Physics

Grammar Schools

GRADE 10

Express Publishing

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Contents

Introduction 4

Module 1: Vectors and Motion 6

Module 2: Forces 38

Module 3: Circular motion 52

Module 4: Fluid mechanics 62

Module 5: Liquids, Solids and Gases 70

Module 6: Thermodynamics and Engines 88

Module 7: Electrostatics 96

Module 8: Conduction 120

Module 9: Electricity and Magnetism 151

Module 10: Applied electricity 180

Glossary: 185

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GrS PHYS Gr 10 Ss Conts.indd 3 5/9/19 4:32 PM

Introduction

For the student

Welcome to your new Physics textbook, *Grade 10 Physics*. Your textbook comes with a **Grade 10 Physics Student's Portfolio** and a range of *digital resources*. As well as deepening your understanding of key areas of Physics, this book aims to develop your learning skills in science. You will develop these skills in class, in laboratory practicals and whilst conducting research within and outside of class with your fellow students. An emphasis will be placed throughout this course on your ability to present core concepts, research and data effectively to others.

Glossary

A comprehensive glossary is included at the back of this book.

For the teacher

Written for the new Grade 10 Physics subject programme in Kazakhstan, *Grade 10 Physics* aims to meet the broad range of learning objectives set out in the Grade 10-11 Physics subject programme document. It focuses on developing learners' knowledge of and about science through the four content and skill strands outlined in the subject programme:

- Understanding of core subject areas in Physics
- Research and experimentation in science
- Communication in science
- Science and society

Key features of the textbook

- **Learning objectives** are clearly stated at the beginning of each module in student-friendly language.
- **Activities** and practical demonstrations allow students to build on their knowledge through guided observation, laboratory practicals and research.
- **Diagrams** have been fully labelled and are drawn in a simple style so that learners can replicate them easily.
- **Questions** are interspersed within sections of the text to offer teachers the opportunity to use a range of teaching strategies. There are regular opportunities for learners to engage in group work and pair work, discussion, giving of presentations and online research.

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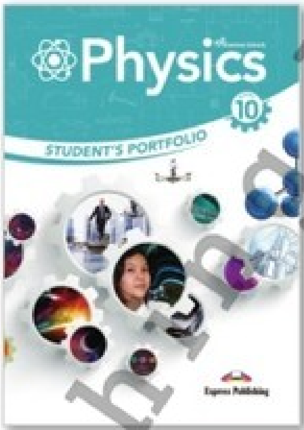
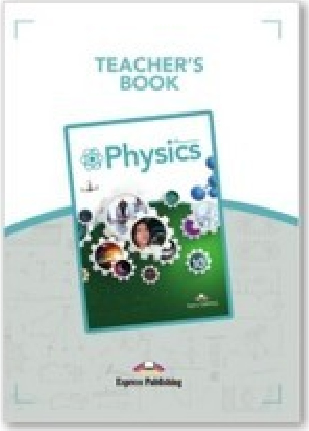
Student's Portfolio



The Student's Portfolio provides additional revision material and further tasks. The Student's Portfolio enables learners to maintain a detailed record of laboratory practicals, giving them space to reflect on the processes and results of their work. In line with the textbook, it provides detailed sample workings of all calculations they are required to make.



Teacher's Book

A Teacher's Book with **full answers** to all questions in both the Textbook and Student's Portfolio and detailed **worked solutions** of all calculations is provided.

Digital resources

Grade 10 Physics **digital resources** for teachers will further enhance classroom learning. These resources work in conjunction with the Textbook and Student's Portfolio. The resources have been designed to fully integrate with the Textbook to compliment lesson content. Following the principles of the new national Physics subject programme, material is provided to suit a range of learner types and to encourage participation and engagement on the part of the learner.

A series of **videos** allow students to observe science in action across all modules. These videos will reinforce the topic at hand, promote discussion about scientific issues in society and enable teachers to bring a range of perspectives on topics in Physics into the classroom.

Further classroom discussion and participation is opened up through **PowerPoint presentations**, including a thematic presentation of information from the Textbook. **Experiment videos** allow for a visual review of laboratory activities and can be used for demonstration or summative plenary work.

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GrS PHYS Gr 10 Ss Conts.indd 5 5/9/19 4:32 PM

Module 1 Vectors and Motion

Learning objectives

- To apply kinematic equations when solving calculations and analysing graphics of motion 10.1.1.1
- To give examples of velocity addition law and displacements from everyday life 10.1.1.2
- To find the centre of mass of a perfectly rigid body and to explain different types of equilibrium 10.1.3.1
- To describe changes in the motion of bodies dropped at an angle to the horizon and vertically 10.1.2.3
- To explain conservation laws of momentum and mechanical energy 10.1.4.1

Vectors and Scalars

Physics is a mathematical science. All of our theories and concepts depend on our ability to clearly understand what we mean by terms such as 'acceleration', 'velocity', 'speed' and 'force', and also on our ability to measure them. To do so, first we have to separate all measurements into two categories: vectors and scalars.

- Vectors have both magnitude and direction.
- Scalars have only magnitude.

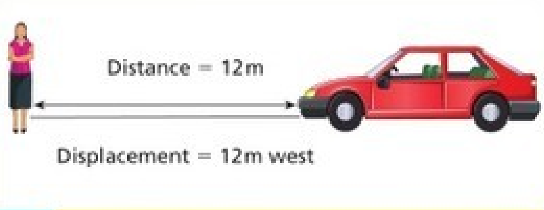
Most measurements that you come across outside the world of science are scalars. Mass, for example, is a scalar. It is measured in kilograms and has no direction. Other scalar quantities are length, volume, time, energy and electric charge.

Examples of vector quantities are velocity, acceleration, momentum, force and weight. All of these have a direction associated with them. A typical measurement of force, for example, might be 10 N east.

The distinction between scalars and vectors can be confused by the fact that we are sometimes only interested in the magnitude of a vector quantity. For example, you may come across situations in which a force is given as, say, 15 N without any direction being mentioned. It is important to remember that this is not good practice. Even when it is not mentioned, a force always has a direction and it should, strictly speaking, be specified.

It can also be confusing that there are a number of situations in which there are closely related measurements, one of which is a vector and one of which is a scalar. Speed, for example, is a scalar. It is specified only in metres per second. The associated vector quantity is velocity, which is measured in metres per second and a direction, e.g. a speed could be 25 $m\,s^{-1}$, whereas a velocity would be something like 25 $m\,s^{-1}$ east.

Another closely related pair is distance and displacement. Distance is a scalar and displacement is a vector. In figure 1.1, the woman is standing 12 m from her car. Her displacement is 12 m west from her car.



1.1 *Distance and displacement*

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One important difference between distance and displacement is that, with displacement, we don't take the path travelled into account. In figure 1.2, a cyclist journeys from school to home along the route shown. When finished, he has travelled a total journey of 3 km. But his displacement is measured in a straight line and is only 2 km east.

1.2 *Velocity equals displacement divided by time*

When first introducing the idea of velocity, we often say that it is speed in a given direction. There are many situations in which this is a reasonable simplification of the situation, but it is not completely true. Strictly, the definitions of velocity and speed are:

$$\text{Velocity} = \frac{\text{Displacement}}{\text{Time}} \qquad \text{Speed} = \frac{\text{Distance}}{\text{Time}}$$

In the example of the cyclist discussed, if the cyclist completes his journey in 1 h, his average speed is $3\,\text{km}\,\text{h}^{-1}$, but his average velocity is $2\,\text{km}\,\text{h}^{-1}$ east.

Vector addition

When adding vectors we are essentially looking to see how two or more vectors could be replaced with a single vector. We want to know how large that single vector would be, and in what direction it would point. It is easiest to picture this by looking at forces.
If two forces, one of 5 N and one of 10 N, push in the same direction, they could be replaced with a single force of 15 N, pushing in the same direction (see figure 1.3).

1.3 *Vector addition*

We say that the total force is given by: FT = 10 + 5 = 15 N, to the right.

If two forces, one of 5 N and one of 10 N, push in opposite directions, they could be replaced with a single force of 5 N, pushing as shown in figure 1.4.

1.4 *Vector subtraction*

We say that: $F_T = 10 - 5 = 5$ N, to the right.

Note that when the two forces were in the same direction, we took them both to be positive, but that when they were in opposite directions, we took one to be negative. This is something we will see a lot of in our study of physics, and motion in particular. It is very important in every situation to be clear about which direction you are thinking of as positive and which direction as negative.

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Triangle law

If forces are at an angle to each other, we can add them according to what is known as the triangle law. Let's say an object is being pushed by two forces, of 3 N and 4 N, whose directions are as shown in figure 1.5.

The object will move as if pushed by a single force of 5 N, whose direction is as shown in figure 1.6.

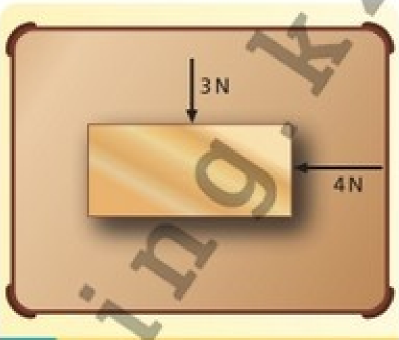
The 5 N is found using a right-angled triangle. The longer side is known as the resultant, and it represents the single vector that would have the same effect as the other two vectors. It is calculated according to Pythagoras' theorem:
$5^2 = 3^2 + 4^2$ (see figure 1.6).

The angle between the different forces can be calculated using trigonometry. Here we can say:

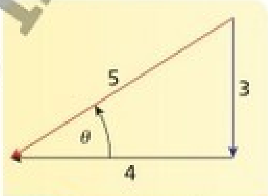
$\tan \theta = \frac{3}{4}$

and therefore the angle θ is 36.86°.

This means that the object will experience a force of 5 N at an angle of 36.86° to the 4 N force, as shown in figure 1.6.



1.5 *Vectors at right angles*



1.6 *The resultant force is 5 N*

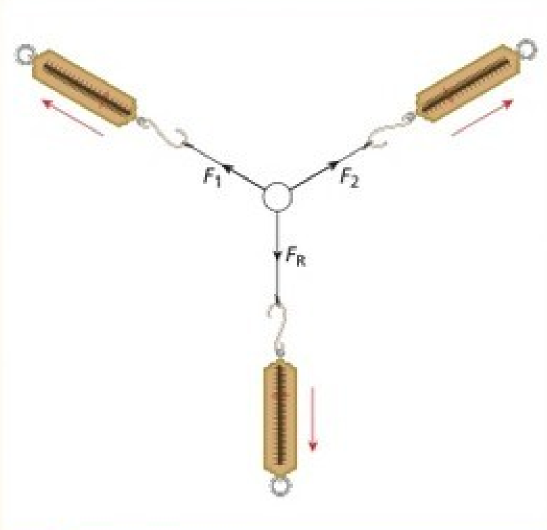
Experiment 1.1: To find the resultant of vectors

Method

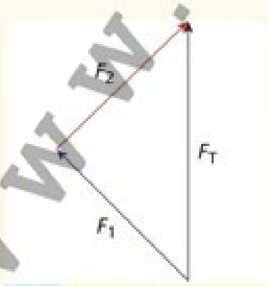
1. Set up the apparatus as shown in figure 1.7.
2. Note the readings on the first two newton meters (spring balances) (F_1 and F_2).
3. Note the reading on the third spring balance (F_R).

Observations

According to Newton's third law, the reading on the third spring balance should be equal in magnitude but opposite in direction to the resultant of the two upper balances.



1.7 *Spring balances*



1.8 *Vector addition*

Note

You can also calculate the resultant of the vectors, F_T, using vector addition. The two methods should give identical values.

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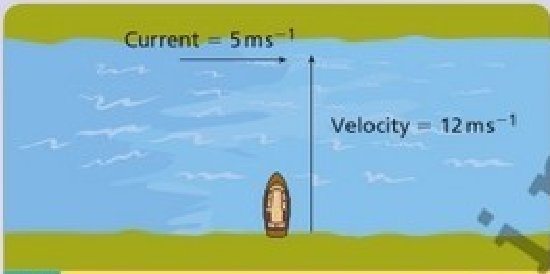
1.1 Sample Question

A boat moves across a river as shown in figure 1.9, so that the forward velocity is $12\,m\,s^{-1}$. The river is flowing with a current of $5\,m\,s^{-1}$. In what direction, and with what velocity, would the boat cross the river?



1.9

Sample Answer

Resultant velocity of boat (v_R):

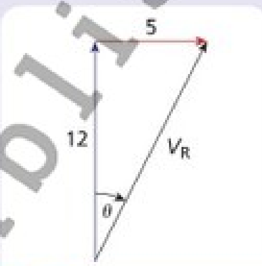
$$v_R^2 = 5^2 + 12^2 = 169$$

$$v_R = 13\,m\,s^{-1}$$

$$\tan\theta = \frac{5}{12}$$

$$\theta = \tan^{-1}\left(\frac{5}{12}\right) = 22.6°$$

The boat would cross the river at $13\,m\,s^{-1}$, at an angle of 22.6°.



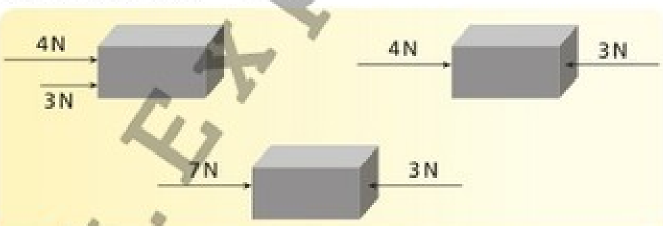
1.10

For you to try

1 Distinguish between the concepts of vector and scalar.

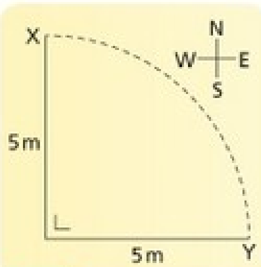
2 Which of these is a vector: mass, weight, distance, speed, velocity, energy, electric charge, acceleration?

3 In the situations shown in figure 1.11, find the magnitude and direction of the resultant force on each block.



1.11 *Question 3*

4 A woman walks along the curve XY shown in figure 1.12.
(a) What distance has she travelled?
(b) When she reaches Y, what is her displacement from X?



1.12 *Question 4*

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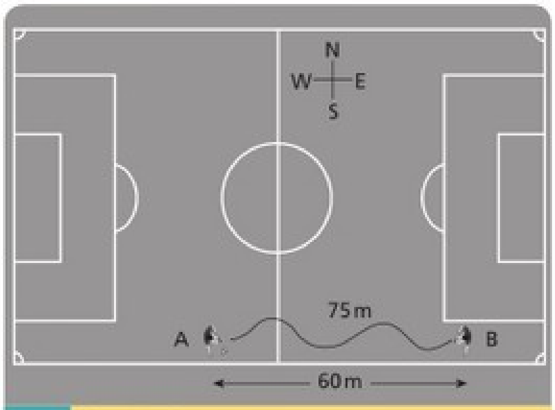
5 A footballer runs from A to B along the path shown in figure 1.13 a total distance of 75 m. He does so in 25 s.

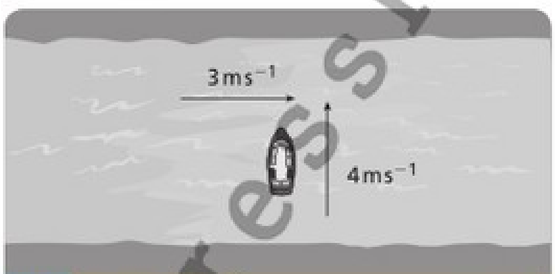


1.13 *Question 5*

(a) What is his average speed on the journey?
(b) What is his average velocity?

6 A square of side 100 m is marked out on grass. If you walk along the lines, starting at a corner and heading north first and then east, what is your displacement from your starting point after you have travelled 175 m?

7 A boat moves across a river so that the forward velocity is 4 m s^{-1}. The river is flowing with a current of 3 m s^{-1}, as shown in figure 1.14. Show on a diagram in what direction, and with what velocity, the boat would cross the river.



1.14 *Question 7*

8 A plane is flying east and measures its velocity (with respect to the air) as being 100 km h^{-1}. The wind speed is in the same direction as the plane and is at 25 km h^{-1}.
(a) What is the resultant velocity of the plane?
(b) Another plane is flying west and also has an air velocity of 100 km h^{-1}. What is its resultant velocity?

Centre of Mass

Although gravity affects every little part of an extended body of mass, its effect sometimes appears to act at a single point somewhere near its centre. Consider a book which is resting on its side close to the edge of the table. As it is pushed slowly over the edge, it will reach a point where gravity suddenly seems to cause the book to fall over the edge. It is not that gravity has changed, but that the point at which gravity seems to be acting on the body has gradually moved beyond the edge of the table. This point is called the centre of mass (sometimes the centre of gravity).

It should be noted that the centre of mass will not always be located close to the geometrical centre of an object. This is especially true when the object is a composite of different density materials. Consider a hammer for example. The centre of mass will be close to the hammer head, and not half way down the handle.

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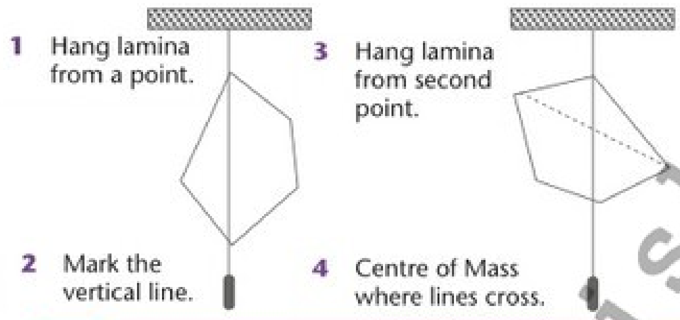
A practical way to locate the centre of mass of an irregular object is to suspend it from any given point,, and also hang a string with a bob on the end to mark a vertical line from the same point. Once the object stops swinging, the centre of mass will lie somewhere along the vertical line marked by the string. An example is given in the diagram below, where an irregularly shaped lamina is suspended from different points. The centre of mass will be where the lines intersect.



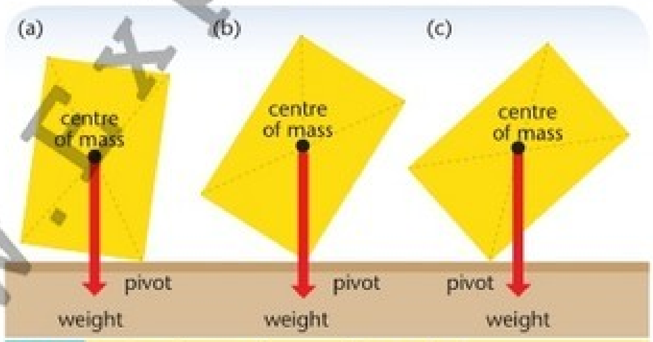
1.15 *Locating the centre of mass of an irregular object*

Method to find the centre of mass of a flat object.

Notice that however the object starts, it will swing back and forth until it settles with the centre of mass directly below the pivot. This is called a **stable equilibrium**.

It is also possible for an object to be in an **unstable equilibrium**. Consider a thin pencil standing upright on a flat table with its point pointing upwards. With sufficient care it is possible to make the pencil stand even though its centre of mass is directly above its support. Experience teaches us that a very slight jolt, or even a slight puff of wind will cause the pencil to fall over onto its side. That is why we call it an unstable equilibrium.

Another type of equilibrium is a **non-determinate equilibrium**. Consider a solid sphere resting on a flat surface. The centre of mass of the sphere is located exactly at the geometrical centre of the sphere, and this will be exactly above the point at which the sphere is supported by the flat surface beneath it. The sphere is in equilibrium, but if it is pushed it will roll without falling because as it rolls, its centre of mass always stays above the point of contact that is supporting it.



1.16 *Position of centre of mass relative to the pivot*

The position of the centre of mass relative to the pivot determines whether an object will fall over or return back to its original position. Provided the centre of mass remains vertically above the width of the base, the object will try to fall back on to its base.

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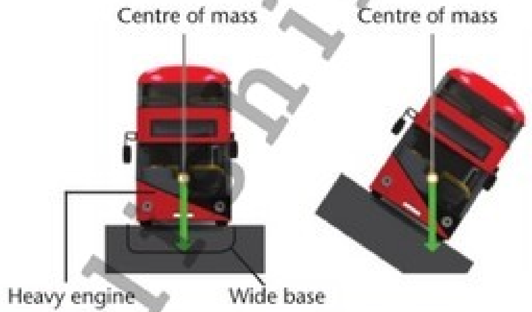
When we stand, our centre of mass is somewhere close to our spine and will be directly above our footprint. If we lean forward we exert additional pressure on our toes, but the centre of mass will still be somewhere inside our footprint. If we lean further forwards, our centre of mass will move to lie in front of our toes (and outside our footprint), and unless we quickly move one foot forwards, we will fall forwards. (Our body will find a position where its centre of mass is as close as possible to the floor!)

When we walk we always maintain the centre of mass of our bodies somewhere above and between the base marked out by the extent of the range of our feet. If we don't, we fall over.

In general objects are at their most stable when their centre of mass has found its lowest position. A book can stand upright on a shelf for a long time, but its most stable position is to lie flat on its side.

The stability of engineering structures and vehicles is an important consideration. Whenever possible, engineers design systems such that the centre of mass is as low as possible.



1.17 *Low centre of mass of a bus and a wide base ensure stability*

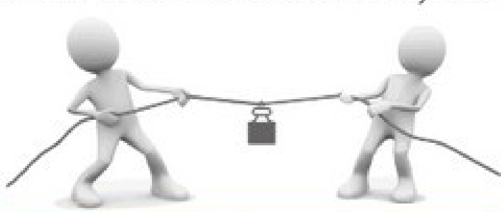
The way to ensure an object is as stable as possible it to give it a low centre of mass, and a wide base. The centre of mass of a bus can be lowered by ensuring that all the massive components (engine, gear box, fuel tank, chassis, etc) and put as low as possible.

Notice that there is often a conflict between artistic appeal and engineering considerations. A flower vase normally has a narrow base and a wide opening at the top. This makes it suitable for flowers to be supported with their heads spread apart so that their beauty can be seen, but it also makes the vase very easy to tip over!

Resolving forces and calculating the components of forces

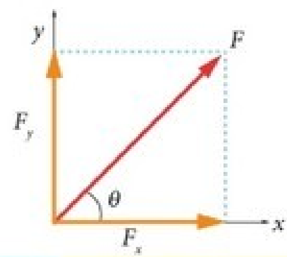
Forces are by their very nature invisible quantities. It requires a trained mind to notice where the forces are acting, in what direction, and what their likely magnitudes must be. We will limit our analysis to systems where the forces are in equilibrium such that the resultant force is always zero.

In the figure 1.18 two people are supporting a weight by means of a rope tensioned between them. It is clear that the string is in tension, and that both persons must be pulling equally, but how does the magnitude of the tension compare to the size of the weight? In order to find answers to questions like these, we must balance all the forces, resolving their vertical and horizontal components.


1.18 *Two people support a weight by means of a rope*

Before proceeding to some practical examples notice that the force F can be thought of as having two components F_x and F_y. In the diagram 1.19 $F_x = F \cos \theta$, and $F_y = F \sin \theta$.

With this understanding we are ready to tackle some practical examples.



1.19 *Resolving a force into two perpendicular components*

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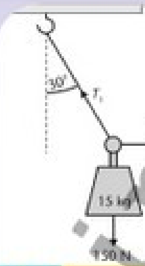
1.2 Sample Question

A mass of 15 kilograms is suspended by a string from a hook in the ceiling. It is pulled sidewise by a horizontal force such that the string from the hook makes an angle of 30 degrees relative to the vertical. Calculate the magnitude of the force pulling to the right, and the tension in the string.



1.20

$g = 10\ ms^{-2}$

Sample Answer

In order to solve this question we need to resolve and balance the forces both vertically and horizontally.

Vertically: downwards = mg, upwards = $T_1 \cos 30°$, so $mg = T_1 \cos 30°$

Horizontally: to the right = T_2, to the left = $T_1 \sin 30°$, so $T_2 = T_1 \sin 30°$

From the first equation we can immediately calculate the tension.

$T_1 = mg / \cos 30°$

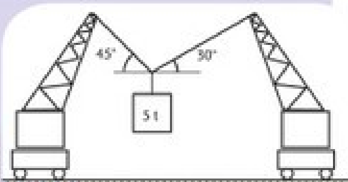
$T_1 = 15 \times 10 / \cos 30° = 173\ N$

Once we have calculated T_1, we obtain T_2 using the second equation.

$T_2 = T_1 \sin 30° = 87\ N$

1.3 Sample Question

Two cranes are jointly lifting a 5 ton (5000 kg) weight, and their cables are making different angles to the horizontal. Calculate the tensions in the two cables.



1.21

$g = 10\ ms^{-2}$

Sample Answer

We will follow the same methodology.

Vertically: downwards = mg, upwards = $T_L \sin 45° + T_R \sin 30°$,

where the suffixes L and R denote the left hand crane and the right hand crane.

So $mg = T_L \sin 45° + T_R \sin 30°$

Horizontally: to the right = $T_R \cos 30°$, to the left = $T_L \cos 45°$

So $T_R \cos 30° = T_L \cos 45°$

Notice that in this case we cannot solve one equation first, and then use the result to solve the second equation. These are simultaneous equations with two unknowns. We have to eliminate one unknown from both equations first.

Rearranging the second equation we obtain:

$T_R = T_L (\cos 45° / \cos 30°)$, now we replace T_R in the first equation with this.

$mg = T_L \sin 45° + T_L (\cos 45° / \cos 30°) \sin 30°$

This reduces to $mg = T_L (\sin 45° + \cos 45° \tan 30°)$

(remembering that $\sin 30° / \cos 30° = \tan 30°$).

$T_L = mg / (\sin 45° + \cos 45° \tan 30°) = 5000 \times 10 / (\sin 45° + \cos 45° \tan 30°) = 44\ 829\ N$

$T_R = T_L (\cos 45° / \cos 30°) = 44\ 829 (\cos 45° / \cos 30°) = 36\ 602\ N$

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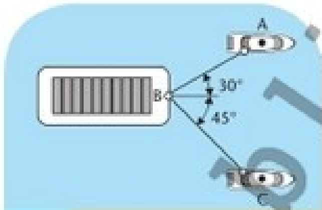
For you to try

1 A heavy landscape picture in an art museum has a mass 50 kg and is supported with a rope attached to both ends as shown in the figure. Calculate the tension in the rope.

1.22 *Question 1*

2 A barge B is pulled along by two boats A and C. The two ropes between the boats and the barge make angles of 30 and 45 degrees respectively with respect to the direction of travel of the barge. Boat A is pulling with a force of 5000 N.



1.23 *Question 2*

(a) Without calculation, try to decide whether Boat C is pulling with a greater, smaller or equal force than boat A.
(b) Calculate the force with which boat C is pulling and see if you were right!
(c) Calculate the drag of the barge B.

Linear motion

The area of physics we call mechanics deals a lot with moving bodies. You will probably recall the relationship between distance, speed and time:

$$\textbf{Speed} = \frac{\textbf{Distance}}{\textbf{Time}}$$

This equation is useful when we are dealing with bodies that are travelling at a constant speed, or where we are only interested in their average speed. However, if we need to take acceleration into account, we require different equations.

The equations of motion

Acceleration and velocity

Acceleration is the rate of change of velocity.

This definition of acceleration is wider than the general meaning of the word in conversation. You will notice, for example, that it refers to a change of velocity rather than speed. Because velocity includes a direction, this means that an object can travel at a constant speed and still be accelerating, if it changes direction. A car turning a corner, for example, is accelerating whether or not it changes its speed.

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From the definition of acceleration we can find a way of calculating its value:

Derivation

Acceleration is the rate of change of velocity, i.e.:

$$\text{Acceleration} = \frac{\text{Change of velocity}}{\text{Time}}$$

or

$$a = \frac{v - u}{t}$$

We can rearrange this to give:

$$at = v - u$$

or

$$v = u + at$$

Here we are using a set of symbols with which you will become familiar:

u – initial velocity

v – final velocity (or velocity after a time, *t*)

a – acceleration

s – displacement

t – time

You might notice that we rarely talk about 'deceleration' in physics. Instead, even when an object is slowing down, we talk about its acceleration – but we take the acceleration to be negative. This is connected to the fact that acceleration is a vector quantity.

- A positive acceleration means an object's velocity is increasing.
- A negative acceleration means an object's velocity is decreasing.

1.4 Sample Question

A car increases its speed from 10 m s^{-1} west to 30 m s^{-1} west over a period of 10 s. What is its acceleration?

Sample Answer

$$v = u + at$$

$$30 = 10 + a(10)$$

$$a = \frac{30 - 10}{10}$$

$$= 2\,\text{m s}^{-2} \text{ west}$$

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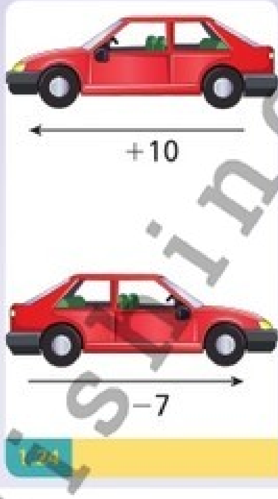
GrS PHYS Gr 10 Ss Mod 1.indd 15 5/9/19 4:33 PM

1.5 Sample Question

A car is travelling at 10 m s^{-1} west and, over a period of 7 s, slows down and turns around so that it is travelling at 7 m s^{-1} east. What is its acceleration?



Sample Answer

$$u = 10\,\text{m s}^{-1}\text{ west},\; v = 7\,\text{m s}^{-1}\text{ east}$$
$$v = u + at$$
$$-7 = 10 + a(7)$$
$$a = \frac{-7-10}{7}$$
$$= -2.43\,\text{m s}^{-1}\text{ west}$$
or
$$= 2.43\,\text{m s}^{-1}\text{ east}$$

For you to try

1. Define 'acceleration'.
2. A car is travelling east and increases its velocity from 12 m s^{-1} to 22 m s^{-1} over a period of 4 s. What is its acceleration?
3. A car is travelling at 20 m s^{-1} west and, over a period of 10 s, turns around so that it is travelling at 10 m s^{-1} east. What is its acceleration?
4. A car begins from rest and with an acceleration of 10 m s^{-2} west. What is its velocity after 5 s?
5. A car begins from rest and accelerates at 5 m s^{-2}. How long does it take to reach a speed of 100 km h^{-1}?
6. A bird is flying at 8 m s^{-1} south and accelerates at 5 m s^{-2} north. What is its velocity after 10 s?

So far we have concentrated on the relationship between velocity, acceleration and time. However, for a moving object, the distance travelled is also important. The following two equations show how distance is related to the other key variables for moving objects:

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

With constant acceleration, the average velocity in any motion will be given by:

Derivation

$$\text{Average velocity} = \frac{u+v}{2}$$

Also, by definition:

$$\text{Average velocity} = \frac{s}{t}$$

Therefore:

$$s = (\text{average velocity})\,(\text{time})$$
$$= \frac{u+v}{2}\,t$$
$$= \frac{u+u+at}{2}\,t$$
$$s = ut + \frac{1}{2}at^2$$

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

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GrS PHYS Gr 10 Ss Mod 1.indd 16 5/9/19 4:33 PM

Derivation

$$v = u + at$$

Square both sides:

$$v^2 = u^2 + 2uat + a^2t^2$$
$$= u^2 + 2a(ut + \frac{1}{2}at^2)$$
$$v^2 = u^2 + 2as$$

Another equation that can be useful relates the average velocity of an object, the time involved and the object's displacement:

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

These equations are very useful in any situation in which we are looking at moving bodies, and you will see a great deal of them in your studies. Because of the variables used, they are sometimes referred to as the UVAST equations.

1.6 Sample Question

A bicycle is travelling at $2\,m\,s^{-1}$ east and accelerates at $2\,m\,s^{-2}$ for 5 s.

(a) What distance does it travel in that time?

(b) What is its velocity after 5 s?

Sample Answer

$u = 2$, $v = v$, $a = 2$, $s = s$, $t = 5$

(a)
$$s = ut + \frac{1}{2}at^2$$
$$= 2 \times 5 + \frac{1}{2} \times 2 \times 5^2$$
$$= 35\,m$$

(b)
$$v = u + at$$
$$= 2 + 2 \times 5$$
$$= 12\,m\,s^{-1} \text{ east}$$

1.7 Sample Question

A bicycle begins from rest and increases its speed to $18\,m\,s^{-1}$ over a distance of 20 m.

(a) What is the magnitude of its acceleration?

(b) How long does it take to do this?

Sample Answer

$u = 0$, $v = 18$, $a = a$, $s = 20$, $t = t$

(a)
$$v^2 = u^2 + 2as$$
$$18^2 = 0^2 + 2a \times 20$$
$$a = \frac{18^2}{2 \times 20} = 8.1\,m\,s^{-2}$$

(b)
$$v = u + at$$
$$18 = 0 + 8.1(t)$$
$$t = \frac{18}{8.1} = 2.22\,s$$

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GrS PHYS Gr 10 Ss Mod 1.indd 17 5/9/19 4:33 PM

1.8 Sample Question

A plane lands at a speed of $240\,km\,h^{-1}$ and travels 2.6 km along the runway before stopping.

(a) What is the average magnitude of its deceleration as it stops?

(b) How long does it take to do this?

1.25

Sample Answer

$u = 240\,km\,h^{-1}$

$= 240 \times \frac{10^3}{3600} = 66.67\,m\,s^{-1}$

$u = 66.67,\ v = 0,\ a = a,\ s = 2600,\ t = t$

(a) $v^2 = u^2 + 2as$

$0^2 = (66.67)^2 + 2a \times 2600$

$a = -\frac{66.67^2}{5200} = -0.85\,m\,s^{-2}$

(b) $v = u + at$

$0 = 66.67 - 0.85t$

$t = 78.4\,s$

1.9 Sample Question

An object starts from rest and accelerates at $3\,m\,s^{-2}$ for 20 s. How far does it travel in this time?

Sample Answer

$u = 0,\ v = v,\ a = 3,\ s = s,\ t = 20$

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

$= 0 \times 20 + \frac{1}{2} \times 3 \times 20^2$

$= 600\,m$

For you to try

1. A car is travelling at a speed of $20\,m\,s^{-1}$ west. For a period of 5 s, it accelerates at a rate of $3\,m\,s^{-2}$ in the same direction. What distance does it travel in this time?
2. The speed of a car increases from $3\,m\,s^{-1}$ to $26\,m\,s^{-1}$ over a period of 8 s.
   (a) What is its acceleration?
   (b) What distance does it travel in this time?

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3 Over a distance of 5 m, the speed of a bicycle increases from $2\,m\,s^{-1}$ to $5\,m\,s^{-1}$.
- **(a)** What is the magnitude of its acceleration in this period?
- **(b)** How long does this take?

4 A truck is travelling at $80\,km\,h^{-1}$ and decelerates at a rate of $3\,m\,s^{-2}$.
- **(a)** How far does it travel before it comes to a rest?
- **(b)** How long does this take?

5 A bird flying at $3\,m\,s^{-1}$ west is given an acceleration of $1\,m\,s^{-2}$ east.
- **(a)** After 5 s, what is its velocity?
- **(b)** How far has it travelled in that time?

6 A car is travelling north at $25\,m\,s^{-1}$ and accelerating at $-5\,m\,s^{-2}$.
- **(a)** After 7 s, what is its speed and direction?
- **(b)** How far is it from its starting point?

7 A skateboarder starts from rest and accelerates to a speed of $15\,m\,s^{-1}$ over a distance of 20 m. What is his acceleration?

8 In good weather cars travel on a stretch of motorway at an average speed of $105\,km\,h^{-1}$. It takes them 30 min to cover the distance between two exits. On a wet day, the average speed falls to $80\,km\,h^{-1}$. How much longer does the journey take?

Measuring velocity and acceleration

You should be familiar with at least one method of measuring velocity and acceleration. The use of both ticker-tape timer and light gates is shown in Experiment 1.2.

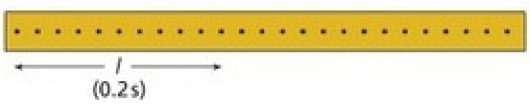
Experiment 1.2: Measurement of velocity and acceleration

Using a ticker-tape timer

Method to measure velocity

1. Set up the apparatus as shown in figure 1.26.
2. Push the vehicle so that it moves along the track at a constant velocity. As this happens the tape is pulled through the timer.
3. After the vehicle has stopped, remove the paper and examine it. It will look something like figure 1.27.

1.26 *A ticker-tape timer*



1.27 *Ticker tape*

Results

Every 0.02 s a mark is made on the paper by the hammer. To calculate the velocity (or speed), mark out the length covered by, say, 11 marks on the paper (i.e. 10 'spaces'). This corresponds to a time of (10 × 0.02) = 0.2 s. To find the velocity, use the formula:

$$\text{Velocity} = \frac{\text{Distance } (l)}{\text{Time}}$$

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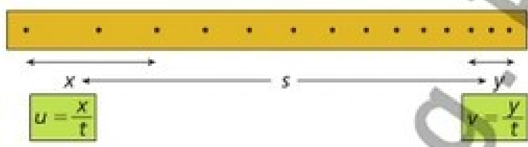
Method to measure acceleration

1. Attach a weight to the vehicle and let it fall, so that the vehicle accelerates along the track.
2. After the vehicle has stopped, remove the paper and examine it. It will look something like figure 1.28.



1.28 *Ticker tape, showing acceleration*

Results

The value of the time, t = (the number of spaces between dots) × (0.02). s is the distance travelled. It is measured from the middle of each section, as we are taking the average speed over each of these sections. To find the acceleration, we use the formula:

$$a = \frac{v^2 + u^2}{2s}$$

(derived from $v^2 = u^2 + 2as$).

Using light gates

Method to measure velocity and acceleration

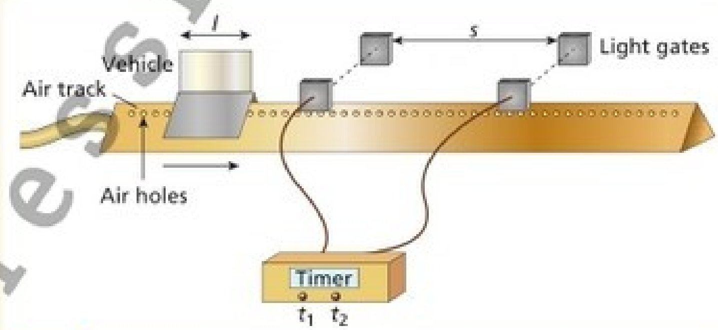
Push the vehicle along the air track, so that it passes through each of the light gates. As it passes through the gates, the light is blocked by the vehicle. The time that it takes to pass is recorded electronically by the timer (see figure 1.29).

Results

As we know the length of the card and the time it takes to pass the first light gate, we can calculate the initial velocity, u, using the formula:

$$u = \frac{l}{t_1}$$

This procedure can be repeated to measure the velocity at the second gate, v.



1.29 *Light gates*

The acceleration can be calculated using the formula:

$$a = \frac{v^2 - u^2}{2s}$$

We have looked at two methods of calculating velocity and acceleration in experiment 1.2. There are other methods, many of which make use of modern electronic devices known as data-loggers. These provide very accurate measurements and are a great way to carry out the experiments involved. However, they are difficult to cover in a textbook because the operation of each device is specific to the manufacturer's instructions.

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GrS PHYS Gr 10 Ss Mod 1.indd 20 5/9/19 4:33 PM

Energy and Work

Every form of energy has one thing in common: it can be converted in some way into movement. We say that work is done when a force makes an object move. This is why we say that energy is the 'ability to do work'. For this reason, the two are measured in the same unit, the joule (J).

- Energy is the ability to do work.
- Work and energy are both measured in joules.

A crucial principle in science is that of the conservation of energy:

The principle of conservation of energy states that energy cannot be created or destroyed, but only converted from one form into another.

Another way of looking at what happens when energy is converted into work is to say that energy is converted into kinetic energy from some other form. Some common examples of energy transfers are:

- In a car, chemical energy is converted into kinetic energy.
- When using a hairdryer electrical energy is converted into kinetic, heat and sound energy.
- A hydroelectric power station converts the kinetic energy of flowing or falling water into electrical energy.

Kinetic and Potential energy

Two particular forms of energy that we often encounter are kinetic energy and potential energy.

Kinetic energy is the energy that an object has due to its motion. The larger the mass of an object, or the greater its velocity, the more energy it has. This leads us to a formula for kinetic energy of an object of mass, *m*, travelling at velocity, *v*:

$$E_k = \frac{1}{2}mv^2$$

where: E_k – kinetic energy
m – mass
v – velocity

1.30 *Hydraulic power station*

Potential energy can come in many forms. If we stretch an elastic band, or a spring, we give it potential energy. Similarly, if we stand on a football so that we squeeze it, we know it will bounce back into shape when we release it. That is another form of potential energy. The energy that electric charges possess in an electric field is also closely related. But a situation we encounter most commonly in Physics problems is the potential energy we give an object simply by lifting it up. This is known as gravitational potential energy, and it can be evaluated using the formula:

1.31 *Compressing a football*

$$E_p = mgh$$

where: E_p – potential energy
m – mass
g – acceleration due to gravity
h – height

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This equation also makes use of the value of g, the acceleration caused by gravity. Neglecting air resistance, all objects will accelerate at the same rate while falling. The value of this acceleration is usually denoted by g, and its value is taken as 9.8 m s^{-2}.

If we lift a mass of 10 kg through a distance of 2 m, we can look at what has happened in different ways. From one perspective we have given potential energy to the mass. This follows the formula above and shows us that, altogether, the mass has gained 196 J:

$$E_p = mgh$$
$$= 10 \times 9.8 \times 2$$
$$= 196 \text{ J}$$

From another perspective, though, we can say that we have done work on the object, as clearly a force was required to lift it up through the 2 m. The force required to lift the object would be equal to its weight, so we can say that the work is also 196 J. (Remember that the weight of an object is equal to its mass multiplied by its acceleration due to gravity: $W = mg$.)

$$W = Fs$$
$$= 98 \times 2$$
$$= 196 \text{ J}$$

It is no coincidence that the two calculations yield the same result. It is inevitable that this will happen: the two formulae are in fact just two ways of looking at exactly the same situation. If we leave out the numbers and rearrange the formulae we can see this:

$$\boldsymbol{W = Fs}$$

but:

F = weight = mg

and:

s = displacement, or in the increase in height

so:

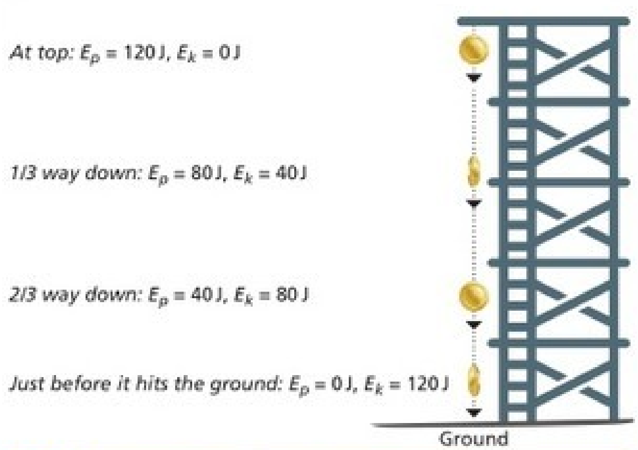
$$\boldsymbol{W = (mg)(h)}$$
$$\boldsymbol{W = E_p}$$

This means that we can say that the work done in lifting a body through a height is equal to the potential energy gained in doing so.

Similarly, when we give an object kinetic energy, the work done will be equal to the energy gained.

Conservation of kinetic and potential energy

If a coin is dropped from a high scaffold, it gains velocity as it loses height. Another way of looking at this is to say that it gains kinetic energy as it loses potential energy. In fact, the kinetic energy it gains is coming from the potential energy it loses. As no other form of energy is involved, we can see that potential energy lost must be equal to the kinetic energy gained.



1.32 *The conservation of kinetic and potential energy*

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Mass energy

Published in scientific papers in 1905, Albert Einstein introduced ideas and formulae that revolutionised the way we see the world. We will consider his most well-known formula here:

$$E = mc^2$$

where:

E – energy
m – mass
c – speed of light

What Einstein realised and showed in this equation is that mass is in fact a form of energy, and that it can be converted into other forms of energy, such as light and heat. The energy contained within a mass of 1 kg is therefore given by:

$$E = (1)(3 \times 10^8)^2$$
$$= 9 \times 10^{16}\ \text{J}$$

This is a huge quantity of energy – 90 thousand million million joules – and the amounts involved when mass is converted into other forms of energy tend to be enormous, too. The energy in a nuclear explosion comes from the conversion of mass, for example.

1.10 Sample Question

A pupil with a mass of 45 kg climbs to a height of 4 m up a rope in a school gym. How much work has he done?


1.33

Sample Answer

Work done = Potential energy gained
$= mgh$
$= 45 \times 9.8 \times 4$
$= 1764$ J

1.11 Sample Question

What is the kinetic energy of a bus with a mass 14200 kg moving at a velocity of 25ms^{-1}?


1.34

Sample Answer

$$E_k = \frac{1}{2} mv^2$$
$$= \frac{1}{2} \times 14200 \times 25^2$$
$$= 4{,}437{,}500\ \text{J}$$

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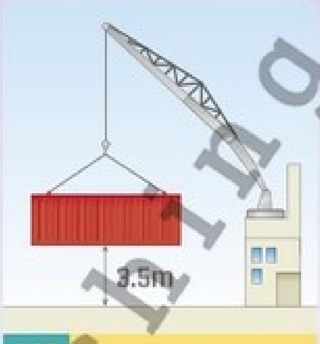
GrS PHYS Gr 10 Ss Mod 1.indd 23 5/9/19 4:34 PM

1.12 Sample Question

A crane lifts a 2 tonne container to a height of 3.5 m. What potential energy is gained by the mass? How much work is done in lifting the mass?



1.35

Sample Answer

$E_p = mgh$

$= 2000 \times 9.8 \times 3.5$

Work done = Potential energy gained = 68600 J

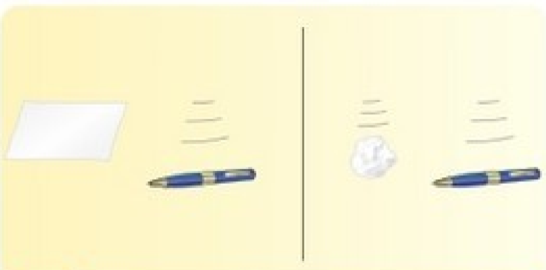
For you to try

1 State the principle of conservation of energy.
2 If a force of 30 N causes an object to move through a distance of 80 m, how much work is done?
3 A stone of mass 800 g is rolled off the edge of a cliff of height 45 m.
   (a) How much potential energy does it have just when it begins to fall?
   (b) At what height does it have a potential energy of 200 J? What is its kinetic energy at that point?
   (c) What is its kinetic energy at the moment just before it strikes the ground? What is its speed at that point?
4 How much energy is involved when 1.5 kg of mass is converted into other forms of energy?
5 A woman of mass 65 kg climbs a stairs of total height 2.4 m. How much work has she done?
6 A crane lifts a weight of 500 kg to a height of 40 m. What potential energy is gained by the mass? How much work is done in lifting the mass?

