ c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \]

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

130 131
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. When you strum the guitar string, waves move in both directions along the string and superpose to give a stationary wave.

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

- The simplest way the string can vibrate is with just one loop.
- You can 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, μ.

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.

\[ c = \sqrt{\frac{T}{\mu}} \]

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 \( c \) (page 125) and so the first harmonic frequency \( f_1 \) is given by:

\[ f_1 = \frac{c}{2L} \]

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 is the first harmonic frequency of the guitar string?

\[
 f_1 = \frac{c}{2L} = \frac{1}{2 \times 0.600 \text{ m}} \sqrt{\frac{78.5 \text{ N}}{7.95 \times 10^{-4} \text{ kg m}^{-1}}} = 262 \text{ Hz (3 s.f.)}
\]

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 movable 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?
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?
Notice at the circuit diagrams in section 3.8.
You can see 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, \(\tau = \text{capacitance, } C \times \text{resistance, } R\)
(seconds) (farads) (ohms)

In fact, the time constant \(\tau\) is the time it takes for the p.d. to fall to \(1/e\) 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 \(1/e\) 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 5\(CR\), 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?

\(\tau = \text{capacitance, } C \times \text{resistance, } R\)

\(\tau = \frac{500 \times 10^{-6} \text{ F} \times 56 \times 10^{3} \Omega}{28} = 28 \text{ seconds}\)

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 \(Q\), the discharge current is \(I\) and the p.d. across the resistor and the capacitor is \(V\).
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
\(\Delta Q = -\frac{Q}{CR} \Delta t\)
(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 \(1/e\) (about \(1/3\)) of \(Q_0\).
After a further time \(CR\), the charge has again fallen by \(1/e\) 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 \(1/e\) every \(CR\) seconds.
We say that the charge falls exponentially with time, and
\(Q_t = Q_0 e^{-t/CR}\)

\(Q_0\) 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 \(Q\).
\(\therefore\) The p.d. \(V\) must also fall exponentially.
\(V = IR\), and so \(I\) is proportional to \(V\).
\(\therefore\) The current \(I\) 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) \(\tau = CR\)
\(\tau = \frac{500 \times 10^{-6} \text{ F} \times 100 \times 10^{3} \Omega}{56 \times 10^{3}} = 50 \text{ s} \) (2 s.f.)
b) \(V_t = V_0 e^{-t/CR}\)
\(V_t = 6.0 \times e^{-t/50} \text{ V} \) (2 s.f.)
c) \(Q_t = CV_t\)
\(Q_t = 500 \times 10^{-6} \text{ F} \times 4.0 \text{ V} \) (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:

$$ V = \frac{kQ}{r_s} $$

For any capacitor $C = \frac{Q}{V}$ and so:

$$ C = Q \cdot \frac{1}{V} = \frac{1}{4\pi \varepsilon_0 r_s} $$

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$^{-1}$)

$$ C = 4\pi \varepsilon_0 r_e $$

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

**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 gun 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 $Q E$ (see page 292), as shown in the diagram.

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 $B Q v$ 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 gun is $Q V_{gun}$ (see page 321), so

$$\frac{1}{2} m v^2 = Q V_{gun}.$$  

But $B Q v = Q E$, so $v = \frac{E}{B}$ and so $v^2 = \frac{E^2}{B^2}$.

Substituting this into the equation above gives:

$$\frac{1}{2} m \frac{E^2}{B^2} = \frac{2 EQ}{m} \sin$$

and dividing both sides by $2 V_{gun}$ gives:

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

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 $d$, given by this experiment.

$$E = \frac{V}{d} = \frac{2900 \text{ V}}{0.1 \text{ m}} = 29000 \text{ V m}^{-1} \text{ (or } 29000 \text{ N C}^{-1})$$. Note that you must use $d$ in metres!

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

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.

**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 $F = B Q v$ (see page 264). Since this provides the centripetal force ($F = m v^2/r$, see page 80), we can write:

$$\frac{m v^2}{r} = B Q v \quad \therefore v = \frac{B Q r}{m}.$$

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 $\frac{\pi m}{B Q}$ seconds.

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

**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 $F = \frac{m v^2}{r}$ 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 ‘pulses’ synchronised with the arrival of pulses of particles.

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.
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, \( p^- \) (‘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 antiparticle. These anti-electrons or positrons \( (e^- \text{ or } e^+) \) 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.

\[
\begin{align*}
\text{antiproton} + \text{positron} & \rightarrow \text{antihydrogen} \\
\bar{p} + e^+ & \rightarrow \bar{\Pi}
\end{align*}
\]

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! At this rate, antihydrogen would have no practical applications.

**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 \( \gamma \)-ray photons of energy:

\[
\Gamma^- + \Gamma^+ \rightarrow 2 \gamma
\]

Why are there 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.
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.