1.36 *Question 3*

Falling bodies

Exactly how falling bodies behave is something that scientists have studied for many centuries. Greek philosopher Aristotle (384-322 BC) believed that heavier objects will always fall faster than lighter ones. This can often seem to be the case, but the difference is caused by air resistance. If we drop a flat piece of paper to the floor alongside a heavier object such as a pen, the pen will always hit the ground first because the paper experiences more air resistance. However, if you crumple up the paper, so that air resistance is reduced while the weight is not changed, and drop both the pen and paper again, they will hit the ground at the same time.


1.37 *The acceleration caused by gravity is constant*

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Italian physicist Galileo Galilei (1564-1642) saw the faults in Aristotle's understanding. He argued that, when we can ignore air resistance, all objects fall at the same rate. He famously demonstrated this by dropping various objects from the Leaning Tower of Pisa.

Galileo argued that his experiments showed that a hammer and a feather would fall at the same rate in the absence of air. This experiment was famously carried out centuries later by American astronaut David Scott (1932-) on the Apollo 15 mission to the Moon.

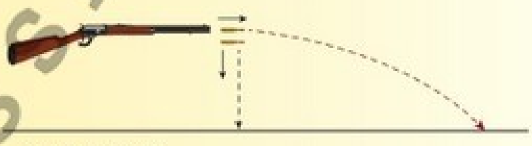
1.38 *The Leaning Tower of Pisa*

English physicist and mathematician Isaac Newton (1642-1727) was born in the same year in which Galileo died, and he carried on with much of Galileo's work and finally developed a theory of gravity. For now we will concentrate on the key part of Galileo's work: that all objects fall at the same rate. This means that they all have the same acceleration. This is usually referred to as the **acceleration caused by gravity** and is denoted by the letter g. Its value is generally taken to be 9.8.

Acceleration caused by gravity, $g = 9.8\,m\,s^{-2}$.

Projectiles

Think about a rifle that is designed to fire a bullet forwards at exactly the same time as it drops a bullet vertically. On level ground, which bullet will hit the ground first?



1.39 *All bodies fall at the same rate*

The answer is that – as long as the bullet is fired horizontally and the person firing the rifle is on level ground – both bullets will hit the ground together. This is another important way of understanding Galileo's work. Just as it is true that all objects will fall at the same rate regardless of their weight, it is also true that all objects will fall at the same rate regardless of whether or not they are moving forwards.

The bullet that is fired forwards will travel a greater distance before hitting the ground. However, while travelling forwards, it also falls with the acceleration caused by gravity.

Falling bodies and the equation of motion

All of the mathematical work covered in the previous section of this module applies to falling bodies, where the acceleration is that caused by gravity. It is important to remember here that acceleration is a vector quantity and so its direction matters. This means that we have to distinguish between the acceleration of those bodies that have been thrown upwards and are slowing down, and those that have been allowed to fall and are gaining speed. Generally, we take the acceleration to be positive when an object is falling (and gaining speed) and negative when it is rising (and slowing down).

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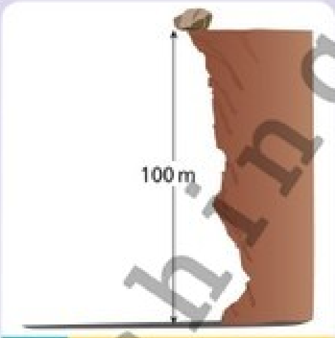
1.13 Sample Question

A stone is dropped from the top of a cliff 100 m high.

(a) With what speed does it hit the ground?

(b) How long does it take to reach the ground?

$u = 0$, $v = v$, $a = g = 9.8$, $s = 100$, $t = t$



1.40

Sample Answer

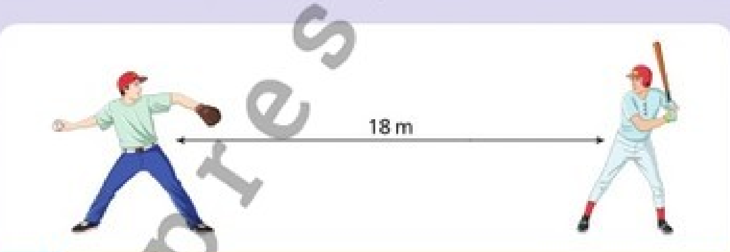
(a)
$$v^2 = u^2 + 2as$$
$$= 0^2 + 2 \times 9.8 \times 100$$
$$= 1960$$
$$v = 44.3\,\mathrm{m\,s^{-1}}$$

(b)
$$v = u + at$$
$$44.3 = 0 + 9.8(t)$$
$$t = \frac{44.3}{9.8} = 4.52\,\mathrm{s}$$

Take g to equal $9.8\,\mathrm{m\,s^{-2}}$.

1.14 Sample Question

A baseball player throws a ball horizontally so that it is moving at $35\,\mathrm{m\,s^{-1}}$. How far has it fallen by the time it reaches the batter, a distance of 18 m away?



1.41

Sample Answer

Horizontal:

$u = 35$, $v = 35$, $a = 0$, $s = 18$, $t = t$

$$s = ut + \frac{1}{2}at^2$$
$$18 = (35)t + \frac{1}{2}(0)t^2$$
$$t = \frac{18}{35} = 0.51\,s$$

Vertical:

$u = 0$, $v = v$, $a = g = 9.8$, $s = s$, $t = 0.51$

$$s = ut + \frac{1}{2}at^2$$
$$= 0(0.51) + \frac{1}{2}(9.8)(0.51)^2$$
$$= 1.27\,\mathrm{m}$$

The ball has fallen 1.27 m.

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1.15 Sample Question

A bullet is shot vertically upwards with a velocity of 15 m s^{-1}. What is the greatest height reached?

Sample Answer

1.42

$u = 15$, $v = 0$, $a = 9.8$, $s = h$, $t = t$

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

$0^2 = 15^2 + 2 \times 9.8 \times h$

$h = \frac{15^2}{11.6} = 11.48\,\text{m}$

1.16 Sample Question

A bullet is shot forwards at 400 m s^{-1} at a height of 1.7 m and on level ground. At the same time, a similar bullet is dropped to the ground from the same height.

(a) The two bullets hit the ground at the same time, but how long does it take for them to do so?

(b) How far does the bullet fired from the rifle travel forwards in this time?

1.43

Sample Answer

(a) $u = 0$, $v = v$, $a = 9.8$, $s = 1.7$, $t = t$

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

$1.7 = 0(t) + \frac{1}{2} \times 9.8 \times t^2$

$t = 0.59\,\text{s}$

(b) $u = 400$, $v = 400$, $a = 0$, $s = s$, $t = 0.59$

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

$= 400 \times 0.59 + 0$

$= 236\,\text{m}$

For you to try

1 A stone is dropped from a tall building and takes 4.1 s to hit the ground. What is the height of the building?

2 A stone is dropped from the top of a cliff.

(a) With what speed does it hit the sea, 120 m below?

(b) How long does it take?

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3 A stone is thrown upwards with a velocity of $22\,m\,s^{-1}$. What is the greatest height reached?

4 A stone is thrown upwards from a height of 1.8 m with a velocity of $21.4\,m\,s^{-1}$.

(a) How long does it take to reach its greatest height?

(b) What is its greatest height?

(c) How long does it take to fall to the ground?

5 A bullet is fired upwards with a velocity of $400\,m\,s^{-1}$.

(a) What is its greatest height?

(b) How long would you expect it to fall back to the height from which it is fired?

6 A bullet is shot forwards horizontally at the same time as a similar bullet is dropped to the ground from the same height. Which bullet will hit the ground first? Explain your answer.

7 A ball is dropped from a height of 1.5 m. How long does it take to hit the ground?

8 A ball rolls off the edge of a table of height 80 cm.

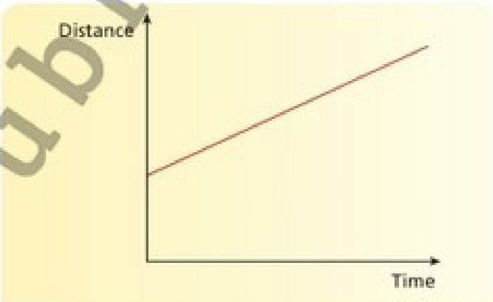
(a) How long does it take to strike the floor?

(b) If it hits the floor at a distance of 1.5 m, horizontally, from the table, with what speed was it initially rolling?

Distance–time graphs

Graphs are often used in science to help us to study various situations. They are of particular use in physics to represent the motion of a body. One way of doing this is to use the y-axis to represent the distance a body has travelled, while using the x-axis to represent time. The resulting graph lets us see at a glance whether the body is moving forwards or backwards and whether it is speeding up or slowing down.

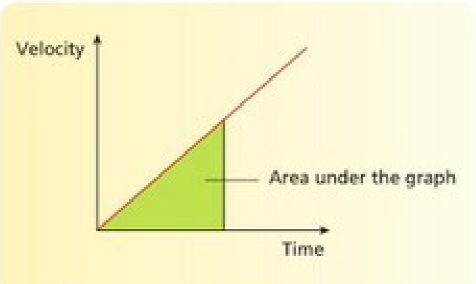
The graph in figure 1.44 represents the distance a car has travelled from a particular point on a road. You can see that it is constantly moving away from that point, and that it is doing so at a constant rate (or speed).



1.44 *This distance–time graph represents the motion of a body travelling at constant speed. The speed is the slope of the graph*

Velocity–time graphs

We can also use the y-axis on a graph to represent the velocity of an object while still using the x-axis to represent time. In the graph shown in figure 1.45, the velocity is constantly increasing. Because the graph has a straight line, we can see that the acceleration is constant. The area between the curve, or line, and the x-axis also holds meaning – it tells us the total distance travelled. This can be explained using the mathematical technique known as integration, which some of you will study in maths class.



1.45 *In this velocity–time graph, the slope is the acceleration. The area under the graph is the distance travelled*

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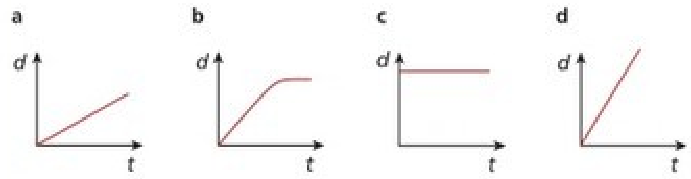
GrS PHYS Gr 10 Ss Mod 1.indd 28 5/9/19 4:34 PM

1.17 Sample Question

The graphs in figure 1.46 represent the motion of a car along a road, with the distance measured from a fixed point on that road.

(a) Which graph represents a car that is motionless?
(b) Which graph represents a car that is slowing down?
(c) Which graph represents the car that is travelling the fastest?



1.46

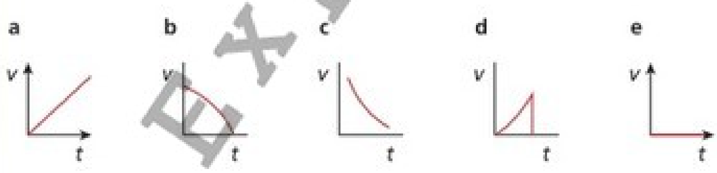
Sample Answer

(a) Graph c represents a car that is motionless.
(b) Graph b represents a car that is slowing down.
(c) Graph d represents the car that is travelling the fastest.

1.18 Sample Question

The graphs in figure 1.47 represent the velocity of various cars along a stretch of road.

(a) Which graphs represent cars that are slowing down?
(b) Which graphs represent cars that have constant acceleration?
(c) Which graph represents a car that has stopped?
(d) Which graph represents a car that initially accelerated before suddenly braking?



1.47

Sample Answer

(a) Graphs b and c represent cars that are slowing down.
(b) Graphs a and e represent cars that have constant acceleration.
(c) Graph e represents a car that has stopped.
(d) Graph d represents a car that initially accelerated before suddenly braking.

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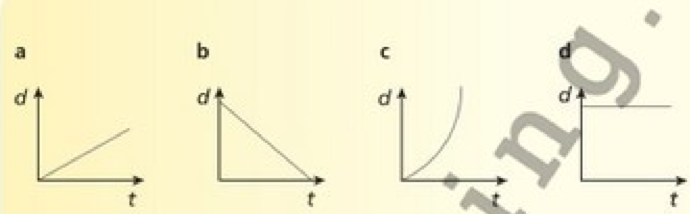
For you to try

1 The graphs in figure 1.48 represent the motion of a car along a road, with the distance measured from a fixed point on that road.



1.48 *Question 1*

(a) Which graph represents a car that is motionless?

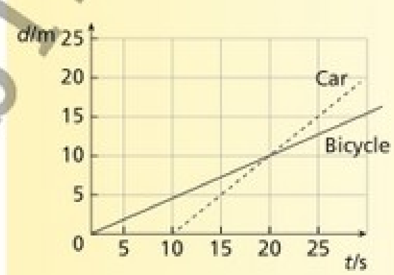
(b) Which graph represents a car that is speeding up?

(c) Which graph represents the motion of a car that is towards the fixed point?

2 A cyclist begins a journey and travels as indicated by the graph in figure 1.49. After 10 s, a car passes the same point on the road.

(a) After how many seconds does the car catch up with the bicycle?

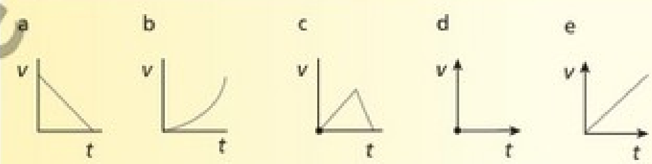
(b) What is the speed of each of the vehicles during the journey?



1.49 *Question 2*

3 A skateboarder begins a journey and slowly increases in speed before stopping. She then returns to her starting point at a constant speed. Represent her journey on a sketch of a distance-time graph.

4 The graphs in figure 1.50, represent the velocity of various cars along a stretch of road.



1.50 *Question 4*

(a) Which graphs represent cars that are speeding up?

(b) Which graphs represent cars that have constant acceleration?

(c) Which graph represents a car that has stopped?

(d) Which graph represents a car that initially accelerated before suddenly braking?

5 A bicycle begins from rest and accelerates at $2\,m\,s^{-2}$ until it is travelling at $20\,m\,s^{-1}$.

(a) After how many seconds is it travelling at $20\,m\,s^{-1}$?

(b) Represent its motion on a graph and, from the graph, find the distance travelled in this time.

Vector resolution

If a person pushes a heavy box along the floor they will often, for convenience sake, do so at an angle to the floor. The man in figure 1.51 is pushing the box with a force of 100 N at an angle of 30°. However, the box doesn't move in the direction in which the man is pushing it. Instead, it moves horizontally along the floor.

1.51 *The box moves horizontally along the floor*

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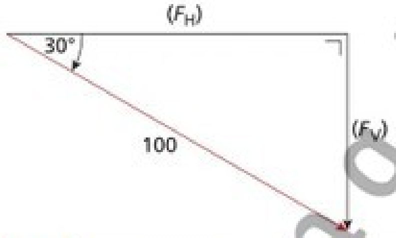
Using trigonometry we can find out how much of the force that the man creates is actually pushing the box forwards along the floor. This is called the **resolution of vectors**. We draw a line to represent the 100 N, and make this the hypotenuse of a right-angled triangle, as shown in figure 1.52.



1.52 *Vector resolution*

The horizontal side of this triangle represents the **horizontal component of the force** (F_H), and the vertical side represents the **vertical component of the force** (F_V). We can find their lengths – and therefore the magnitude of the forces – using trigonometry:

$$\sin 30° = \frac{\text{Opposite}}{\text{Hypotenuse}} = \frac{F_V}{100}$$

$$F_V = 100 \sin 30° = 50\,\text{N}$$

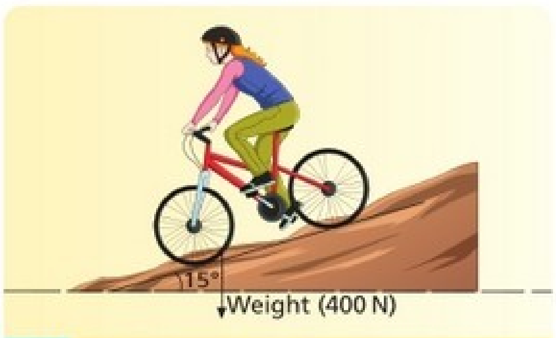
$$\cos 30° = \frac{\text{Adjacent}}{\text{Hypotenuse}} = \frac{F_H}{100}$$

$$F_H = 100 \cos 30° = 86.7\,\text{N}$$

This means that the man is creating a single force that is exactly equivalent to creating two separate forces: one of 86.7 N horizontally, and the other of 50 N vertically. The 86.7 N is the force that actually pushes the box forwards. The 50 N also has an effect: it is pushing the box down onto the ground, increasing friction and making it more difficult to push the box forwards.

What is clear is that it would be more efficient to push the box directly forwards along the ground. None of the effort required to create 100 N would then be wasted, and the friction would be minimised. Most of us would do this instinctively when pushing a heavy weight.

Another way of resolving vectors into two components arises when we study objects that are not on level ground. The cyclist in figure 1.53 has a total weight of 400 N and is on ground at an angle of 15° to the horizontal. Her weight pushes vertically down towards the centre of the Earth, as you would expect, but she isn't able to move vertically downwards, so the weight instead causes her to roll down the hill. We can again use trigonometry to calculate what component of her weight is operating along the direction in which she moves.



1.53 *A cyclist moving downhill*

We draw a downwards arrow to represent the direction in which the cyclist's weight operates, the length of which represents the magnitude of her weight, or 400 N. We then draw a right-angled triangle so that this line is the hypotenuse. The smaller angle in the triangle is 15°, the same as the angle between the ground and the horizontal.

The components of the cyclist's weight parallel to the ground ($F_{\parallel}$) and perpendicular to it ($F_{\perp}$) are again found using trigonometry:

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$$\sin 15° = \frac{\text{Opposite}}{\text{Hypotenuse}} = \frac{F_{//}}{400}$$

$$F_{//} = 400 \sin 15° = 103.5\,\text{N}$$

$$\cos 15° = \frac{\text{Adjacent}}{\text{Hypotenuse}} = \frac{F_{\perp}}{400}$$

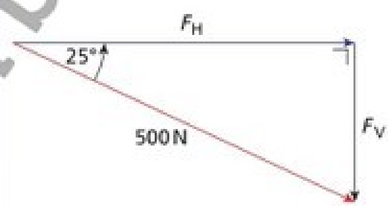
$$F_{\perp} = 400 \cos 15° = 386.4\,\text{N}$$

It is often easiest to see the significance of the resolution of vectors when we are dealing with forces, but it should be remembered that any vector can be resolved into two or more components.

1.54 *Vector resolution*

1.19 Sample Question

A heavy object is pushed along a horizontal floor with a force of 500 N, at an angle of 25° to the horizontal. What are the horizontal and vertical components of this force?



1.55

Sample Answer

$$\sin 25° = \frac{F_V}{500}$$

$$F_V = 500 \sin 25° = 211.3\,\text{N}$$

$$\cos 25° = \frac{F_H}{500}$$

$$F_H = 500 \cos 25° = 453.2\,\text{N}$$

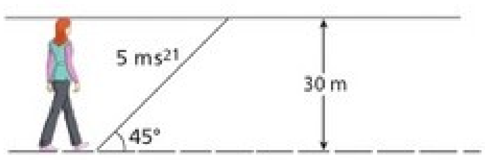
1.20 Sample Question

A woman walking at $4\,\text{m}\,\text{s}^{-1}$ crosses a road of width 35 m, at an angle of 45° to the side of the road, as shown in figure 1.56.

(a) What is the component of her velocity parallel to the side of the road?

(b) What is the component perpendicular to the side of the road?

(c) How long will it take her to cross the road?



1.56

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Sample Answer

(a) $v_{//} = 4\cos 45° = 2.83$

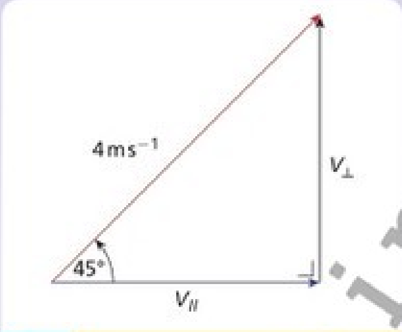
$= 2.83\,\mathrm{m\,s^{-1}}$

(b) $v_{\perp} = 4\sin 45° = 2.83\,\mathrm{m\,s^{-1}}$

(c) $s = ut + at^2$

$35 = 2.83t + \frac{1}{2}(0)t^2$

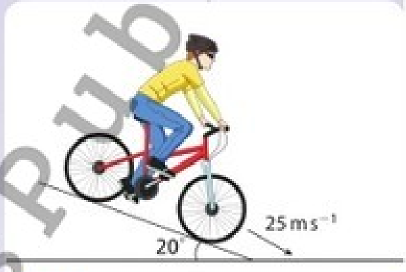
$t = \frac{35}{2.83} = 12.37\,s$



1.57

1.21 Sample Question

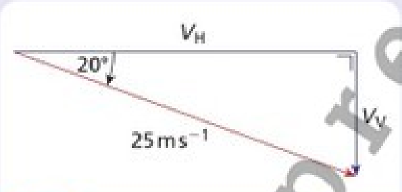
A hill is at an angle of 20°. A bicycle is moving down the hill with a velocity of 25 m s⁻¹. Resolve this into horizontal and vertical components.



1.58

Sample Answer

$v_V = 25\sin 20° = 8.55\,\mathrm{m\,s^{-1}}$
$v_H = 25\cos 20° = 23.49\,\mathrm{m\,s^{-1}}$



1.59

1.22 Sample Question

A BMX bicycle has a weight of 120 N and is on a ramp that is at an angle of 18° to the horizontal.

(a) What is the component of the bicycle's weight parallel to the ramp?

(b) What is the component perpendicular to it?

1.60

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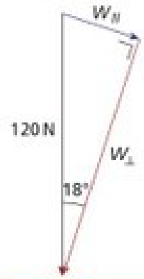
Sample Answer

(a) $W_{//} = 120 \sin 18° = 37.08\,N$
(b) $W_{\perp} = 120 \cos 18° = 114.13\,N$



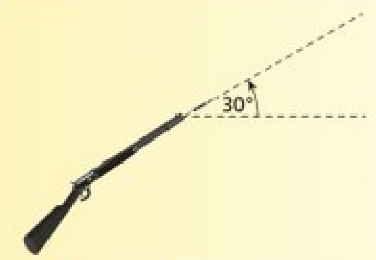
1.61

For you to try

1 Find the horizontal and vertical components of a 450 N force acting at an angle of 60° to the horizontal.

2 A rope is used to pull a sleigh along horizontal, snow-covered ground. The force created by the rope on the sleigh is 1500 N, and the rope is at an angle of 20° to the horizontal.
 (a) What are the horizontal and vertical components of this force?
 (b) Is the vertical component of the force making it easier or harder to pull the sleigh?

3 Find the horizontal and vertical components of the velocity of the bullet shown in figure 1.62 as it leaves the barrel of a rifle at $380\,m\,s^{-1}$.



1.62 *Question 3*

4 What are the horizontal and vertical components of the acceleration of $5\,m\,s^{-2}$ at an angle of 45° to the horizontal?

5 A bicycle is accelerating down a hill with an acceleration of $5\,m\,s^{-2}$. The hill is at an angle of 25° to the horizontal. Resolve this into horizontal and vertical components.

6 A skateboarder has a weight of 650 N and is on a ramp that is at an angle of 22° to the horizontal.
 (a) What is the component of the skateboarder's weight parallel to the ramp?
 (b) What is the component perpendicular to it?

7 A stone on a roof has a weight of 2.4 N. The roof is at an angle of 35° to the horizontal. What are the components of the stone's weight parallel and perpendicular to the roof?

Momentum

The momentum of a body is defined as the product of its mass and velocity:

$$p = mv$$

A 1000 kg car moving in traffic at, say, $5\,m\,s^{-1}$ would have a momentum of 1000 × 5 = $5000\,kg\,m\,s^{-1}$. An artillery shell of mass 12.5 kg travelling at $400\,m\,s^{-1}$ would also have a momentum of $5000\,kg\,m\,s^{-1}$ (12.5 × 400). The two are very different objects and very different situations, but they have this in common if nothing else: you wouldn't like to be standing directly in the path of either of them.

Momentum is a vector quantity. Its unit is $kg\,m\,s^{-1}$.

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GrS PHYS Gr 10 Ss Mod 1.indd 34 5/9/19 4:34 PM

1.23 Sample Question

What is the momentum of a bullet of mass 5 g travelling at 380 m s^{-1} east?

Sample Answer

Momentum, $p = mv$

$= 0.005 \times 380 = 1.9$ kg m s^{-1} east

Conservation of momentum

Momentum is a very useful concept when we are studying the way that two different bodies collide with, or push against, each other. In such situations, as long as there are no external forces affecting the two bodies, we can say that momentum is conserved. This is known as the **principle of conservation of momentum**.

The principle of conservation of momentum states that the total momentum of two bodies before an interaction is equal to the total momentum after the interaction, provided no external forces are acting on the system.

In many cases, our use of this principle involves a few assumptions about external forces. When two balls on a snooker table collide, we usually assume that momentum is conserved and we ignore the fact that friction between the balls and the table must have some effect, and that this would be an external force. This is a reasonable compromise as long as we look at the total momentum immediately before the collision and immediately afterwards. In the very short time in between, friction would have a very small effect.

In the case of somebody kicking a football, however, we wouldn't attempt to use the principle of conservation of momentum. We could measure the momentum of the kicker's foot immediately before the collision and that of the ball immediately afterwards, but it is impossible to ignore the external forces involved: the kicker's legs and whole body are playing some sort of role, and they are having far too great an effect for us to ignore them.

The principle of conservation of momentum can be treated mathematically using this equation:

$$m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2$$

where:

- m – mass
- u – velocity before the interaction
- v – velocity after the interaction

1.24 Sample Question

A bullet of mass 25 g travels at a speed of 200 m s^{-1} and strikes a wooden block of mass 1 kg that is free to move. The bullet is embedded in the block, and after the collision the two move together. What is their combined velocity?

1.63

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GrS PHYS Gr 10 Ss Mod 1.indd 35 5/9/19 4:34 PM

Sample Answer

Momentum before = Momentum after OR

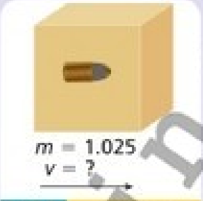
$$p_{before} = p_{after}$$

$$(mu)_{bullet} + (mu)_{block} = (mv)_{bullet+block}$$

$$(0.025 \times 200)_{bullet} + (1 \times 0)_{block} = (1.025v)_{bullet+block}$$

$$1.025v = 5$$

$$v = \frac{5}{1.025} = 4.88\,\mathrm{m\,s^{-1}}$$



1.64

It is important to realise that conservation of momentum is not only useful when we are looking at collisions. It also applies when two bodies push against each other and move off in opposite directions. This is the case when a bullet is fired from a pistol, for example. Beforehand, the total momentum is zero. Afterwards the momentum of the bullet – with low mass and high velocity – and the gun – with high mass and low velocity – will be equal in magnitude but opposite in direction. The total of the two is still zero.

1.25 Sample Question

A pistol of mass 360 g fires a bullet of mass 7.5 g at 400 m s^{-1}. What is the recoil velocity of the pistol?

Sample Answer

$$p_{before} = p_{after}$$

$$0 = 0.360v + (0.0075)(400)$$

$$v = \frac{-3}{0.360} = -8.33\,\mathrm{m\,s^{-1}}$$

The pistol moves at 8.33 m s^{-1}, in the opposite direction to that in which the bullet moves.

1.65

As seen in sample question 1.22, recoil velocity is the term we use to describe the speed of the pistol immediately after firing. This movement has to be controlled by the user, and if they are not properly prepared, it can easily injure them.

Bigger guns that fire larger bullets or shells can have a very large recoil velocity, and it can be very hard to control them. The recoil of cannons on ships in the 1700s could be big enough to tear the cannon from its bearings and to cause very serious damage. Modern artillery guns often use powerful springs built into the gun itself to absorb the recoil to avoid damage.

1.66 *The recoil velocity is small where there is no actual bullet*

When actors fire pistols in movies, they are usually firing blank cartridges. These contain gunpowder, but no actual bullet. Because of this they have a much lower mass than a regular cartridge, and the recoil velocity is much less than it would usually be. This allows actors to treat the firing of a pistol rather casually.

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For you to try

1 What is meant by the term 'momentum'?

2 What is the unit of momentum?

3 What is the momentum of a car of mass 1050 kg travelling at 80 km h^{-1}?

4 Which has a higher momentum, a car of mass 1100 kg travelling at 22 m s^{-1}, or a bullet of mass 30 g travelling at 190 m s^{-1}?

5 Two cars are travelling in the same direction on a straight road. One has mass of 1070 kg and is travelling at 18 m s^{-1} north. The other has a mass of 950 kg and is travelling at 22 m s^{-1} north. What is the total momentum of the two cars?

6 A cyclist, whose total mass including her bike is 68 kg, is travelling at 13 m s^{-1} but applies her brakes and slows down to 5 m s^{-1}. What is the change in her momentum?

7 What is the principle of conservation of momentum?

8 A bullet of mass 45 g is travelling horizontally at 400 m s^{-1} and strikes a block of wood of mass 5 kg, which is at rest. If the bullet becomes embedded in the block, what is its initial velocity immediately after impact?

9 A car of mass 900 kg travelling at 20 m s^{-1} collides with another car of mass 1050 kg that is initially at rest. If the two cars stick together and travel in the same direction as the first car was moving, what is the initial velocity of the wreckage?

10 A pistol of mass 600 g is at rest. It fires a bullet of mass 8 g horizontally at velocity 390 m s^{-1}. What is the recoil velocity of the pistol?

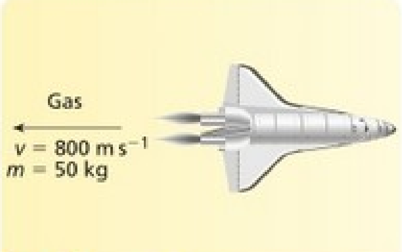
11 A red snooker ball is at rest when it is struck by the yellow ball, of identical mass, moving at 5 cm s^{-1}. The two balls then move along the same line in which the yellow ball was moving. The red ball has an initial velocity of 3 cm s^{-1}. What is the initial velocity of the yellow ball?

12 A rocket of mass 10 000 kg is travelling forwards in space at 3 km s^{-1}. It fires a mass of 50 kg of gas as shown in figure 1.67, with a velocity of 800 m s^{-1}.

(a) What is the total magnitude of the momentum of the gas?

(b) What is the magnitude of the momentum of the rocket after the gas is ejected? (Ignore the loss in mass of the rocket.)

(c) What is the magnitude of the velocity of the rocket after the gas is emitted?



1.67 *Question 12*

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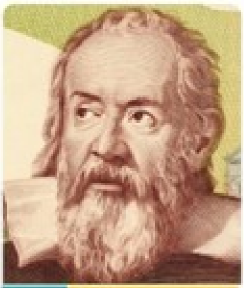
Module 2 Forces

Learning objectives

- To understand Newton's laws and determine the resultant force in calculations 10.1.2.1
- To understand the Law of Universal Gravitation and describe the motion of space vehicles 10.1.2.2

Galileo and Newton

When Galileo Galilei attended university as a young man in Italy in the 1600s, he initially studied medicine, which then would have included philosophy and ethics as well as what we now think of as science and mathematics. When he learnt about physics, much of the current knowledge was based on the work of the ancient Greek philosophers such as Aristotle (384–322 BC) and Archimedes (287–212 BC). Some of this was of great value and is still studied today, but much of it was flawed: Aristotle, for example, believed that heavier objects will always fall faster than lighter bodies.



2.1 *Galileo Galilei (1564-1642)*

Galileo saw that this was untrue and argued that – in the absence of air resistance – all bodies fall at the same rate. You will already have learnt about this. However, a key part of his work was not just this new knowledge, it was his whole approach to how we should learn about the world and deepen our understanding. He believed that we should always test our ideas out with experiments and that we should be open to changing our ideas once we saw the results of those experiments.

So when Galileo dropped a cannonball and a musket ball from the Leaning Tower of Pisa, he wasn't just establishing the truth of how these objects fall. He was also helping to establish the scientific method: that all of our ideas should be subject to test and verification. This approach gradually led to the splitting of science from the world of philosophy. This process continued after he died and was greatly advanced by the work of Isaac Newton (1642–1727).

Newton built on what Galileo and others had done, and much of what are called 'Newton's laws' were known and understood before him. However, he developed the mathematical techniques that allowed these ideas to be clarified and, crucially, verified.

Newton's laws of motion

Newton's laws of motion were laid down in his great work, *Philosophiae Naturalis Principia Mathematica* (often called simply the Principia), which was first published in 1687.

1. A body will continue in a state of rest or of uniform velocity unless an unbalanced external force acts upon it
2. The rate of change of a body's momentum is proportional to the force that causes it and takes place in the direction of that force
3. If body A exerts a force on body B, then body B exerts an equal but opposite force on body A.

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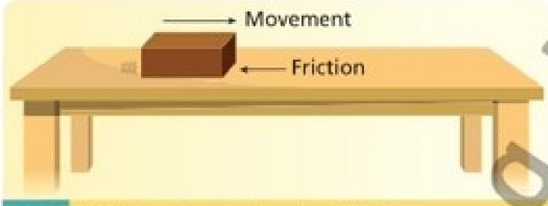
Newton's first law, in particular, owes a lot to Galileo.



2.2 *Friction causes moving objects to stop*

Many of us are happy to accept that moving objects slow down and stop because of friction. And similarly, we know that when we reduce friction objects can travel further. However, we often struggle to accept the obvious conclusion of this, which is **Newton's first law**: that in the absence of friction a moving object would travel forever. In many ways, the genius of Galileo and Newton was to recognise the obvious.

Put in other words, the first law tells us that, just as it is true that an object at rest will remain at rest unless a force makes it move, it is equally true that once an object is moving, it will keep moving unless a force makes it stop.

You may notice this in a car. If the car stops suddenly, you feel yourself being apparently pushed forward. In fact, what is happening is that you are continuing to travel at a constant speed, until the seat belt forces you to stop, as described by the first law.


2.3 *Apollo 13 travelled over 500 000 km with almost no fuel in 1970. In the absence of air resistance, no fuel was needed*

The first law is central to space travel. Spacecraft require large quantities of fuel to take off from Earth and to effectively escape the Earth's gravitational pull, but once they have done so they can switch off their engines. Typically they travel at speeds of several kilometres per second, and will continue to do so indefinitely: in the absence of friction and air resistance, there is no force in space to cause them to slow down and stop.

The **second law** is crucial to making sense of all of Newton's work. In it, he defined what exactly he meant by 'force'. This allowed force to be measured, which meant that all of his other theories could be tested and verified.

The second law can be used in combination with the law of gravitation to predict exactly how long it should take Earth – and each of the planets – to travel around the Sun. Because these 'predictions' match the reality with great precision, it means that we can trust the laws of motion, and gravitation, to be true.

F = ma

From the second law, we can see that force is proportional to the rate of change in a body's momentum. That is, for a body of mass m, changing from a velocity u to one of v:

Derivation

$$F \propto \frac{mv - mu}{t}$$

$$\text{so } F \propto \frac{m(v-u)}{t}$$

$$\text{so } F \propto ma \qquad \left(\text{as } a = \frac{v-u}{t}\right)$$

$$\text{so } F = kma$$

As this is the formula that is used to define the unit of force, the Newton, we can choose a value for k, and we choose the value of 1, so:

F = ma

GrS PHYS Gr 10 Ss Mod 2.indd 39 5/9/19 4:36 PM

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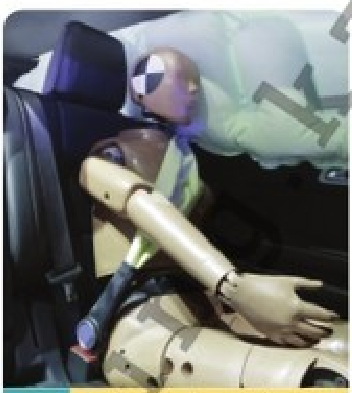
The third law is seen in effect in the use of seat belts. When a person is thrown forwards, the belt expands slightly, which extends the time over which the person slows down. This decreases the value of a, the acceleration, and with it reduces the value of F, the force on the person.

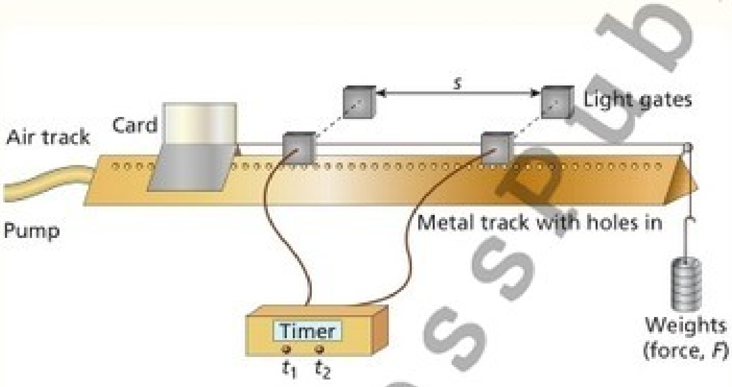
From the second law, we can take a definition of force:

A force is anything that causes or tends to cause an acceleration.

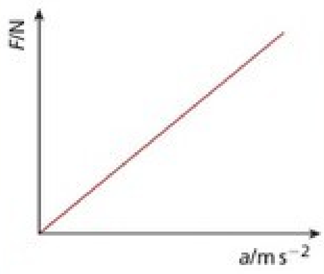


2.4 *Air bags and seat belts reduce the forces experienced during a crash*

Experiment 2.1: Verification that acceleration is proportional to force (i.e. $a \propto F$)



2.5 *Experimental apparatus*



2.6 *A straight line through the origin verifies that acceleration is proportional to force*

Method

1. Set up the apparatus as shown in figure 2.5.
2. Set the weights (F) and release the vehicle from rest.
3. Calculate the initial velocity, *u*, and the final velocity, *v*.
4. Find the acceleration, using $a = \frac{v^2 - u^2}{2s}$.
5. Remove one 1-N disc from the slotted weight, attach it to the vehicle, and repeat.
6. Continue for a number of values of F, and record the results.
7. Draw a graph of F in N against a in m s^{-2}.

Results and conclusions

A straight line through the origin shows that, for a constant mass, the acceleration is proportional to the applied force. (The mass of the system is given by the slope of the line.)

Accuracy

- The weights are transferred between the string and the vehicle to keep the total mass constant. They must be stuck onto the vehicle so that they will move with it.
- The air track reduces friction, improving accuracy.

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2.1 Sample Question

A mass of 12 kg is made to accelerate at 3 ms^{-2}. What is the magnitude of the force acting on it?

Sample Answer

$$F = ma$$
$$= 12 \times 3$$
$$= 36\text{ N}$$

2.2 Sample Question

A force of 150 N acts on a body of mass 18 kg. What is the acceleration?

Sample Answer

$$F = ma$$
$$a = \frac{F}{m}$$
$$= \frac{150}{18} = 8.33\text{ m s}^{-2}$$

2.3 Sample Question

A car of mass 1050 kg accelerates from rest to a speed of 80 $km\,h^{-1}$ over 9 s. What is the force acting on it?

Sample Answer

$$v = u + at$$
$$v = \frac{80 \times 1000}{(60 \times 60)} = 22.22\text{ m s}^{-1}$$
$$22.22 = 0 + 9a$$
$$a = \frac{22.22}{9} = 2.47\text{ m s}^{-2}$$
$$F = ma$$
$$= (1050)(2.47) = 2593.5\text{ N}$$

Newton's **third law** is both widely known and widely misunderstood. The common statement that 'every action has an equal but opposite reaction' is a valid way of expressing this law, but it is important to know when using it that the word 'action' here has a very specific meaning: that one body is creating a force on another. Because this is easily misinterpreted, we tend to avoid the use of the word 'action' altogether in modern books.

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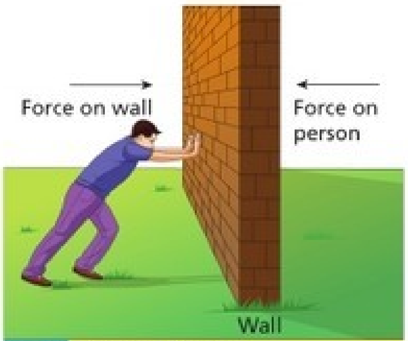
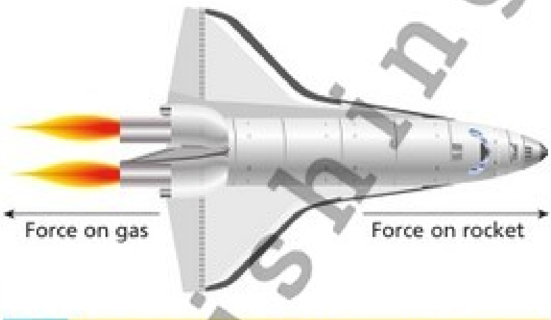
GrS PHYS Gr 10 Ss Mod 2.indd 41 5/9/19 4:36 PM

We encounter the third law all the time. Indeed, it is such an integral part of our daily lives that it is easy to miss it. If you push against a wall, you clearly create a force (see figure 2.7). The wall will create an equal force in the opposite direction, pushing back on you. If you push very hard, it is unlikely that the wall will fall, but it is very likely that you will be pushed into an upright position. This is the effect of the 'reaction', the force created by the wall.



2.7 *Newton's third law*



2.8 *The third law is seen in rocket propulsion. The large force created towards the rear of the rocket creates an equal, but opposite, force forwards. The rocket moves forwards as a result*

Experiment 2.2: To demonstrate Newton's third law

Method 1

1. Connect two newton meters (spring balances), as shown in figure 2.9.
2. Pull on one of the balances and note the readings on both.

2.9 *Demonstrating Newton's third law*

Observations

The two spring balances will always show identical readings, as the forces are exactly equal in magnitude, although opposite in direction.

Method 2

1. Inflate a balloon and hold the end between your fingers, before letting go.
2. Observe the balloon as it flies around the room (see figure 2.10).

2.10 *Newton's third law*

Observations

The force created by the balloon on the air, forcing it through the narrow opening, is equal in magnitude to the force created on the balloon by the air, propelling it forward. Note that this is similar to the forces created during rocket propulsion in space travel.

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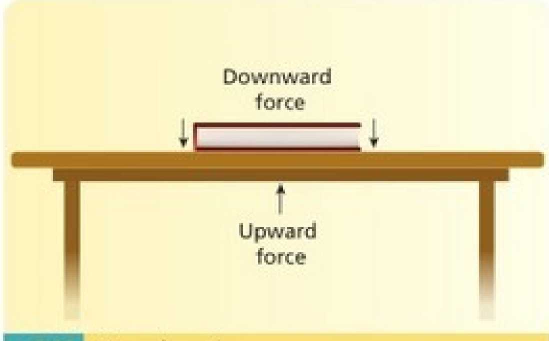


2.11 *Normal reaction*

Normal reaction

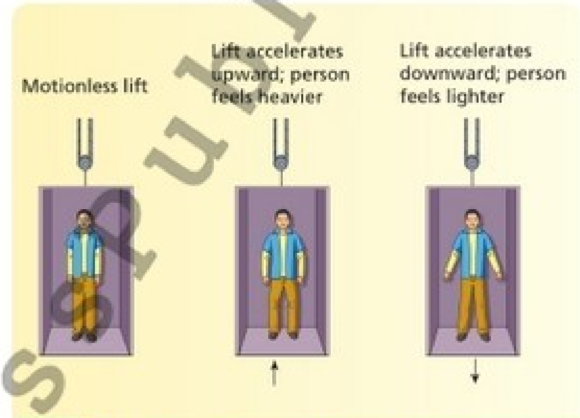
When one object rests on another it is important to remember that each is creating a force on the other. If a book is sitting on a table, as shown in the figure 2.11, it creates a downward force on the table, and the table creates an equal, but opposite, upward force on the book. This is the **normal reaction**.

If you stand on the ground, your weight is acting downwards, and this causes you to create a downward force on the ground. At the same time, the Earth is creating an upward force on you.

Again, this is the normal reaction. The force that we are aware of when we think about our own weight is in fact the normal reaction, not the weight itself. This is obvious when you think about it: if you jump off a height, your weight doesn't disappear while you are falling, but you are unaware of any force acting on your body until you hit the ground, when the normal reaction makes itself felt.

It is also the normal reaction that creates the reading on a weighing scale and allows us to, indirectly, measure our own weight.

The normal reaction has an effect in lifts (see figure 2.12). If a lift is motionless, or moving at constant velocity, your weight creates the force acting on the floor, which is equal to the normal reaction. If you were standing on a weighing scales, the reading would be equal to your weight. If the lift accelerates upwards, however, the normal reaction is greater than your weight, and this causes you to feel temporarily heavier, a sensation that would be matched by an increased reading on the scales. Similarly, if the lift accelerates downwards, the normal reaction is reduced, the reading on the scales is reduced, and you, briefly, feel lighter.



2.12 *The effects of the normal reaction in a lift*

When astronauts are in orbit aboard the International Space Station (ISS), they are about 400 km above the surface of the Earth. This height is enough to reduce their weight, but only by a very small amount. They feel weightless, however, because of the absence of the normal reaction.

Their situation is a little like being in a lift that is falling freely at the acceleration caused by gravity. If you can imagine yourself in such a situation, you would be able to float about inside the lift as if you were weightless. Remember that when a lift accelerates downwards, you feel lighter for a moment because the normal reaction is reduced. So, when the lift is in free fall, the normal reaction is reduced to zero.

2.13 *Astronauts on the ISS experience a feeling something similar to being in a free-falling lift. Orbit is often described as being in 'perpetual free fall'*

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2.4 Sample Question

A man of mass 70 kg is standing on a weighing scales in a lift. When the lift is motionless, the reading on the scales is 686 N. What is the reading when the lift is:

(a) Travelling upwards with a constant velocity of 4 m s^{-1}

(b) Accelerating upwards with an acceleration of 2 m s^{-2}

(c) Travelling downwards and slowing down with a deceleration equal to 1.5 ms^{-2}?

Sample Answer

(a) Constant velocity, so no acceleration. The reading on the scales:
Weight = $70 \times 9.8 = 686$ N

(b) Accelerating upwards, so the reading on the scales is increased (he feels heavier):
Weight = $686 + (70)(2) = 826$ N

(c) Accelerating downwards, so the reading on the scales is decreased (he feels lighter):
Weight = $686 - (70)(1.5) = 581$ N

Friction is a force that tends to oppose relative motion. It is encountered whenever one body slides, or attempts to slide, across the surface of another. It is both beneficial and problematic: one the one hand, without friction we could not walk or drive but would instead slide about the world; on the other hand, friction increases wear in machinery and reduces efficiency.

For you to try

1. State Newton's first law.
2. If a cyclist is travelling at a constant speed (say, 6 m s^{-1}), is there any net force acting on him?
3. A parachutist is falling with a constant speed of 2 m s^{-1}. Her weight is 90 kg. What is the total upward force acting on her?
4. State Newton's second law.
5. State Newton's third law.
6. A mass of 25 kg is made to accelerate at 8 m s^{-2}. What is the magnitude of the force acting on it?
7. A force of 150 N acts on a body of mass 18 kg. What is the acceleration?
8. A car of mass 900 kg is simultaneously experiencing two forces, as shown in figure 2.14. What is its acceleration?
9. A car accelerates from rest to 27 m s^{-1} due north in 6 s. Its mass is 1250 kg. What is the net force acting on it?
10. A bullet of mass 30 g is travelling at 280 m s^{-1} when it strikes a tree. It travels 9 cm into the tree before coming to rest. What is the average force created by the tree on the bullet?

2.14 *Question 9*

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GrS PHYS Gr 10 Ss Mod 2.indd 44 5/9/19 4:36 PM

11 An arrow has a mass of about 65 g. If a bow could create forces of 400 N on this arrow when the string was pulled back by 70 cm, with what speed would an arrow leave the bow?

2.15 *Question 11*

2.16 *Question 12*

12 A catapult-type device is used on aircraft carriers to accelerate aircraft from $0\,m\,s^{-1}$ to $60\,m\,s^{-1}$ in a distance of 80 m. What force does this create on an aircraft of mass 14 tonnes?

13 A woman of mass 60 kg is standing on a weighing scales in a lift. When the lift is motionless, the reading on the scales is 588 N. What is the reading when the lift is:

(a) Accelerating upwards with an acceleration of $3\,m\,s^{-2}$

(b) Travelling upwards with a constant velocity of $5\,m\,s^{-1}$

(c) Travelling downwards and slowing down with a deceleration equal to $2\,m\,s^{-2}$

(d) Falling with an acceleration equal to $9.8\,m\,s^{-2}$?

Gravity

Remember that in his third law of motion Newton said that whenever one body creates a force on another, the second body will also create an equal but opposite force. Hold a pen in front of you and think about the forces acting on it. The pen has weight, and you know already that this is a force created by the Earth. But if the Earth is creating a force on the pen, where is the other force, predicted by Newton's third law, that must match it?

2.17 *Both the Earth and the pen experience a force*

The answer, surprising in some ways, is that the pen is also creating a force on the Earth. Just as the pen is pulled down to the Earth, the Earth is pulled upwards towards the pen, and the two forces are exactly equal in magnitude, although opposite in direction.

This can be hard to accept, but remember that while the two forces are equal in size, they need not be equal in effect. The pen, with a mass of a few grams, is clearly going to fall downwards due to this force. The Earth, by contrast, with a mass of 6×10^{24} kg, is not going to move much as the result of such a tiny force.

The idea that forces occur in pairs, and that this idea applies even to gravity, is the essence of Newton's law of gravitation:

Newton's law of gravitation states that the force of attraction between any two point masses is directly proportional to the product of the masses, and inversely proportional to the square of the distance between them:

$$\mathbf{F} = \frac{Gm_1m_2}{d^2}$$

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GrS PHYS Gr 10 Ss Mod 2.indd 45 5/9/19 4:36 PM

This law tells us that all objects with mass create gravity, and the size of the gravitational force is determined by the masses of the bodies and by the distance between them.

Two masses, each of 1 kg, sitting on a table in front of you are attracted to each other by gravity, just as they are attracted downwards towards the centre of the Earth. However, we have discovered that the force between them is very, very small.

Gravitational forces are generally small unless very large objects – such as the Earth or another planet – are involved. The gravitational force created by the Earth – or other planets – on an object is what we call its 'weight'. This is due to the size of G, the gravitational constant, which is usually given as $6.7 \times 10^{-11}\ \text{Nm}^2\ \text{kg}^{-2}$.

We use the concept of centre of gravity when finding the distance between two objects and calculating gravitational forces. For large spheres such as the Earth, this means that we measure all distances from the centre of the Earth.

Isaac Newton

Isaac Newton lived from 1642 to 1727. He showed no aptitude for the farming life into which he had been born and was sent to school and to university instead, where it was hoped he might take religious orders and manage to provide for himself. Instead he dedicated himself to his studies and became the central figure in the scientific revolution, making contributions to many areas of science and mathematics that are covered throughout this course.
Newton was an intense and difficult figure. He had few friends and never married. He was deeply uncomfortable with any form of criticism and tended to hold a grudge against anybody who questioned his work. At the same time, he was jealous of other scientists and often quarrelled with his contemporaries. It is even possible that he was only driven to publish his great work on gravity by the fear that others would make similar discoveries and would take the credit.

He spent many years away from his more successful scientific studies working on such matters as alchemy and studying the Bible with great intensity. He seems to have been a devout but unorthodox Christian, who never took holy orders. He also served in Parliament for a period and in later life he was appointed to run the Royal Mint – the British institution responsible for the printing of money.

Inverse square laws

Newton's law of gravitation is an example of an inverse square law. This means that the forces created are inversely proportional to the square of the distance between them. Mathematically:

$$F \propto \frac{1}{d^2}$$

There are other laws that follow a similar pattern, describing for example the forces created through magnetism and electricity. Finding a link between them all is one of the great quests of modern physics. Einstein spent the last few years of his career attempting to find such a link, and others have tried since, but no one has so far succeeded in finding one.

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2.5 Sample Question

What is the gravitational force created by two masses of 1 kg, placed 50 cm apart?

Sample Answer

$$F = \frac{Gm_1m_2}{d^2}$$

$$= \frac{(6.7 \times 10^{-11})(1)(1)}{(0.5)^2}$$

$$= 2.68 \times 10^{-10} N$$

2.18

2.6 Sample Question

What is the weight of a man of mass 80 kg, when he is standing on the surface of the Earth?

Radius of Earth = 6.4×10^6 m
Mass of Earth = 6×10^{24} kg

Sample Answer

$$F = \frac{Gm_1m_2}{d^2}$$

$$= \frac{(6.7 \times 10^{-11})(80)(6 \times 10^{24})}{(6.4 \times 10^6)^2}$$

$$= 785.16 N$$

2.7 Sample Question

A woman has a weight of 600 N on the surface of the Earth. What weight would she have on a planet with a radius three times that of the Earth, and a mass twice that of the Earth?

m_e = mass of Earth
m_w = mass of woman
r_e = radius of Earth

Sample Answer

On Earth:

$$F = \frac{Gm_em_w}{r_e^2} = 600 N$$

On other planet:

$$F = \frac{Gm_{planet}m_w}{(r_{planet})^2}$$

$$F = \frac{G2m_em_w}{(3r_e)^2}$$

$$= \frac{2}{9}\left(\frac{Gm_em_w}{r_e^2}\right)$$

$$= \frac{2}{9} \times 600$$

$$= 133.33 N$$

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Henry Cavendish

Greek philosophers found a way of measuring the circumference of the Earth, using astronomy, as far back as 300 BC. Over time, that measurement has become more and more accurate. But how do we know the mass of the Earth?

British scientist Henry Cavendish (1731-1810) devised an experiment in 1798 to establish the mass of the Earth. He used a balance in which two lead balls hung from a 2 m-long arm. Gravitational attraction caused the balance to swing towards another pair of heavier lead balls. The strength of this force could be measured by measuring how far the balance rotated.

In modern terms, this allowed us to find a value for G, the gravitational constant.

2.19 Part of Cavendish's apparatus

For you to try

Radius of Earth = 6.4×10^6 m
Mass of Earth = 6×10^{24} kg

1 State Newton's law of gravitation.
2 If a ball is kicked into the air, the Earth creates a force on the ball that acts downwards. According to Newton's third law, an equal but opposite force is also created. What is this force, and on what object does it act?
3 What is an inverse square law?
4 A can of coffee has a mass of 454 g. What is its weight?
5 A person has a weight of 735 N on Earth. What is their weight on another planet, with a mass three times that of the Earth, and a radius twice that of the Earth? (Try to do the question without using the given values for the mass and radius of the Earth.)
6 Two objects, each of mass 10 kg, are situated 2 m apart in space.
   (a) What is the gravitational force on each of them?
   (b) What acceleration would this create on either one of the masses?
   (c) How long would it take until the objects collided?

Radius of Moon = 1.7×10^6 m
Mass of Moon = 7×10^{22} kg
Radius of Mars = 3.39×10^6 m
Mass of Mars = 6.46×10^{23} kg

7 A neutron star has a mass about the same as that of our Sun, 2×10^{30} kg, and a radius of 5×10^3 m. If an object of mass 10 kg were on the surface of the star, what gravitational force would it experience?
8 The Hubble Space Telescope has a mass of 11 600 kg. What is its weight when it is:
   (a) On Earth
   (b) In orbit, at a height of 600 km above the Earth?

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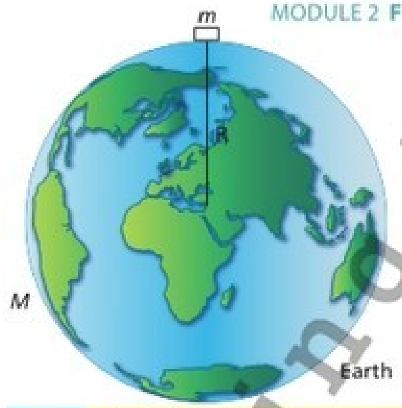
Weight



2.20 A body of mass m on the Earth

Newton's law of gravitation offered mathematical support to theories that Galileo had developed years earlier. In particular, Galileo had argued that, when we can ignore air resistance, all objects will fall at the same rate. He had done experiments to show that this was true, but Newton's work offered further verification. We can see how Newton did this if we think about a body of mass, m, on the surface of the Earth (with mass *M*) (see figure 2.20).

The weight of the body is how we describe the force acting on the body and pulling down towards the centre of the Earth. There are two separate ways that we can look at this force mathematically.

Firstly, we can use Newton's law of gravitation, which gives us:

Derivation

$$F = \frac{GMm}{R^2}$$

However, the weight is also a force, so we can also calculate the value of the weight using Newton's formula, $F = ma$. This gives us:

$$F = mg$$

Equating these two, we can see that:

$$mg = \frac{GMm}{R^2}$$

If we simplify this, we get:

$$g = \frac{GM}{R^2}$$

This equation shows us that, as Galileo had predicted, the acceleration of a falling body does not depend on the mass of the body, but only on the mass and the radius of the Earth.

We usually take the value of g to be $9.8\,\text{m}\,\text{s}^{-2}$, but this figure is not a constant, as its value is dependent on the value of R, the radius of the Earth, which is itself not a constant.

This means that if you are on top of a high mountain, for example, you are further from the centre of the Earth than you would be at sea level, and the value of g is therefore a little smaller. Also, remember that the Earth is not a perfect sphere, but that it is slightly flattened at the poles, and bulges a little at the equator. This means that the value of g is lower on the equator, where it is $9.78\,\text{m}\,\text{s}^{-2}$, than it is at the north or south pole, where it is $9.83\,\text{m}\,\text{s}^{-2}$.

It is also important to note that the weight of a body is given by:

$$W = mg$$

This is really a rewriting of $F = ma$, but because weight is such a key measurement, we often use this version of the formula.

Also, you can see from the equation that a body is almost never truly weightless. Although when it is far from any planet the value of g – and therefore the weight – may be very small, it will never be zero. In a spacecraft in orbit, both astronauts and shuttle are caught in what is essentially perpetual free fall. The astronauts appear weightless, but the acceleration due to gravity in those orbits is actually close to its value on the surface of the Earth (generally, it is about $8.7\,\text{m}\,\text{s}^{-2}$).

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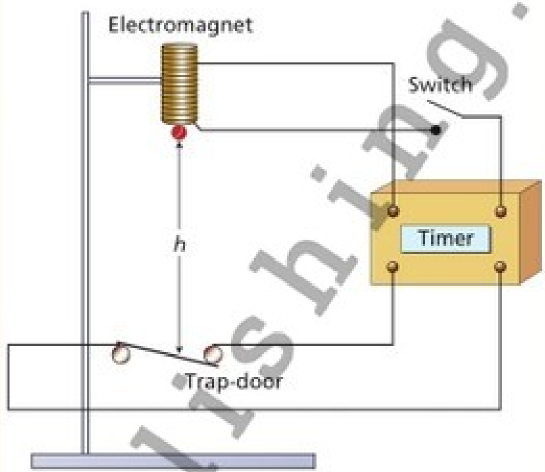
Experiment 2.3: Measurement of g (by free fall)

Method

1. Set up the apparatus as shown in figure 2.21. The millisecond timer starts when the ball is released and stops when the ball hits the trap-door.
2. Measure the height, h, as shown, using a metre stick.
3. Release the ball and record the time, t, from the millisecond timer.
4. Repeat three times for this height, h. Take the smallest time as the correct value for t.
5. Repeat for different values of h.



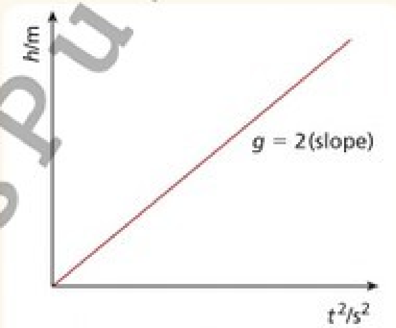
2.21 *Experimental apparatus*

Results and Conclusions

Calculate the values for g using the equation:

$$h = \frac{1}{2} g t^2$$

Obtain an average value for g.
Alternatively, draw a graph of h against t^2 (figure 2.22).



2.22 *Height against t^2*

Accuracy

- The shortest of the three times is taken as t, as various factors can delay the falling of the ball, but nothing should speed it up. A piece of paper between the ball bearing and the electromagnet will help ensure a quick release.
- Larger values of h will decrease the percentage error.

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2.8 Sample Question

What is the acceleration due to gravity on the surface of the Earth?

Sample Answer

$$g = \frac{GM}{d^2}$$

$$= \frac{(6.7 \times 10^{-11})(6 \times 10^{24})}{(6.4 \times 10^6)^2}$$

$$= 9.81 \text{ ms}^{-2}$$

Radius of Earth = 6.4×10^6m
Mass of Earth = 6×10^{24} kg
$G = 6.7 \times 10^{-11}$ N m^2 kg^{-2}

2.9 Sample Question

What is the acceleration due to gravity on the International Space Station, about 400 km above the Earth?

Sample Answer

$$g = \frac{GM}{d^2}$$

$$= \frac{(6.7 \times 10^{-11})(6 \times 10^{24})}{(6.4 \times 10^{6} + 4 \times 10^{5})^2}$$

$$= 8.69 \text{ ms}^{-2}$$

For you to try

1 Calculate the acceleration due to gravity on the Moon's surface, given that the mass of the Moon is 7×10^{22} kg and the radius of the Moon is 1.7×10^{6} m.

2 Show how to derive the formula $g = \frac{GM}{d^2}$

3 Geostationary orbits are all positioned at a height of 35 900 km above the surface of the Earth. What is the acceleration due to gravity at that height?

4 The Andromeda Galaxy has a mass of 6×10^{41} kg.

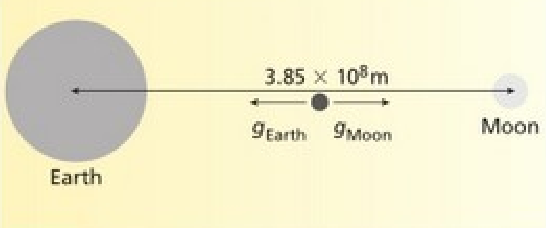
(a) What is the acceleration due to gravity created by that mass on our galaxy, the Milky Way, which is 2×10^{22} m away?

(b) What is the total force on the Milky Way, which has a mass of 7×10^{41} kg, towards the Andromeda Galaxy?

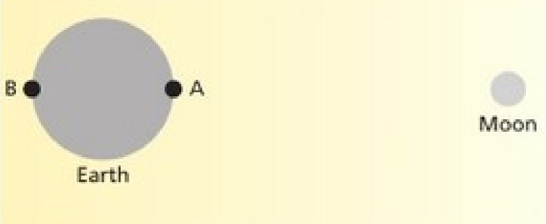
5 How far from the centre of the Earth would you have to be for the acceleration due to gravity to be equal to 1 m s^{-2}? How high above the surface of the Earth is this?

6 Figure 2.23 shows the Earth and the Moon, a distance of 3.85×10^{8} m apart. At what distance from the Earth does the acceleration due to gravity created by the Earth equal that created by the Moon?

7 The distance from the centre of the Moon to the centre of the Earth is 3.85×10^{8} m. The Earth has a radius of 6.4×10^{6} m. The Moon creates a gravitational force on Earth and hence an acceleration caused by gravity, g_m. What is the difference in the values of g_m at the two points shown in figure 2.24?



2.23 Question 6



2.24 Question 7

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Module 3 Circular motion

Learning objectives

- To define the quantities characterising curvilinear motion 10.1.1.3

Circular motion

There are many situations in which we see a moving object follow a circular path. Examples include an object tied to the end of a string, a planet in orbit, the rotating drum of a washing machine or the wheel of a car. These are all very different, but there are very simple mathematical rules that they all obey, regardless of the exact process that causes them to follow a circular path. In this part of the module, we look at the maths governing circular motion.

3.1 *Wind turbines, one of many examples of objects in circular motion*

Linear and angular velocity

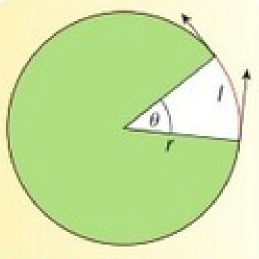
We can measure the velocity of an object travelling in circular motion in two very different ways. The **linear velocity** is measured in the same way as it would be for an object following a straight-line path. Essentially, linear velocity (and speed), v, is found using the formula:

$$\text{Speed} = \frac{\text{Distance}}{\text{Time}}$$

or

$$v = \frac{l}{t}$$

For an object following circular motion, the distance travelled, l, forms the arc of a circle, as shown in figure 3.2.



3.2 *Circular motion*

Instead of measuring the distance the object moves every second, however, we could also measure the angle, θ in radians, through which it moves every second. This is known as the **angular velocity**, usually denoted by the letter ω and measured in radians per second, rad s^{-1}. To calculate it, we use this formula:

$$\omega = \frac{\theta}{t}$$

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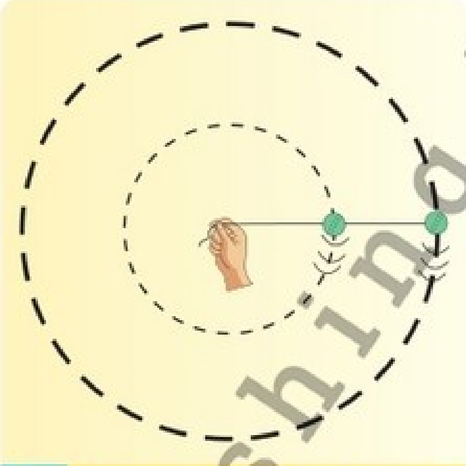
Linear velocity (v) and angular velocity (ω) are connected. Think of a string being rotated in a circle onto which two objects have been attached at different points, as shown in figure 3.3. Both objects are moving through the same angle each second, and therefore have the same angular velocity. However, the object at the end of the string is travelling through a greater distance every second and, therefore, has a larger linear velocity than the object closer to the centre of the string. The greater the radius of the motion, the greater the linear velocity tends to be.



3.3 *Two objects attached to a single string*

Connecting v and ω

The connection between linear and angular velocity can also be seen mathematically:
We know that linear velocity follows this formula:

$$v = \frac{l}{t}$$

However, from your studies of maths, you also know the arc of a circle, l, is connected to the angle at its centre by this formula:

$$l = r\theta$$

Substituting this into the above formula:

Derivation

$$v = \frac{r\theta}{t}$$

$$v = r\frac{\theta}{t}$$

But as $\omega = \frac{\theta}{t}$ we can therefore say:

$$v = r\omega$$

Period

Objects travelling in circular motion repeat the same motion over and over again. With any situation like that, it can be useful to measure how long exactly it will take for one complete motion, or cycle, to be completed. This is time is known as the **period** of the motion.

We can do this by rearranging the formula for angular velocity, which gives us:

$$t = \frac{\theta}{\omega}$$

When an object travels through one complete circle, the angle through which it has moved is 2π radians. This means that the period, T, of a particle in circular motion is given by:

$$T = \frac{2\pi}{\omega}$$

We can also talk about the frequency of the motion. The frequency of a circular motion measures the number of full rotations, or circles, travelled in one second. It is measured in hertz.

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GrS PHYS Gr 10 Ss Mod 3.indd 53 5/9/19 4:38 PM

Just as is the case when we analyse wave motions, the frequency and period of circular motion are related to each other:

$$f = \frac{1}{T}$$

The unit of measurement is Hz or s^{-1}.

3.1 Sample Question

An object is in circular motion with an angular velocity of 9 rad s^{-1} and a radius of 20 cm. What is its linear velocity?

Sample Answer

$v = r\omega$
$= 9 \times 0.2$
$= 1.8\,m\,s^{-1}$

3.2 Sample Question

A bicycle wheel of radius 45 cm spins so that it completes three complete rotations each second.

(a) What is the frequency of the motion?
(b) What is the period of the motion?
(c) What is the linear velocity of the object?

Sample Answer

(a) Three rotations per second is the frequency, i.e. $f = 3$ Hz.

(b) $T = \frac{1}{f} = \frac{1}{3} = 0.33$ s

(c) $T = \frac{2\pi}{\omega}$

so $\omega = \frac{2\pi}{T} = \frac{2\pi}{0.33} = 19.04$ rad s^{-1}

$v = r\omega$

$= (0.45)(19.04)$

$= 8.57\,m\,s^{-1}$

3.3 Sample Question

When vinyl records were the main method by which people listened to music, a 'single' had a radius of 8.9 cm and spun at 45 rpm (revolutions per minute).

(a) What was the period of its motion?
(b) What was the linear velocity of a point on its edge?

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GrS PHYS Gr 10 Ss Mod 3.indd 54 5/9/19 4:38 PM

Sample Answer

(a) f = 45 revolutions per minute, so revolutions per second:

$$= \frac{45}{60} = 0.75\,\text{Hz}$$

$$T = \frac{1}{f} = \frac{1}{0.75} = 1.33\,\text{s}$$

(b) $T = \frac{2\pi}{\omega}$

so $\omega = \frac{2\pi}{T} = \frac{2\pi}{1.33} = 4.72\,\text{rad s}^{-1}$

$$v = r\omega$$
$$= (0.089)(4.72)$$
$$= 0.42\,\text{ms}^{-1}$$

For you to try

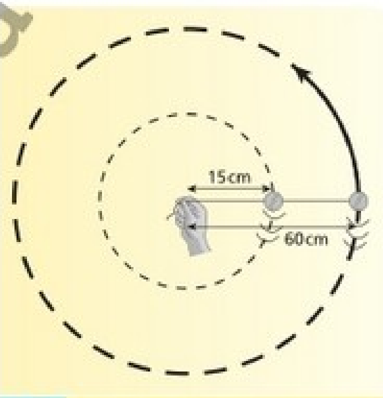
1 What do we mean by the term 'angular velocity'?

2 What is the relationship between angular velocity and linear velocity?

3 An object is in circular motion with an angular velocity of $5\,\text{rad s}^{-1}$ and a radius of 15 cm. What is its linear velocity?

4 A wheel of radius 50 cm rotates so that a point on its surface is travelling at $4\,\text{m s}^{-1}$. What is the angular velocity of the wheel?

5 A string of length 60 cm is being spun in a circle with an angular velocity of $6\,\text{rad s}^{-1}$. It has two weights attached to it, one at a distance of 15 cm from the centre and one at the edge, as shown in figure 3.4. What is the linear speed of each of the weights?



3.4 Question 5

6 What do we mean by the 'period' of a circular motion?

7 A standard vinyl record has a radius of 15 cm and spins at 33 rpm (see figure 3.5). What is its angular speed?

3.5 Question 7

8 **(a)** The Earth spins about its axis once each day. Given that the radius of the Earth is 6400 km, what is the linear speed of an object placed on the equator due to this motion?

(b) The Earth also rotates about the Sun once each year. The distance to the Sun is 150 million kilometres. What is the speed of the Earth due to this motion?

Centripetal acceleration

At every moment while an object is travelling in a circle, its direction is at a tangent to that circle: for example, if a weight is tied to the end of a piece of string and is rotated in a circle and then released, the weight will fly off at a tangent to the circle. However, as the object travels in the circle, its direction constantly changes. Remember that velocity is a measure of both speed and direction. This means that an object travelling in a circle may have a constant speed but, because its direction is always changing, it cannot have a constant velocity.

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GrS PHYS Gr 10 Ss Mod 3.indd 55 5/9/19 4:38 PM

Remember too that acceleration is the rate of change of velocity, and this means that any object with a changing velocity (including an object travelling in a circle) has an acceleration. We refer to the acceleration of an object travelling in a circle as **centripetal acceleration**.

Acceleration is a vector quantity and, therefore, must always have a direction. The direction of centripetal accelerations is always towards the centre of the circle.

Centripetal acceleration is the acceleration of an object in circular motion. Its direction is towards the centre of the circle.

The value of the centripetal acceleration is related to both the linear and angular velocity of an object, and to the radius of motion, using the formulae:

$$a = \frac{v^2}{r} \text{ and } a = r\omega^2$$

These formulae are derived using vector addition and subtraction.

Centripetal force

We know from Newton's second law, and the formula $F = ma$, that whenever there is an acceleration, there must also be a force. The force experienced by an object in circular motion is known as the **centripetal force**.

Centripetal force is the force on a body in circular motion. Its direction is towards the centre of the circle.

As $F = ma$, we can say that the centripetal force is given by:

$$F = m\frac{v^2}{r} \text{ and } F = mr\omega^2$$

It is important to remember that any force that ensures an object travels in a circle is a centripetal force. This means that when a weight is tied to the end of a string and is rotated at speed, the tension in the string is the centripetal force. And when a disk drive spins in a computer, the centripetal force is created by the electric motor. And when a planet rotates around the Sun, or a satellite rotates around the Earth, the centripetal force is created by gravity.

These situations differ from each other in many details, but the mathematical formulae we have looked at in this module apply to all of them.

3.4 Sample Question

A bicycle travels around a circular bend with a radius of 12 m. It has a constant speed of 15 m s^{-1}. What is its centripetal acceleration?

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Sample Answer

$$a = \frac{v^2}{r}$$
$$= \frac{15^2}{12} = 18.75\,\text{m}\,\text{s}^{-2}$$

3.5 Sample Question

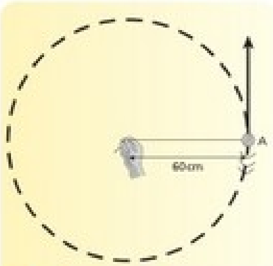
One section of a roller-coaster involves a circle of radius 9 m. A car of mass 300 kg travels at $10\,\text{m}\,\text{s}^{-1}$ on this section. What centripetal force does it experience?

Sample Answer

$$F = m\frac{v^2}{r}$$
$$= 300 \times \frac{10^2}{9} = 3333\text{ N}$$

For you to try

1 What is meant by 'centripetal acceleration'?
2 What is the direction of centripetal acceleration?
3 What is meant by 'centripetal force'?
4 If an object travels in a circle with a constant speed, does it have an acceleration? Explain your answer.
5 A car is travelling around a circular bend with a radius of 20 m. It has a constant speed of $22\,\text{m}\,\text{s}^{-1}$. What is its acceleration?
6 The drum of a washing machine has a radius of 25 cm and spins at 1200 rpm during its spin cycle.
   (a) What is its angular velocity?
   (b) If it has a mass of 1.5 kg, what is the centripetal force involved?
7 A mass of 500 g is tied to the end of a string and is spun in a circle of radius 60 cm, as shown in figure 3.6.
   (a) If its angular velocity is $9\,\text{rad}\,\text{s}^{-1}$, what is its linear velocity?
   (b) The mass is released at point A, when it is 1.25 m above ground level and travelling vertically upwards. On a diagram, show what path it then follows. What is the greatest height that it reaches?
8 A model plane is being flown attached to a string that can withstand up to 180 N of tension. The mass of the plane is 750 g, and it travels at $15\,\text{m}\,\text{s}^{-1}$. Assuming the string is horizontal, what is the radius of the smallest circle in which the plane can be flown?



3.6 Question 7

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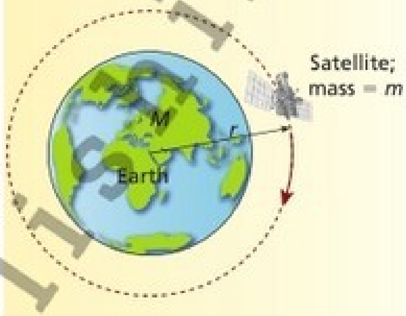
Satellites

As we have seen, there are many different processes by which an object can be made to travel in a circular path. A satellite is any object travelling in orbit around another object. Examples are the motion of the Earth and the other planets around the Sun, the movement of the Moon around the Earth, and the movement of the many thousands of artificial satellites that have been placed in orbit around the Earth over the last few decades. All of these are maintained in their circular paths because of the effect of gravity.

This means that for satellites, the centripetal force is created by gravity. And it also means that the formulae we have to describe gravitational forces, from Newton's law, must agree with the formulae we derived for centripetal forces.



3.7 *A satellite in orbit around the Earth*

Period of satellites

Think of an artificial satellite of mass m travelling in an orbit of radius r around the Earth (which has mass, M), as shown in figure 3.7.

When an object is in orbit, the centripetal force it experiences is created by gravity. This means that the force can be described either by our formula for the centripetal force, or our formula for the gravitational force. The two must be equal.

Derivation

$$\frac{GMm}{r^2} = mr\omega^2$$

Also, remember that in terms of the period, T, of a motion:

$$\omega = \frac{2\pi}{T}$$

$$\frac{GMm}{r^2} = mr\left(\frac{2\pi}{T}\right)^2$$

$$\Rightarrow T^2 = \frac{4\pi^2 mr^3}{GMm}$$

Or, simplifying:

$$T^2 = \frac{4\pi^2 r^3}{GM}$$

This is a very interesting result. If we arrange it to just look at the variables, it can be further simplified as:

$$T^2 \propto r^3$$

This gives us the relationship between the period of a satellite and the radius of its motion. It is very important historically, because it fits in with Kepler's law.

Kepler had studied the motion of the planets for many years (see the box on Kepler opposite) and he had finally arrived at exactly this mathematical relationship between the period and radius of their motions.

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GrS PHYS Gr 10 Ss Mod 3.indd 58 5/9/19 4:38 PM

When Newton could then do the maths shown here and prove that his gravitational law fitted in exactly with what Kepler had already established, and with the observed motion of all of the planets in the solar system, it meant that his equations could be trusted. They had survived the crucial scientific test of being verifiable by experience.

Another way of looking at the motion of a satellite is to think of its speed rather than its period. As we have argued above, the centripetal force is equal to the gravitational force:

$$\frac{GMm}{r^2} = m\frac{v^2}{r}$$

Simplifying this equation yields:

$$v^2 = \frac{GM}{r}$$

The values of *G* and *M* will not change, so this equation tells us that the velocity of an object travelling in circular motion about the Earth is controlled only by the radius of its motion. This is very important for space engineering.

Think about a situation in which astronauts in a space shuttle are given the job of making repairs to a satellite situated a few hundred metres ahead. In order to catch up with the satellite, most of us would instinctively fire up the rockets to make the shuttle go a little faster. But the problem with this is that it will push the shuttle out to a further orbit, away from the satellite.

Both equations for the motion of satellites show that the velocity of a satellite can be controlled only by the height of its orbit: to increase velocity, the satellite must reduce *r* – that is, it must move closer to the Earth – and to slow down it must move further away.

What the astronauts need to do is to move downwards towards the Earth a little, where the reduced value of *r* will yield a larger value for *v*. The shuttle will then quickly catch up with the satellite, and then it can return to its original orbit and carry out the repairs.

Johannes Kepler

3.8 *Johannes Kepler (1571–1630)*

The names of Nicolaus Copernicus (1473–1543) and Galileo Galilei (1564–1642) are famous throughout the world. In the popular imagination they are the men who established that the Earth is not the centre of the universe, but instead that it is rotating about the Sun. Both deserve credit, but in many ways the central figure in the story should be Johannes Kepler.

Copernicus was a Polish mathematician and astronomer who, just before his death, published a book called *On the Revolutions of the Celestial Spheres*, in which he outlined a theory that all of the planets are in orbit around the Sun. His ideas slowly spread around Europe and became the basis of a new understanding of astronomy. However, his theory did have flaws: because he believed the orbits had to be perfect circles, his maths did not quite fit the reality of the motion of the planets.

Galileo deserves credit for the development of the telescope and for his astronomical observations, particularly the discovery of the moons of Jupiter. His famous battles with the Church of the day, though, have perhaps helped to obscure the work of Kepler.

Kepler was a German scientist and mathematician. He studied the wonderfully precise observations of the planets made by Danish astronomer Tycho Brahe (1546–1601), and combined them with the work of Copernicus to produce mathematical formulae that described with great precision the motions of the planets. This work then provided Newton with a basis on which to build his famous theory of gravity a generation later.

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Geostationery satellites

The first artificial satellite was launched by the Soviet Union in 1957. It stayed in orbit for three months and did nothing but constantly broadcast a series of beeps, which could be picked up from Earth.

Since then, many thousands of satellites have been placed in orbit, with many purposes. They can help with weather forecasting, spying missions, space exploration and communications.

The most obvious connection most of us have with communications satellites is the satellite dishes used on many homes to provide TV programmes. These dishes all point to the particular satellite from which they receive a signal. For this reason, it is important that the satellite stays in the same place from our perspective here on Earth.

To do this, the satellite has to move with the Earth, constantly staying above one point on the Earth's surface and moving through one complete orbit every day. Such satellites are known as **geostationary satellites**.

To match the spin of the Earth, these satellites must be above the equator and must have a period of exactly one day. Following on from the maths we've already seen, this means that they must all have the same radius of motion and travel at the same speed: they are all at a height of approximately 36 000 km above the Earth's surface, and they travel at close to $3\,\text{km}\,\text{s}^{-1}$.

The need for these satellites to share an orbit can lead to disputes, which are generally dealt with through an agency that is part of the United Nations.

3.9 *Geostationary orbit*

3.6 Sample Question

(a) What is the radius of orbit of a geostationary satellite?

(b) How high above the Earth's surface is this?

(c) At what speed is it travelling?

> Mass of the Earth = 6×10^{24} kg
> Radius of the Earth = 6.4×10^{6} m

Sample Answer

(a) $T^2 = \dfrac{4\pi^2 r^3}{GM}$

$T = 24\,\text{h} = 86\,400\,\text{s}$

$r^3 = \dfrac{GMT^2}{4\pi^2}$

$= \dfrac{(6.7 \times 10^{-11})(6 \times 10^{24})(86\,400^2)}{4\pi^2}$

$r = 4.23 \times 10^{7}\,\text{m}$

(b) $4.23 \times 10^{7} - 6.4 \times 10^{6}$

$= 3.59 \times 10^{7}\,\text{m}$

$\approx 36\,000\,\text{km}$

(c) $v^2 = \dfrac{GM}{R} = \dfrac{(6.7 \times 10^{-11})(6 \times 10^{24})}{4.23 \times 10^{7}} = 9\,503\,546$

$v = 3083\,\text{m}\,\text{s}^{-1}$

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GrS PHYS Gr 10 Ss Mod 3.indd 60 5/9/19 4:38 PM

For you to try

1. Name three scientists who contributed to our understanding of planetary motion.
2. What is the period of a satellite that is in orbit around the Earth, with a radius of motion of 6.6×10^6 km?
3. (a) What is the period, in seconds, of a satellite that completes seven complete orbits of the Earth every 24 hours?
   (b) What is the radius of its motion?
4. A satellite is placed in orbit 600 km above the surface of Jupiter. Jupiter has a radius of 7.1×10^7 m and a mass of 1.9×10^{27} kg. What is the period of the satellite?
5. The International Space Station (ISS) is in orbit at a height of 400 km above the Earth's surface.
   (a) What is the period of the space station's motion?
   (b) How many orbits will it make of the Earth in a 24-hour period?
6. (a) What is the period of a satellite that is in orbit around the Earth and whose radius of motion is twice the radius of the Earth?
   (b) What is its speed?
7. Venus has a mass of 5×10^{24} kg. It rotates very slowly about its axis with a period of 243 days.
   (a) What is the period of an object in geostationary orbit around Venus?
   (b) What is the radius of its motion?

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GrS PHYS Gr 10 Ss Mod 3.indd 61 5/9/19 4:38 PM

Module 4 Fluid mechanics

Learning objectives

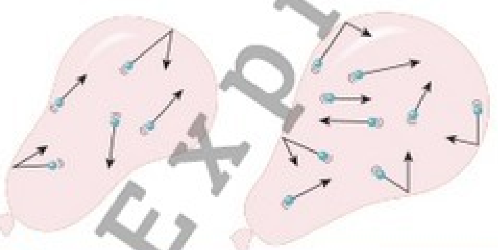
- To describe Pascal's law and its application 10.1.3.2
- To explain the term hydrostatic pressure 10.1.3.3
- To describe the flow of liquids and gases 10.1.5.1
- To determine dependent, independent and controlled (constant) physical quantities and take into account the accuracy of measurements 10.1.5.2
- To define factors that influence the results of the experiment and to suggest ways to improve it 10.1.5.3

Fluid mechanics

In this module we shall look at the areas of fluid statics and fluid mechanics. Fluid statics – which is often referred to as hydrostatics – is the study of pressures exerted by a fluid at rest. Fluid dynamics which makes up the second half of this module, is the study of how forces affect fluids. As we shall see across the module, in both areas there are many and varied applications in engineering from the design of hydraulic systems to the effective operation of pipelines.

How is pressure created in a fluid?

To picture how pressure is created in a gas, it is useful to remember that a gas, just like a solid or liquid, is made of atoms and/or molecules and therefore contains many thousands, or millions, of fast-moving particles.



4.1 *More particles create more pressure*

When inflating a balloon, the more air you blow into it, the larger the balloon becomes. Every time you blow into it, you are introducing many more fast-moving particles. The balloon expands because it is being struck far more often from the inside by these particles, while there is no change on the outside of the balloon.

In many ways, that is what pressure measures in a gas: how often, and with what force, the walls of a container are struck by the particles in the gas.

The particles in a fluid have a disordered motion creating forces in all directions at once. For this reason, it becomes meaningless to discuss the direction in which pressure acts so **pressure is taken to be a scalar quantity**.

Pressure in a fluid is calculated according to:

- the density of the fluid p
- the gravitational filed strength g
- the depth that pressure is measured at h.

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Effect of depth on the pressure in fluids

Each layer in a fluid needs to support the weight of the layers above it. That means that the pressure at the bottom of a fluid will be higher than the pressure at the top. In gases the increase in pressure with depth is very slight, because gases have low densities. You need to climb a high mountain before you start to notice any changes in pressure. In liquids, however, the pressure changes with depth are very pronounced. If you dive under water, even just 1 metre under the surface you will notice a slight pain in your ears. A depth of only 10 metres in water produces a pressure which is roughly equal to the pressure exerted by the entire atmosphere at sea level!

The pressure P due to a depth of fluid above it is $P = \rho g h$, where ρ is the density, g is the acceleration due to gravity and h is the height of the fluid above. In this equation, the h is sometimes called 'head of pressure'.

The bends, or **decompression sickness**, is a problem experienced by divers. It is caused by the fact that the pressure increases as a diver moves down through the water. This increase is sufficient to 'push' more nitrogen into the bloodstream, where it is dissolved. As the diver rises and the pressure lessens, this nitrogen comes back out of the blood as small bubbles – very like the bubbles that form in fizzy drinks when a bottle is opened – which can cause great damage as they pass through the brain.

4.2 *Scuba divers performing a decompression stop after a dive. They are waiting beneath their boat to prevent decompression sickness, which occurs when a diver ascends too fast after a dive*

4.1 Sample Question

What is the pressure created by water at a depth of 1km?

Sample Answer

$P = \rho g h$
$= (1000)(9.8)(1000)$
$= 9\,800\,000 \text{ Pa}$

! Density of water = 1000 kg m^{-3}
$g = 9.8 \text{ m s}^{-2}$

4.2 Sample Question

A water tower contains a large tank with its level 20 metres above ground level, calculate the pressure of the water at the foot of the tower. (The density of water is approximately 1000 kg/m³)

Sample Answer

$P = \rho g h = 1000 \times 10 \times 20 = 200 \text{ kPa}$

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4.3 Sample Question

An engineering press requires a pressure of 350 kPa in order to operate correctly. The engineer wants to design a system whereby this pressure can be delivered by a water tank located uphill from the press. Calculate the minimum height required to deliver this pressure.

Sample Answer

$P = \rho g h$ so $h = P / \rho g$ $h = 350000 / (1000 \times 10) = 35$ metres

For you to try

1 A water pump is capable of pumping water at a maximum pressure of 5 bar. Calculate the maximum height to which water could be pumped. (1 bar = 1 atmosphere = 100 kPa)

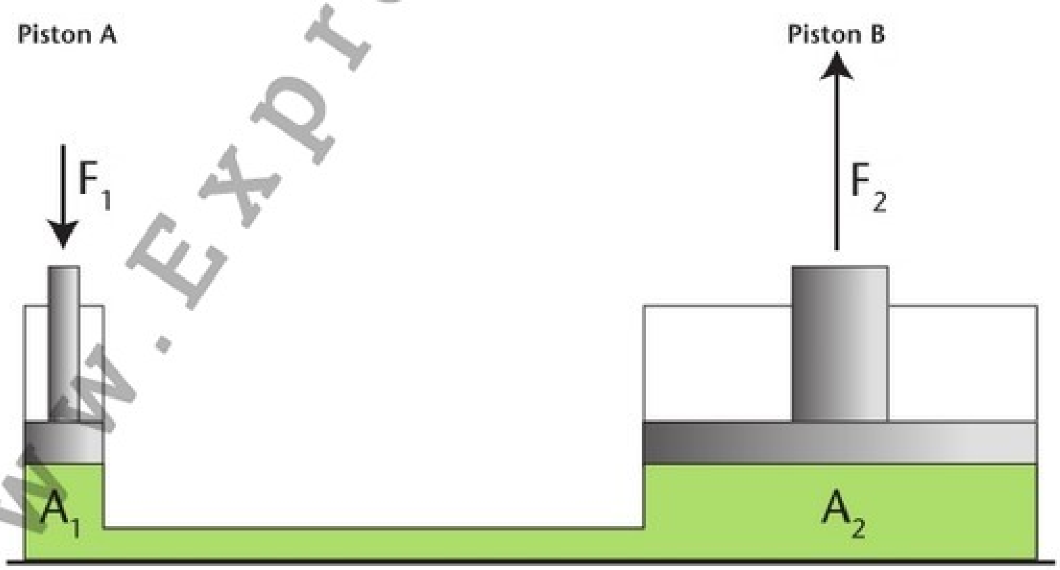
2 If this same pump were to be used to pump oil (density of oil = 910 kg/m³) without doing any calculations, decide whether this pump could pump the oil to:

(a) a greater height **(b)** a lesser height **(c)** the same level.

3 What if the water was sea water (ρ = 1029 kg/m³). How would this affect the level?

Pascal's law

Pascal's law states that when a force is applied to an incompressible fluid in a container, the pressure increases equally in all directions throughout the fluid. Thus, in a hydraulic system exerting pressure on one piston produces an equal pressure on a second piston in the system.



$P_1 = \frac{F_1}{A_1}$ Pascal's principle $P_1 = P_2$ $P_2 = \frac{F_2}{A_2}$

4.3 *Pascal's principle*

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GrS PHYS Gr 10 Ss Mod 4.indd 64 5/9/19 4:39 PM

If, as in figure 4.3, the second piston has an area five times that of the first piston, the force on the second piston is five times greater, even though the pressure on both pistons is the same. The effort force exerted on piston A puts greater pressure in the closed system and this pressure is transmitted throughout the system. The water pushes against piston B exerting a load force on it – a force which is five times that of the effort force exerted because the cross-sectional area of piston B is five times greater. This is the basic principle involved in the design of hydraulic systems such as those in car braking systems and chairs at the hairdresser's.

4.4 Sample Question

Look at figure 4.3 which represents a hydraulic jack. If the force exerted on piston A is 50 N and the cross-sectional area of piston A is 0.25 m² calculate the pressure in piston A.

Sample Answer

pressure = force ÷ cross-sectional area
= 50 ÷ 0.25
= 200 Pa

4.5 Sample Question

Calculate force the applied to piston B which has a cross-sectional area of 1.25 m² if the pressure within the closed system is 200 Pa.

Sample Answer

force = pressure × cross-sectional area
= 200 × 1.25
= 250 N

From the example in the sample questions above, it can be seen that within this hydraulic system an effort force of 50N results in a force load of 250N

For you to try

1 A small van is on a frame on the larger piston of a hydraulic lift. The larger piston has an area of 0,9 m² and the van has a weight of 1.2×10^4 N. How much force must be applied on the smaller piston (area 0,2 m²) to support the van?

2 A hairdresser uses the hydraulic system of a chair to raise customers into position. She applies a force 180 N to a hydraulic piston of an area 0.02 m².The chair is on a piston with an area 0.14 m² and the chair has a mass of 8 kg. If this represents the maximum force on the chair, what is the maximum weight of customer that the chair can lift?

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Density and Viscosity of liquids

We have already seen that the density of an object is its mass per unit volume:

$$\rho = \frac{m}{v}$$

and it is measured in kilograms per cubic metre (kg m^{-3}). It is often referred to commonly as the weight of a fluid but more specifically is a measurement of the number of molecules × molecular weight/volume occupied.

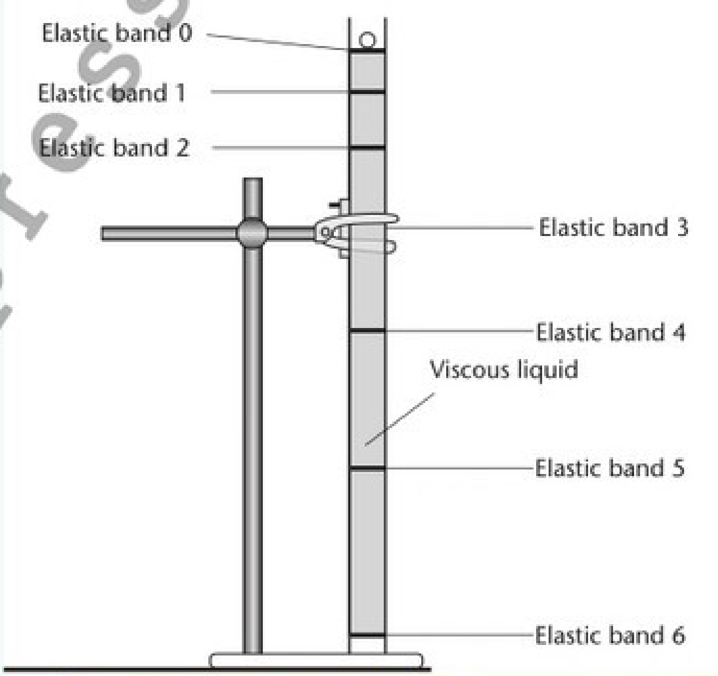
Viscosity is often commonly referred to as the thickness of a fluid but more specifically is a measurement of the intermolecular forces and the shape of molecules of a liquid. It is essentially a measure of the friction between two layers of a liquid. Compare pouring honey with pouring water from a jar. Water and honey have very different viscosities. The unit of measurement of viscosity is the pascal second (Pa·s), or (N·s)/m^2 and precise measurement of viscosity is very important in industries where lubricants are used such as in the auto industry or in drilling. A key difference between density and viscosity is how they change with temperature. Viscosity decreases rapidly as temperature increases, whereas density will only change slightly.