#### 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 a 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:

- The human eye has a very limited range of sensitivity. 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.

#### 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

\[
\sin \theta \geq \frac{A}{b}
\]

where \( b \) is diameter of the objective mirror.

\[
A = 2.4 \ \mu m = 2.4 \times 10^{-6} \ m \quad \text{and} \quad b = 10 \ m
\]

\[
\sin \theta \geq \frac{2.4 \times 10^{-6} \ m}{10 \ m} = 2.4 \times 10^{-7} \Rightarrow \theta \geq 0.000014^\circ = 0.050 \ \text{seconds of arc (2 s.f.)}
\]

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

#### Radio telescopes

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.
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 × 10⁻⁵ kg and charge −4.0 × 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 θ 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 V m⁻¹. An electron travels through holes X and Y in the plates. The electron has a horizontal velocity of 5.0 × 10⁶ 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. [2]

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] b) 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] (OCR)

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 supplied various currents. The following readings are obtained. Plot these results on a graph (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 Ω 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 simple 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 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 λ 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 ratio of change of its refractive index with wavelength. At a particular wavelength D = Δn/Δλ. 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 a is of the form n = a + b/λ² where a and b are constants. Another suggestion for the relationship between n and λ can be determined graphically. Plot a graph of 1/n² against 1/λ² to test the relationship. [1] d) Use your graph to determine a. [3] e) State the significance of a. [1] f) Another suggestion for the relationship between n and λ is of the form n = cλ² where c and d are constants. Explain how c 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 student measures the product PV for 20 minutes. 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 θ in degrees Celsius of a fixed mass of gas. The results are used to plot the graph of PV against θ.

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 refresh 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 will be able to explain an idea in several different ways in order to help you understand it.

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.
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 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 skillfully,
- 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.

**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?

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 1.10 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.

**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.

<table>
<thead>
<tr>
<th>Diameter (mm)</th>
<th>Cross-sectional area</th>
<th>Resistance (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1.2</td>
</tr>
<tr>
<td>0.5</td>
<td>0.25</td>
<td>4.9</td>
</tr>
<tr>
<td>0.3</td>
<td>0.09</td>
<td>13.0</td>
</tr>
</tbody>
</table>

- three readings isn’t enough
- readings should be repeated
- the current and previous voltage readings should have been noted too

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

Parallax error

- reading will be too small
- incorrect position
- reading will be too large
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:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>∝</td>
<td>is proportional to</td>
</tr>
<tr>
<td>∼</td>
<td>is approximately equal to</td>
</tr>
<tr>
<td>&gt;</td>
<td>is greater than</td>
</tr>
<tr>
<td>&gt;=</td>
<td>is greater or equal to</td>
</tr>
<tr>
<td>&lt;&lt;</td>
<td>is much less than</td>
</tr>
<tr>
<td>&gt;&gt;&lt;&gt;</td>
<td>is much greater than</td>
</tr>
<tr>
<td>±</td>
<td>plus or minus</td>
</tr>
<tr>
<td>Δx</td>
<td>a small change in</td>
</tr>
<tr>
<td>x√</td>
<td>the square root of</td>
</tr>
<tr>
<td>x̄</td>
<td>the mean of the values of</td>
</tr>
<tr>
<td>'</td>
<td>therefore</td>
</tr>
</tbody>
</table>

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.)
  - 1200 (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. For example:
  - 56.21 × 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 × 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 × 2 × 2 and 5^2 = 5 × 5 × 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
- \( y^a \times y^b = y^{a+b} \)
- \( y^a / y^b = y^{a-b} \)
- \( (y^a)^b = y^{ab} \)

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

For example:
- \( 10^{-1} = 1/10 \) = 0.1
- \( 10^{-2} = 1/100 \) = 0.01

Standard Form
Many quantities used in Physics are very small or very large. Eg. mass of the Earth is \( 6000000000000000000 \) kg.
The diameter of an atom is about \( 0.0000000000001 \) 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 × 10³
- 0.0128 = 1.28 × 10⁻²

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

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 EXP 3.

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

If you saw \( 2.00 \) on your calculator, would this mean 2³?
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](http://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:

\[ \frac{\Delta x}{\Delta t} = -\lambda x \]

where \( x \) is the amount remaining, and \( \lambda \) is the rate at which it is decaying 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:

\[ A = A_0 e^{-\lambda t} \]

where \( A \) is the activity (the rate of decay), \( A_0 \) 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:

\[ \frac{\Delta Q}{\Delta t} = -\frac{1}{CR} Q \]

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.

**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.

**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](http://www.oxfordsecondary.co.uk/advancedforyou)

In it the data is processed using a simple formula \( R = \frac{V}{I} \). 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.
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  - Help with Maths.

‘Everything should be made as simple as possible, but not simpler’
– Albert Einstein