In common experiments to test the viscosity of liquids, we often investigate shear force which refers to the force that occurs when two objects slide parallel to one another and calculate **terminal velocity** which represents the point at which the force exerted by gravity on a falling object equals the fluids resistance to that force.

Laboratory work 4.1: Determining the terminal velocity of two viscous liquids

Method

1. You will be measuring the terminal velocity of a ball bearing as it falls through two different viscous liquids.
2. You will need to set up the apparatus as shown in the diagram for each viscous liquid.



4.4 *Measuring terminal velocity of a ball-bearing*

For this experiment you will need:

- Measuring cylinder
- Beaker containing viscous liquid A
- Beaker containing viscous liquid B
- lab balance
- Glass tube for the viscous liquid (as in diagram)
- Elastic bands to mark distances along the tube
- Steel ball bearings of one size
- Magnet to remove ball bearings from bottom of tube
- Metre rule
- Stopwatch
- Paper towels

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Initial measurements

You will need to measure and calculate the following before you begin the experiment.

- volume of liquids to be placed in each glass tube
- density of the liquids
- the mass and diameter of the ball-bearings used

Discuss how you will do this and then record your results and check with others.

Method

1. Drop the ball-bearing and mark the positions of the ball at fixed time periods using the elastic bands. You will need to repeat your measurements several times and adjust the position of the bands.
2. For each time period measure the distance travelled between the consecutive elastic bands. Record the time period and use this time to calculate the average velocity of the ball.
3. Plot a graph of velocity v on the y-axis and cumulative time from the release of the ball, t on the x-axis and draw a smooth curve.
4. Find the time at which the ball reached its terminal velocity.
5. Use your graph to determine the best value of terminal velocity.
6. Identify the range of values for terminal velocity and calculate the maximum percentage variation from your best value.
7. Repeat each step for viscous liquid B.

Results and Conclusions

Now think about the following:

- the steps you took in the experiment to reduce the margin for error
- whether you could do anything differently to reduce the margin for error further
- what your results show about the relative viscosities of liquid A and liquid B
- what you predict would happen if you used a ball-bearing with greater mass and diameter.

Laminar and Turbulent flow

Liquids and gases have some similarities and some differences. Their main similarity is that both flow easily, and because of this they do not have any shape. They take the shape of their container or the solid boundaries around them.

Liquids are on the whole approximately 1000 times denser than gases, for this reason they will stay in a container even if it does not have a lid. Gravity is sufficient to keep liquids inside an open topped container. Gases on the other hand will readily escape through the top of an open top vessel.

Liquids are largely incompressible; their volume is very nearly fixed. Gases, on the other hand, are very compressible because the molecules in a gas are flying at great distances from each other.

When gases or fluids are in motion, or when a solid is moving through them, the molecules need to move around them to allow movement to happen.

At slow speeds the movement of the liquid or gas will be laminar. By this we mean that the layers in the fluid flow parallel to each other and there is no mixing. This is sometimes also called streamlined flow.

At greater speeds, it is difficult to sustain laminar flow, and turbulence often sets in. In turbulent flow, layers in the fluid no longer move parallel to each other but start to mix together in a rolling type of motion that can be quite chaotic.

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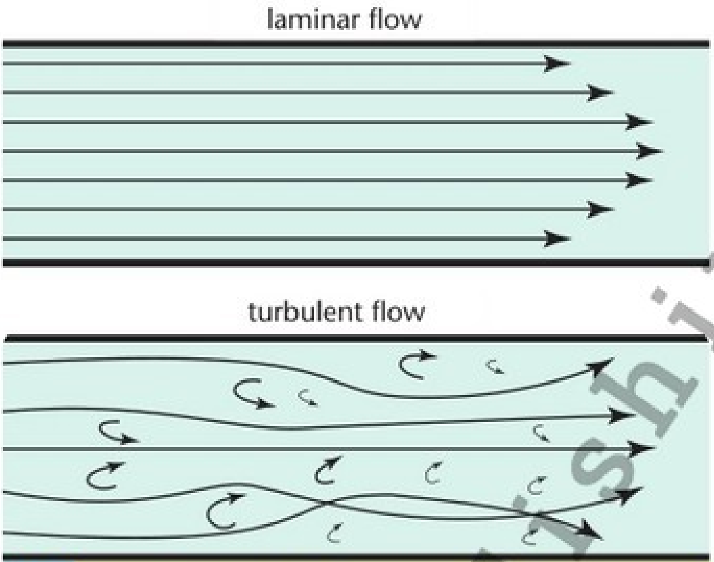
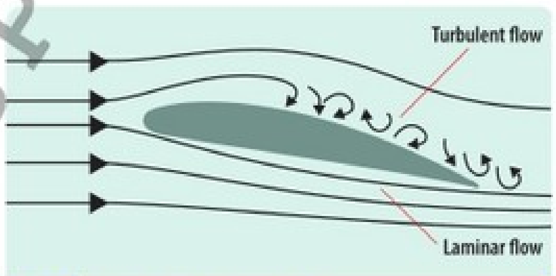


4.5 *Laminar and turbulent flow*

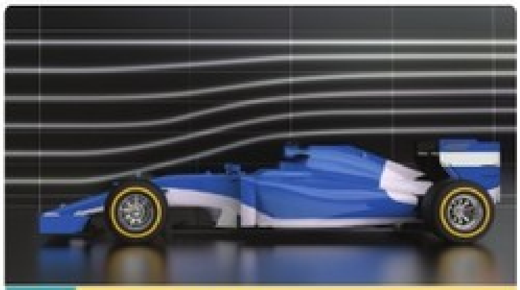
Turbulent flow normally dissipates energy and causes the flow to slow down. It is far more efficient to use a larger bore pipe and allow the liquid to flow slower in a laminar way than to use a narrower bore pipe and force the water through at high pressure.

In the case of an aeroplane or a fast car moving through the air at high speed, turbulent flow increases drag, and makes the aeroplane or the car slow down. To maintain a higher speed it will be necessary to use far more fuel, making the vehicle very inefficient. This is the reason why engineers pay so much attention to the shape of cars and aeroplanes.



4.6 *Laminar and turbulent flow*

At high speeds it is nearly impossible to have perfectly laminar flow. Some turbulence normally sets in. The engineers task is to try to minimise the turbulence. Often a 'Wind Tunnel' is used to study the effects of shape designs before they are put into production.



4.7 *Racing car prototype*

Some wind tunnels have artificial smoke lines injected into them so that the flow can be seen visually. The best designs produce the least disturbance in the smoke lines behind the car.

The continuity of flow

When a liquid flows through a long chain of pipes, and these pipes have different diameter in different places, it causes the flow to speed up or slow down. This needs to happen in order to maintain a constant rate of flow throughout the entire length. Where the diameter is smallest, the speed will be highest.

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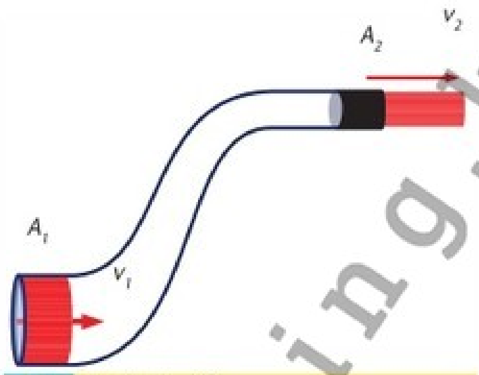
This is a consequence of the conservation of the volume of liquid. Figure 4.8 gives a clear visual explanation as to why this must be true.

The speed of the flow of liquid along the length of a pipe is affected by the cross-sectional area at any given point.



4.8 *Continuity of flow*

For the flow rate to be constant, the volume per second must be equal everywhere along the length. A volume element is equal to the cross-sectional area A multiplied by a length *L*. If we consider a volume rate, then we must divide this by time. The flow rate at any point will be *A* x *L*/*t*. Notice that *L*/*t* is a velocity, so the flow rate can be expressed as *A* times *v*.

Since the flow rate is constant throughout,

$$A_1v_1 = A_2v_2 = A_3v_3 = \ldots$$

This is known as the continuity of flow equation.

4.6 Sample Question

Water is flowing at 20 cm/s along a pipe that has an internal diameter of 3 cm. Further down the line the pipe has an internal diameter of 1 cm. At what speed must the water be flowing at this new point?

Sample Answer

$A_1v_1 = A_2v_2$ so $v_2 = v_1A_1 / A_2$.

The ratio of the cross sectional areas is equal to the square of the ratio of the internal diameters, so we can say

$v_2 = v_1(D_1 / D_2)^2 = 20\ (3/1)^2 = 180$ cm/s

4.7 Sample Question

The flow of water through a tube is 0.30 m/s where the internal bore is 25 mm in diameter. What diameter bore would be necessary in order to slow down the flow to 1 mm/s?

Sample Answer

The first thing to notice is that there are a number of different units being used in this question, so we must be extra careful.

$A_1v_1 = A_2v_2$ so $A_1 = A_2v_2 / v_1$ so $(D_1)^2 = (D_2)^2\ (v_2 / v_1)$

$(D_1)^2 = (25)^2\ (300 / 1)$ $(D_1)^2 = 187\ 500$ $D_1 = 433$ mm

For you to try

1 If you want to double the speed of flow of water through a section of tube, by what ratio must you reduce its diameter?
2 If you double the diameter of a tube, by what ratio have you slowed down the flow of water through it?

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Module 5 Liquids, Solids and Gases

Learning objectives

- To describe molecular-kinetic theory and the ideal gas 10.2.1.1
- To describe models of solids, liquids and gases in terms of molecular-kinetic theories 10.2.1.2
- To distinguish between the structures of crystalline and amorphous bodies 10.2.1.3
- To apply ideal gas formulas in calculations and distinguish graphs of gas processes 10.2.2.1
- To determine the relative humidity of air 10.2.4.1
- To explain the nature and role of surface tension and the role of the capillary phenomenon in everyday life 10.2.4.2

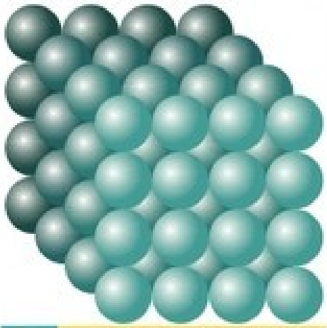
The names of laws used for the Gas Laws in this Module are those common in English scientific literature.

Particles in Solids, Liquids and Gases

Particles in a solid:

- are closely packed, and tightly bound to each other. As a result, solids have a fixed volume and a fixed shape.
- constantly vibrate; this is the only movement that they are capable of, because they are tightly bound.
- vibrate, on heating, more and more until, at the melting point, they break free from each other and a liquid is formed.

When a solid melts, there is usually an increase in volume of between 5% and 30%. This is because, in a liquid, the particles are usually more loosely arranged than in a solid.



5.1 *Arrangement of particles in a solid*

Particles in a liquid:

- are still close together
- can slip by one another easily – as a result, liquids can flow, and do not have a fixed shape.

The volume of a liquid at a particular temperature is fixed, because of the forces that hold its particles together. On heating, the particles move with greater speed and, at the boiling point, they escape completely from the other particles, and a gas is formed.

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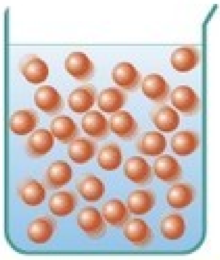

5.2 *Arrangement of particles in a liquid*

5.3 *Arrangement of particles in a gas*

When a liquid changes to a gas, there is a very large increase in volume. For example, when 10 cm³ of water boils at 100°C and at a pressure of 101,325 Nm^{-2}, about 16,000 cm³ of water vapour are formed. This happens because, in a gas, the particles are separated by relatively large distances. The particles of a gas:

- are relatively free of each other, and so a gas has no fixed shape or volume at a particular temperature
- move very rapidly and in a random manner, colliding with each other and with the walls of their container.

Because gas particles are separated by relatively large distances, gases are easily compressed, unlike solids and liquids. For example, if 100 cm³ of air is subjected to a tenfold increase in pressure, its volume is reduced to 10 cm³ (approximately).

For you to try

1. Three types of particle can make up solids, liquids and gases. What are they?
2. Why does a solid usually expand on melting?
3. Why does a liquid have a fixed volume at a particular temperature?
4. Why does a liquid not have a fixed shape?
5. Why does the volume of a gas get much smaller when it changes to a liquid?
6. Why are gases easily compressible?
7. Why are solids not easily compressible?
8. What effect has increased pressure on the volume of a liquid?

Diffusion

There is strong experimental evidence for the existence of particles. Diffusion experiments provide some of this evidence. **Diffusion is the spontaneous spreading out of a substance, and is due to the natural movement of its particles.**

Diffusion of gases

Diffusion of gases may be easily observed. For example, if a gas tap is turned on in a laboratory, and left on for a little while, the smell of the gas is soon noticeable throughout the room, even in the absence of draughts. This happens because the particles of the gas move rapidly and randomly throughout the room.

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Demonstration

Diffusion of smoke in air

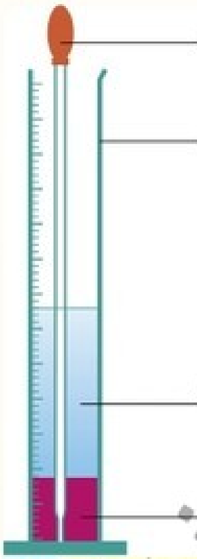
Equipment needed

Brown paper
Matches

Procedure

NB: Wear your safety glasses.

1 Get a smouldering piece of brown paper.
2 Observe and describe the movement of the smoke.
3 Explain why the smoke moves in this way.



5.4 *Diffusion of potassium manganate(VII) in water*

Diffusion in liquids

Diffusion in liquids is much slower than diffusion in gases. Nevertheless, diffusion in liquids can be easily observed. For example, if a layer of potassium manganate(VII) solution, which is purple, is carefully placed under water in a graduated cylinder (Figure 5.4), the purple colour slowly spreads throughout the liquid, due to diffusion of the potassium manganate(VII) particles.

Ink diffuses in a manner similar to potassium manganate(VII) solution.

Demonstration

Diffusion of ink in water

In this demonstration, diffusion in a liquid is observed.

Chemicals needed

Blue ink

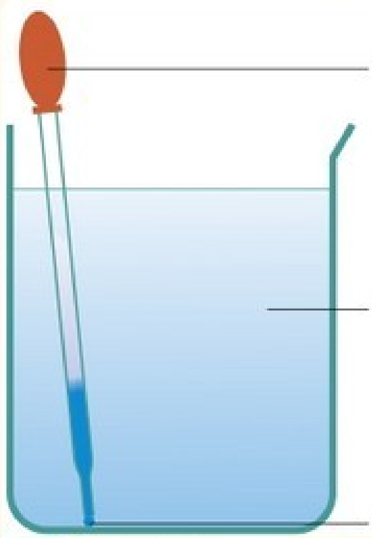
Equipment needed

Beaker
Pipette
White paper

Procedure

NB: Wear your safety glasses.

1 Three-quarters fill a beaker with water.
2 Using a pipette, carefully place some blue ink under the water at the bottom of the beaker.
3 Using a background of white paper, describe and draw what you see.
4 Allow to stand overnight.
5 Using a background of white paper, describe and draw what you see.
6 Explain in terms of particles what has happened.



5.5 *Diffusion of ink in water*

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Gas Laws: Boyle's Law and Charles' Law

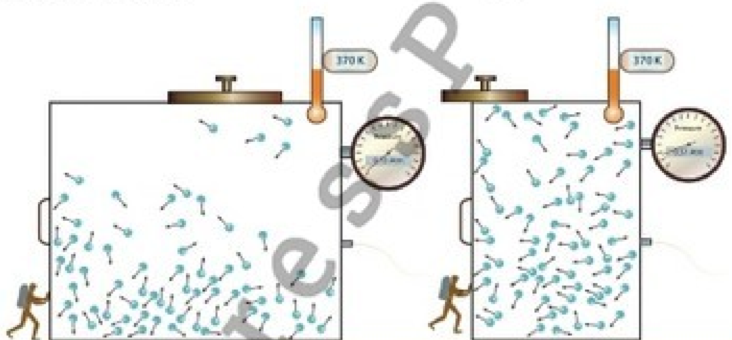
Boyle's law

Boyle's law states that, at constant temperature, the pressure on a fixed mass of gas is inversely proportional to its volume.

When you picture a mass of gas as being made of many thousands of millions of tiny particles moving at speed and colliding with each other and with the walls of a container, Boyle's law can seem a statement of the obvious. To appreciate the historical significance of the law, and to appreciate Boyle's achievement, it is important to realise that he was operating at a time when the presence of atoms, as we now know them, was not at all clear. Beyond that, air itself had hardly been studied and the discovery of oxygen was still decades in the future. In fact, it is largely due to Boyle and his contemporaries that we now know so much about the nature of matter.

If you look at figure 5.6, each diagram represents a situation in which the same mass of gas is held in a container. As the particles move about, they collide with each other and with the walls of the container, which creates pressure on the walls.

When the left-hand wall is pushed in (shown in the diagram on the right), the same number of particles, moving at the same speed, is now trapped in a smaller space. Therefore, those particles collide with the walls more often, and the pressure increases. A decrease in volume leads to an increase in pressure.



5.6 *A decrease in volume will lead to an increase in pressure*

Boyle's law goes a little beyond this. Boyle did not just say that a decrease in volume would cause an increase in pressure. He said that the two were inversely proportional. This means that if we were to halve the volume, the pressure would double, that if we were to multiply the volume by three, the pressure would be divided by three, and vice versa: the relationship between the two should be mathematically precise.

The easiest way to write this in mathematical form is to say that the pressure is proportional to the inverse of the volume:

$$P \propto \frac{1}{V}$$

where:

P – pressure

V – volume

Alternatively, we can say that the product of pressure and volume must be constant:

$$PV = constant$$

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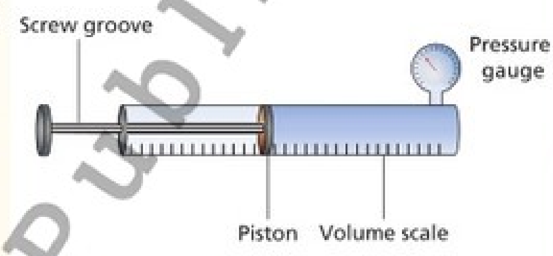
Effects and applications

- Boyle's law is seen in effect in a bicycle pump. If you hold your finger over the end of the pump as you push in the handle, you can feel the pressure increase as the volume decreases.
- The carbon dioxide bubbles that appear in soft drinks are usually formed low down in the drink and rise to the surface. As they rise, they increase in volume, due to the diminishing pressure.
- Helium balloons released into the atmosphere to study effects in the higher parts of the atmosphere are only partially inflated when they are released. This is because the volume grows as the balloon rises and the atmospheric pressure decreases. If fully inflated, the balloons would burst before they reached a high altitude.

Experiment 5.1: Verification of Boyle's law

Method

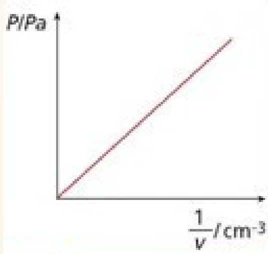
1 Using the apparatus as shown in figure 5.7, seal the cylinder so that no air can enter or leave.
2 Note the volume and pressure of the air inside.
3 Use the piston to reduce the volume by a fixed amount.
4 Again, note the pressure and volume. Because the volume is likely to be small, it might be easier to measure it in cm^3, rather than m^3.
5 Repeat this procedure for several volumes.
6 Record results and plot a graph of P against $\frac{1}{V}$.



5.7 *Apparatus to verify Boyle's law*

Results and Conclusions

A straight-line graph through the origin will verify that, for a fixed mass of gas at constant temperature, the pressure is inversely proportional to the volume, i.e. Boyle's law.



5.8 P vs. $\frac{1}{V}$

Accuracy

- It is important to allow the temperature to return to normal after the pressure has been changed.
- Boyle's law tends to be more accurate at relatively low pressures.

Charles' law

The volume of a gas also changes when the temperature is changed. In 1787, the French physicist Jacques Charles discovered that equal volumes of different gases at constant pressure all expanded by the same amount for a given rise in temperature. Charles' results are summarised in the modern form of Charles' law:

Charles' law – At a constant pressure, the volume of a given mass of any gas is directly proportional to the Kelvin temperature.

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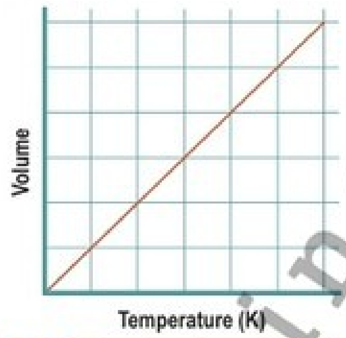
5.9 *Jacques Charles*

In mathematical form, V / T = constant, where V = volume of the gas, and T = Kelvin temperature of the gas. For example, if the temperature of 100 cm³ of nitrogen gas is increased at constant pressure from 300 K to 600 K, the volume increases proportionately, that is, to 200 cm³.



5.10 *The volume of a gas is directly proportional to the Kelvin temperature at constant pressure Charles*

The Law of Gay-Lussac

Very early in the nineteenth century, the French chemist Joseph Gay-Lussac measured the combining volumes of gases in a number of chemical reactions. He found, for example, that two volumes of hydrogen combine with one volume of oxygen to give water. Some other volume ratios for reacting gases are given in Table 5.1.

Table 5.1

Reaction	Gas volume ratio for reactants
Ammonia + hydrogen chloride → ammonium chloride	1:1
Hydrogen + chlorine → hydrogen chloride	1:1
Carbon monoxide + oxygen → carbon dioxide	2:1
Methane + oxygen → carbon dioxide + water	1:2

Notice that all of the ratios were whole number ratios. By 1808, Gay-Lussac was able to state his law of combining volumes:

> Gay-Lussac's law of combining volumes – When gases react, the volumes consumed in the reaction bear a simple whole number ratio to each other, and to the volumes of any gaseous product of the reaction, all volumes being measured under the same conditions of temperature and pressure.

There are differences in the naming of these laws in English and Russian scientific literature. The table below gives a brief summary of these differences.

Table 5.2

Russian name	English name	Formula
The Law of Gay-Lussac	Charles' Law	P = const (isobaric process), V/T = const
Charles' Law	The Law of Gay-Lussac or Second Law of Gay-Lussac	V = const (isochoric process), P/T = const

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The Combined Gas Law

Boyle's law, Charles' law and Avogadro's law are combined to give the combined gas law:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

where P_1, V_1 and T_1 are the initial pressure, volume and Kelvin temperature respectively, and P_2, V_2 and T_2 are the final pressure, volume and Kelvin temperature respectively.

The most useful application of the combined gas law is to find the volume of a definite mass of gas at s.t.p., when its volume at a different pressure and temperature is known. A knowledge of the volume at s.t.p. of a gas is particularly useful, because the number of moles of the gas in that volume can very easily be calculated.

5.1 Sample Question

If a definite mass of gas occupies 250 cm³ at a pressure of 100,000 Pa and a temperature of 91 °C, what is its volume in cm³ at s.t.p.?

Sample Answer

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

$P_1 = 100,000$ Pa　　$P_2 = 101,325$ Pa

$V_1 = 250$ cm³　　$V_2 = ?$ cm³

$T_1 = 91$ °C　　$T_2 = 273$ K

$= 91 + 273$ K

$= 364$ K

$$\frac{100,000 \times 250}{364} = \frac{101,325 \times V_2}{273}$$

$$V_2 = \frac{100,000 \times 250 \times 273}{364 \times 101,325}$$

$= 185$ cm³

For you to try

1. What is the volume at s.t.p. of a definite mass of gas that occupies a volume of 530 litres at 20°C and 102,000 Pa?
2. What is the volume at s.t.p. of a definite mass of oxygen gas that occupies a volume of 560 cm³ at 30°C and 100,500 Pa?
3. The volume of hydrogen collected in a reaction between zinc and hydrochloric acid was 240 cm³, measured at the laboratory conditions of 18°C and 101,000 Pa. Calculate the volume of hydrogen at s.t.p.
4. What is the volume at 819 K and 100,000 Pa of a fixed mass of gas that occupies a volume of 5 litres at 91 K and 200,000 Pa?

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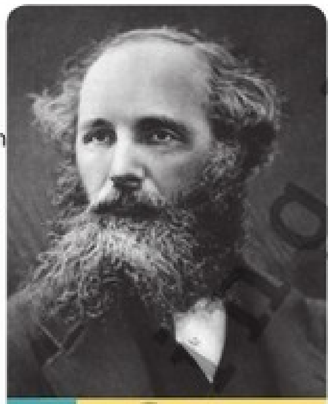
The Kinetic Theory of Gases



5.11 *James Clerk Maxwell*

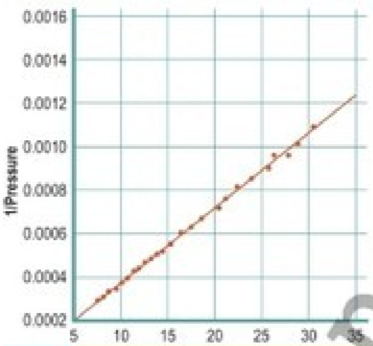
The **kinetic theory of gases** was developed by James Clerk Maxwell and Ludwig Boltzmann towards the end of the nineteenth century. In this theory, it is assumed that:

- Gases are made up of particles whose diameters are negligible compared to the distances between them.
- There are no attractive or repulsive forces between these particles.
- The particles are in constant rapid random motion, colliding with each other and with the walls of the container.
- The average kinetic energy of the particles is proportional to the Kelvin temperature.
- All collisions are perfectly elastic (for example, if a particle travelling at 450 ms^{-1} collides with a wall of its container, it rebounds with the same speed).

5.12 *Ludwig Boltzmann*

This theory can be used to mathematically derive gas laws such as Boyle's law and Charles' law. It can also be used to explain properties of gases such as diffusion. A gas diffuses quickly because its particles are moving constantly and rapidly, frequently colliding with each other and with the walls of its container. This results in the gas quickly spreading out in all directions.

The kinetic theory and gas laws



5.13

Gas laws, such as Boyle's law and Charles' law, are only approximately obeyed by real gases. Figure 5.13 shows a graph of volume versus 1 / pressure using data gathered by Robert Boyle in his original experiments. (The data has been converted to metric units.) The fact that all of the plotted points are not exactly on a straight line indicates that Boyle's law is only approximately obeyed by air, the gas used in those experiments.

Ideal gases and real gases

The kinetic theory is only completely valid for ideal gases. Since the gas laws can be exactly derived mathematically from the kinetic theory, it follows that the gas laws are completely valid only for ideal gases. The behaviour of real gases deviates from that of an ideal gas to a greater or lesser extent, depending on the situation.

> An ideal gas is a gas that perfectly obeys all of the gas laws under all conditions of temperature and pressure.

The behaviour of real gases deviates from that of an ideal gas to the greatest extent at **low temperatures** and at **high pressures**.

- One of the assumptions of the kinetic theory is that the diameters of gas particles are negligible compared to the distances between them. At low temperatures and at high pressures, the diameters are not negligible compared to the distances between them.

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- Another assumption of the kinetic theory is that there are no attractive or repulsive forces between these particles. At low temperatures and at high pressures, this assumption is not valid, because the gas particles are in close proximity to each other. Attractive forces between the molecules, such as van der Waals' forces and, if the molecules are polar, dipole-dipole forces or hydrogen bonding, will have noticeable effects when the particles are close to each other. The stronger the intermolecular forces, the more unlike an ideal gas will be a real gas under these conditions.

Real gases behave most like an ideal gas at high temperatures and at low pressures. Under these conditions, the particles of a real gas are relatively far away from each other, and the assumptions of the kinetic theory are reasonably valid. However, the assumption that collisions between molecules are perfectly elastic is never true for a real gas.

For you to try

1. Explain in terms of the kinetic theory of gases why a gas diffuses rapidly.
2. What is an ideal gas?
3. Under what conditions do real gases behave most like an ideal gas?
4. Under what conditions are the assumptions of the kinetic theory of gases least valid?

The Equation of State for an Ideal Gas

Boyle's law, Charles' law and Avogadro's law can be expressed as follows:

Boyle's law:

PV = CONSTANT at constant T and n

Charles' law:

V* is proportional to *T at constant P and n

Avogadro's law

V* is proportional to *n at constant T and P

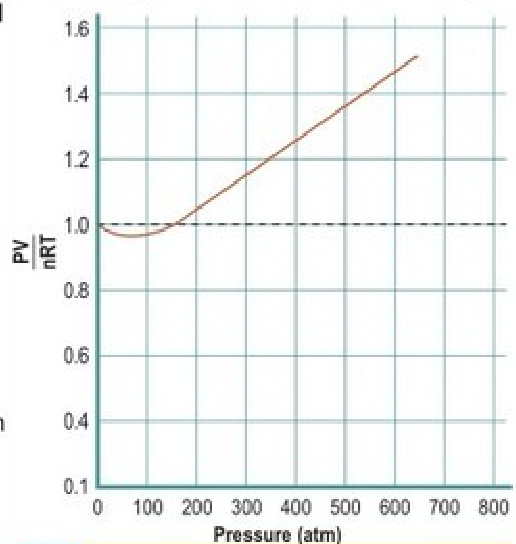
where V = volume, P = pressure, T = Kelvin temperature and n = number of moles.

Combining the three laws, **PV = CONSTANT × T × n**. Written as an equation, this becomes $PV = R \times T \times n$, where R is a constant known as the **universal gas constant**. This relationship is known as the **equation of state for an ideal gas**, and is usually written as follows:

$$PV = nRT$$

The value of R is 8.31 J K^{-1} mol^{-1}.

The relationship $PV = nRT$ is referred to as the equation of state for an **ideal** gas because it is obeyed only approximately by real gases. Figure 5.14 shows how the real gas, nitrogen, deviates significantly from ideal gas behaviour at higher pressures. For an ideal gas, $PV / nRT = 1$, but it is only at lower pressures that nitrogen even approximates to this value. All real gases deviate from ideal gas behaviour; the extent to which a particular gas does so depends on the nature of the gas.



5.14

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GrS PHYS Gr 10 Ss Mod 5.indd 78
5/9/19 4:41 PM

Calculations involving the ideal gas law

It is important to use units that are consistent with those of the universal gas constant, *R*, when doing calculations involving the ideal gas law. The units of *R* are $J\ K^{-1}\ mol^{-1}$. The units for *V*, *P*, *T* and n that are consistent with this are shown in Table 5.2.

Table 5.2

	Unit
Volume	m^3
Pressure	Pa
Temperature	K
Number of moles	mol

5.2 Sample Question

8.4 g of a gas occupies a volume of 3 l at 77 °C and 100,000 Pa.

(a) How many moles of the gas are present?

(b) What is the relative molecular mass of the gas?

Sample Answer

(a) $PV = nRT$

$P = 100{,}000$ Pa

$V = 3\ l = 3 \times 10^{-3}\ m^3$

$R = 8.31\ J\ K^{-1}\ mol^{-1}$

$T = 77\ °C = 350\ K$

n = amount of gas in moles $= PV / RT = \dfrac{100{,}000 \times 3 \times 10^{-3}}{8.31 \times 350}$

$= 0.103$

(b) 0.103 moles of the gas have a mass of 8.4 g

1 mole has a mass of 8.4 / 0.103 g = 81.55 g

Relative molecular mass = 81.55

For you to try

1 A definite mass of gas has a volume of 2 m^3 at 300 K and 100,000 Pa. How many moles of gas is this?

2 A chemical engineer wants to store a gas produced during a process at a chemical plant at a pressure of 100,000 Pa and a temperature of 20°C. The process produces 2,000 litres of gas per hour, measured at 500,000 Pa and 160°C.

(a) What volume will this amount of gas occupy under the storage conditions?

(b) How many moles of gas are being produced per hour?

3 A mass of 8.4 g of a gas occupies a volume of $5 \times 10^{-3}\ m^3$ at 27°C and 1×10^5 Pa. Calculate the relative molecular mass of the gas.

4 A mass of 5.5 g of a gas occupies a volume of $1 \times 10^{-2}\ m^3$ at 330°C and 1×10^5 Pa. Calculate the relative molecular mass of the gas.

Humidity in air

Air normally contains a certain amount of water vapour in it. Although we cannot see the vapour, human bodies can feel the difference between high and low humidity. Measuring humidity is quite a difficult thing to do. The instruments that measure humidity are called hygrometers. Most hygrometers measure relative humidity rather than absolute humidity.

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Absolute humidity is the amount of water vapour contained in a sample of air. It is measured in grams per cubic metre.

Relative humidity is the percentage of water vapour present in a sample of air compared to the maximum amount the sample could hold at that given temperature.

The maximum amount of water vapour that a sample of air can contain depends on the temperature of the air; hotter air can hold more water vapour than cold air. As air cools down the excess water vapour condenses out of the air and drops out as dew. This is why grass normally gets wet at night (when the temperature falls) even if it has not rained.

5.15 *Dew forms on the grass when the temperature of the air falls below the 'dew point'.*

During the day the sun evaporates the dew and plants will transpire additional moisture so that there is more moisture in the air. There is more absolute humidity in the air, but the relative humidity may be lower because warmer air can hold more moisture.

If the air is too dry it can cause skin, eye and lung irritation, and if the humidity is too high it can make it uncomfortable for us as it makes it more difficult to control our body temperature through perspiration.

Humidity also has effects on our buildings and human environment: very low humidity encourages electrostatic charging which in extreme cases can cause injuries and even explosions. High humidity causes mould to grow in buildings and also encourages the growth and reproduction of dust mites!

5.16 *A hygrometer*

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GrS PHYS Gr 10 Ss Mod 5.indd 80 5/9/19 4:41 PM

An inexpensive hygrometer uses a coiled foil spring coated with hygroscopic salt crystals. It is only accurate to about 5%.

It is particularly important to control humidity in museums where paintings, wooden artefacts and musical instruments are kept. Humidity changes cause dimensional changes, and after many cycles paint can start to crack and instruments may sta

Measurement of relative humidity is normally inferred by measuring some other physical property instead (mass, resistance, capacitance, temperature, length, etc).

The simplest hygrometers use a long human or animal hair. The length of hair increases with humidity. Long hairs increase by only about 2.5% in length as the relative humidity increases from 0% (completely dry) to 100% (saturated air). A long hair is fixed at one end, and the other is wrapped around a small radius pulley on which an indicator needle is fixed.

5.17 *A hair hygrometer uses the extension and contraction of hair as a measure of relative humidity*

An inexpensive way of measuring relative humidity is by means of a metal foil spiral which is coated on one side with salt impregnated paper. When the humidity rises, the salt absorbs some of the moisture and it causes the paper to swell and so the foil straightens out a little. It makes the system act like a bimetallic spring. These methods are only accurate to about 5%.

The most reliable way to measure relative humidity is to find the 'dew point' (the temperature at which water starts to condense out of the air). A mirror is cooled artificially and when the surface starts to go dull, it means that water is starting to form on the surface. A formula is used to calculate the relative humidity from the room dew point temperature.

5.18 *Psychrometer*

One last way of calculating the relative humidity involves using two thermometers, a 'wet' one and a 'dry' one. The combination of the 'wet' and 'dry' thermometers is called a 'Psychrometer'. The wet one has a 'sock' covering its bulb, and the bottom of the sock is in a container with distilled water. The water wicks up (through capillary action) and makes the bottom of the thermometer wet. The sock around the bulb slowly evaporates water into the air, and this evaporation causes the sock to become a little cooler than the dry thermometer. The lower the relative humidity of the air, the faster the sock will evaporate water, and so the 'wet' temperature will be lower that the 'dry' temperature. Conversely, if the air is 100% saturated with humidity already, then no more water will be able to evaporate from the sock, so the 'wet' temperature will be the same as the 'dry' temperature.

To calculate the relative humidity from the 'wet' and 'dry' temperatures a special table called a 'phychrometric chart' is used.

GrS PHYS Gr 10 Ss Mod 5.indd 81 5/9/19 4:41 PM

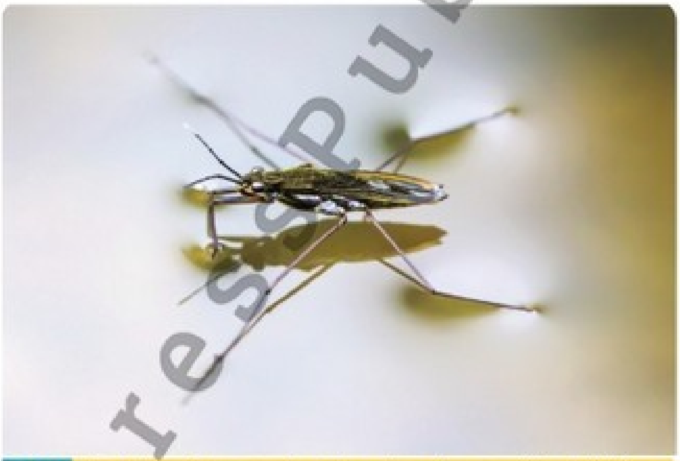
For you to try

1. When you breathe out onto a piece of glass or shiny metal the glass 'fogs up'. Why is that?
2. Why does dew fall during the night, and not during the day?
3. Why is 'dry heat' easier to bear than 'humid heat'?

Surface Tension

There are interesting phenomena that can be noticed at the surface of liquids. Have you noticed how some insects manage to stand on the surface of water without sinking into it? Or that when a water spout falls vertically, after some distance the solid cylindrical flow of water breaks up into separate droplets? Or that soap bubbles tend to be spherical, even if they are blown from a rectangular hoop? These are all called **Surface Tension** effects.

Liquids behave in such a way as to try to minimise the amount of surface that they are making with the air above or around them. The minimum amount of surface containing a given volume is always a sphere, so water droplets and soap bubbles always try to take on a spherical shape. But why do liquids want to minimise the amount of surface? What physical principle lies behind this?



5.19 *'Pond skaters' can stand on the surface of water without sinking through it; it is almost like the water has a skin on top of it.*

Atoms in a solid are held in position by rigid bonds to their neighbouring atoms. Molecules in gases do not form bonds to their neighbouring molecules, and so they are not fixed in space; the molecules can fly around in any direction bouncing off the walls of the container. Liquids are somewhere in between. Water molecules deep inside the water are completely surrounded by neighbouring molecules, and they make very weak bonds with them. It requires energy to break these weak bonds. The molecules at the surface of the water do not have neighbouring molecules above them, and so are less strongly bonded and, therefore, are in a slightly higher energy state than the rest of the molecules deep under the surface.

All systems in the universe try to settle in the lowest possible energy state. Things fall downwards, where their gravitational potential energy is lowest. Hot objects normally cool down, until they find the lowest possible temperature that puts them in thermal equilibrium with their surroundings. In the same way, liquids try to arrange themselves in the lowest energy state, and that means having as few molecules on the surface as possible. In this way, liquids try to have the smallest amount of 'skin' possible. This 'skin' seems to be in tension all the time, a little like a stretched rubber membrane.

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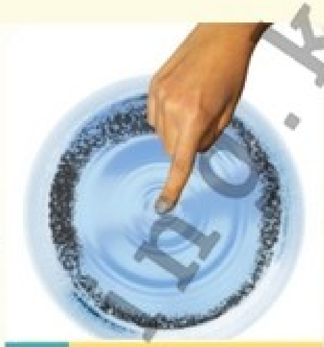
Experiment 5.2: Surface Tension

A

Method

1 Take a bowl and fill it with water.
2 Sprinkle some pepper or talcum powder lightly on the surface, and notice how it sits on the 'skin' of the surface.
3 Put a small drop of liquid soap on the tip of a finger, and gently touch the surface of the water at the centre of the bowl.



5.20 *Testing for surface tension*

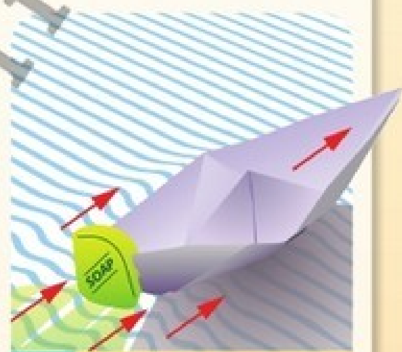
Results and Conclusions

- What do you observe?
- Why do you think this is happening?

B

Method

1 Find a large bowl (at least 30 cm in diameter – the bigger the better).
2 Make a small paper (or aluminium foil) boat which is only around 3 cm long.
3 Float your boat on the surface of the water.
4 Take a small thread of string, and immerse it in liquid soap. Wipe the excess off.
5 Hang the soapy thread off the back end of the boat so that part of it is inside the boat, and the other part is in the water.



5.21

Results and Conclusions

- What do you notice?
- Why do you think this is happening?

Definition of Surface Tension

Surface tension is given the symbol γ, and is defined as the energy (in Joules) per unit area (in square metres).

$$\gamma = \frac{E}{A}$$

where:

E is energy (in Joules) and

A is the area in metres squared

Here is an interesting thing you can do with physics equations, you can break them up and express quantities differently. Energy has identical units to work: so we can replace E with $F \times L$ (Force in Newtons multiplied by Length in metres). We can also replace Area with $L \times L$ (Length in metres multiplied by Length in metres). So the equation now becomes:

$\gamma = \frac{F \times L}{L \times L}$ which simplifies to $\gamma = \frac{F}{L}$, a force per unit length. So an equivalent definition of surface tension is the Force per unit length (the force produced by a unit length of the skin of the liquid).

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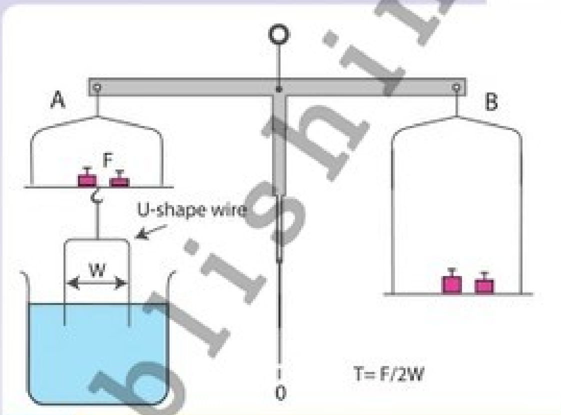
GrS PHYS Gr 10 Ss Mod 5.indd 83 5/9/19 4:41 PM

Experiments can be done to try to measure the surface tension γ of liquids. They need to be sensitive experiments because surface tension is a fairly weak effect. The surface tension of water (to air) is only around 72 mN per metre (a mN is a milli-Newton. 1 mN is approximately the weight of 0.1 g.)

5.3 Sample Question

A student makes a wire U shape as shown in the figure 5.22. He brings the system to balance with the U shape partially immersed in the soapy liquid, but without a film filling the frame. He then immerses the U shape entirely under the surface of the soapy water. He then notices that he needs to add some masses to the right hand side in order to lift the soapy film upwards and lift it to the same balancing position as was achieved before. The width of the U is 10 cm, and the mass he needed to add in order to bring it back into equilibrium was only 0.4 g. What is the surface tension of the soap solution?



5.22

Sample Answer

We start with the equation for surface tension $\gamma = \frac{F}{L}$ but we must notice that the soap film actually has two surfaces facing the air, so the force measured is that due to two surfaces. So the force due to a single surface would be the half of the force he measured.

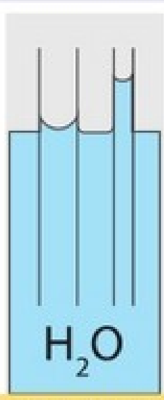
We say $\gamma = \frac{\frac{F}{2}}{L}$, or $\gamma = \frac{\frac{mg}{2}}{L}$. Inserting the measured values we get

$$\gamma = \frac{\frac{0.0004 \times 10}{2}}{0.1}, \quad \gamma = 0.02 \text{ N/m} \quad \text{or} \quad \gamma = 20 \text{ mN/m}.$$

Notice that the surface tension of soapy solutions are typically around 1/3 of the surface tension of water. It is this reduction in surface tension that drives the little boat in the experiment above.

Surface Tension and the capillary action of a narrow bore glass tube

A clean narrow glass tube appears to 'suck water up' by a certain amount. The height depends on the internal diameter of the bore.



5.23 *Capillary action of a narrow bore glass tube*

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If the adhesion forces between the water molecules and the glass are greater than the cohesion forces between the water molecules themselves, then a concave meniscus, and the tension in the surface pulls the surface upwards until the total upward force provided by the perimeter of the meniscus becomes equal to the weight of the water that is being pulled up. Once this equilibrium is reached, the capillary level stops rising. In equation form we write:

Upward Force = $2 \pi r \gamma$ and downward force = $\pi r^2 h \gamma g$ where r is the internal radius of the capillary bore, h is the height of the water column above the outside level, γ is the density of the water and g is the acceleration due to gravity.

When these are equal $h = \frac{2\gamma}{r p g}$.

5.4 Sample Question

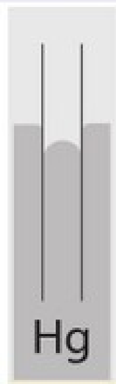
The internal bore of a capillary is 0.2 mm in diameter, calculate the maximum height to which the water may be drawn up if a perfect concave meniscus forms.

Sample Answer

$h = \frac{2\gamma}{r p g}$, $h = \frac{2\ (75 \times 10^{-3})}{0.0001 \times 1000 \times 10}$, $h = 0.15$ m

The water level inside the capillary will rise 15 cm.

In some liquids, the cohesive forces between the molecules are greater than their adhesive forces to the glass. In this case, the reverse thing happens. A convex meniscus forms, and the level of the liquid inside the capillary tube is pushed down. The origin of the force is again surface tension. Mercury is an example of a liquid where the cohesive forces are greater than the adhesive forces towards glass.



5.24 *A convex meniscus*

For you to try

3 When sand on the beach is completely dry, it is easy to push it around, and slides out from under your feet when you walk on it. When it is completely covered by water, it also slides out from under your feet. However, when sand is just wet (but not excessively) it goes very hard. Why do you think this is?

4 Soap bubbles fall slowly through the air. If you blow up from beneath them you can push them up higher again. What do expect the pressure inside the soap bubbles to be: higher, lower or equal to the atmospheric pressure around them?

5.25 *Soap bubbles*

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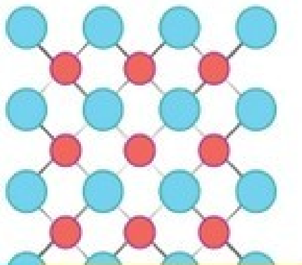
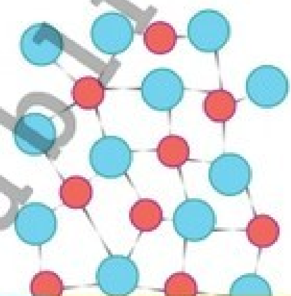
Crystalline and Amorphous solids

All solids have at some point in their existence been liquid. Most of the elements we know are believed to have been formed by fusion in some ancient star that then exploded sending fragments out into space. Even on Earth, some of the rocks have solidified after flowing out from volcanoes as lava.

When we touch a solid and feel it in our hands we cannot know how the atoms are organised inside the solid. All we can normally tell is how dense it is, and how rigid it is. In order to tell something about the arrangement of the atoms inside a solid we need to study them in greater detail. A crude way of testing them is by breaking them and studying the fragments. If the pieces have particular flat faces which are orientated at well-defined angles, it is likely that the atoms were organised in a well-defined pattern. We say the material is crystalline. However, if the fragments have many random angles and the fracture surfaces are not flat, it is likely that the atoms and molecules in the material were not arranged in a well-determined pattern. We say the material is amorphous.



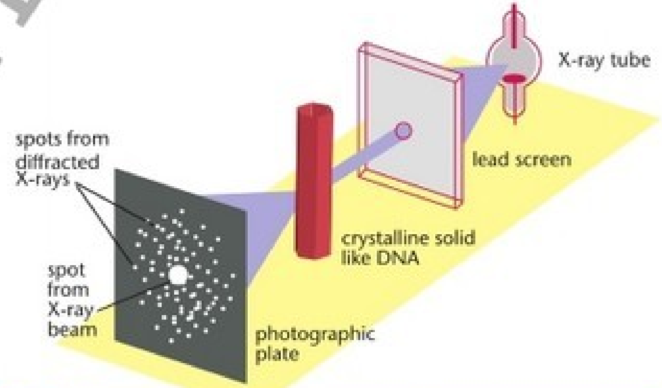
5.26 *Crystalline solid*



5.27 *Amorphous solid*

The process of solidification (whether it is slow or fast, whether in the presence of impurities, etc) determines how the atoms will arrange themselves relative to their neighbours. Generally (though not always), the longer the time the atoms have before they get locked into a solid, the better they arrange themselves in nice orderly patterns (without dislocations or misalignments). When this happens the solid frequently becomes crystalline. By this we mean that atoms are neatly arranged in columns and planes, and a pattern repeats itself again and again. We call this pattern a 'crystal lattice'.

The best way to determine whether a particular material is amorphous or crystalline is to use an 'X ray diffractometer'. X rays have very short wavelengths and can penetrate some way into solids. If the atoms are arranged in a crystal lattice, the positions of the atoms interfere with the X rays passing through the solid and make them come out in very particular directions. If the solid is amorphous, there are no clear patterns in the X rays coming out the other side.



5.28 *X-ray diffraction technique*

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An experiment to try out at home

A simple experiment you can try at home involves dissolving some salt in hot water. Mix in as much salt as will dissolve. Then drain the salty water away from any remaining solid salt at the bottom of the container. Pour it into a shallow plate and leave it by a window where the sun can slowly evaporate the water away. After a few days you will start to see salt crystals forming.

Amorphous solids are those where there is no clear arrangement of the atoms inside the solid. Generally, if a solid is flexible (it can be bent), and if it is ductile (it can be extruded or hammered into different shapes) then the solid is amorphous. Rubber, glass and metals are all amorphous solids.

Because of the special geological conditions required to produce crystals, many crystals are quite valuable. They are often cut at very precise angles, and polished to make expensive jewellery.

Crystalline materials often have important commercial applications, and so materials such as quartz and silicon are grown in carefully controlled conditions in order to ensure their crystal lattices are free from dislocations and any contamination.


5.29 *Crystals*

For you to try

1 What makes crystalline solids different from amorphous solids?
2 Why is very slow cooling needed in order to encourage solids to become crystalline?

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Module 6 Thermodynamics and Engines

Learning objectives

- To explain the meaning of the first and second laws of thermodynamics 10.2.3.1
- To describe the operating principle and application of a heat engine 10.2.3.2

The First Law of thermodynamics

The First Law of thermodynamics is the law of conservation of energy applied to heating, cooling and working. The first law of thermodynamics states:

Heat energy cannot be created or destroyed but it can be transferred from one place to another or converted into another form of energy.

The First Law can be expressed in different ways, according to the sign convention used. In applying the First Law to 'systems' here, it is written:

$$Q = \Delta U + W$$

where:

Q – energy supplied by heat transfer
If energy is **removed** by heat transfer, for example when a gas is cooled, Q is **negative**.

ΔU – change in internal energy.
If ΔU is **positive** there is an **increase** in internal energy, if **negative** there is a **decrease** in internal energy.

Energy supplied or removed by heat transfer = change in internal energy + work done on or by the gas.

Defining a system

In talking about engines and ideas such as their efficiency, we need to define what we mean by the term a 'system'. To solve problems which involve calculating changes: 'system', 'boundary' and 'surroundings' have to be understood.

A system is a region in space that contains a quantity of gas or vapour. In open systems the gas or vapour flows into, out of, or through the region. The gas may pass across the boundary between the system and its surroundings.

Examples of open systems are:

- Steam passing through a turbine.
- Gas expanding through a nozzle from an aerosol can.

In a *closed system* the gas or vapour remains within the region. The boundary between the closed system and its surroundings, however, may not be fixed. It may, for example, expand or contract with changes in the volume of the gas.

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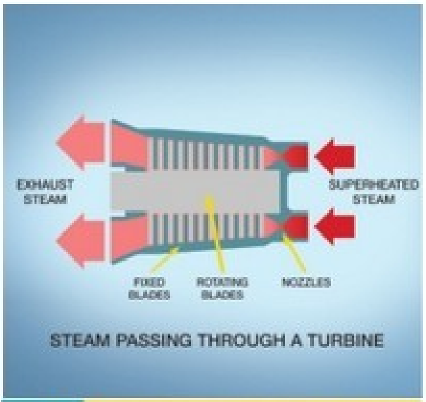
Examples of closed systems are:

- Air in a balloon being heated.
- A gas expanding in a cylinder and moving a piston.

In both open and closed systems heat and work can 'cross' the boundary.

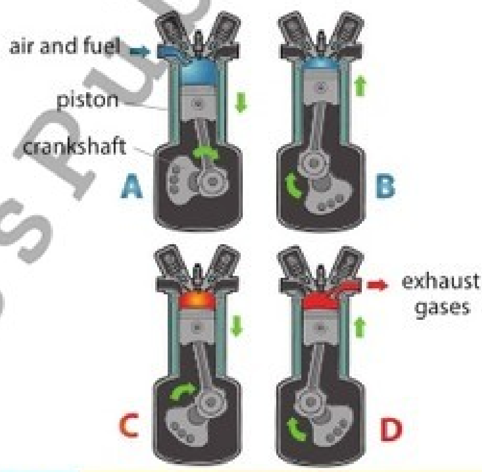


6.1 *Steam passing through a turbine*

6.2 *Hot air balloon*

Internal combustion engine

The principle of the internal combustion engine is very simple. A mass of air is compressed at a low temperature and expanded at a high temperature. Because the work needed to compress the air at a low temperature is less than the work done by the air when it expands at a high temperature, there is a net output of work. The air in the engine must be heated in order to raise its temperature between the compression and the expansion. It is called an internal combustion engine because this heating is done inside the engine.

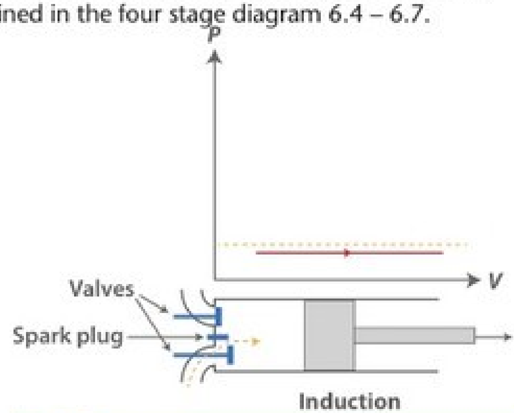


6.3 *Internal Combustion Engine*

In a petrol or diesel engine a piston moves easily up and down in a cylinder with an almost gas-tight fit between the two. Each movement of the piston up or down is called a stroke. In a four-stroke engine, the fuel is burned once every four strokes. The sequence of operations for one complete four-stroke petrol engine cycle comprising induction, compression and exhaust strokes is outlined in the four stage diagram 6.4 – 6.7.

Induction

The piston travels down the cylinder. The volume above it increases the mixture of air and petrol vapour is drawn into the cylinder via the outer valve. The pressure in the cylinder remains constant, just below the atmospheric pressure.



6.4 *Induction*

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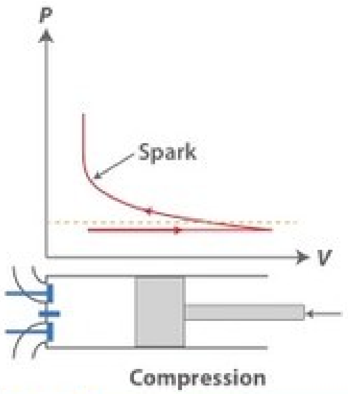


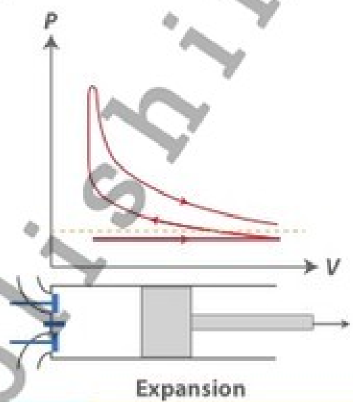
6.5 Compression

Compression

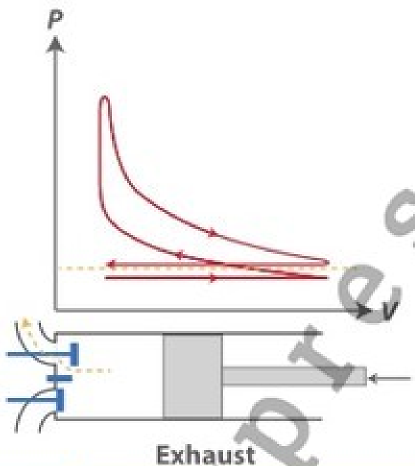
Both valves are closed. The piston travels up the cylinder, the volume decreases and the pressure increases. Work is done on the air to compress it. Very near the end of the stroke the air/petrol mixture is ignited by a spark at the spark plug, resulting in a sudden increase in temperature and pressure at almost constant volume.

Expansion

Both valves remain closed, and the high pressure forces the piston down the cylinder. Work is done by the expanding gas. The exhaust valve opens when the piston is very near the bottom of the stroke, and the pressure reduces to nearly atmospheric.



6.6 Expansion



6.7 Exhaust

Exhaust

The piston moves up the cylinder, expelling the burnt gases through the open exhaust valve. The pressure in the cylinder remains at just above atmospheric pressure.

The Second Law of thermodynamics

The Second Law of Thermodynamics

Heat transfer occurs naturally from regions of higher–to lower–temperature but not naturally in the reverse direction.

All engines must obey the Second Law of Thermodynamics. This law also tells us that the efficiency of any process for converting heat into work cannot approach 100%. In other words, an ideal engine which satisfies both the first and second laws of thermodynamics must have a source and a sink. The engine must be subjected to heating from the source and it must reject some energy to the sink. The source must be at a higher temperature than the sink.

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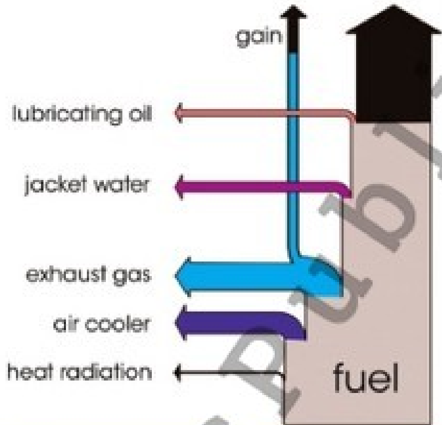
Engine efficiency

An internal combustion engine is supplied with energy in the form of the chemical energy of the fuel. The chemical energy is transformed into internal heat energy which the engine in turn converts into mechanical energy. The overall efficiency of the engine is the ratio:

$$\frac{\textbf{Useful energy or work output}}{\textbf{energy input}} \times 100\%$$

We want an engine of a given size to provide as much power as possible for every kg of fuel used, so the more efficient the engine the greater the km per litre of fuel and the less the cost of running the car. Also, if less fuel is used, less CO_2 will be released into the surrounding atmosphere.

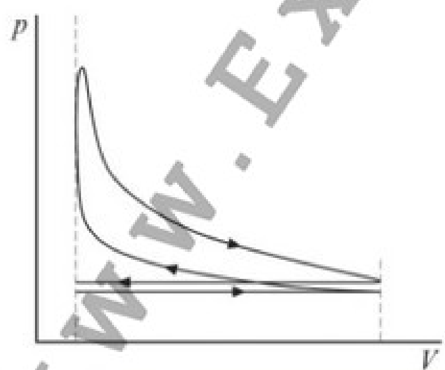


6.8 *Representation of internal combustion engine energy loss*

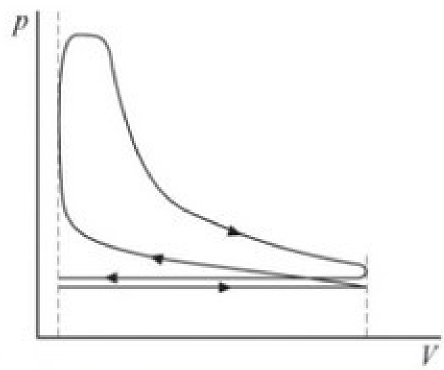
Indicator graphs

The *p*–*V* graphs below are called indicator graphs. They are produced using computer software by engineers to evaluate engine efficiency. They vary with parameters such as engine load and speed, and the timing of the spark (petrol), or fuel injection (diesel).

Figures 6.9 and 6.10 show typical indicator graphs for four-stroke petrol and diesel engines for one complete mechanical cycle.



6.9 *Petrol engine*



6.10 *Diesel engine*

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The work done **on** the gas during the compression stroke is given by the area underneath the compression curve, and the work done **by** the gas during the expansion stroke is given by the area underneath the expansion curve. Therefore, the **net work done** by the air is given by the **area enclosed by the loop** on the p-V diagram.
If the net work done is divided by the time for one cycle, the indicated power is obtained.
Time for one cycle = 1/cycles per s

Therefore:

indicated power = area enclosed by loop of $p - V$ diagram × number of cycles per second

If there is more than one cylinder in the engine

indicated power = area of $p - V$ diagram × number of cycles per second × number of cylinders

Because there is one power stroke for every two revolutions of the crankshaft this can be changed to:

indicated power = area enclosed by of $p - V$ diagram × $\frac{1}{2}$ (rev min^{-1}/60) × number of cylinders

The area of the small loop formed between induction and exhaust strokes is negative work, and should be subtracted from the main loop area to give the true net work, but in a real indicator diagram the area is so small as to be negligible. In fact, the induction and exhaust strokes usually show up as a single horizontal line.

Some of the power developed by the air in the cylinder is expended in overcoming the frictional forces between the moving parts of the engine and the viscous resistances of the lubricating oil and cooling water. This is called the **friction power**. The output power will, therefore, be less than the indicated power by an amount equal to the friction power.

Calculations of power and efficiency

The calorific value of a fuel is the amount of heat produced by the combustion of a fuel mass, and is typically expressed in joules per kilogram.

input power = calorific value of fuel × fuel flow rate

For liquid fuel, the flow rate will be in kg s^{-1} and the calorific value in MJ kg^{-1}.

For a gas, flow rate is usually in m^3 s^{-1} and the calorific value in MJ m^{-3}.

Indicated power = power developed in the cylinders of the engine =
area of p–V diagram × number of cycles per second × number of cylinders

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GrS PHYS Gr 10 Ss Mod 6.indd 92 5/9/19 4:43 PM

6.1 Sample Question

Test measurements made on a single-cylinder 4-stroke petrol engine produced the following data:

- mean temperature of gases in cylinder during combustion stroke 820°C
- mean temperature of exhaust gases 77°C
- area enclosed by indicator diagram loop 380 J
- rotational speed of output shaft 1800 rev min^{-1}
- power developed by engine at output shaft 4.7 kW
- calorific value of fuel 45 MJ kg^{-1}
- flow rate of fuel 2.1×10^{-2} kg min^{-1}

Calculate:

(a) the rate at which energy is supplied to the engine

(b) the indicated power of the engine

(c) the thermal efficiency of the engine.

(a) The energy supplied = calorific value x rate of flow

Sample Answer

= 45 x 106 J/kg x (2 x 10^{-2} kg/min ÷ 60 s)

= 15 800 J/s

(b) Engine goes through the power cycle once every two revolutions.
There are 15 cycles per second: Indicated power = 380 J x 15 s^{-1} = 5700 J/s

(c) Thermal efficiency = indicated power ÷ input power

= 5700 ÷ 15 000

= 0.38 (38 %)

6.2 Sample Question

The power gained from the fuel of the engine was 15.8 kW. If the power output is 4.7 kW, what is the overall efficiency?.

Sample Answer

Overall efficiency = output power ÷ input power from fuel

Mechanical efficiency = 4700 W ÷ 15800 W

= 0.297 (29.7%)

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For you to try

1 A car engine has a power output of 6.2 kW and uses fuel which releases 45 MJ per kg when burned. At a speed of 30 m s^{-1} on a level road, the fuel usage of the vehicle is 18 km per kg. Calculate:
   (a) The useful energy supplied by the engine in this time
   (b) The overall efficiency of the engine.

2 The energy content of petrol is about 44.1MJkg^{-1}. Calculate the input power when 5.20 kg of fuel flowed into an engine in one minute.

3 Diesel fuel has a calorific value of 42.9MJkg^{-1}. Calculate the input power if the flow rate is 6.00×10^{-2} kgs^{-1}.

4 Calculate the thermal efficiency for a car, for which the following data is given:
   input power = 462 000 W
   indicated power = 122 000 W

5 The area of an indicator diagram gives 960 J. If a four-stroke engine is rotating at 4200 rpm, calculate the indicated power per cylinder.

The home refrigerator

This is a beautiful example of the interchange between work and heat. At the heart of refrigerators and air conditioning units is what we call a 'heat pump'. To understand it properly it is best to consider each part of the operation separately:

Step 1

The electrical energy supplied by the power station is used to drive an electrical motor which operates a compressor to pump gas from a low pressure reservoir to a higher pressure reservoir. This work that is being done on the gas molecules causes the gas to heat up (the individual molecules are moving randomly at faster velocities). This may seem like a strange thing to do if you want to try to cool the inside of the refrigerator! The important thing to remember is that compressing a gas is hard work, and it produces heat (you may have noticed the valve of a bicycle tyre gets hot when you actively pump air into it).

Step 2

This heat produced by the compression needs to be dissipated through the use of a 'radiator' that is normally located at the back of the refrigerator. Heat is conducted into a grid of metal wires (sometimes called a 'condenser'). These heated wires then release the heat to the air by convection. By the time the compressed gas comes out the other side of this heat exchanger the gas is nearly back to room temperature. This heat has been 'wasted'! (It could be used to help to dry towels or some other application, but generally no use is made of it).

Step 3

Now the compressed gas is made to pass through a small nozzle (sometimes called an 'expansion valve') so that it can expand into another set of tubes inside the cool box. The action of expanding means that the gas is having to do work in pushing back the frontiers of the space it will occupy. It does this work at the expense of its internal energy, and as a consequence of this the random motion of the molecules slows down and the mean temperature of the gas drops. You may have noticed that when you spray an aerosol can of perfume the nozzle, the can, and even the gas coming out of the can cools down.

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Step 4

The cooled tubes inside the refrigerator cold box can get so cold that water condenses out of the air on to them, and can even form ice! Now it is time for the food inside the refrigerator to lose its heat to the cold surroundings inside the cold box. This is how the contents of the refrigerator are cooled down. However, the cold gas will gradually warm up as it absorbs the heat extracted from the food inside.

Eventually the low pressure gas will need to be brought out of the cold box and re-compressed (back to step 1), and the cycle repeats again and again. You may have heard the compressor of your home refrigerator switching on and off periodically. Every time that the temperature inside the cold box creeps up above the thermostat set point, the compressor switches on, and it keeps on running until the temperature inside the cold box drops below the thermostat set point.

If you notice that the compressor of your refrigerator seems to be running most of the time, it may mean that:

(a) the door of the refrigerator is not closed properly,
(b) the thermal insulation of the cold box is no longer adequate or
(c) the refrigerant gas inside the system has slowly leaked out.

A refrigerator contains a fixed amount of gas which it compresses (outside) and expands (inside), and in the process 'pumps heat' out of the cold box to the outside world.

6.11 *Refrigerator showing the interchange between work and heat*

For you to try

1. Why does the nozzle of a bicycle wheel get hot when you are pumping up the tyres?
2. Why might a CO_2 fire extinguisher get very cold when it is used? (So cold, that if you hold the venting horn with your bare hands, your fingers will freeze on to it!)
3. Why does a car run less efficiently (getting fewer kilometres for a litre of fuel) if the air-conditioning is switched on?
4. A student notices that if he breathes out against his hand with his mouth wide open, the air coming from his mouth feels warm. However, when he tightens his lips to make a small exit and blows hard on his hand, the air feels cold. Can you explain this difference?

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Module 7 Electrostatics

Learning objectives

- To recognise the properties of electric fields and perform electric field strength calculations 10.3.1.1
- To describe the effect of electrostatic fields on the motion of charges 10.3.1.2
- To compare the characteristics of gravitational and electrostatic fields 10.3.1.3
- To explain the role of the capacitor in a simple circuit 10.3.1.4

History

You do not need any education or specialist knowledge to be aware of electricity. Lightning, and the associated thunder, is a spectacular natural phenomenon that has been known to all cultures throughout history. The symbol of the most powerful Greek god, Zeus, was the thunderbolt, and many other cultures throughout Europe, South America and India have associated lightning with their gods.

7.1 *Lightning is a natural phenomenon caused by electricity*

In some parts of the world, people are familiar with other natural sources of electricity such as electric eels and some breeds of catfish.

There are also pre-Christian accounts noting that when one rubs fur against the naturally occurring material known as amber, the amber can then be used to lift small and light objects such as pieces of straw.

All of these are phenomena associated with electricity.

Static electricity

If you take a plastic rod and rub it against a different material, such as your hair, you should notice an effect similar to that mentioned above involving amber. You might be able to pick up small pieces of paper using the rod. American scientist and politician Benjamin Franklin (1706–1790) studied this effect using glass rubbed against a piece of silk. He described the charge on the glass as **positive** and that on the silk as **negative**, the first time that these terms had been used.

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Experiment 7.1: To investigate electric charge

Method 1

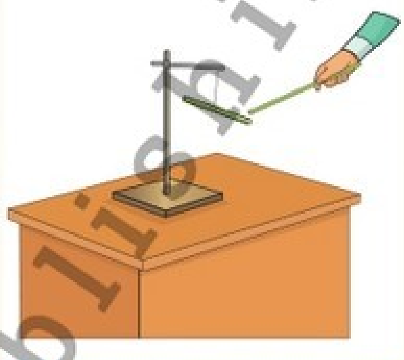
1 Tear up a piece of paper into sections only a few centimetres across.
2 Take a plastic rod and rub it against your hair to charge it.
3 Hold the rod close to the pieces of paper and observe what happens.

Observations

You should find that the pieces of paper are attracted upwards towards the plastic rod.

Method 2

1 Place a plastic rod in a stirrup suspended from a wooden retort stand, as shown in figure 7.2.
2 Take a second plastic rod and rub it against your hair to charge it.
3 Hold the second rod close to the first one and observe what happens.



7.2 *Investigating static electricity*

Observations

You should find that the first rod, suspended in the stirrup, is attracted to the second one, in your hand.

Method 3

1 Take a plastic rod and rub it against your hair to charge it.
2 Place the charged plastic rod in a stirrup suspended from a wooden retort stand, as shown in figure 7.2.
3 Take a second plastic rod and rub it against your hair to charge it.
4 Hold the two charged rods close to each other and observe what happens.

Observations

You should find that the two charged rods repel each other.

Method 4

1 Turn on a tap so that there is a gentle but steady flow of water.
2 Take a plastic rod and rub it against your hair to charge it.
3 Hold the charged rod close to the water stream and observe what happens.

7.3 *An effect of static electricity*

Observations

You should find that the stream of water is deflected by the presence of the electric charge.

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Method 5

1 Rub a balloon against your hair to charge it.
2 Hold the charged balloon against a smoothly plastered wall.

Observations

If the charge is sufficient you should find that the balloon sticks (briefly) to the wall.

7.4 *An effect of static electricity*

Charges

All of the effects described above come about because of something called **electric charge**, of which there are two types: positive and negative. We often summarise how these charges interact with each other using the key phrase:

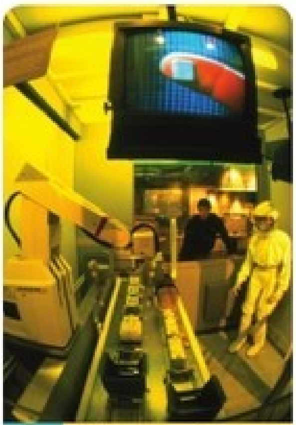
> Like charges repel, unlike charges attract.

In other words, if we place two positive charges close to each other, they will be repelled from each other. The same happens with two negative charges. By contrast, if we place a positive charge close to a negative charge, the two will be attracted towards each other. Sometimes, if the charges are significant, there can be a spark as the charges jump towards each other.

This can be problematic in many ways. Workers in electronic industries often wear special clothing to prevent damage to circuitry from the small charges that can build up on clothes. Airport workers have to be very conscious of the dangers that come from static charges when they are refuelling aircraft. Workers in flour mills have similar concerns.

There is an obvious comparison to be made between electricity and magnetism, which also involves like poles repelling and unlike poles attracting. The two phenomena are indeed tightly interconnected, as we will see in more detail when we study the area of electromagnetism. At the same time, it is important to keep the two ideas separate in your thinking.

Electric charge cannot exist by itself. It is a property of tiny particles known as subatomic particles. There is a wide variety of such particles, many of which – such as pions and W bosons – you are unlikely to have heard of, but may learn about when you study modern physics. Generally though, when you encounter electric charge in ordinary situations, that charge is likely to be associated with more familiar particles: protons and electrons.



7.5 *A clean room in an Intel plant, showing the protective clothing used by technicians in the manufacture of semiconductor chips*

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Protons and electrons are two of the key particles that make up atoms. Recall the basic structure of the atom: the protons are positively charged and are found, alongside a number of non-charged neutrons, in the nucleus; the negatively charged electrons are found circling the nucleus.

It is worth noting that the use of 'positive' and 'negative' as labels to describe the different types of electric charge is a scientific convention. We could just as easily have labelled them 'up' and 'down' charges, or 'left' and 'right'. Positive and negative is just one convenient pair of opposites that is easily understood.

7.6 *The negatively charged electrons are found in shells surrounding the positive nucleus*

Every object contains a very large number of atoms and, therefore, an enormous number of electric charges. A typical plastic rod, like that you used in Experiment 7.1, would contain about 1 000 000 000 000 000 000 000 000 atoms and an even larger number of protons and electrons. However, because it will generally contain the same number of protons and electrons, it has no overall charge. We say that it is **electrically neutral**.

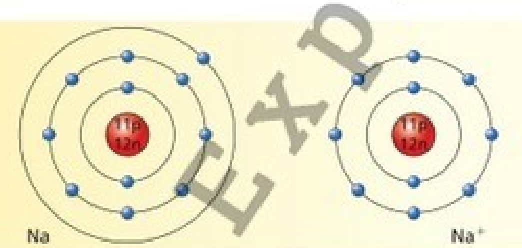
If the rod gains even a few electrons, though, it will have more negative than positive charge and will become negatively charged overall. Similarly, gaining extra protons would make it positively charged.

If you look at the diagram of the atom in figure 7.6, you will see that it is always easier to add or remove the relatively loosely bound electrons on the outside of the atom than to vary the number of protons, which are located deep inside the nucleus. For this reason, it is almost always the addition or removal of electrons that causes an object to become either negatively or positively charged.

If an object is electrically neutral, it has the same number of protons and electrons. **If it gains electrons** it will have more electrons than protons and will be negatively charged. **If it loses electrons** there will then be a majority of protons and the object will be positively charged.

Ions

When atoms either gain or lose electrons and therefore become charged, we refer to them as **ions**. So, for example, if an atom gains electrons it is a **negative ion**. This often happens with atoms such as chlorine. Alternatively, other atoms such as sodium tend to lose electrons and become **positive ions**, as shown in figure 7.7.



7.7 *A sodium atom (on the left) and a positive sodium ion (on the right)*

Charging by contact

As you saw in Experiment 7.1, small electric charges can be built up by rubbing one material against another. When this is done, electrons are physically removed through friction, from one of the materials and added to the other. This is called **charging by contact**.

Charging through contact involves the physical transfer of electrons from one object to another when the objects are in contact.

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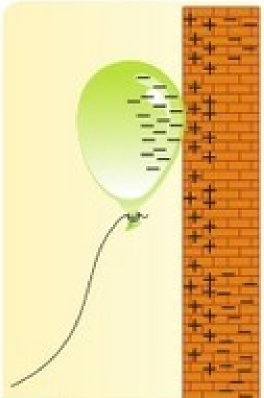
Because of this effect, mirrors and TV screens should not be cleaned using a dry cloth. The friction between the two builds up a charge, which then causes dust to settle on the mirror or the screen. On a larger scale, a static electric charge built up in this way can create a hazard in flour mills, where a spark from a built-up charge can cause an explosion. Aircraft are always carefully earthed before refuelling to remove any charge that might have built up during a flight.

Charging through induction

When a balloon is charged by rubbing it against your hair, as in Experiment 7.1, it usually builds up a negative charge by collecting additional electrons in the manner we have already discussed. However, if the balloon is made to stick to a wall as shown in figure 7.9, there must also be a charge of some sort on the wall. It is the attraction of opposite charges, after all, that makes it stick there. Where does the positive charge on the wall come from?

7.8 *Aircraft are earthed before refuelling*

The answer is that the negative charge on the balloon has repelled electrons from the surface of the wall as it approached. This left a small area of positive charge on that portion of the wall, and the force of attraction between the opposite charges was enough to keep the balloon there.



7.9 *The negative charge on the balloon induces a positive charge on the wall*

An object that becomes charged in this way – without any contact with another body – has been **charged by induction**.

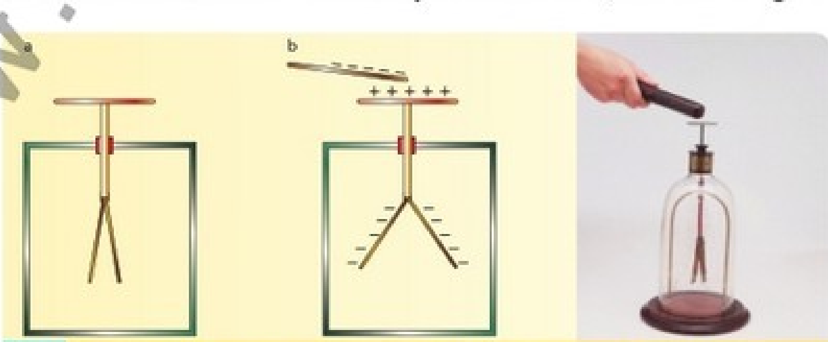
Something similar happens when a flow of water is displaced by electric charge. A positive rod held near the flow of water will cause negative charges to accumulate in the side of the water that is nearest the rod. The attraction of opposite charges will then cause the flow of water to divert, towards the rod.

> Induction is the creation, or redistribution, of electric charge on an object through the action of nearby charges.

Gold leaf electroscope

The gold leaf electroscope is a device that allows us to study how an object can be charged through induction. The traditional electroscope consists of a metal cap connected with a metal bar to two gold leaves below, as shown in figure 7.10.

If a negatively charged plastic rod is brought close to the cap, it repels electrons from the cap. They are forced down through the connecting bar to the leaves below. The two leaves then have the same negative charge and are repelled from each other. As they are so light, this repulsion is sufficient to cause them to lift away from each other, as shown in figure 7.10.



7.10 *The charge on the cap and leaves of a gold leaf electroscope is created without contact and is therefore induced*

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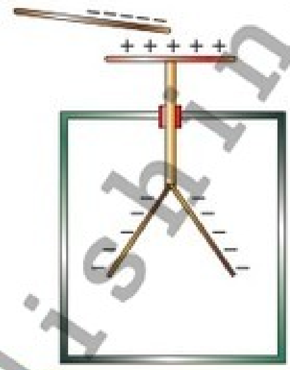
Experiment 7.2: To investigate an electroscope, and demonstrate charging by induction

Method

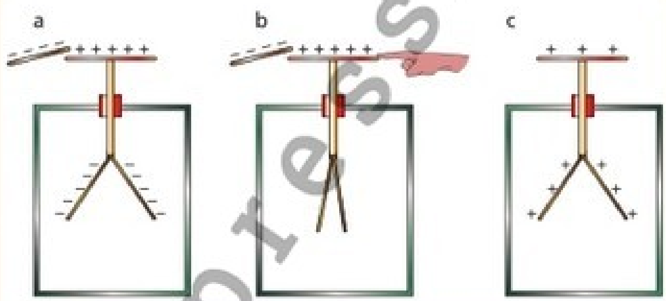
1. Set up a non-charged electroscope.
2. Take a plastic rod and rub it against your hair to charge it.
3. Hold the charged rod close to the cap of the electroscope and observe what happens to the leaves (see figure 7.11).
4. To make the charge 'permanent', bring the charged plastic rod close to the electroscope, and when the leaves are spread out, gently touch the cap of the electroscope with your finger.
5. Remove your finger, and then remove the plastic rod. Observe what happens now.



7.11 *A charged electroscope*

Observations

When you hold the charged rod to the cap of the electroscope, you should see the leaves diverge. When you touch the cap of the electroscope with your finger, you should notice that the leaves collapse. When you remove your finger and the charged rod, you should see the leaves spread out once more. This effect is not truly permanent, as the induced charge will leak into the atmosphere over a number of minutes.



7.12 *Creating a positively charged electroscope*

Earthing

In Experiment 7.2 you found that the leaves on an electroscope will collapse when the cap is touched. This is because we have effectively **earthed** the cap.

An electric charge will always tend to spread itself out as much as possible. For example, if a metal sphere has a negative charge, this means that it has acquired a number of extra electrons. These electrons are all repelled from each other and move as far apart from each other as possible. On a metal sphere this is easy, as both the shape and the material allow the charge to spread itself evenly across the whole surface.

On plastic objects, which do not allow electrons to move easily, the effect can be reduced. The charges are forced to stay in one area.

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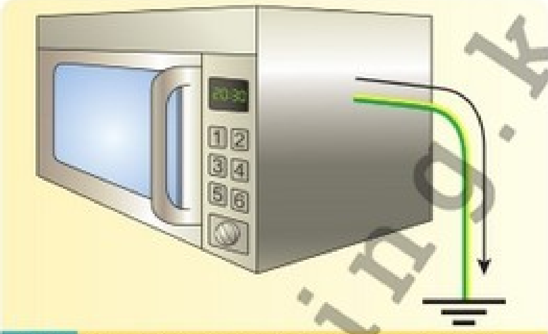
When a charged object is connected to the earth, the charge spreads out so much it effectively disappears. We refer to this as **earthing** the object. It is built in as a safety feature in electrical wiring, using the earth wire. This is a green and yellow wire that will carry any charge building up on malfunctioning devices to earth before they cause harm to users.

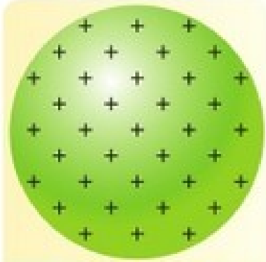
With the electroscope in Experiment 7.2, the charge effectively disappears when we touch it because we are so much larger than it is. We are operating as the 'earth'.



7.13 *In a malfunctioning electrical device, charge is carried to earth to avoid danger*

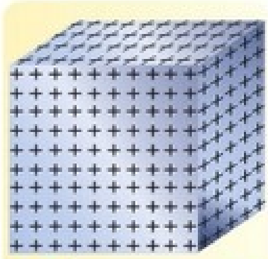
Point effect

We have seen how electric charge will always spread out as much as possible. On a metal sphere this always works well because it is a smooth, symmetrical surface and it easy for the charges to find an arrangement whereby they are all as far away from each other as possible (see figure 7.14).



7.14 *The charge is evenly distributed*

If a metal cube becomes charged, the charges will still spread out to be as far from each other as possible. However, if you look at the corners in figure 7.15, you can see how this becomes problematic: charges are pushed away from the centre of each face of the cube so they can spread out as much as possible, but when they are pushed into a corner, this means that they are being pushed towards the other similar charges on an adjacent face. Nature will try to strike a balance between all the competing forces, but there is no perfect arrangement and there is an inevitable build-up of charge at the corners.



7.15 *There is a build-up of charge at the corners*

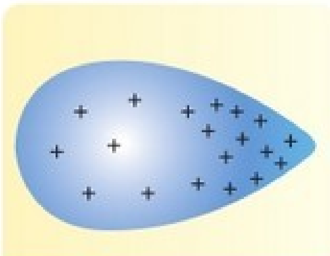
The cube is just one example of a shape in which this problem occurs. In every shape, other than a sphere, something similar happens. This is known as the **point effect**.

> The point effect describes how if an object is less curved than a sphere, and particularly if it has sharp points, there will be a build-up of charge.

Point discharge

The point effect can lead to the object becoming discharged.

Remember that air is made up of molecules and that these molecules consists of protons and electrons like all other materials. If there is, say, a very large positive charge at a point on a conductor, this will attract the negatively charged electrons within the molecules in the air towards it and push away the positively charged protons. If the charge is sufficient, the negatively charged electrons can be removed from their



7.16 *Where the curve is reduced and a point develops, there is a build-up of charge*

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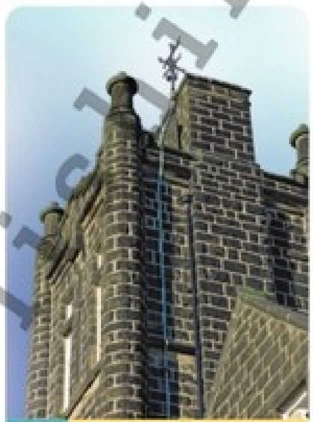
atoms in the air, leaving behind positively charged ions. The electrons are then attracted to the metal surface and neutralise the positive charge that was there, while the positively charged protons are repelled from the surface. The result of this is that the charge is taken from the conductor.

Point discharge is the loss of charge through a point on an object.

Lightning conductors

Most tall buildings have a lightning conductor something like that shown in figure 7.17 attached to the highest point on their roof, and connected to earth by means of a metal strip that runs down through the building.



7.17 *Lightning conductor on a school tower. The conductor consists of a metal strip, usually copper, of very low resistance connected to the ground below. A good connection to the ground is essential and is made by burying a large metal plate deep in the earth*

You are probably already aware of lightning conductors and understand that they are there to protect a building from lightning. It is important to be aware, however, that they do this in two ways. It is true, as is widely understood, that in the event of a lightning strike the lightning conductor provides a relatively safe path to earth for the charge. This can minimise damage, but it does not always eliminate it. The enormous charge running through the metal and the great heat generated as a result can still cause damage in surrounding materials, and there is always a risk that some charge may spark across to the electrical wiring within the building and cause substantial damage there.

It is less widely understood that if lightning strikes the building, the lightning conductor has to an extent already failed. Its primary purpose is to prevent a strike in the first place.

When an electrical storm is developing, a large amount of charge builds up in the atmosphere. This build-up will have the effect of inducing a charge to grow at the point of any lightning conductor in the vicinity: a large positive charge in the atmosphere, for example, will attract a comparable negative charge to the point of the conductor, drawing that charge from the earth.

7.18 *The positive charge in the air attracts a negative charge to the lightning conductor. The two neutralise each other*

The negative charge on the conductor then draws the positive charge in the atmosphere towards itself. The large electric charges also causes the surrounding air to become charged (or ionised), which makes the air a better conductor than would normally be the case and allows the charge to flow through the air. When the positive charges meet the negative, both are cancelled out. This process will then repeat on an ongoing basis as long as there is charge in the atmosphere, and has the obvious effect of slowly removing most of that charge from the atmosphere, at least in the vicinity of the tall building. In this way a lightning strike is prevented by the lightning conductor.

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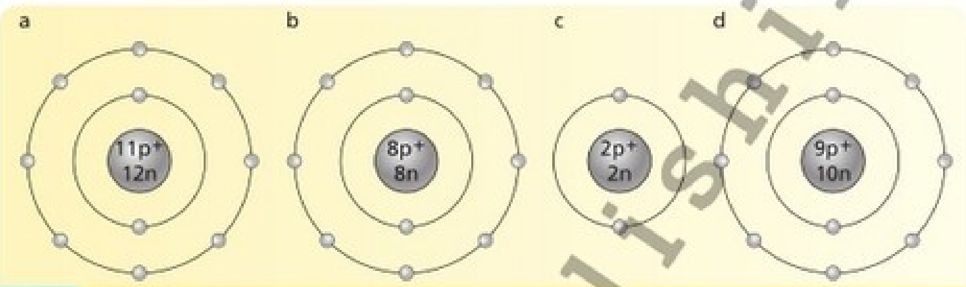
GrS PHYS Gr 10 Ss Mod 7.indd 103 5/9/19 4:44 PM

For you to try

1. Distinguish between charging by friction and charging by induction.
2. Give examples of how a body can be charged by friction.
3. It is always advisable to clean a mirror with a damp cloth rather than a dry one. Why?
4. What is an ion?
5. What is the overall charge on each of the atoms or ions represented in figure 7.19?

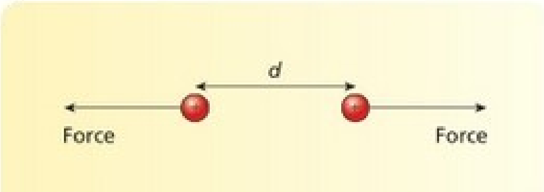


7.19 *Question 5*

6. What do we mean by the term 'earthing'?
7. What is the point effect?
8. Explain how a lightning conductor protects a tall building from damage.

Coulomb's law

We know already that like charges repel each other and that opposite charges attract. Repulsion and attraction are examples of **force**. Forces are vector quantities, which means that they have both a magnitude and a direction.



7.20 *The force between two point charges is related to the product of the charges and the distance between them*

Look at figure 7.20, and ask what force exists on the positive charge. It is immediately obvious what the direction of that force will be: as a positive charge it will be repelled from the other positive charge, a distance d away. However, we also need to be able to determine what the magnitude of that force will be. This is where **Coulomb's law** comes in. Charles-Augustin de Coulomb (1736–1806) was a French physicist who in 1785 laid down the law now named after him:

Coulomb's law states that the force between two point charges is directly proportional to the product of the charges, and inversely proportional to the square of the distance between them:

$$F \propto \frac{Q_1 Q_2}{d^2}$$

where:

F – force

$Q_1 Q_2$ – charges

d – distance between charges

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The coulomb is a very large charge. It takes billions upon billions of electrons to build up a total charge of 1 C, for instance. For this reason, you will often find yourself dealing with charges that are a fraction of a coulomb, such as a millicoulomb, or microcoulomb.

$$1\,\text{mC} = 1 \times 10^{-3}\,\text{C}$$
$$1\,\mu\text{C} = 1 \times 10^{-6}\,\text{C}$$

Coulomb's law is an example of an **inverse square law**. This tells us that the force between charges diminishes as charges move apart, and that if we double the distance between them, the force is divided by four (2^2), or if we increase the distance between the charges by a factor of 3, that the force will be divided by nine (3^2), and so on. Newton's law of gravitation is also an inverse square law.

Whenever two measurements are proportional to each other, as here, we can also say that one is a constant times the other. The constant here is represented by the following expression:

$$\frac{1}{4\pi\varepsilon}$$

So the equation becomes:

$$F = \frac{1}{4\pi\varepsilon}\frac{Q_1 Q_2}{d^2}$$

Permittivity (ε)

Think about two positive electric charges placed close together with air between them. We know that they will create a repulsive force on each other, and we have just seen that Coulomb's law allows us to calculate how large that force will be. Then think about how the two forces might affect each other if they were immersed in water, or a lump of plastic, or metal. It's not difficult to see that the material between the charges will affect the forces created between them.

The **permittivity** (ε) is how we deal with this issue. Each material has a specific permittivity value, and this value is part of the calculation in Coulomb's law. A large value for permittivity indicates a reduced value for the force between charges, whereas a low value for the permittivity indicates a higher value for the force.

You will often come across what we call the **permittivity of free space**, indicated by ε_0. This indicates the permittivity of a vacuum. Air has very little effect on the force between two charges, and so free space, in this instance, is usually taken to represent air as well as a vacuum.

Permittivity of free space, $\varepsilon_0 = 8.854 \times 10^{-12}\ Fm^{-1}$

Relative permittivity

Rather than listing a value for the permittivity of each material, it is often easier to just compare the permittivity with that of free space. Thus, a relative permittivity of 2 indicates a permittivity twice that of free space.

Relative permittivity: $\varepsilon_r = \dfrac{\varepsilon}{\varepsilon_0}$

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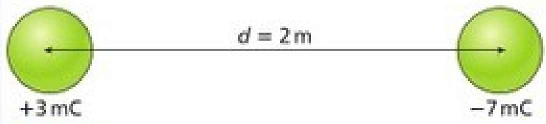
GrS PHYS Gr 10 Ss Mod 7.indd 105 5/9/19 4:44 PM

7.1 Sample Question

What is the force between two charges of +3 mC and –7 mC, a distance of 2 m apart?



7.21

Sample Answer

$$F = \frac{1}{4\pi\varepsilon_0}\frac{Q_1Q_2}{d^2}$$

$$= \frac{(3\times10^{-3})(7\times10^{-3})}{4\pi(8.854\times10^{-12})(2^2)}$$

$$\approx 47186\,\text{N}$$

(The charges are attracted towards each other.)

$\varepsilon_0 = 8.854\times10^{-12}\ \text{F m}^{-1}$

Remember, as we saw with Newton's laws, forces always occur in pairs, and the two forces are always equal in magnitude but opposite in direction. In Sample Question 7.1, therefore, the positive charge is attracted towards the negative and the negative towards the positive. And, despite the fact that one charge is more than double the other, the forces are equal in magnitude.

7.2 Sample Question

What is the value of the permittivity of a plastic, with a relative permittivity of 5.9?

Sample Answer

$$\varepsilon = \varepsilon_r\varepsilon_0$$

$$= (5.9)\ (8.854 \times 10^{-12})$$

$$= 5.224 \times 10^{-11}\ \text{Fm}^{-1}$$

$\varepsilon_0 = 8.854\times10^{-12}\ \text{F m}^{-1}$

7.3 Sample Question

Two identical charges are placed a distance of 25 cm from each other in a vacuum. The force between them is 1.2 N. What is the size of the charge?

Sample Answer

$$F = \frac{1}{4\pi\varepsilon_0}\frac{Q_1Q_2}{d^2}$$

$$1.2 = \frac{1}{4\pi(8.854\times10^{-12})}\frac{Q_2^{\,2}}{0.25^2}$$

$$Q_2^{\,2} = (0.25^2)\ (4\pi)(8.854 \times 10^{-12})\ (1.2)$$

$$Q_2^{\,2} = 7.345 \times 10^{-12}$$

$$Q = 2.89\times10^{-6}\,\text{C}$$

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7.4 Sample Question

Three positive charges are arranged as shown in figure 7.22. What is the total force on the charge of 2 mC and in what direction?

7.22

Sample Answer

F_4 (force on 2 mC created by 4 mC) $= \dfrac{(4\times10^{-3})(2\times10^{-3})}{4\pi(8.854\times10^{-12})(0.2)^2}$

$= 1.798\times10^{6}$ N, to the right

F_6 (force on 2 mC created by 6 mC) $= \dfrac{(2\times10^{-3})(6\times10^{-3})}{4\pi(8.854\times10^{-12})(0.4)^2}$

$= 6.741\times10^{5}$ N, to the left

$F = 1.798\times10^{6} - 6.741\times10^{5}$

$= 1.124\times10^{6}$ N, to the right

For you to try

1 State Coulomb's law.

2 What is the magnitude and direction of the force on the 5 mC charge shown in figure 7.23?

7.23 Question 2

3 A charge of +3 μC is placed at a distance of 30 cm from a charge of +4 μC, in a vacuum. What is the magnitude of the force between them?

4 Two charges are situated a short distance apart in air. The space between them is then filled with oil of relative permittivity 2. Does the force between the charges increase or decrease?

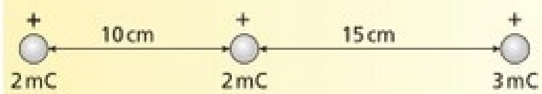
5 A charge of 2 mC is embedded in plastic of relative permittivity 7.1, at a distance of 20 cm from another charge of 4 mC. What is the force between the two charges?

6 A charge of –3 μC is placed at a distance of 1.2 m from a charge of +5 μC, in air. What is the magnitude and direction of the force on the negative charge?

7 In the situation shown in figure 7.24, the 2 mC charges are in air.

(a) Find the magnitude of the force on the central charge.

(b) What is the direction of the force charge?

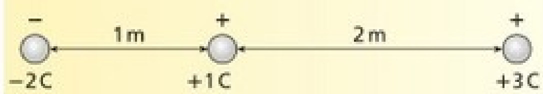


7.24 Question 7

8 In the situation shown in figure 7.25, a number of charges are arranged in air.

(a) What is the direction of the force created on the +3 C charge?

(b) What is the magnitude of this force?



7.25 Question 8

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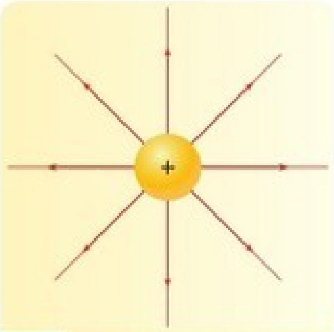
GrS PHYS Gr 10 Ss Mod 7.indd 107 5/9/19 4:44 PM

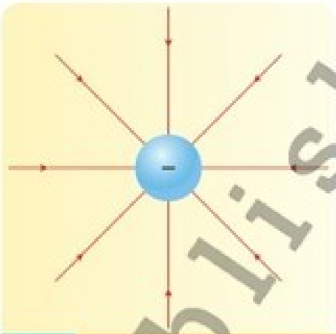
Electric fields

An electric field is the area around a charge where its effect can be felt.

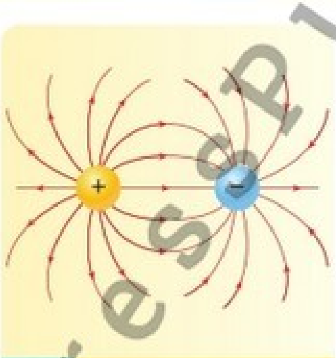
In drawing diagrams to show the shape of the electric field around an electric charge, we always draw the arrows to show the path a positive charge would take. Various examples of such diagrams are shown in figures 7.26–7.29.



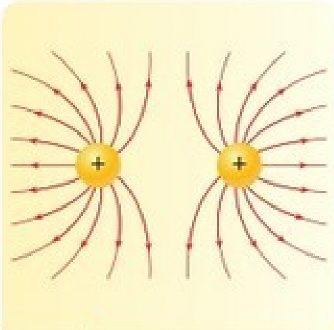
7.26 *The field around a single positive charge*



7.27 *The field around a single negative charge*



7.28 *The field between a positive and negative charge*



7.29 *The field between two positive charges*

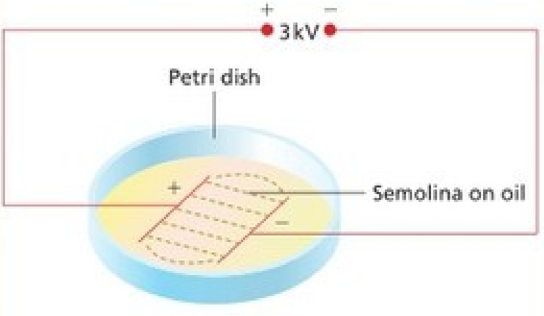
Experiment 7.3: To demonstrate an electric field

Method

1. Add some grains of semolina to a shallow dish of oil and set up the circuit as shown in figure 7.30. Note the very high voltage being used, and be careful!
2. Close the switch and note the movement of the floating particles.

Observations

You should find that the semolina particles become slightly charged at each end, and line up along the lines of force, showing the shape of the field.



7.30 *To demonstrate an electric field*

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GrS PHYS Gr 10 Ss Mod 7.indd 108
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Electric field strength

As we have seen, when drawing electric fields we use arrows to show the direction a single small positive charge would move. In analysing electric fields mathematically we follow a similar logic. To determine the strength of an electric field at any particular point, for example, we ask what force would exist on a charge of +1 C if it were placed in the electric field at that point.

The purpose of calculating the electric field strength is to have a way in which we can compare the effect of different charges, and different arrangements of charges, with each other.

Electric field strength is the force per unit positive charge at a point in an electric field. It is measured in newtons per coulomb ($N C^{-1}$).

$$E = \frac{F}{Q}$$

where:

E – electric field strength

F – force

Q – charge transferred

Electric field strength is a vector quantity.

Another way of looking at this is to use Coulomb's law, taking the size of one of the charges to be 1 C: to find the strength of the electric field around a charge Q, at a distance d from the charge, we simply ask what the force would be on a charge of 1 C if it were placed at that point.

From Coulomb's law we can say:

$$F = \frac{1}{4\pi\varepsilon_0}\frac{Q_1 Q_2}{d^2}$$

Remember that this is the force that would exist on a charge of +1 C at that point, if such a charge were placed there. This is, therefore, equal to the value for the electric field strength:

$$E = \frac{1}{4\pi\varepsilon_0}\frac{Q}{d^2}$$

7.5 Sample Question

A charge of 3 mC is placed in an electric field at a distance from its centre, and experiences a force of 1.2×10^{-3} N. What is the electric field strength at that point?

Sample Answer

$$E = \frac{F}{Q} = \frac{1.2 \times 10^{-3}}{3 \times 10^{-3}} = 0.4\ N C^{-1}$$

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7.6 Sample Question

(a) What is the strength of the electric field at the point shown in figure 7.31, a distance of 1.2 m from a +7 mC charge?

(b) If we placed a charge of +2 mC at that point, what force would it experience?

7.31

Sample Answer

(a) $E = \frac{1}{4\pi\varepsilon}\frac{Q}{d^2}$

$= \frac{7\times10^{-3}}{4\pi(8.854\times10^{-12})(1.2)^2}$

$= 4.37\times10^{7}\,NC^{-1}$

(b) $E = \frac{F}{Q}$

$F = E \times Q$

$= (4.37\times10^{7})(2\times10^{-3})$

$= 87\,400\ N$

7.7 Sample Question

What is the electric field strength at the point *p* shown in figure 7.32?

7.32

Sample Answer

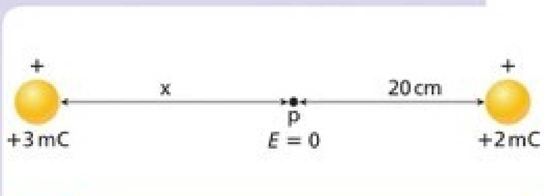
$E = \frac{1}{4\pi\varepsilon}\frac{Q}{d^2}$

$= \frac{3}{4\pi(8.854\times10^{-12})(12)^2}$

$= 1.872\times10^{8}\,NC^{-1}$

7.8 Sample Question

The electric field is zero at the point *p* in figure 7.33. What is the distance x?



7.33

Sample Answer

There are two electric fields at *p*. For the total field to be zero, the fields must be equal in magnitude.

$= \frac{1}{4\pi\varepsilon}\frac{2\times10^{-3}}{0.2^2}$

$= \frac{1}{4\pi\varepsilon}\frac{3\times10^{-3}}{x^2}$

$x^2 = \frac{(0.2)^2(3)}{2}$

$= 0.06$

$= 0.24\ m$

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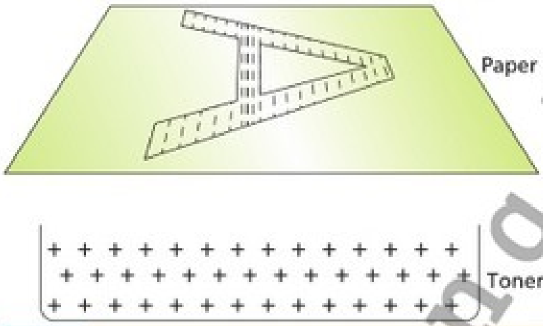
Photocopying

Photocopying makes use of electric fields. A rotating drum inside the photocopying machine is charged and an image of the document to be copied is projected onto the drum. A light then discharges those parts of the document that are white. Charged toner (ink) is then attracted to the remainder, and the copy is printed.



7.34 *The positively charged ink is attracted to the negative charges on the paper and takes on their shape*

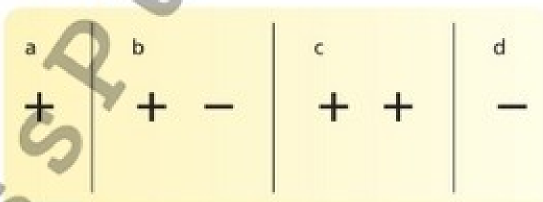
For you to try

1 What is meant by the term 'electric field'?

2 Look at figure 7.35.
  (a) In what direction would a positive charge move if placed in an electric field at the point *p*?
  (b) In what direction would a negative charge move?

7.35 *Question 2*

3 Copy and complete the diagrams in figure 7.36, representing the shape of the electric field in each case.



7.36 *Question 3*

4 A charge of 5×10^{-6} C is placed in an electric field and experiences a force of 3×10^{-3} N.
  (a) What is the electric field strength at that point?
  (b) If a charge of 2 mC was placed at the same point, what force would it experience?

5 What is the electric field strength at the point *p* in figure 7.37?

7.37 *Question 5*

6 A charge of 2 C is placed in an electric field as shown in figure 7.37. What force does it experience?

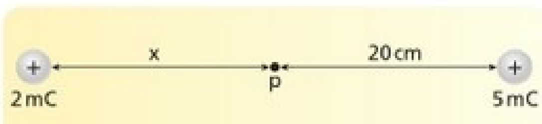
7.38 *Question 6*

7 Two charges are arranged as shown in figure 7.39.

7.39 *Question 7*

  (a) What is the electric field at the point p?
  (b) What force would an electron experience at that point?

8 The electric field is zero at the point indicated in figure 7.40, a distance x from a charge of 2 mC. What is the distance x?



7.40 *Question 8*

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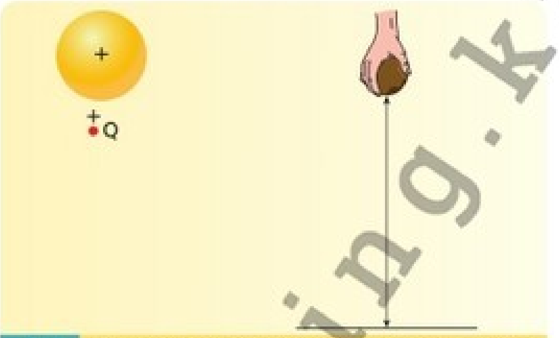
Electric potential

When we lift up an object such as a stone we give it potential energy, and when we release it, it will fall, converting the potential energy into kinetic energy.

Look at figure 7.41 and you will see that there is an obvious comparison between the stone in that example and the electric charge, *Q*.



7.41 *The positive charge Q has energy because of the nearby charge. The stone has energy because it has been lifted up*

The positive charge, *Q*, is close to another positive charge, and if released would move away from it in much the same way that the stone would fall if released. Energy is essentially the ability to make an object move, so this means that the charge, *Q*, has energy due to its position, just as the stone has. There is obviously a distinction between the two situations: the stone has gravitational potential energy, whereas the charge, *Q*, has electric potential energy. However, the comparison is nonetheless perfectly valid.

Potential difference

The comparison can even be extended. We have chosen to measure electrical potential in such a way that we can say a positive charge will move from high potential to low potential, just as a stone will fall from a high point to a lower one. And it is usually the difference in potential between two points that determines whether a charge will move or not, just as it is the difference in height between two points that will determine whether a stone will fall.

However, we should not overstrain the comparison. Gravity and weight are in many ways very straightforward concepts. Essentially, everything falls downwards. With electric charge it can be more complex than this. A positive charge moves away from another positive, as we have seen, but it could also move towards a negative. The presence of many different electric charges creates a complex electric field, and it can be very difficult to predict how exactly a charge will move through that field. The shape of charged objects and the material of which they are made can also have an effect.

A difference in electrical potential can be created through a number of factors, but we can still define the concept in a fairly simple way:

> The potential difference (p.d.) between two points is the work done in moving a unit positive charge from one point to the other. The unit of potential difference is the volt.

> The potential difference between two points is 1 volt (1 V) if the work done in moving a charge of one coulomb (1 C) from one point to the other is one joule (1 J).

This means that if we let a charge of +1 C move between two points, and the charge gains 15 J of energy in doing so, then the potential difference between the two points must be 15 V.

From this we get the formula:

$$V = \frac{W}{Q}$$

where:

- *V* – voltage
- *W* – work done
- *Q* – charge transferred

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Negative charges

You might notice that the above examples are all based on positive charges, and that this was also the case with our definition of electric fields. The nature of the charges involved makes no difference to the size of the measurements that might be taken, such as potential difference and electric field strength. But we must remember that for negative charges, the directions are reversed.

This means that negative charges will move from areas of low potential to areas of high potential. This in turn means that they will move in the opposite direction to that of an electric field.

Zero potential

Although we are normally only interested in measuring a potential difference between two points, rather than the actual level of potential, we still need something to measure this against. The Earth is always taken as being at zero potential (0 V) for this purpose. To return to the comparison with which we started: with falling bodies we are usually only interested in the height through which they can fall, but when we need to we can compare any height to that of sea level.

7.9 Sample Question

The potential difference between two points is 15 000 V. How much work is done in moving a charge of 1.5 μC between the two points?

Sample Answer

$$V = \frac{W}{Q}$$

$$W = QV$$

$$= (1.5 \times 10^{-3})(15\,000)$$

$$= 0.0225 \text{ J}$$

7.10 Sample Question

Two points A and B are separated by a distance of 1.2 m. Point A is at a potential of 25 V, point B is at a potential of 12 V.

(a) What is the potential difference between the two points?

(b) If a charge of 2 C is released directly beside point A, how much work is done is moving it from A to B?

Sample Answer

(a) $25 - 12 = 13 \text{ V}$

(b) $W = QV$

$= (2)(13)$

$= 26 \text{ J}$

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For you to try

1 What is the definition of one volt (1 V)?

2 Look at figure 7.42.

(a) In what direction would a positive charge move in this electric field?

(b) In what direction would an electron move?

7.42 *Question 2*

3 In an electric field, a charge of +4 C moves from point A to B, as shown in figure 7.43.

(a) Which of the two points is at a higher potential?

(b) If the charge gains 15 J of kinetic energy as it moves from A to B, what is the potential difference between the points?

7.43 *Question 3*

4 Two points are at potentials of 15 V and 12 V, as shown in figure 7.44.

(a) What is the potential difference between the points?

(b) How much work is done in moving a charge of 2 mC between the two points?

7.44 *Question 4*

Capacitance

Previously, we looked at how to build up a charge on a plastic rod, and we used that rod to examine the effect of static electric charges. We also looked at how to use the Van de Graaff generator to build up a large charge and to examine the associated effects of that charge. Although both objects could build up a charge, it was obvious that the metal dome was capable of holding an enormous charge compared with the plastic rod.

Every object has a limited ability to hold charge. Capacitance is a measure of how much charge it can hold. We can compare this to the concept of capacity. A small tumbler will hold much less water than a pint glass – we say that its capacity is less, just as the capacitance of a plastic rod is less than that of a metal sphere.

The capacitance of a body is defined as the ratio of the charge on the body to its potential:

$$C = \frac{Q}{V}$$

The unit of capacitance is the farad:

A body has a capacitance of one farad (1 F) if the addition to the body of one coulomb (1 C) raises the potential of the body by one volt (1 V).

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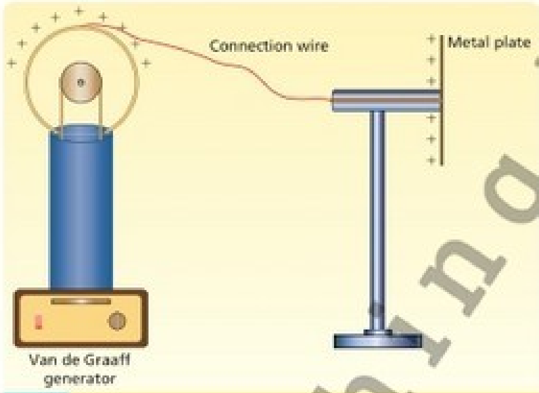
GrS PHYS Gr 10 Ss Mod 7.indd 114 5/9/19 4:44 PM

Parallel plate capacitor

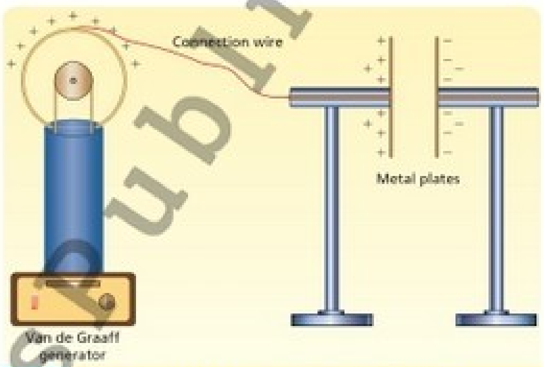
If a metal plate is attached to a Van de Graaff generator, as shown in figure 7.45, it will quickly build up a positive charge. The size of this charge is limited by the capacitance of the metal plate, which in turn is controlled by a number of factors such as its shape and the material from which it is made, as well as by its surroundings.



7.45 *A charge builds up on the metal plate*

If we bring another metal plate beside it, however – as shown in figure 7.46 – its capacitance is increased. This happens because the positive charge attracts a negative charge to the surface of the second metal plate. This negative charge then attracts an increased charge to the positive plate, which, in turn, attracts an increased charge to the negative plate.

This all happens in a very short period of time, and soon an equilibrium is reached between the two plates. But as the total charge on each plate is higher than it could ever be for a single comparable plate, we can see that this arrangement increases the capacitance of each plate. This is known as a **parallel plate capacitor**, and it is a device that is common in many modern electronic devices.

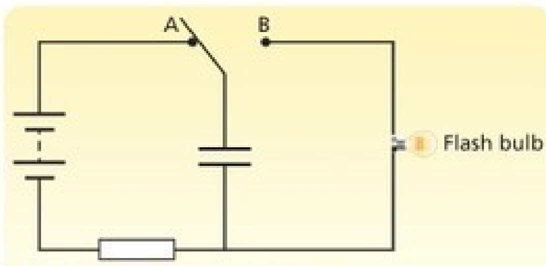


7.46 *A second plate increases the capacitance*

Uses of a parallel plate capacitor

Electronic camera flash

The bulb used in camera flashes is unusual for a bulb, in that it gives off a very bright light for a short period of time. This can be done using a circuit like that shown in figure 7.47.



7.47 *Circuit for a camera flash*

When the switch is in position A, a current will flow until the capacitor is fully charged and then stop. When a photograph is taken, the switch is triggered to move across to position B. Now the voltage stored on the capacitor is applied to the light bulb, where it causes a sudden flash of very bright light.

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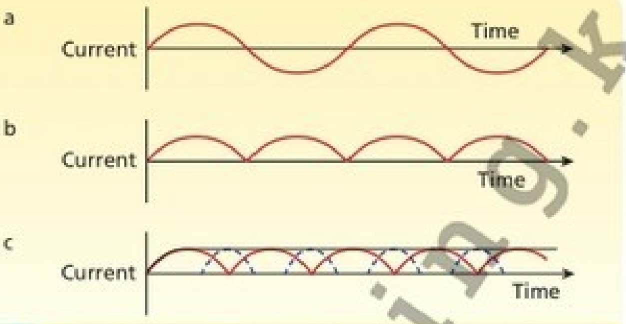
Smoothing currents

Most modern electronic devices require a direct current (d.c.). If they are running off a battery, this is no problem, but if they are connected to the mains, they will be provided with an alternating current (a.c.) instead. There are various ways that this can be changed to d.c., in a process known as rectification. Then the current flows only in one direction and is, therefore, technically d.c., but it is still a very uneven current, as shown in the graphs in figure 7.48.



7.48 *Graph a shows a.c.; graph b shows a rectified current; graph c shows a rectified current smoothed out by the use of capacitors*

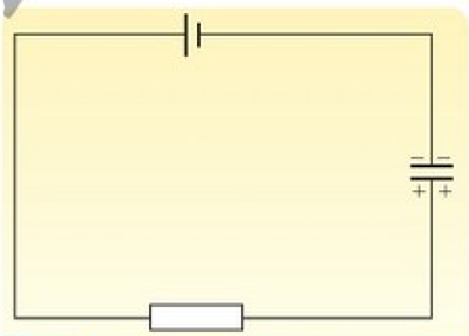
7.49 *The dial of a radio showing the different stations and frequencies, which are selected using capacitors*

Capacitors in the circuit can be used to smooth off the rectified current. Essentially what happens is that when the value of the rectified current falls (indicated by the red line in figure 7.48), the charge stored on the capacitor flows through the circuit (indicated by the blue line). This creates a smoother flow of total current (indicated by the black line).

Capacitors are also used in the tuning of a radio. A radio aerial picks up a large number of transmitted signals, but when we tune to a station we are choosing a specific value for the capacitance of the circuit, and this has the effect of amplifying only the signal transmitted at a particular frequency.

Capacitors conduct a.c., but they block the flow of d.c.

If we attach a capacitor to a battery as shown in figure 7.50, a d.c. flows for a short period of time, until the capacitor is fully charged. At that point, because no charge can flow through the capacitor, no current can flow in the circuit. In this way, capacitors always block the flow of d.c.



7.50 *In a d.c. circuit, the current will flow only until the capacitor is charged*

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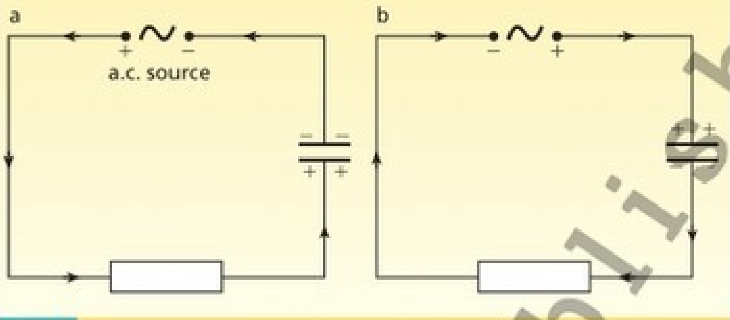
If the capacitor is attached to an a.c. supply, however, a current flows continuously.

This happens in the following manner. Initially a current flows and builds up a charge on the capacitor, as shown in figure 7.51a. Just as this charge reaches a peak, however, the direction of flow of the current reverses. This causes the capacitor to lose its charge and then build up a charge in the opposite direction, as shown in figure 7.51b. Again, just as this charge reaches a peak, the process is reversed. This process continues, repeatedly charging the capacitor, discharging it and recharging with the opposite polarity. This means that, although no current flows across the capacitor, a current is always flowing in the circuit.

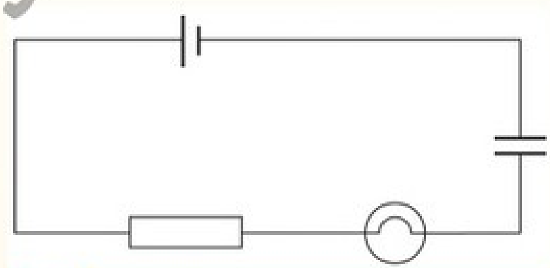


7.51 *In an a.c. circuit containing a capacitor, current flows constantly*

Experiment 7.4: To demonstrate that capacitors allow a.c. to flow, but block d.c.

Method 1

1. Set up a d.c. circuit as shown in figure 7.52.
2. Observe what happens to the bulb.



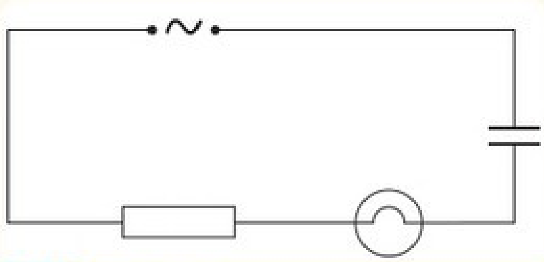
7.52 *A d.c. circuit*

Observations

You should find that the bulb lights for only a short time. This is because once the capacitor is fully charged it blocks the flow of direct current.

Method 2

1. Set up an a.c. circuit as shown in figure 7.53.
2. Observe what happens to the bulb.



7.53 *An a.c. circuit*

Observations

You should find that the bulb remains lit while the circuit is complete. This is because the capacitor allows an alternating current to flow.

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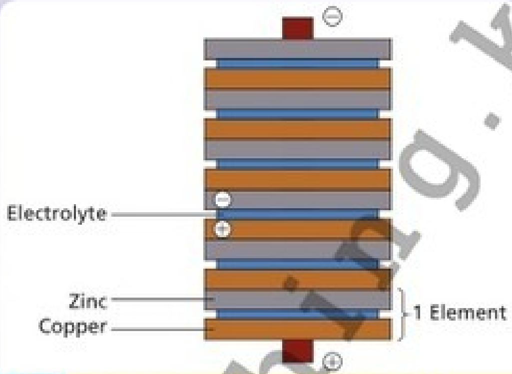
Alessandro Volta

Alessandro Volta (1745–1827) – after whom the volt is named – lived in Como in Northern Italy, where he was a teacher of physics in the local school. He read a piece of work by Benjamin Franklin that described something he called 'flammable air', and he was fascinated. He searched for such a material and finally succeeded in isolating the gas involved. It is now known to us as methane.



7.54 *A battery, based on work done by Volta*

Another Italian, Luigi Galvani, had discovered a phenomenon whereby a frog's legs could be made to twitch by joining them together with different metals. He thought the effect was caused by electricity inside the animal, but Volta realised that the key to the effect was in fact the use of two different metals. He went on to show that an electric current can be created using two different metals separated by a chemical known called an electrolyte. In doing so, he created the first electric cell. A series of these cells connected in series then gave rise to what we now call a battery.

7.11 Sample Question

If a charge of 12 C increases the voltage of an object by 3 V, what is the capacitance of the object?

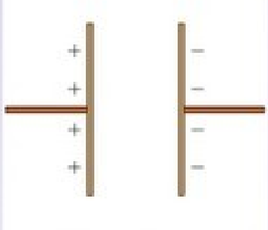
Sample Answer

$$C = \frac{Q}{V}$$
$$= \frac{12}{3} = 4\text{ F}$$

7.12 Sample Question

(a) In the capacitor shown in figure 7.55, which plate is at a higher potential?

(b) If the capacitance of the capacitor is 6 μF, and each plate holds a charge of 3 μC, what is the potential difference between the plates?



7.55 *Question 8*

Sample Answer

(a) The positive plate is at a higher potential.

(b) $C = \frac{Q}{V}$

$$V = \frac{Q}{C}$$
$$= \frac{3 \times 10^{-6}}{3 \times 10^{-6}}$$
$$= 0.5\ V$$

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GrS PHYS Gr 10 Ss Mod 7.indd 118 5/9/19 4:44 PM

For you to try

1 What is meant by the term 'capacitance'?

2 In what unit is capacitance measured? What is the definition of this unit?

3 Outline three uses of capacitors.

4 If a charge of 15 C increases the voltage of an object by 2V, what is the capacitance of the object?

5 If a charge of 1.5 μC increases the voltage of an object by 2V, what is the capacitance of the object?

6 If a charge of 1.2 mC increases the capacitance of an object by 2 μF, what is the voltage of the object?

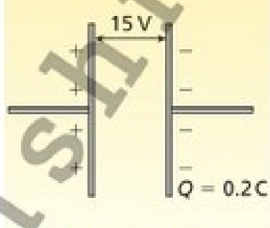
7 What capacitance would you expect to find on an object that is at a voltage of 20 V and holds a charge of 2 μC?

8 In figure 7.56, where there is a potential difference between the two plates of 15 V, and the charge on each plate is 0.2 C, what is the capacitance of the capacitor?

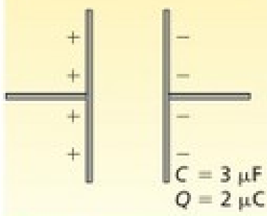
9 **(a)** In the capacitor shown in figure 7.57, which plate is at a higher potential?

(b) If the capacitance of the capacitor is 3 μF, and each plate holds a charge of 2 μC, what is the potential difference between the plates?

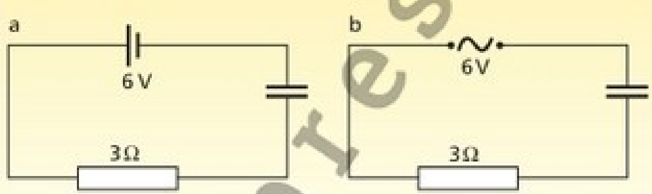
10 Through which of the circuits in figure 7.58 will a current continuously flow? What is the maximum voltage across each capacitor?



7.56 *Question 8*



7.57 *Question 9*



7.58 *Question 10*

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Module 8 Conduction

Learning objectives

- To explain the concepts of electromotive force and internal resistance 10.3.2.1
- To explain the difference between a drop in voltage and electromotive force in an external circuit (in terms of energy) 10.3.2.2
- To apply Ohm's law in complete circuits and recognise the consequences of a short circuit 10.3.2.3
- To make work, power and cost calculations relating to household appliances 10.3.2.4
- To explain the principles of the appearance of electric current in different mediums 10.3.3.1
- To describe experimental procedures involving electrolytes 10.3.3.2
- To give examples of the use and principles of semi-conductor devices 10.3.3.3
- To describe the phenomenon of superconductivity and give examples of its practical application 10.3.3.4

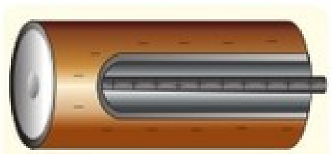
Electric current

In the 1700s Italian physician and physicist Luigi Galvani (1737–1798) noticed that he could cause a frog's legs to twitch by creating a circuit that connected the legs together using two different metals. He thought his experiment showed that animals generate their own electricity. Although it is true that muscles are controlled by tiny electric currents flowing through the body's nervous system, this was not in fact what Galvani had discovered.

Later experiments by another Italian physicist, Alessandro Volta (1745–1827), showed that the arrangement Galvani had used, making use of two different metals, was actually generating an electric current itself – through a process now known as **electrolysis.** Essentially, a very slow chemical reaction was taking place between the materials involved by forcing electrons to move through the connecting wires.

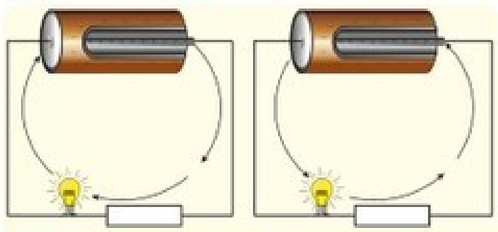
Volta replicated the arrangement in a device now known as an electric cell to create an electric current. Several cells joined together form a **battery**.

The battery



8.1 *A simplified view of a battery*

A simplified – but functional – view of a battery is to think of it as containing two chambers, one full of positive charges and the other full of negative charges, as shown in figure 8.1. There is an attraction between the positive and negative charges in the battery, but they are separated by a barrier that prevents them moving to connect to each other. When we join the two ends, or **poles**, of the battery together using electrical wire, however, we provide a path through which the charges can combine. With this simplified arrangement we cannot say whether it would be the positives that move to meet and neutralise the negatives, or vice versa.



8.2 *Simple electric circuits*

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We now know that it is in fact the negative charges – the electrons – that move. However, the study of electricity was well advanced – indeed many cities had access to electric light – before the electron was discovered. And in that era the assumption had become common that it was the positive charges that move.

The reality is that it makes very little difference to the study of electric circuits which particle actually moves. The key thing is that when electric charge moves through the circuit, it must also move through whatever device we place in the circuit, whether that be a simple device such as a light or a heater, or a much more complex one such as a computer or a TV set.

Because it makes very little practical difference to how we imagine a circuit working and which charge we picture as moving, the tradition from the nineteenth century is often maintained today and current is represented as going from plus to minus rather than the opposite. When we do this it is called **conventional current**, and we will generally show current travelling in this manner in this book.

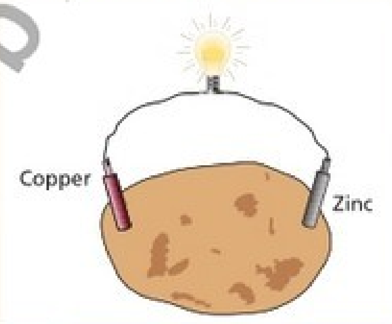
Experiment 8.1: To construct a potato-fuelled circuit

Method 1

1. Take a potato, two different strips of metal (e.g. one strip of copper and one strip of zinc), two wire clips and a small light-emitting diode (LED). Assemble as shown in figure 8.3
2. Observe what happens to the LED.

Observations

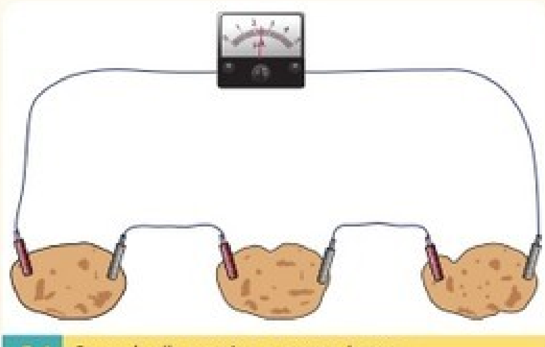
You should find that the light turns on. This is due to a chemical reaction slowly taking place between the zinc, the copper and the potato.



8.3 *A potato acting as a cell*

Variation

1. Set up the apparatus shown in 8.3, but replace the LED with a micro-ammeter.
2. Measure the current.
3. The voltage and current can be increased by using two or more potatoes connected 'in series', as shown in figure 8.4.
4. You can also replace the potato with a weak acid, such as vinegar. (It is the very small quantity of acid in a potato that allows the chemical reaction to take place.)



8.4 *Several cells creating a potato battery*

Electric circuits

Figure 8.5 represents a basic circuit and shows some of the symbols most commonly used in electric circuits.

An electric current is a flow of charge. A current of one amp (or ampere) is a movement of one coulomb per second:

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$$I = \frac{Q}{t}$$

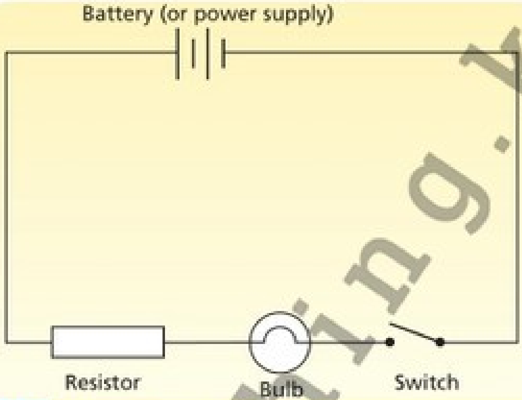
where:

I – current

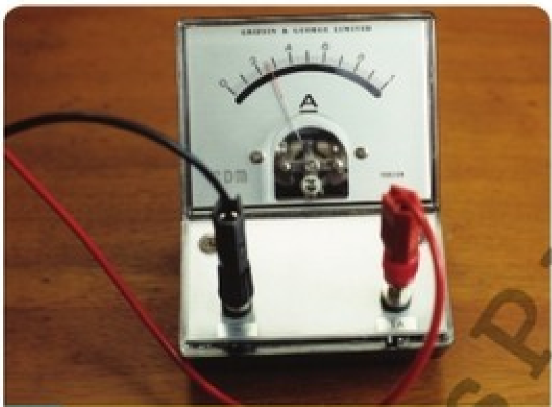
Q – charge transferred

t – time

If a current of one amp is flowing in a conductor, one coulomb is the quantity of charge passing a point on that conductor in one second.



8.5 *A simple electric circuit*



8.6 *An ammeter showing a current of about 2.6 A*

This gives us a definition of the **coulomb**:

The coulomb (C) is a very large charge, and so we often encounter smaller units such as millicoulombs (mC) or microcoulombs (μC). The same follows for current, and most modern electronic devices run off a current of a fraction of one amp (1 A).

Conductors and Insulators

A **conductor** is a material that allows electrons to move through it freely. The type of bonding common in most metals allows electrons to move easily from one atom, or group of atoms, to another. This is why metals are generally described as good conductors. In most other materials, the electrons are tightly connected to a particular atom or group of atoms and cannot move easily. This means that they are generally not good conductors, and they are described as **insulators**.

Although it is true that, generally speaking, metals are good conductors and other materials are not, you should not think of this as a rule that is always followed. There are many exceptions. Carbon, for example – particularly in the form of graphite – is a non-metal that is a good conductor. Ionic compounds such as sodium chloride (table salt) are not good conductors in the solid state but allow a large current to flow when dissolved in water.

We all learn to be careful about electricity and water because of the danger of electrocution. However, pure water is in fact not a conductor. It is the dissolved solids within it that allow water to conduct electricity. Water is such a good solvent, though, that it almost always contains dissolved solids, especially ionic compounds, and as such water is usually thought of as a conductor.

Voltage

We have already learnt about potential difference (p.d.) and voltage. Remember that voltage measures the energy lost or gained by a positive charge of 1 C as it moves from one point to another.

A voltage (V), when applied to a circuit, is known as the electromotive force (emf).

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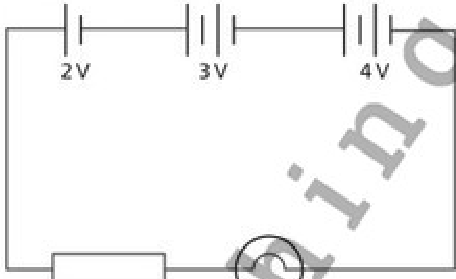
A cell is a commonly used source of emf. Several cells joined together form a battery and give a higher voltage: other sources are the electrical mains and a thermocouple.

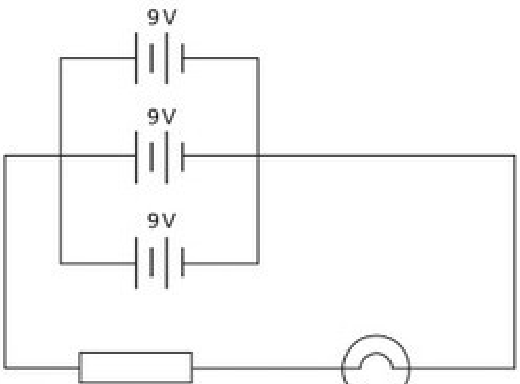
Batteries in series and parallel

A number of batteries connected in series creates a larger voltage, as shown in figure 8.7, where the total voltage in the circuit would be (2+3+4) = 9V.

When batteries are connected in parallel their lifetime is extended, but the voltage is not increased. In the circuit shown in figure 8.8, the total voltage is 9 V.



8.7 *Batteries in series*



8.8 *Batteries in parallel*

8.9 *Typical 1.5 V batteries*

Ammeters and Voltmeters

Ammeters and voltmeters are commonly used in studying electric circuits. The most basic design of each usually includes a circular dial and a needle, like those shown in figure 8.10. The current is read by noting where on the scale the needle is pointing.

Although useful when you are learning about circuits, meters such as ammeters and voltmeters are rarely used now by electricians and engineers. Instead they use a modern device known as a multimeter. This has a central dial that can be turned to different positions depending on whether you want to measure voltage, current or resistance. To allow greater accuracy, there are different settings for measuring high currents as opposed to low currents, etc.

8.10 *An ammeter and voltmeter*

8.11 *A modern multimeter which can act as a voltmeter, ammeter or ohmmeter*

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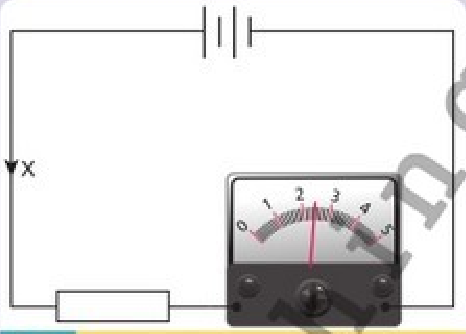
8.1 Sample Question

Identify the current X in figure 8.12.



8.12

Sample Answer

X = 2.4V

8.2 Sample Question

If a current of 2 mA flows for 3 s, how much charge passes a particular point in the circuit?

Sample Answer

$I = \frac{Q}{t}$

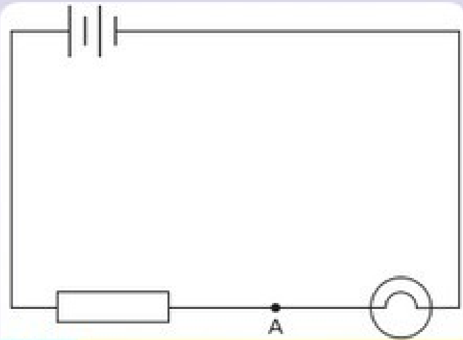
$Q = It$

$= (2 \times 10^{-3})(3)$

$= 6 \times 10^{-3}$ C

8.3 Sample Question

If a current of 3 A flows in the circuit shown in figure 8.13, how many electrons pass point A every second?



8.13

Sample Answer

$Q = It$

$= 3 \times 1 = 3$ C

number of electrons $= \frac{3}{1.6 \times 10^{-19}}$

$= 1.875 \times 10^{19}$ electrons

Take the charge on the electron to be 1.6×10^{-19} C.

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For you to try

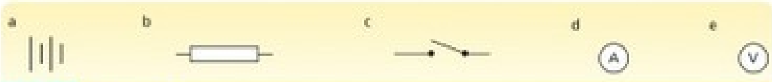
1 When an electric current flows through a metal wire, which charges are moving?

2 What do we mean by the term 'conventional current'?

3 Draw a diagram to show how a potato can be used to drive a current through an LED.

4 What is meant by the term 'emf'?

5 Identify the electrical components represented by the diagrams in figure 8.14.



8.14 *Question 5*

6 If the current in figure 8.15 flows for 5 s, how much charge has passed a particular point in the circuit?

8.15 *Question 6*

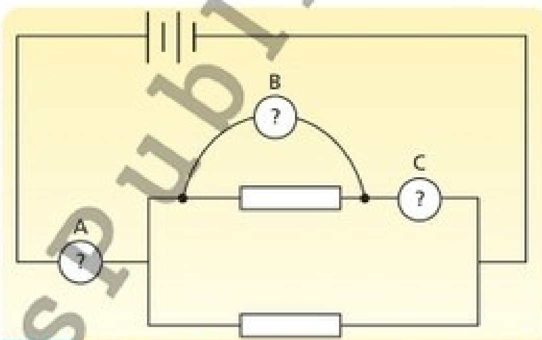
7 If a current of 2 mA flows for 3 min, how much charge has passed a particular point in the circuit?

8 If a current of 2 µA flows for 3 h, how much charge has passed a point in the circuit?

9 A charge of 5 C passes a point within a circuit over a period of 2 s. What is the current?

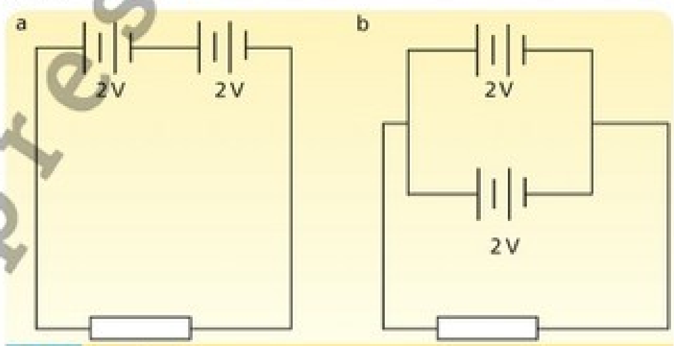
10 If 4.8×10^{20} electrons flows pass a particular point in an electric circuit in 1 min, what is the current?

11 In figure 8.16, identify which meters are ammeters and which are voltmeters.



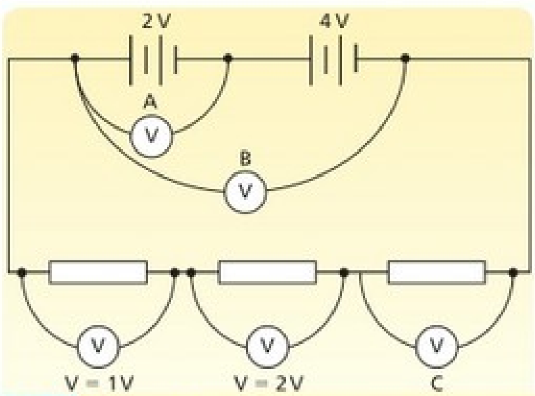
8.16 *Question 11*

12 What is the total voltage in each of the circuits shown in figure 8.17?



8.17 *Question 12*

13 What voltage would you expect to see on each of the voltmeters shown in figure 8.18?



8.18 *Question 13*

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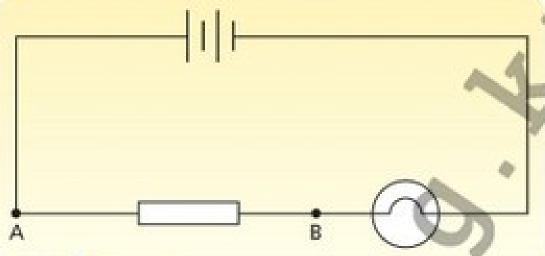
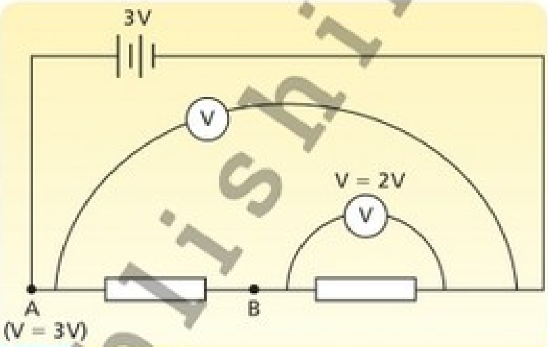
14 Look at figure 8.19. If the potential at point A is 9 V, and the potential drop across the resistor is 3 V, what is the potential at point B?



8.19 *Question 14*

15 If the potential at point A is 3 V, and the reading on the voltmeter is as shown in figure 8.20, what is the potential at point B? And what would you expect the reading on the second voltmeter to be?



8.20 *Question 15*

Resistance

The flow of an electric current through metal wires is often compared to the flow of water through pipes. Just as higher water pressure creates an increased current in the flow of water, a higher voltage tends to increase the current in an electric circuit. And just as the flow of water can be reduced by constrictions in a pipe – such as the kinks that can develop in a hose – the flow of an electric current can be reduced by something called **resistance**.

Sometimes we deliberately introduce resistance into part of a circuit, so that the current is not too big. But whether we want a high resistance or a low one, there is always some resistance on a circuit. Even metals, such as copper, that we use to make conducting wires are not perfect conductors. Electrons still have to do some work to travel through the wires, and this tells us that they carry a resistance.

In fact, many resistors are manufactured from metals such as nickel–chrome (nichrome) that would often be thought of as conductors, but if manufactured to the right specifications offer enough resistance to allow us to control a current.

A good insulator would block a current entirely and would therefore not be a useful resistor.

Ohm's law

The connection between voltage, current and resistance was discovered by German physicist and teacher Georg Ohm (1789–1854) in 1827.

Ohm's law states that, for a metallic conductor at constant temperature, the current will be proportional to the voltage: $V \propto I$.

When two items are proportional, we can say that the ratio of one to the other is a constant:

$$\frac{V}{I} = \text{a constant.}$$

Ohm realised that the value of this constant in an electric circuit is essentially the same thing as the resistance:

$$\frac{V}{I} = R$$

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where R – resistance.

This gives us a key formula for the study of electric circuits as well as a useful way in which to define exactly what we mean by the term ‘resistance’:

$$V = IR$$

The resistance of an object in an electrical circuit is defined as the ratio of the voltage across it to the current flowing through it:

$$R = \frac{V}{I}$$

The **unit of resistance** is the **ohm**, and its value is set using the above formula:

A conductor has a resistance of one ohm (1 Ω), if a current of one amp (1 A) flows when a voltage of one volt (1 V) is applied.

Ohm’s law should not be thought of as a fundamental law of nature. Unlike Newton’s laws, for example, there are many situations in which Ohm’s law is not valid. We will study these in more detail, but the current flowing through a gas, an ionic solution and a vacuum tube are just some of the situations in which the law is not followed. However, in studying standard electric circuits, Ohm’s law is a very useful guide to the relationship between current, voltage and resistance.

8.4 Sample Question

If a voltage of 9 V is applied across a resistor and a current of 3 A flows through it, what is the resistance of the resistor?

Sample Answer

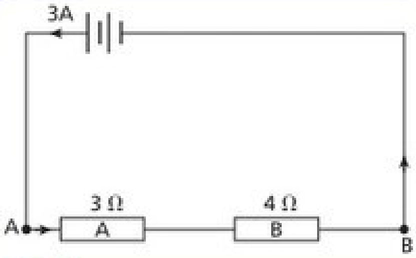
$$R = \frac{V}{I} = \frac{9}{3} = 3\,\Omega$$

8.5 Sample Question

A current of 3 A flows through two resistors of 3 Ω and 4 Ω, as shown in figure 8.21.

(a) What is the potential drop across each of the resistors?

(b) What is the voltage between points A and B?



8.21

Sample Answer

(a) $V_A = (3)(3) = 9\,V$; $V_B = (3)(4) = 12\,V$

(b) $V_{AB} = 9 + 12 = 21\,V$

GrS PHYS Gr 10 Ss Mod 8.indd 127 5/9/19 4:47 PM

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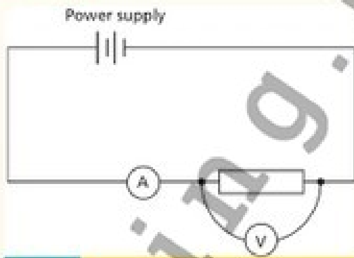
Experiment 8.2: To investigate Ohm's law

Method

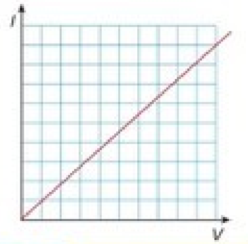
1. Set up a circuit as shown in figure 8.22, allowing you to measure both the current through, and the voltage across, the resistor.
2. Set the power supply to a low voltage. Note the readings on the ammeter and voltmeter.
3. Increase the voltage using the power supply and again note the readings on the two meters.
4. Repeat for several settings of the applied voltage and record your results.
5. Draw a graph of voltage against current using your results.



8.22 *Experimental circuit*

V/V						
I/A						

8.23 *Use a table like this one to record your results*



8.24 *A straight line through the origin*

Results and conclusions

A straight line through the origin (as on the graph in figure 8.24) will confirm that voltage is proportional to current (Ohm's law).

Resistance and Temperature

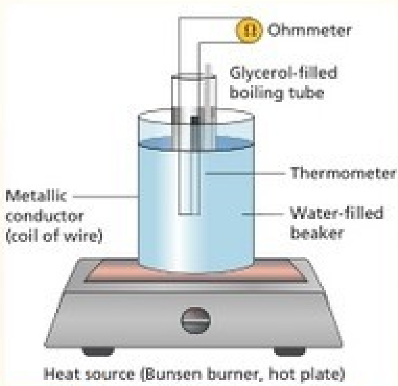
The resistance of an object depends (among other things) on its temperature. The variation of resistance with temperature, however, is not the same for all materials.

The connection between resistance and temperature can be investigated experimentally.

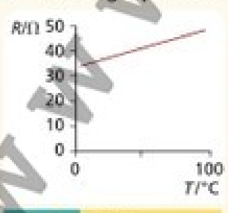
Experiment 8.3: Investigation of the variation of resistance with temperature for a metal

Method

1. Set up the apparatus as shown in figure 8.25.
2. Use the thermometer to note the temperature of the glycerol, which is also the temperature of the coil of wire.
3. Record the resistance of the coil of wire using the ohmmeter.
4. Slowly heat the beaker.
5. For each 10°C rise in temperature record the resistance and temperature using the ohmmeter and the thermometer.
6. Plot a graph of resistance against temperature.



8.25 *Experimental apparatus*



8.26 *Resistance vs. temperature for a metal*

Results

You should find that your graph is similar to that shown in figure 8.26.

It is important to heat the water slowly, to avoid a situation in which the liquid will be much hotter than the wire.

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GrS PHYS Gr 10 Ss Mod 8.indd 128 5/9/19 4:47 PM

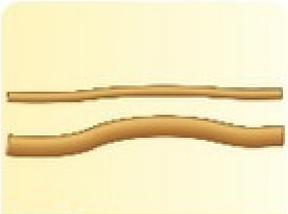
Resistivity

Look at the two wires represented in figure 8.27. Which one do you think has the greater resistance?

As long as everything else is the same, the longer wire will have the greater resistance. Electrons have to work to move through even the best conductors – therefore the longer the wire the more work they have to do, and the greater the resistance.

8.27 *Resistance is proportional to length*

Now look at the two wires in figure 8.28. Again, which would you expect to have the greater resistance?



8.28 *Resistance is proportional to 1/area*

This time the narrower wire will tend to have the higher resistance. Remember that an electric current is the movement of electric charge. The wider wire – with the greater diameter – provides a wider path for the electric charge to move. As more charge can move through the wire, the resistance is reduced.

Now look at the two wires in figure 8.29. One cannot tell by looking, but even if the length and diameter of the two wires were identical, the nichrome would have the greater resistance. This is because of a property called **resistivity**.

8.29 *Resistance is proportional to resistivity*

We cannot say that metals have low resistance. It is often true, but not necessarily true. A narrow wire thousands of kilometres long, for instance, does not have a low resistance. We can, however, say that metals **tend to** have a low resistivity.

To summarise:

As well as temperature, the resistance of an object also varies with:

- The length, l, of the object (the longer the object, the greater the resistance)
- The cross-sectional area, A, of the object (the wider the object, the lower the resistance)
- The material from which the object is made (the property of a material that controls the resistance is the resistivity, ρ, of the material).

This leads to a key formula:

$$R = \frac{\rho l}{A}$$

The resistivity of a material is the resistance of a unit cube of that material:

$$\rho = \frac{RA}{l}$$

The unit of resistivity is the ohm-metre (Ωm).

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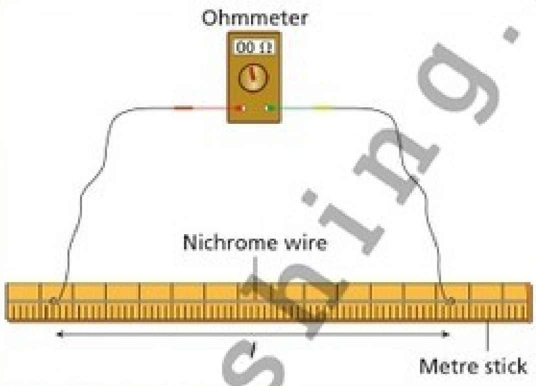
GrS PHYS Gr 10 Ss Mod 8.indd 129 5/9/19 4:47 PM

Experiment 8.4: Measurement of the resistivity of a wire

Method

1. Set up the apparatus as shown in figure 8.30. Ensure that the resistance of the leads is zero when the crocodile clips are connected together.
2. Stretch a length of nichrome along a metre stick as shown in figure 8.30. Ensure there are no kinks or 'slack' in the wire.
3. Note the resistance, R, for a particular length, l, of wire.
4. Increase the distance between the crocodile clips and note the new values of R and l.
5. Use the micrometer to find the diameter of the wire at different points, taking the zero error into account. Find the average value of the diameter, d.
6. Repeat this procedure for a number of different lengths of wire.



8.30 *Experimental apparatus*

Results

For each set of results, calculate the resistivity using the formula:

$$\rho = \left(\frac{R}{l}\right)A$$

where:

$$A = \pi r^2$$

The average value is the resistivity.

Accuracy

- Kinks in the wire will affect the measurement of both length and cross-sectional area.
- The use of greater lengths will reduce the percentage error.

8.6 Sample Question

A piece of metal has a length of 15 cm, a resistivity of 2.3 Ωm and a circular cross section of diameter 1 mm. What is its resistance?

Sample Answer

$$A = \pi r^2$$
$$= \pi(0.5 \times 10^{-3})^2$$
$$= 7.85 \times 10^{-7}\ \text{m}^2$$
$$\rho = \frac{RA}{l}$$
$$R = \frac{\rho l}{A}$$
$$= \frac{(2.3)(0.15)}{7.85 \times 10^{-7}}$$
$$= 439490.4\ \Omega$$

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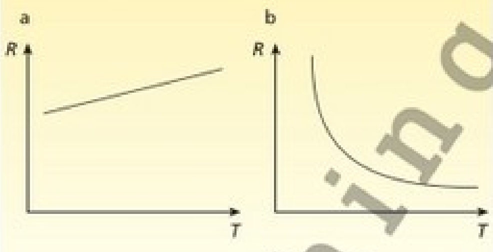
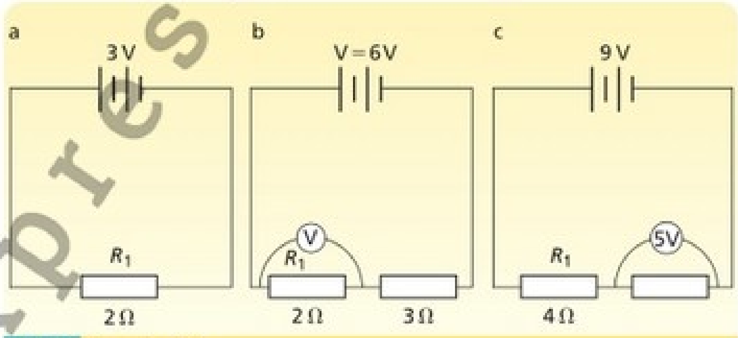
For you to try

1 What is resistance?
2 What is the definition of 1 Ω?
3 The graphs in figure 8.31 represent the variation of resistance with temperature. Which one would you expect to represent a metal and which one would you expect to represent a thermistor?



8.31 *Question 3*

4 What voltage will produce a current of 3 A in a resistor of resistance 15 Ω?
5 Arctic explorers sometimes use socks lined with electrical wire for heating. They run off a 9 V battery and draw a current of 0.1 A. What resistance does the electrical wire have?
6 If a current of 3 A flows through a resistor when a voltage of 6 V is applied to it, what is the resistance of the resistor?
7 A toaster is plugged into a mains source providing 230 V. The resistance is 30 Ω. What current flows in the toaster?
8 A piece of metal has a length of 30 cm, a resistivity of 4.5 Ωm and a circular cross section of diameter 1 mm. What is its resistance?
9 If a transatlantic cable is 5000 km long and consists of several strands of copper (resistivity 1.7×10^{-8} Ω m) 1 mm in diameter, what is the total resistance of one such strand?
10 Does the resistance of a copper wire increase or decrease when both length and cross-sectional area are doubled? Explain your answer.
11 Copper and nichrome have very different resistivities. If we take two pieces of wire of the same length, one made from nichrome and one from copper, is it possible that they would have the same resistance?
12 In each of the circuits shown in figure 8.32, what current would you expect to flow in the resistor R_1?



8.32 *Question 12*

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Resistors in series

When an electric circuit is arranged so that the same electric current flows through several resistors, we say that those resistors are **in series** with each other.

This tells us that, to find the total resistance when a number of resistors are joined together in series, we simply add together all the individual resistances.

Derivation

For this setup, the total voltage drop from A to B is given by: $V_{AB} = V_1 + V_2 + V_3$

where V_1 is the voltage drop across R_1, and so on.

Following Ohm's law, we can say:

$R = \frac{V}{I}$

which gives:

$IR_T = IR_1 + IR_2 + IR_3$

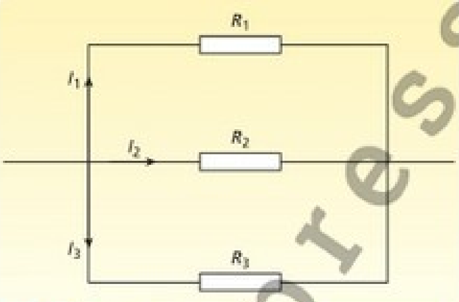
Dividing by I:

$R_T = R_1 + R_2 + R_3$

8.33 *Resistors in series*

Resistors in parallel

When resistors are used in a circuit in such a way that the current flowing must at some point be divided between alternative paths, we say that the circuit is connected **in parallel**. The example in figure 8.34 shows three resistors in parallel.



8.34 *Resistors in parallel*

We do not mean geometrically parallel: the angle between the resistors in the diagram is of no significance.

Derivation

In the circuit shown in figure 8.34, the total current is given by:

$I_T = I_1 + I_2 + I_3$

The total voltage drop across the group of resistors is the same, regardless of the path followed, so, as $I = \frac{V}{R}$:

$$\frac{V}{R_T} = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3}$$

And dividing across by V gives:

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

This is the formula that we must follow if we are to find the total resistance of a circuit in which resistors are wired in parallel.

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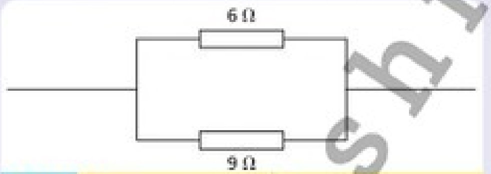
8.7 Sample Question

What is the total resistance of the circuits in figures 8.35 and 8.36?

Sample Answer

8.35 *(a)*



8.36 *(b)*

(a) $R^T = 20 + 30 + 5 = 55\Omega$

(b) $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2}$

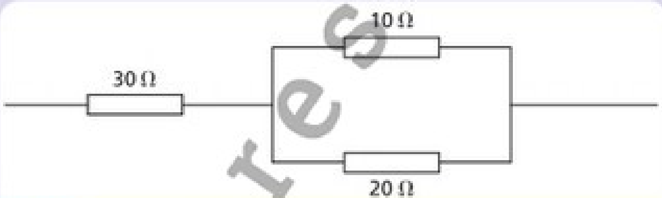
$$\frac{1}{6} + \frac{1}{9} = \frac{5}{18}$$

$$R_T = \frac{18}{5} = 3.6\Omega$$

Sample question 8.7 deals with relatively straightforward situations in which resistors are either in series or parallel. However, it is possible to have a combination of both occurring in one circuit. This is dealt with in sample questions 8.8 to 8.11.

8.8 Sample Question

What is the total resistance of the circuit in figure 8.37?



8.37

Sample Answer

$R_{\parallel}$ = total resistance of the resistors in parallel

$$\frac{1}{R_{\parallel}} = \frac{1}{10} + \frac{1}{20} = \frac{3}{20}$$

$$R_{\parallel} = \frac{20}{3} = 6.67\Omega$$

$$R_T = 30 + 6.67 = 36.67\Omega$$

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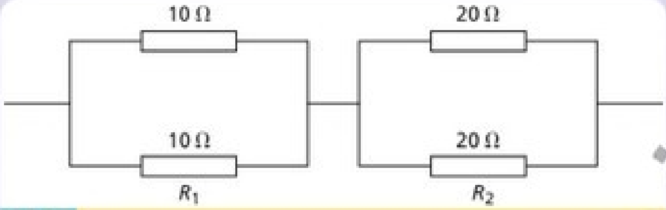
5/9/19 4:47 PM

8.9 Sample Question

What is the total resistance of the circuit in figure 8.38?



8.38

Sample Answer

Divide into R_1 and R_2.

$$\frac{1}{R_1} = \frac{1}{10} + \frac{1}{10} = \frac{2}{10},\ R_1 = \frac{10}{2} = 5\Omega$$

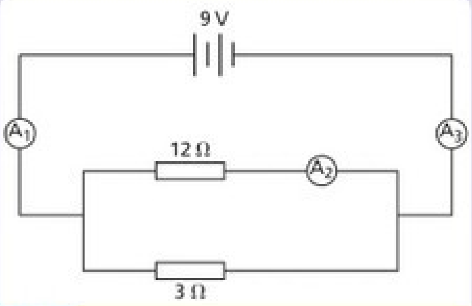
$$\frac{1}{R_2} = \frac{1}{20} + \frac{1}{20} = \frac{2}{20},\ R_2 = \frac{20}{2} = 10\Omega$$

$$R_T = R_1 + R_2 = 5 + 10 = 15\Omega$$

8.10 Sample Question

(a) What is the total resistance of the circuit in figure 8.39?
(b) What current would you expect to see in each ammeter?

Sample Answer



8.39

(a) $\frac{1}{R_T} = \frac{1}{12} + \frac{1}{3} = \frac{5}{12}$

$R_T = 2.4\,\Omega$

(b) $V = IR$

$I_T = \frac{V}{R} = \frac{9}{2.4} = 3.75\,\text{A}$

So $= A_1 = A_3 = 3.75\,\text{A}$

The total current splits between the two paths. The current will split in the opposite proportion to the resistances; the resistors are in the ratio 12:3 or 4:1, so the current will split in the ratio 1:4. The smaller current will flow in the 12 Ω resistor:

$A_2 = \frac{1}{5} \times 3.75 = 0.75\,\text{A}.$

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8.11 Sample Question

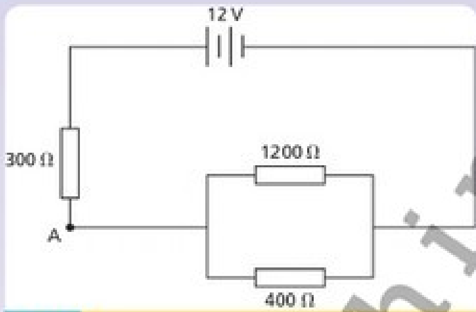
Look at the circuit shown in figure 8.40.

(a) What is the total resistance?

(b) What is the total current?

(c) What current flows through the 400 Ω resistor?

(d) What is the potential at point A?



8.40

Sample Answer

(a) $R_{\parallel}$ = resistance of the 1200 Ω and 400 Ω system

$$\frac{1}{R_{\parallel}} = \frac{1}{1200} + \frac{1}{400} = \frac{1}{300}$$

$R_{\parallel} = 300\,\Omega$

R_T = total resistance = 300 + 300 = 600 Ω

(b) $I = \frac{V}{R_{\parallel}} = \frac{12}{600} = 0.02\,\text{A}$

(c) The resistors are in the ratio 12:4 or 3:1, so the current is in the ratio 1:3. The current through the 400 Ω resistor will be the larger:

$I400 = \frac{3}{4} \times 0.02 = 0.015\,\text{A}$

(d) V = the potential drop across the 300 Ω resistor.

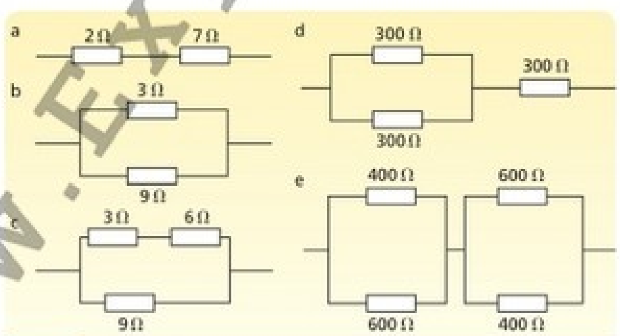
$V = IR$

$= (0.02)(300) = 6\,\text{V}$

Potential at A = 12 − 6 = 6 V

For you to try

1 What is the total resistance in each of the arrangements shown in figure 8.41?



8.41 *Question 1*

2 How many 2 Ω resistors must be connected in parallel to create a total resistance of 0.25 Ω?

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3 Look at the circuit in figure 8.42.

(a) What is the total resistance?

(b) What is the current flowing in each of the ammeters?

4 What is the total resistance of the circuit in figure 8.43? What is the total current flowing in each ammeter?

5 Look at the circuit in figure 8.44.

(a) What is the potential difference across each of the resistors?

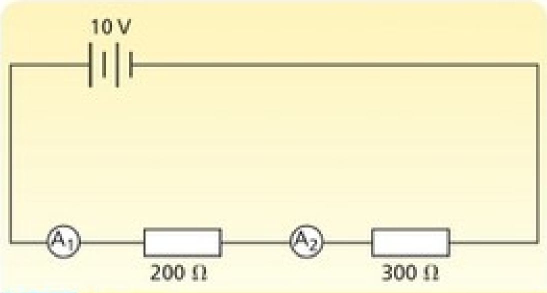
(b) What is the emf of the circuit?

6 The total resistance of the circuit in figure 8.45 is 25 Ω.

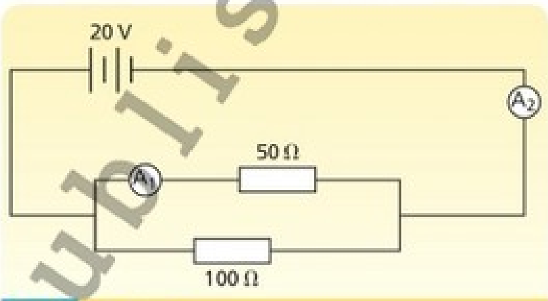
(a) What is the resistance of the resistor marked X?

(b) What current flows through that resistor?

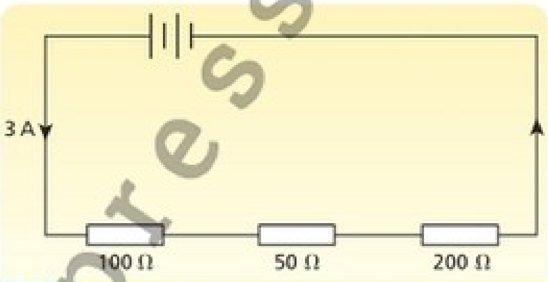
(c) What is the potential at points A, B and C?



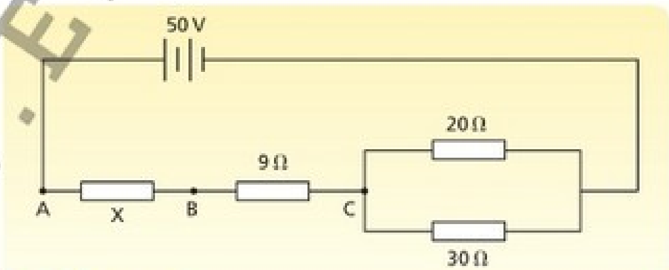
8.42 *Question 3*



8.43 *Question 4*



8.44 *Question 5*



8.45 *Question 6*

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Joule's law

The heating effect of an electric current was studied by English physicist James Joule (1818–1889) in the 1840s, when he carried out many experiments. It is perhaps obvious that if electric current produces heat, larger currents will produce larger quantities of heat. However, Joule saw that the connection between the two is not quite as simple as this: he realised that if you double the current, there is four times as much heat produced every second. And if you multiply the current by 3, the heat produced every second is multiplied by 9.

He summarised this in what became known as Joule's law:

Joule's law states that the rate at which heat is produced by an electric current is proportional to the square of the current:

$$P \propto I^2$$

The constant involved is the resistance, giving:

$$\mathbf{P = RI^2}$$

If we substitute in an expression for the voltage, using $V = IR$, we get:

$$\mathbf{P = VI}$$

Remembering that $P = \frac{W}{t}$ (work or energy divided by time), we can conclude that the heat energy produced in an electric circuit, W, is given by:

$$\mathbf{W = RI^2t}$$

8.12 Sample Question

An electric iron is connected to a 230 V supply and has a total resistance of 30 Ω.

(a) What is its average power consumption?

(b) How much energy does it use in half an hour?

Sample Answer

(a) $V = IR$

$I = \frac{V}{R}$

$\frac{230}{30} = 7.67\,\text{A}$

$P = VI$

$= 230 \times 7.67 = 1764.1\,\text{W}$

(b) $W = RI^2t$

$= (30)(7.67)^2(1800)$

$= 3\,176\,761\,\text{J}$

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8.13 Sample Question

A device requires 230 V to produce a current of 3 A.

(a) What is its power consumption?

(b) What is its resistance?

Sample Answer

(a) $P = VI$

$= 230 \times 3 = 690\,\text{W}$

(b) $R = \frac{V}{I}$

$= \frac{230}{3} = 76.67\,\Omega$

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Experiment 8.5: Verification of Joule's law (as $\Delta\theta \propto I^2$)

Joule's law actually states that $P \propto I^2$, where P is power.

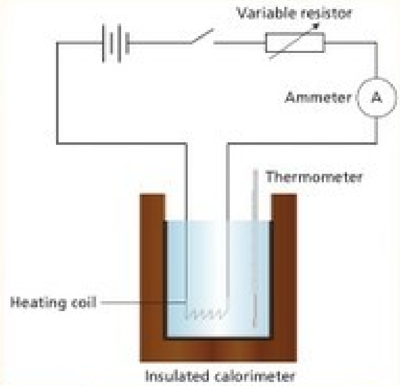
However:

$$P = \frac{energy}{time} = \frac{mc\Delta\theta}{t}$$

If mass and time are kept constant, as is the case here, we can say that:

$P \propto \Delta\theta$

Therefore, if $\Delta\theta \propto I^2$, we can deduce that $P \propto I^2$.



8.46 *To verify Joule's law*

Method

1. Set up the apparatus as shown in figure 8.46.
2. Note the initial temperature of the water.
3. Switch on the power and simultaneously start the stopwatch. Allow a current of 0.5 A to flow for 5 min, adjusting the rheostat if necessary to keep the current constant.
4. Stir and note the highest temperature. Calculate the change in temperature ($\Delta\theta$).
5. Repeat the above procedure for increasing values of current, I. Each time, use the same mass of water and allow the current to flow for the same time. Take several readings.

Results

Plot a graph of $\Delta\theta$ against I^2. A straight-line graph through the origin will verify that $\Delta\theta \propto I^2$, i.e. Joule's law.

Heat loss will be reduced by insulating the calorimeter. Also, starting with cooled water will ensure that heat gained below room temperature will be cancelled by heat lost above room temperature.

GrS PHYS Gr 10 Ss Mod 8.indd 138 5/9/19 4:47 PM

James Joule

James Joule grew up near Manchester and began his working life in the family-owned brewery, while studying science as a hobby. He and his brother were fascinated by electricity and carried out many experiments that involved electrocuting each other (and occasionally family servants!). As a young man Joule oversaw the introduction of newly invented electric motors into the family business, and this led to more detailed studies into the efficiency of machines. Over time this developed into an understanding of how energy can be converted from one form into another. For this work, the SI unit of energy, the joule (J), was named after him.

Later, Joule worked with Lord Kelvin in developing the absolute scale of temperature and discovered the connection between current and heat produced, which is now known as Joule's law.

8.47 *James Prescott Joule (1818–1889)*

For you to try

1 State Joule's law.

2 (a) If 230 V drives a current of 6.5 A through an electric kettle, what is its power rating?
(b) How many joules of energy does it require every second?
(c) How much energy does it require if it operates for a period of 45 s?

3 A 30 W speaker system requires a total current of 130 mA to operate when connected to a 230 V supply. What is its total resistance?

4 An electrical device is manufactured in America and is designed to carry a current of 0.27 A when connected to a 110 V supply.
(a) What is its resistance?
(b) If it is brought to Ireland and attached to a 230 V supply, what current will flow through it? Is it likely to operate safely?

5 An electric iron is connected to a 230 V supply and has a total resistance of 30 Ω.
(a) What is its average power consumption?
(b) What current flows in it?

The National Grid

We have seen that electric current will always give rise to heat. This can be useful, but it can also be wasteful. The electronic circuits in computerised devices create a lot of heat, for example, and this has to be constantly taken away from the system using fans or other cooling devices.

Heat production is also a problem in transporting electrical energy across large distances, as we do in the National Grid.

8.48 *High-voltage wires*

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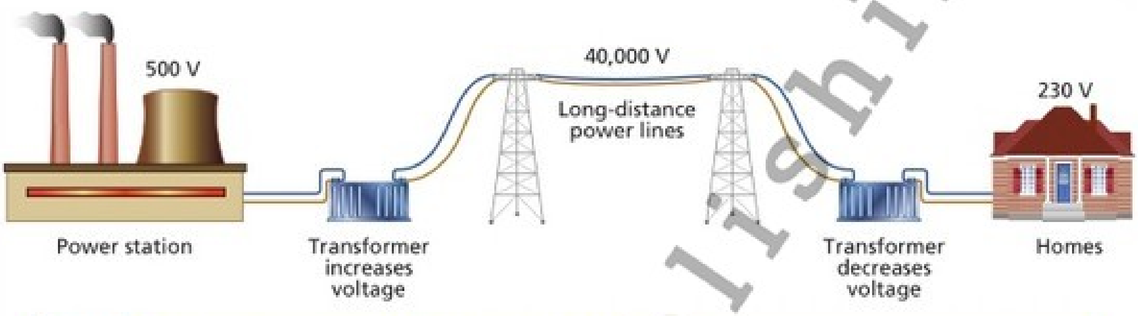
Moving electrical energy from power stations to towns involves bringing current through many kilometres of electric wire. Any heating effect in these wires is very wasteful: it essentially means we are using precious resources to release heat into the air across the country.

As Joule's law explains, the heat produced every second is larger if the current is larger. We know, too, that the power is directly proportional to the voltage, or to the square of the current. As a high power corresponds to a high loss of energy from a system, we are better off transmitting energy at high voltage rather than at high current. This is known as an extra high tension (EHT) system.

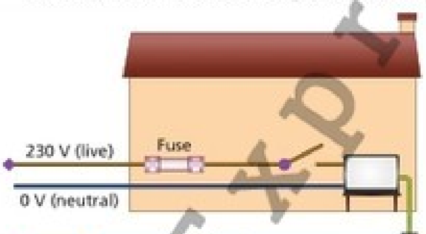


8.49 *EHT: electricity is transmitted at high voltage and low current*

Domestic wiring

In a very simplified form, all homes are connected to the National Grid by two wires: one at 230 V (the live wire) and the other at 0 V (the neutral wire). Whenever a connection is made between the two wires – as happens when a device is both plugged in and switched on – a current will flow from the high voltage to the low, flowing through the device and allowing it to function.

A fuse is simply a short piece of relatively weak wire, designed to break if a current above a certain safety limit flows through it. As this will break the circuit, it protects devices elsewhere in the circuit. Fuse ratings describe the maximum current that a particular fuse will allow: for example, a 1 A fuse will allow current up to a maximum of 1 A and can be used in a circuit where the current should be less than that, whereas a 13 A fuse will allow any current up to 13 A to flow.



8.50 *All switches and fuses should be on the live wire, so that once a device is switched off, no part of it is at high voltage*

Only certain ratings are easily available: usually 1 A, 2 A, 3 A, 5 A and 13 A. The lowest fuse rating possible should be used. For example, if a device requires a current of 2.3 A, the 3 A fuse should be used. If a device uses a current of 7 A, you would use the 13 A fuse and so on.

An alternative safety feature is a **miniature circuit breaker** (MCB), which contains both an electromagnet and a bimetallic strip. Like the fuse, these will break the circuit if a current above a certain safety limit flows through it.

Residual circuit breakers (RCDs) function by detecting a difference between the current flowing in the live and neutral wires. These should be the same: if 5 A flows into a device, for example, and only 4.9 A flows out, where is the missing 0.1 A? There cannot be a good answer to that question. The RCD is designed so that if the currents vary by a significant amount, the circuit is broken.

Both MCBs and RCDs are commonly called 'trip switches'.

Electric devices can be attached to the mains supply using either ring circuits or radial circuits.

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A ring circuit is one in which all the components are wired in turn before the wiring connects back to the mains. Power sockets are usually wired in this fashion.

A radial circuit is one in which the components radiate out from a central point, with each one wired separately. This is usually used for high current devices such as electric ovens and showers.

8.50 *A typical set of trip switches*

All metal appliances should be earthed. This means they should have a third wire connecting them directly to earth. If a fault develops, the current will flow to earth, rather than through the next person who touches the appliance. Appliances that are doubly insulated do not require an earth wire, and for this reason many devices do not have an earth connection.

In addition, all metal surfaces used near water (pipes, taps, etc.) should be bonded, i.e. connected to earth. This is to protect from injury, should any part of them become connected to a power supply.

The kilowatt-hour

When we pay for electricity, we pay for the quantity of electrical energy that has been supplied to us. Generally, energy is measured in joules, but the joule is a very small quantity, and it would be impractical to keep count of the number of joules supplied to each electricity user. For simplicity a larger unit is used, the kilowatt-hour.

Remember that

$$\textbf{Power} = \frac{\textbf{Energy}}{\textbf{Time}}$$

If we multiply both sides by time, we get:

$$\textbf{Power x Time = Energy}$$

The kilowatt is a measurement of power, and the hour is a measurement of time, so we can see that the kilowatthour is a measurement of energy. It is often referred to as one 'unit' of electricity. The cost of one unit of electricity will change over time and can vary from one supplier to another, but it is currently in the region of 15–20 c.

To calculate the number of 'units' of electricity that a device will use, we can multiply its power rating by the number of hours for which it will run. Typical power ratings for some everyday items are given in Table 8.1.

Table 8.1

Appliance	Power rating (watts)
Electric alarm clock	3
Energy-saving lamp	10-20
Typical fluorescent tube	40
Laptop	20-75
Incandescent light bulb	100
Satellite decoder	70
Printer	100
Chest freezer (110 litres)	110
32-inch LCD TV	150

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8.14 Sample Question

A 2 kW kettle runs for a total of 20 min in a week. How many units does it use?

Sample Answer

No. units = (No. kilowatts)(No. hours)

$= (2)\left(\frac{20}{60}\right)$

= 0.67 units (kWh)

8.15 Sample Question

A 150 W TV runs for 4 h in one evening. How much energy does it use?

Sample Answer

150 W = 0.15 kW

No. units = (No. kilowatts)(No. hours)

= (0.15)(4)

= 0.60 units (kWh)

For you to try

1. Electricity is generally brought from a generating station to urban areas at very high voltage. Why is this?
2. (a) If electrical energy is carried through long copper wires of total resistance 20 Ω at a current of 1000 A, what would the expected energy loss be per second?
   (b) If the current is reduced to 100 A, what would the expected energy loss be per second?
3. At what voltage would you expect the live wire to be in a home in Kazakhstan?
4. If a device requires a current of 3.2 A to operate, should you use a 3 A or 5 A fuse?
5. What is meant by the term 'bonding', in terms of electrical safety?
6. Briefly outline the principle of operation of an MCB.
7. Briefly outline the principle of operation of an RCD.
8. A 1.2 kW device operating for 3 h will use how many kilowatt-hours of energy?
9. An 800 W microwave oven requires 2 min to cook a bowl of porridge. How much does this cost at a rate of €0.16 per unit?

Electromotive force

At this point it is helpful to learn the meaning of a new term. Electromotive force (EMF for short) is a term used to describe the voltage across a battery, a generator or some other source of electricity. The reason why it is helpful to use EMF is that it helps us to remember that this is a source of energy, whereas other voltage differences can be drains of energy.

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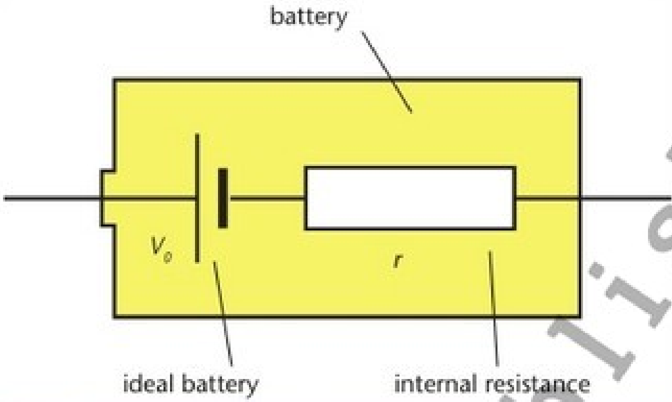
Batteries and Internal resistance

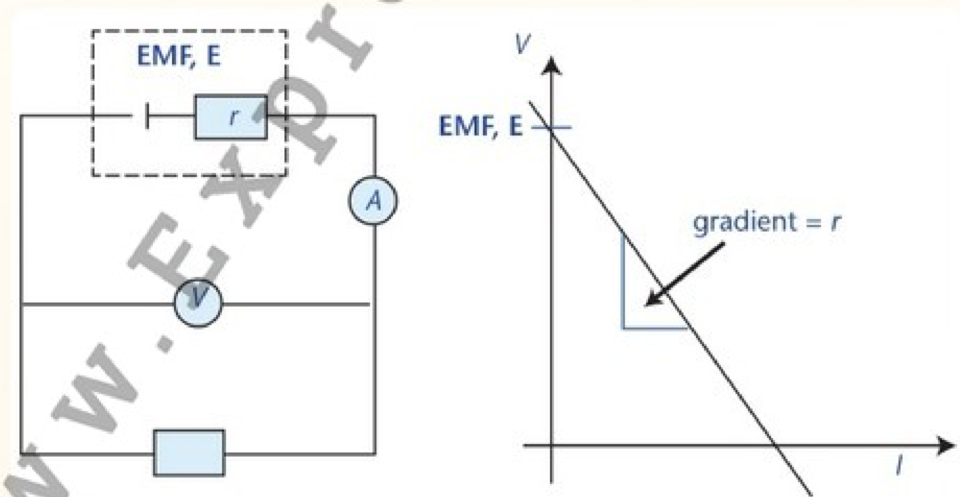
Normally we only think as batteries as sources of constant voltage, however, real batteries do not behave that way. The more current is drawn from them, the more their apparent EMF falls. It is almost as if a battery consisted of an ideal battery and a resistor connected in series. Sometimes the EMF is referred to as V_0 to denote the fact that it is the voltage of the battery when zero current is flowing.



8.51 *A real battery behaves like an ideal battery and a resistor in series.*

Experiment 8.6: To measure the EMF and internal resistance of a battery

In order to measure the internal resistance of a battery we need an ammeter a voltmeter and a few resistors (or a variable resistor). The circuit should be connected as shown below.



8.52 *Circuit to measure the internal resistance of a battery*

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The procedure consists of measuring the voltage across the battery, and the current flowing through the resistor at the same time. This procedure should be repeated for several different values of resistance. It is good if the range of the values of the resistors is as wide as possible, and the resistances start from values as low as 5 Ohms.

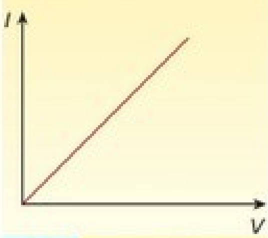
The measurement data can then be plotted on a graph as shown in the figure above, with the currents along the X axis and the Voltages along the Y axis. A line of best fit is then drawn through the data so that it intercepts the Y axis. Now we are ready to analyse the graph.

The intercept with the Y axis represents the Voltage when no current is flowing. This is Vo or the EMF of the battery. The slope of the line is the internal resistance of the battery. The better the quality of the battery, the smaller the slope will be. In real batteries, often the internal resistance of the battery changes as they age. The older they get, the higher the internal resistance. Finally they reach the point that when a small current flows, the little energy that is delivered is dissipated inside the battery; they become useless!

Voltage–current graphs

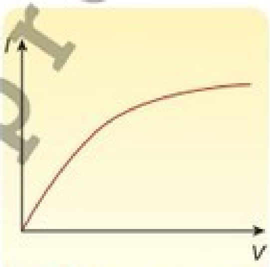
We looked at Ohm's law and learnt that for metals and some other conductors, the current flowing through a resistor will be proportional to the voltage across it. This means that the relationship between voltage and current follows the graph shown in figure 8.53 – a straight line through the origin.

However, it should be remembered that Ohm's law applies only in limited circumstances. In particular, it applies mainly to metallic conductors and only if those conductors are maintained at constant temperature. There are many electric circuits that use components that do not follow Ohm's law. Some of these are outlined below.



8.53 *Current against voltage*

8.54 *A filament bulb*



8.55 *I against V for a filament bulb*

Filament bulb

The traditional light bulb used in most homes consists of a very narrow piece of tungsten metal, known as the filament. Although a conductor, the very narrow cross section of the wire creates a high resistance in the tungsten, and when current flows through it a great deal of heat is produced. This causes the bulb to give out light. However, because the temperature of the wire varies, it is obvious that Ohm's law cannot apply. The relationship between current and voltage in this example is shown in the graph in figure 8.55.

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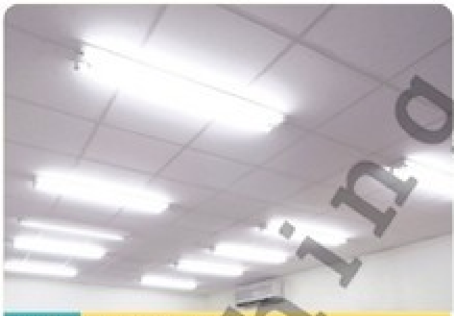
Gas

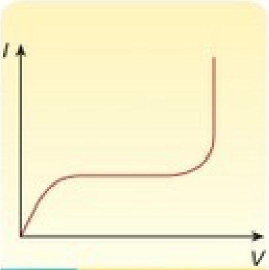
Fluorescent lights are often used in schools and factories because they require only a very low current and are, therefore, relatively cheap to run. Within a tube there is a mix of stable gases between the two electrodes at either end. The attraction of negative to positive causes some electrons to move from the negative towards the positive connection. As these electrons move, they collide with the gas particles that fill the tube. This collision can have sufficient energy to 'knock' electrons off the gas atoms, which leaves both an extra free electron and a positively charged ion (a charged atom). This happens repeatedly throughout the gas, so that a great deal of ions are created. These positive ions then move through the tube towards the negative connection.



8.56 *Fluorescent lighting*

8.57 *Conduction in a gas*

In this way electric charge moves through the gas and an electric current flows. However, there is a limit to how many ions can be created. This means that although an increase in the voltage will increase the current, the connection is not linear and instead follows the curve shown in the graph in figure 8.58.



8.58 *I against V for a gas*

Vacuum

In a cathode ray tube (CRT), an electric circuit is created with a gap between two electrodes (the negative **cathode** and positive **anode**). You have learnt already that current generally cannot flow once there is a gap in the circuit, but there are two important aspects of this circuit that allows a current to flow.

Firstly, a heater is placed behind the negative connection – the cathode – and this provides additional energy to the system. The electrons on the cathode use this energy to escape from their atoms and from the surface of the metal. This process is known as **thermionic emission**.

Secondly, a vacuum has been created in the space between the two electrodes. The absence of air molecules means that there is no impediment to the movement of the electrons from the cathode to the anode. This allows the electrons to cross the gap and to continue to flow through the circuit.

There is a limit, however, to the total number of electrons that can be released at the cathode via thermionic emission. This means that above a specific level of applied voltage, the current no longer increases significantly. This accounts for the levelling off of the graph.

8.59 *A cathode ray tube (CRT)*

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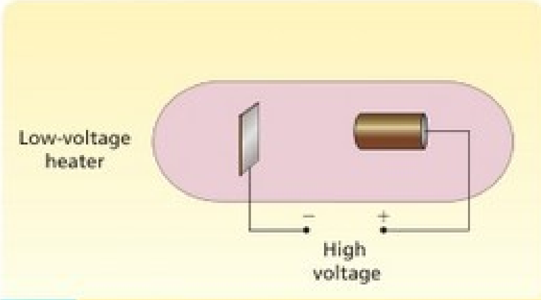
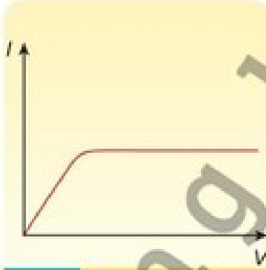


8.60 *Conduction in a vacuum*



8.61 *I against V for a vacuum*

Electrolytes

An electrolyte is a substance that contains free ions and acts as an electrically conductive medium. Most common electrolytes consist of ions in solution and these are called ionic solutions. A strong electrolyte is one which has many ions present in the solution and it will act as a good conductor of electricity. A weak electrolyte will have few ions present and will be a poor conductor of electricity.

There are two stages in Experiment 8.6 below. In each you will need to devise an effective way to record your results and at the end of the experiment you will be asked to describe procedures you followed and explain your results to members of another group.

In Stage 1 you will compare:

(a) the conductivity of solid salt (NaCl) crystals and NaCl (aq).
(b) the conductivity of different solutions to determine which are strong, weak and non-electrolytes.

In Stage 2, you will take two of the strong electrolytes you have identified in Stage 1 and in groups devise experiments to compare how the following factors impact conductivity readings.

- concentration of ions
- temperature of solution
- surface area of electrodes
- distance between electrodes

Laboratory work 8.7: To test the conductivities of a range of substances

In this experiment you will be testing the conductivities of:

- solid salt (NaCl) crystals
- tap water, sugar solution, alcohol, common energy drink
- solutions of salts : NaCl, $CaCl_2$, HCl

Method

Stage 1

1 Set up the experiment as shown in the diagrams below. In the diagram, X represents the substance or solution that you will be testing.
2 Diagram A shows that crocodile clips to be used should be attached directly to the end of the salt crystals. Diagram B shows that the crocodile clips are attached to two carbon electrodes and the placed in a beaker of the solution you are testing.
3 Allow the current to flow for approximately 30 seconds in both a and b and record readings from the ammeter.

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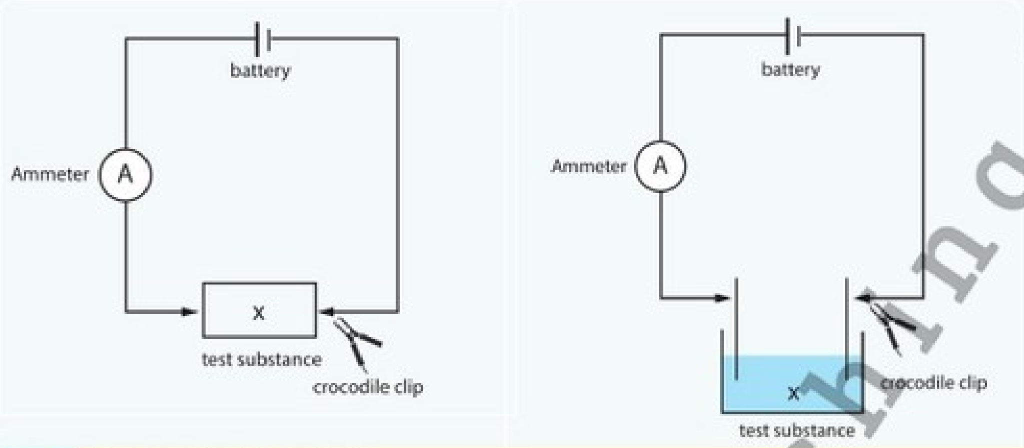


8.62 *Circuit in electrolyte experiment*

Stage 2

1 Take two of the strong electrolytes you have identified from Stage 1 and form a hypothesis as to how you think changing the following factors will impact on the ammeter reading.
- concentration of ions
- temperature of solution
- surface area of electrodes
- distance between electrodes

2 In groups design and carry out experiments using similar or modified equipment to test these hypotheses.

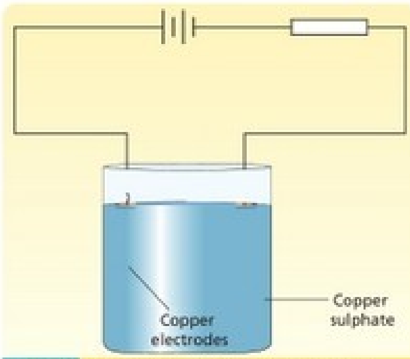
3 Record your results

Electrolysis

Electric current is generally carried by electrons but as we saw above it is sometimes carried by ions (charged atoms). This happens when current passes through a gas, for example, and also when it passes through an ionic solution as we saw in Experiment 8.6.

In copper sulfate, for example, the individual molecules contain two charged particles: the positively charged copper ions (Cu^{++}) and the negatively charged sulfate group (SO_4^{--}). The attraction between positive and negative is generally what holds this molecule together.

However, if the copper sulfate is dissolved in water and two electrodes are placed in the solution as shown in figure 8.63, the molecules begin to break up. This is because the positive copper ions, while still attracted to the negative sulfate ions, are also attracted to the negative electrode; some of the copper ions will leave their molecules and move towards that electrode. When they get there, they collect electrons from the electrode and become copper atoms, which usually then form a coating on the electrode. A similar process can be used to create a thin layer of gold or silver on the surface of otherwise cheap jewellery.



8.63 *Conduction in an ionic solution*

Meanwhile, the sulfate ions move over to the positive electrode and give up their electrons to the circuit.

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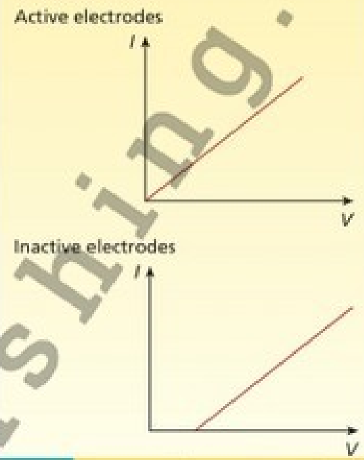
As this process carries on over and over again there is a constant flow of electrons to the liquid and out of the liquid. Though the current crosses the liquid itself by the movement of the ions within, it does not mean that a current is not flowing: as long as there is constant movement of charge, the current is clearly flowing.

This process can take place with what we call **inactive electrodes** – electrodes that do not take place in a reaction themselves but instead serve as the surface at which electron transfer can take place. An example of an inactive electrode is a carbon rod.

We can also have **active electrodes** – electrodes that are themselves part of the electrolysis process. For example, during electroplating, electrolysis deposits a thin layer of one metal on another metal in order to improve beauty or resistance to corrosion. Using copper electrodes in a copper sulfate solution is an example of the use of active electrodes.

With active electrodes, this creates a circuit that obeys Ohm's law. With inactive electrodes, where a few volts have to be applied before a current begins to flow, the graph is a straight line, but it does not go through the origin and, therefore, it is not obeying Ohm's law.

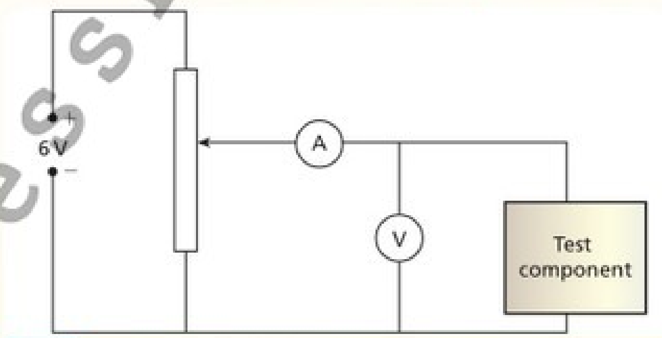


8.64 *I against V for an ionic solution*

Experiment 8.8: Investigation of the variation of current with p.d. for various electrical components

Method

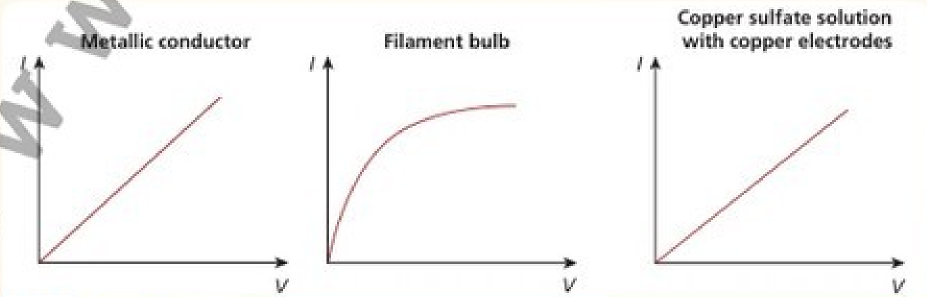
1. Set up the circuit as shown in figure 8.65, using a wire as the test component, and set the voltage supply (e.g. at 6 V d.c.).
2. Move the slider along the resistor to obtain different values for the voltage *V* and hence for the current *I*.
3. Obtain a number of values for *V* and *I* and plot a graph of *I* against *V*.
4. Repeat, replacing the wire with other devices: a filament bulb, copper sulfate solution.



8.65 *Experimental circuit diagram*

Results

You should find that your graph is similar to those shown in figure 8.66.



8.66 *I against V curves*

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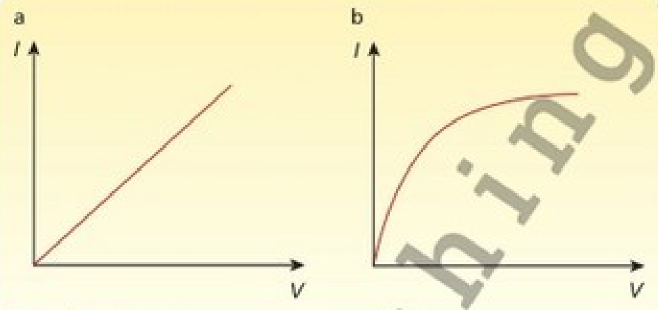
For you to try

1 One of the graphs in figure 8.67 represents the voltage – current relationship for a metal and the other for a filament bulb. Which is which?
2 Which of the two graphs in figure 8.66 follows Ohm's law?
3 Explain why the graph for the filament bulb in figure 8.66 has the shape that it does.



8.67 *Questions 1–3*

4 Which other graph would you expect to follow Ohm's law?
5 Draw the *I–V* graph for a gas and briefly explain why it has the shape that it does.
6 Draw the *I–V* graph for a vacuum and briefly explain why it has the shape that it does.
7 What are ions?
8 Give two circuits in which the principal charge carriers are electrons and two in which the principal charge carriers are ions.
9 Tables 8.2 and 8.3 represent the results of an investigation into the *I–V* graphs for two components, A and B. Sketch the graph for each one and suggest which component each may be.

Table 8.2 Component A

V/V	0	2	4	6	8	10	12
I/A	0	0.6	1.1	1.9	2.4	3.0	3.5

Table 8.3 Component B

V/V	0	2	4	6	8	10	12
I/A	0	0.9	2.0	2.5	3.1	3.9	4.1

Power in electrical circuits

Power is defined in mechanics as 'work done divided by the time taken to do the work'. In electrical circuits we can still calculate powers, but we must note a few changes. Work is measured in joules, the unit of energy. In a circuit, charges carry energy from the battery and dissipate it somewhere else in the circuit where the current experiences some resistance.

The voltage tells us how much energy is given to each coulomb, and the current tells us how many coulombs per second are going past any point in the circuit. So the amount of energy per second can be written as joules/coulombs x coulombs/second. The coulombs cancel out, leaving joules/second which is the definition of power.

In this way we have shown that Power (watts) = Voltage (volts) x Current (amperes). It may seem obvious that Voltage is measured in volts, but remember that we could also have written this expression as Power (watts) = EMF (volts) x Current (amperes). The first expression would tell us how much power is being dissipated in any given component in the circuit, this later expression (involving EMF) tells us how much power the source is delivering to the circuit.

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Normally in circuit calculations, we assume that the wires have no resistance at all. This means that no energy is ever wasted in transmission: it is all delivered from the battery to the components. In real life, even the best conductors have some resistance, and this causes some power to be wasted along the way.

Some thoughts about 'superconductivity'

Scientists have discovered that at very low temperatures (around –200°C) some materials become 'superconductors'. By this we mean that their resistance is exactly zero. This means that once a current starts to flow through them it can flow indefinitely without causing any heating. Unfortunately it is very expensive to achieve the low temperatures needed to reach superconductivity; it requires liquid nitrogen. Although nitrogen is abundant in the atmosphere, it is expensive to cool it down to the point where it condenses out of the atmosphere.

We do not know if in the future it might be possible to discover materials that are superconductive at room temperatures, however, if this were to become possible, it would revolutionise the way in which we transport electricity. Some of the consequences of superconductivity at room temperature would be the following:

- No need for dangerously high voltages
- Much greater efficiency in all electrical appliances
- Fantastically efficient electric cars
- Mobile phones that only need to be charged once per month

Can you think of any other benefits from superconductivity?

8.16 Sample Question

What is the power of an electric heater that operates at a voltage of 220 V and draws a current of 10 amperes?

Sample Answer

Power = Voltage x Current, so Power = 220 x 10 = 2200 watts

8.17 Sample Question

An electric hair dryer operates at a voltage of 220 V, the manufacturer states that its power is 750 W. What is the current flowing through it?

Sample Answer

$P = VI$ so $I = P/V$ $I = 750/220 = 3.41$ amperes

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8.18 Sample Question

A water pump needs to lift water from a well that is 10 metres deep. We require the pump to be capable of delivering 20 litres per minute. The pump will be operated from a 220 V supply. Assuming the efficiency of the electric pump to be around 25%, calculate how much current the pump will draw.

Sample Answer

First of all, let us calculate what power is needed:
The amount of gravitational potential energy being delivered to the water is = *mgh*.
The density of water is 1 kg/litre, so the mass is 20 kg.
Energy supplied = 20 kg x 10 ms^{-2} x 10 m = 2000 Joules.
We require this much energy in 1 minute (= 60 seconds).
Power needed = Energy/time = 2000/60 = 33.3 W.
The question asks us to assume that the conversion will only be 25% efficient, that means that we will need a pump that is 4 times more powerful.
That is 33.3 x 4 = 133.3 watts.
Power = Voltage x Current, so Current = Power/Voltage = 133.3 / 220 = 0.6 amps.

For you to try

For all the questions that follow, assume a mains voltage of 220 V.

1 A mains bulb has a resistance of 800 Ohms. What will its power output be when connected to a mains voltage of 220 V?
2 An electric kettle is rated at 2000 W. If it is switched on for 3 minutes, how much energy has been converted?
3 An electric heater needs to have a power output of 3500 W, what should its resistance be?
4 Two electrical heaters are connected to the mains in series with each-other. The first has a resistance of 50 Ohms, and the second a resistance of 35 Ohms. What will their power outputs be?

Semiconduction

A semiconductor is a material with a resistivity that lies between that of a conductor and that of an insulator.

There are many examples of semiconductors. Germanium, gallium arsenide and zinc sulfide are just a few of those used. However, the best-known semiconductor and the example that we will study in detail is silicon.

Silicon has a valency of four. This means that it has four electrons in its outermost shell but, like other atoms, would 'prefer' to have eight.

In a silicon crystal, in order to achieve a situation in which each atom is surrounded by eight electrons, the atoms arrange themselves in such a way that each atom shares an electron with each of four neighbours (see figure 8.68).

8.68 *Silicon atom*

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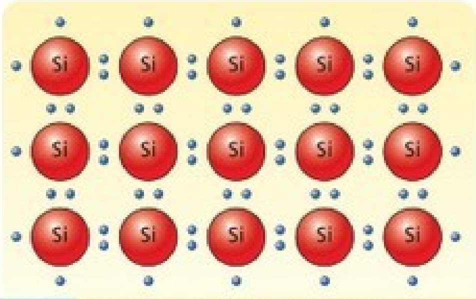


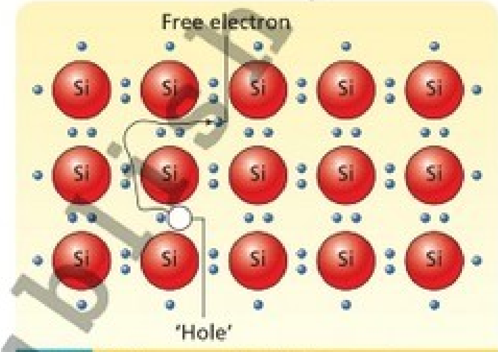
8.69 *A silicon crystal at low temperature*

At a temperature of 0 K, this a perfect insulator. No electrons are free to move and they are therefore not free to carry a current.

Above 0 K, the added heat energy is distributed throughout the crystal as kinetic energy. From time to time, an electron will gain sufficient energy to escape from its place and move through the crystal. It leaves a 'hole' behind it.

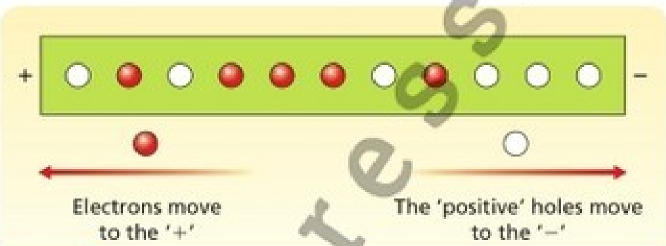
Intrinsic conduction

Once electrons gain enough energy to escape from their places, they are available to carry a current if the crystal is placed in a circuit. In such a case, the free electrons will move towards a positive connection, and the holes will end up effectively moving towards the negative connection. They have no charge, of course, but as they will always move towards a negative connection, it is useful to think of them as being positive; and they are often referred to as **positive holes**.



8.70 *A silicon crystal at high temperature*

We can simplify a crystal as shown in figure 8.71.



8.71 *Intrinsic conduction in silicon*

Extrinsic conduction

Conduction can be improved by either adding extra free electrons **(n-type doping)** or extra holes **(p-type doping)**.

n-type doping

When constructing a silicon crystal, we can introduce a small number of phosphorous atoms. These will try to fit into the overall crystal structure, sharing one electron with each of four neighbours. But they have five electrons in their outer shell and will, therefore, have one 'extra electron'. This is likely to break free from the atom and to become available for conduction. As there are extra free electrons, conductivity is improved. Addition of a small quantity of an impurity in this way is known as doping.

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p-type doping

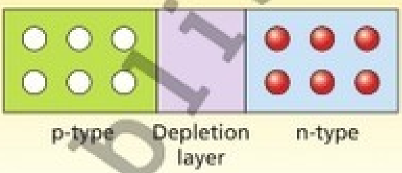
If we add a small quantity of boron to a growing crystal of silicon, the boron atoms will try to fit into the structure of the crystal. Each one has only three electrons in its outer shell, however, so an extra 'hole' will be created. As we have seen, holes act like positive charges and are sometimes referred to as positive holes – they are often thought of as actually carrying the current. In p-type material, we even say that holes are the **majority charge carriers**. In reality, they act as stepping stones for the moving electrons, which improves the conductivity.

Doping is the addition of small quantities of an impurity to a semiconductor in order to improve conductivity.

p-n junction

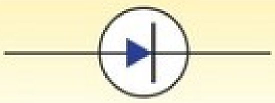
n-typing and p-typing are really only of any use to us when we place the two together at a p-n junction. The simplest example of this is in a **diode**.

At the junction of the two materials, the extra free electrons tend to occupy the extra free holes. This is known as the **depletion layer**. It acts as a block of insulating material in the middle of the diode (see figure 8.72).



8.72 *A p–n junction*

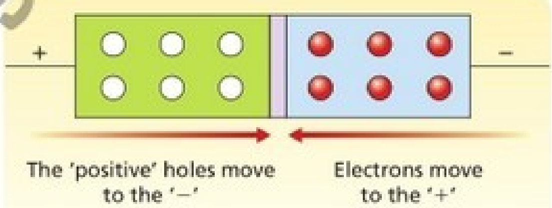
The symbol for a diode is shown in figure 8.73. The significance of the diode is that it allows current to flow in one direction and not the other.



8.73 *The symbol for a diode*

Forward bias

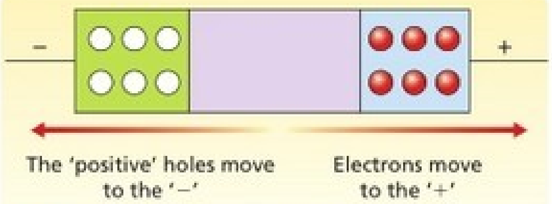
If the diode is placed in a circuit so that the p-type material is attached to a positive connection, current will flow. This is because the electrons are drawn towards the positive, and the holes to the negative: the depletion layer shrinks and allows current to pass through it (see figure 8.74).



8.74 *In forward bias, the depletion layer shrinks and a current flows*

Reverse bias

For reverse bias, the p-type material is attached to the negative terminal, and the n-type to the positive. The electrons are drawn backwards from the centre and the depletion layer grows. A current will not be able to move through the device (see figure 8.75).



8.75 *In reverse bias, the depletion layer grows and no current can flow*

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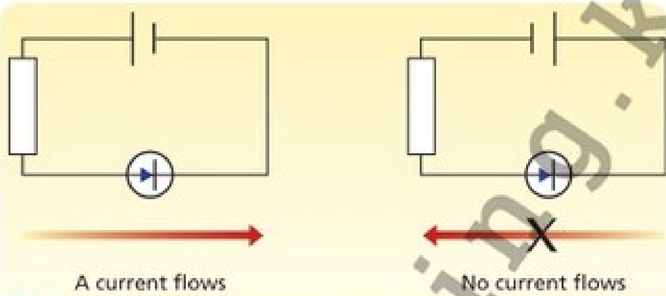
GrS PHYS Gr 10 Ss Mod 8.indd 153
5/9/19 4:48 PM

Using electrical symbolism, these circuits could be shown as in figure 8.76.

One use of a diode is in **rectification** – the conversion of a.c. to d.c. (which we came across in Module 7). The diode blocks the current flow in one direction, allowing it through only when it is in forward bias. The current is not constant and it flows only in one direction and is therefore d.c.



8.76 *Circuit diagrams to represent the situations in forward bias (when a current flows) and in reverse bias (when no current flows)*

Another example of a diode is the **light-emitting diode** (LED). LEDs are diodes in which a current crossing the p-n junction causes a small amount of light energy to be released.

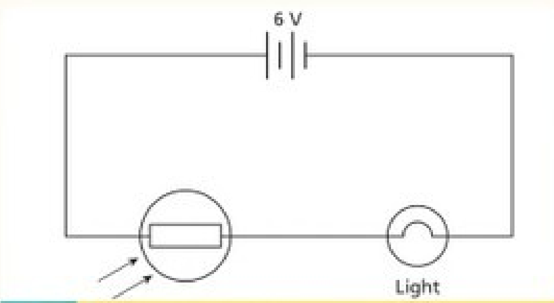
For you to try

1. What is a semiconductor? Give three examples.
2. Briefly explain each of the terms 'intrinsic conduction', 'extrinsic conduction', 'p-type doping' and 'n-type doping'.
3. What is a p-n junction?
4. Briefly explain how a depletion layer is formed at a p-n junction.
5. Draw a diagram of a p-n junction, showing the depletion layer.

Experiment 8.9: To demonstrate the operation of an LDR (Light Dependent Resistor)

Method

1. Set up a circuit as shown in figure 8.77.
2. Close the switch to allow the current flow and observe what happens.
3. Cover the top of the LDR with a finger and observe what happens.



8.77 *Experimental circuit diagram*

Observations

You should find that the bulb lights up when the current flows (you may have to shine a torch, or some light source onto the LDR to make the bulb light up). Then you should find that the bulb switches off when the LDR is covered.

This demonstrates the effect that light has on the LDR and on the circuit.

A more complex arrangement is needed to create a light that will come on in the dark and switch off in the light (which would obviously be a little more useful).

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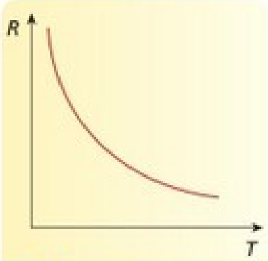
Thermistors are semiconductors in which the resistance is controlled tightly by temperature. Any increase in temperature creates a large decrease in resistance.

Integrated circuits (ICs) are small electrical components containing a combination of diodes, resistors, capacitors and other devices all built into one 'chip' of silicon. Chips smaller than a fingernail can contain several million components. Figure 8.79 shows the surface of an IC in the motherboard of a PC, which contains several ICs and is connected up using a variety of resistors and connecting metal strips.



8.78 *For a thermistor, the resistance falls as the temperature increases*

8.79 *A magnified image of the surface of an integrated circuit*

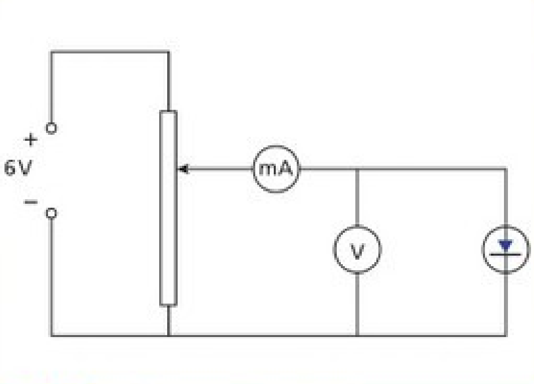
V–I curves

The current in a diode increases as the applied voltage increases, but it does not do so in a straight line. The reverse bias current is often described as being zero, but in fact an extremely small current does flow. It is typically measured in micro-amps.

Experiment 8.10: Investigation of the variation of current (*I*) with p.d. (*V*) for a semiconductor diode

Method

1 Set up a circuit as shown in figure 8.80, so that the diode is in forward bias.
2 By making use of the potential divider, set the voltage that is being applied to the diode at a low level (close to 0 V).
3 Record the values of both the voltage and current.
4 Increase the applied voltage to 0.1 V and again measure the current. Record both values and plot a graph to show how current varies with voltage.



8.80 *Circuit diagram for experiment*

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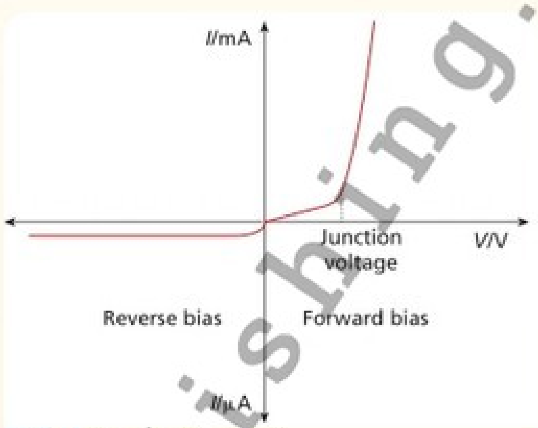
5 Repeat this process for several values of voltage, up to about 0.7 V.
6 Reverse the connection to the diode, so that it is in reverse bias.
7 Replace the milli-ammeter with a microammeter and position it so that it only reads the current through the diode.
8 Repeat steps 2-5.

Results

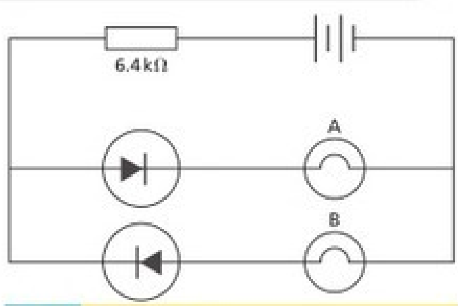
Your graph should look similar to figure 8.81.



8.81 *I against V for a diode*

For you to try

1 What happens to the size of the depletion layer when a diode is connected in forward bias? Does a current flow?
2 What happens to the size of the depletion layer when a diode is connected in reverse bias? Does a current flow?
3 In the circuit in figure 8.82, which of the two lights A and B would you expect to light?



8.82 *Question 3*

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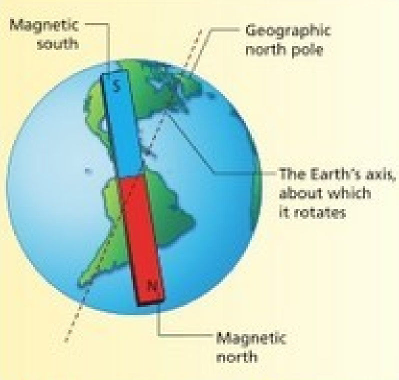
Module 9 Electricity and Magnetism

Learning objectives

- To describe the characteristics of the magnetic field of conductors 10.3.4.1
- To apply the left-hand rule and describe the effect of magnetic fields on moving charged particles and on conductors with a current 10.3.4.2
- To describe the contemporary scope of using magnetic substances and modern applications 10.3.4.3
- To experimentally assemble an artificial magnet and explain its field of application 10.3.4.4
- To explain factors affecting the magnetic field of a solenoid 10.3.4.5
- To explain the occurrence of an electromotive force at a change of magnetic flux 10.3.5.1
- To explain Lenz's rule 10.3.5.2
- To explain the principle of the operation of electromagnetic devices 10.3.5.3
- To explain the practical importance of magnetic resonance tomography 10.3.5.4

The Earth's magnetic field

A magnet that is left free to rotate (away from any other magnets, as is the case in a compass) will always come to rest with one end – the north pole (N) – pointing to the north, and the other – the south pole (S) – pointing to the south. This is due to the Earth's magnetic field. It is as if there were a large bar magnet at the centre of the Earth. The reason for this is that there is a great deal of molten iron in the Earth's core, and it is this iron that creates the magnetic field.



9.1 *The Earth's magnetic field*

One of the problems associated with the concept of magnetic poles is evident in looking at the Earth's magnetic field. For many centuries navigators were happy to think about the pole of the magnet that points north as being the north pole of that magnet. But as we have come to understand magnetic fields better, we know that a north pole will always be attracted to a south pole. This means that, confusingly, we have created a labelling system for magnets that means the magnetic pole located near the geographic north pole is in fact a magnetic south.

Magnetic declination

From figure 9.1 you will see that the magnetic poles and geographic poles are not perfectly aligned. This has obvious effects in navigation: depending on where a magnet might be used, it may or may not be pointing towards the geographic pole. To further complicate matters, the magnetic pole is not fixed and moves constantly. It has been in Northern Canada for many years but moves at a rate of several kilometres per year, and it looks like it will move into Siberia over the next few decades. The angle between a line pointing to the geographic and magnetic poles is known as the angle of declination. Knowledge about the angle has been very important to navigators, but with the widespread use of the satellite-based Global Positioning System (GPS), it is less of an issue than it once was.

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Experiment 9.1: To investigate magnetic declination

Method

1 Set a smartphone with a magnet reading on top of a sheet of paper, as shown in figure 9.2. (Not all phones have this function, but many do. Ensure that it is set to show true north, which the phone will locate using GPS.)
2 Mark the direction of north on the paper.
3 Replace the phone with a compass.
4 Allow the needle to settle, and again mark the direction of north. This is showing the direction of magnetic north.

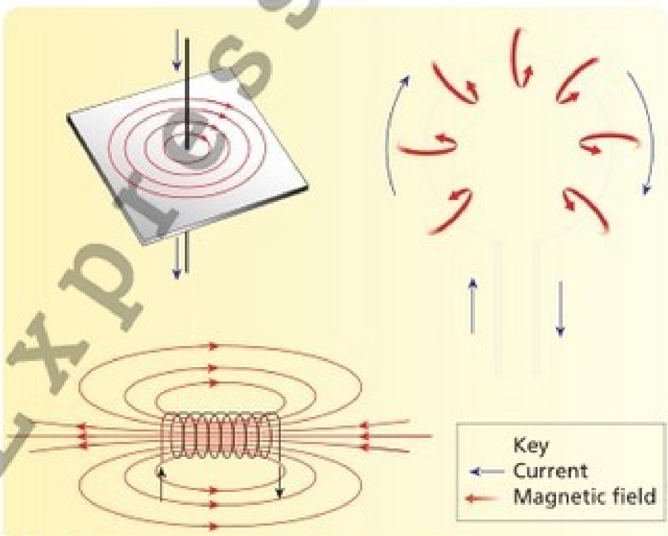
Observations

The angle between the two lines is the angle of declination at that location.

9.2 *A smartphone, indicating true north*

Magnetic fields around electrical objects

We have seen already that all magnetism is created either directly or indirectly by the presence of moving electric charge. It follows that any electrical current will create a magnetic field. However, the shape of that field will be determined by the arrangement of the electric circuit. The shape of the magnetic fields due to the electrical current in a long straight wire, a loop and a solenoid are shown in figure 9.3.



9.3 *Magnetic fields around electric currents*

For you to try

1 Are the Earth's magnetic poles fixed permanently in place? Explain your answer.
2 **(a)** What is meant by the term 'magnetic declination'?
(b) What are the consequences of this effect for those navigating by compass?

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GrS PHYS Gr 10 Ss Mod 9.indd 158 5/9/19 4:48 PM

A current-carrying conductor in a magnetic field experiences a force

We have seen that an electric current will always create a magnetic field. We also know that any two magnets will create forces on each other if they are close enough for their magnetic fields to overlap. It follows that if an electric current passes through a magnetic field, it will experience a force. This can be demonstrated using a strip of tinfoil, which carries a current in a magnetic field (see Experiment 9.2).

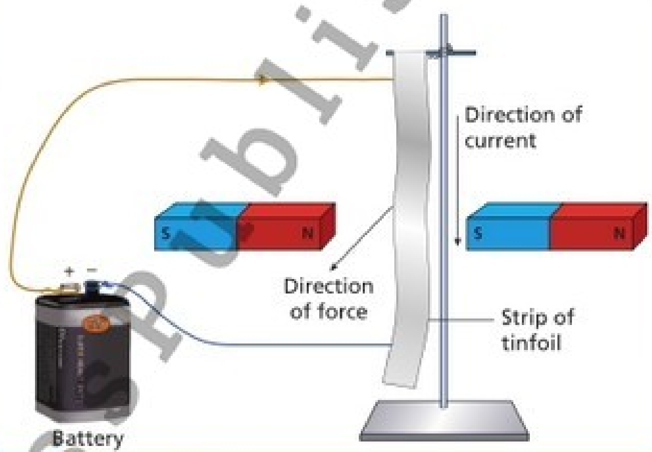
Experiment 9.2: To demonstrate that a current-carrying conductor in a magnetic field experiences a force

Method

1. Set up a circuit like that shown in figure 9.4, with a piece of tinfoil suspended from a retort stand.
2. Close the switch so that a current will flow.

Observations

You should see the tinfoil visibly move. If set up as shown in figure 9.4, the tinfoil will move forward, but the direction of movement depends on the exact arrangement of magnets and the current.



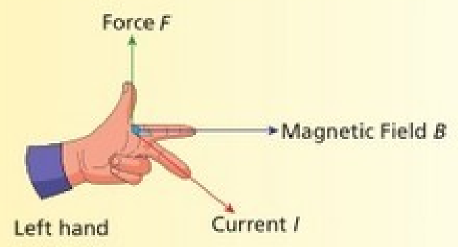
9.4 *Experimental setup*

The direction of the force

As we have seen, a current-carrying conductor in a magnetic field will experience a force. In Experiment 9.2, we use tinfoil so that the metal will be light enough to move in response to this force, allowing us to detect its presence.

If you swap around the connections to the power supply so that the current flows in the opposite direction, you should notice that the foil still moves, but that it moves in the opposite direction. Similarly, if you swap the two magnets, you will see that the direction of movement reverses again.

The connection between the directions of the current, magnetic field and force was established by English electrical engineer and physicist John Ambrose Fleming (1849–1945) in the late 1800s. Fleming explained the connection using what he called the **left-hand rule**. If you look at figure 9.5, you will see a left hand with the fingers arranged so that the thumb, index and second fingers are all at right angles to each other.



9.5 *Fleming's left-hand rule*

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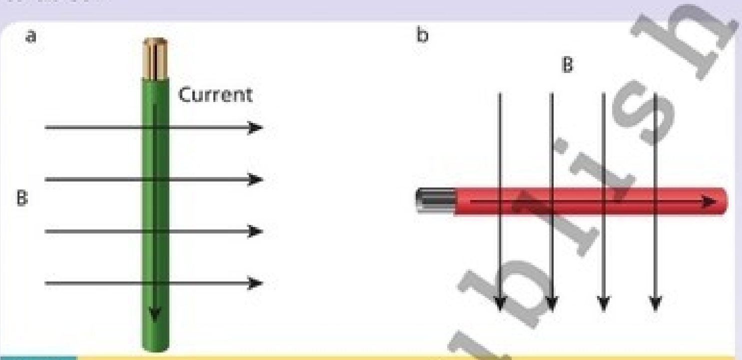
The index finger is used to represent the direction of the magnetic field, the second finger shows the direction in which the current is flowing, and the thumb shows the direction of the resulting force.

9.1 Sample Question

The diagrams in figure 9.6 show electrical wires carrying a current and flowing through a magnetic field represented by B. Which way would the wires move, if free to do so?



9.6

Sample Answer

(a) Following the left-hand rule, the wire would move 'out of' the page.
(b) Following the left-hand rule, the wire would move back 'into' the page.

The strength of the force

The left-hand rule tells us the direction of the force created when a current-carrying conductor passes through a magnetic field. The magnitude of this force also depends on the magnetic field and the current. It is described by the formula:

$F = BI\ell$ (for a conductor with a current perpendicular to the magnetic field)

and $F = I\ell B\sin\theta$ (for a conductor at an angle θ to the magnetic field)

where:

F – force
I – current
ℓ – length of the wire within the magnetic field
B – magnetic flux density, which is how we measure the strength of the magnetic field.

The magnetic flux density (B) is a measurement that you are unlikely to have encountered before. It is one of the ways in which we measure the strength of a magnetic field. The above formula can be used to help define what exactly we mean by this measurement.

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9.7 *Nikola Tesla (1856–1943), a Serbian American scientist who developed early a.c. transmission systems and designed early transformers*

Magnetic flux density (B) is the force experienced by a conductor of length 1 m carrying a current of 1 A at right angles to the magnetic field. Its direction is the direction of the magnetic field lines:

$$B = \frac{F}{I\ell}$$

The unit of magnetic flux density is the tesla (T).

If a wire of length 1 m carries a current of 1 A and experiences a force of 1 N while passing through a magnetic field, the magnetic flux density is 1 T.

9.2 Sample Question

An electrical wire carries a current of 1.5 mA and passes through a magnetic field of length 2 cm and of magnetic flux density 4 T. What force does it experience?

Sample Answer

$$\begin{aligned} F &= BI\ell \\ &= (4)(1.5 \times 10^{-3})(0.02) \\ &= 1.2 \times 10^{-4}\,\text{N} \end{aligned}$$

9.3 Sample Question

An electrical wire carries a current of 3.2 A and passes through a magnetic field of length 15 cm and of magnetic flux density 2 T. What force does it experience?

Sample Answer

$$\begin{aligned} F &= BI\ell \\ &= (2)(3.2)(0.15) \\ &= 0.96\,\text{N} \end{aligned}$$

Subatomic particles and the left-hand rule

We have already looked at the forces created on a conductor when a current flows through a magnetic field. That analysis can be adapted to help us see what happens to an individual electric charge, such as a proton or electron, when it moves into a magnetic field.

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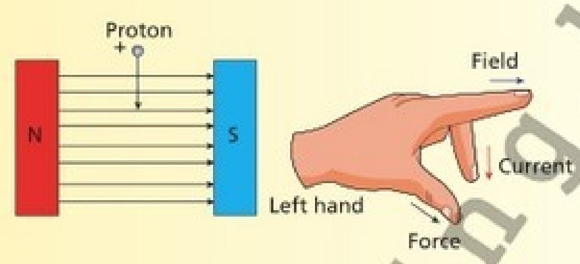
GrS PHYS Gr 10 Ss Mod 9.indd 161 5/9/19 4:48 PM

An individual proton like that shown in figure 9.8 is a moving electric charge. As such, it has its own magnetic field and will be affected by any other magnetic field through which it moves. In such a case, the proton essentially follows the left-hand rule: the second finger now shows the direction of movement of the charge, while the index finger and thumb still represent the direction of the magnetic field and force, respectively. Looking at figure 9.8, the proton experiences a force that pushes it towards us (i.e. out of the page). However, as a small particle, it responds to this force immediately and changes its path accordingly. As the direction of its motion changes, the direction of the resulting force also changes. The proton responds to the new direction of the force and changes path accordingly. This will happen continuously as long as the charge stays inside the magnetic field. As a result, the proton will follow a curved path through the magnetic field.

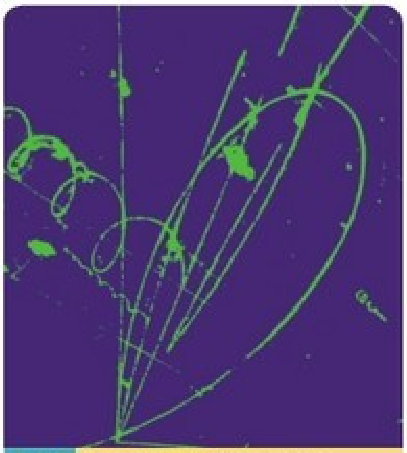


9.8 *A proton moves through a magnetic field*

A negative particle, such as an electron, is also affected by a magnetic field, but it experiences a force in the opposite direction: in other words, it moves in exactly the opposite direction to that predicted by the left-hand rule.

A positive charge obeys the left-hand rule. A negative charge does not and moves in the opposite direction.

The charges of subatomic particles discovered in large particle accelerators like those at CERN (the European Organization for Nuclear Research) on the Swiss–French border can be determined by looking at photographs showing their path through a magnetic field. In figure 9.9, the path of the positive charges can be clearly seen to be in one direction, while the negative charges spiral off in the opposite direction. To tell which is which, you would need to know the details of how the magnets were arranged.


9.9 *This photograph shows the tracks left when a subatomic particle decayed, creating six new particles, of various mass and charge. The different tracks represent the paths of these particles through a magnetic field*

The ampere

The definition of the ampere ('amp' for short) is also based on the concept that a current-carrying conductor in a magnetic field experiences a force. However, for this purpose we do not think of a current running through a wire placed between two magnets. Instead we think of two wires placed side by side. Each one is carrying a current and creating a magnetic field. This means that both of them are in the magnetic field created by the other. We can use this scenario as a way of developing a definition of the ampere.

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GrS PHYS Gr 10 Ss Mod 9.indd 162 5/9/19 4:48 PM

The ampere is the constant current that will produce a force of 2×10^{-7} newtons per metre of length between two straight, parallel conductors of infinite length and negligible circular cross section placed one metre apart in a vacuum.

Table 9.1	
Unit	**Measures**
Metre	Length
Kilogram	Mass
Second	Time
Ampere	Electric current
Kelvin	Temperature
Candela	Luminous intensity
Mole	Amount of substance

The ampere is one of the seven base units on which the SI system is based. The other base units are shown in Table 9.1.

Although there is no real debate about the magnitude that each of these units should have, the precise definition is often complex and subject to much academic argument. The unit of length – the metre – is currently taken to be the distance that light travels in 1/299 792 458th of a second, but was previously the distance between two marks on a metal bar held in Paris. The kilogram is still defined as being the mass of a prototype, a block made from a platinum alloy, that has been held in a secure vault in Paris since the late 1800s.

The definition of the ampere is obviously problematic: where are we supposed to find two infinitely long wires, for instance, or even a perfect vacuum? There are people who argue that it should be changed to be a multiple of the charge on, say, an electron. But these arguments take many years to sort out.

In the meantime, although it is not a formal definition, it can help us to remember the simple relationship between the amp and the coulomb: 1 A = 1 C per second.

The formula $F = I\ell B$ does not really work for a subatomic particle of no real length, but it can be adapted, as shown here, to yield a similar formula:

Derivation

$$F = I\ell B$$

$$I = \frac{q}{t}$$

$$v = \frac{\ell}{t}$$

$$\ell = vt$$

$$F = \frac{q}{t}vtB$$

Substituting for I and ℓ in the original formula:

$\boldsymbol{F = qvB}$

for a particle moving at angle θ to the magnetic field, the formula is:

$\boldsymbol{F = I\ell B\sin\theta}$

9.4 Sample Question

What is the force on a proton travelling at $2 \times 10^6\,\text{m s}^{-1}$ in a magnetic field of flux density 2.1 T?

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Sample Answer

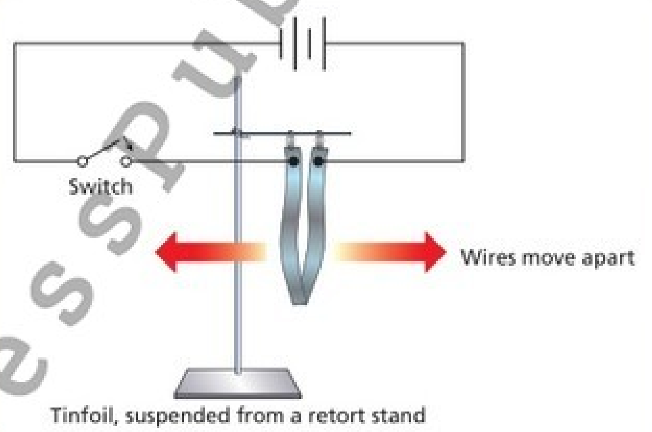
$F = qvB$
$= (1.602 \times 10^{-19})(2 \times 106)(2.1)$
$= 6.728 \times 10^{-13}$ N

The charge on the proton has the same magnitude as that on the electron.

Experiment 9.3: To demonstrate the principle on which the definition of the ampere is based

Method

1 Set up a circuit as shown in figure 9.10, supporting the tinfoil with a retort stand.
2 Switch on the current and observe what happens.



9.10 *Experimental setup*

Observations

You should find that the strips of tinfoil move apart, indicating that parallel wires conducting a current will experience a force, the principal on which the definition of the ampere is based.

Electric devices

The electric motor is the basis of a lot of large household items, such as washing machines, dryers and dishwashers as well as power tools, blenders, vacuum cleaners, clocks, turntables and smaller items such as disk drives. In all situations the basics of the design are the same in that they make use of the fact that an electric current in a magnetic field will experience a force.

We can see the basis of the operation of a d.c. motor very easily (see Experiment 9.4).

9.11 *A d.c. motor*

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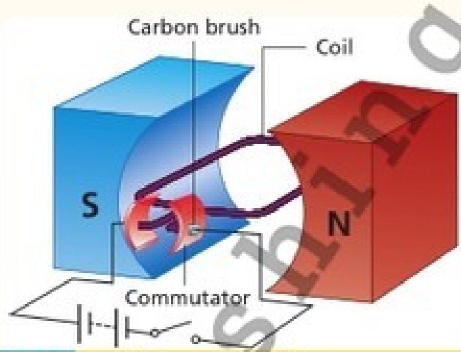
GrS PHYS Gr 10 Ss Mod 9.indd 164 5/9/19 4:48 PM

Experiment 9.4: To demonstrate the force on a current-carrying coil in a magnetic field

Method

1. Connect a basic d.c. motor – which consists of a coil between two curved magnets – to a battery as shown in figure 9.12.
2. Allow the current to flow and observe what happens.



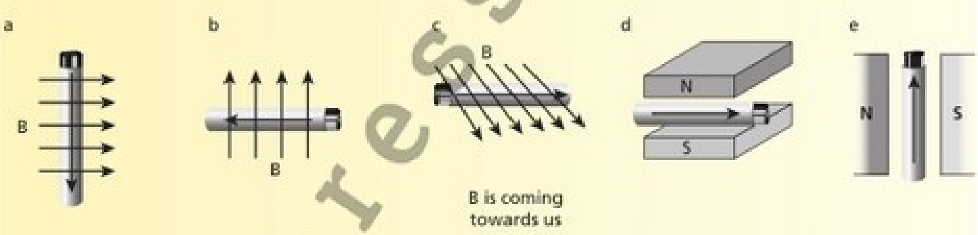
9.12 *A coil in a magnetic field*

Observations

You should see that when the current flows, the coil rotates.
This demonstrates the force on a current-carrying coil in a magnetic field.

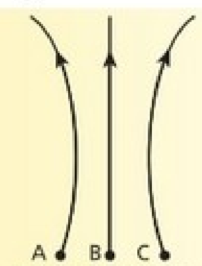
For you to try

1. What is the direction of the force created in each of the wires shown in figure 9.13?



9.13 *Question 1*

2. An electrical wire carries a current of 3 A and passes through a magnetic field of length 2 m and of magnetic flux density 4 T. What force does it experience?
3. An electrical wire carries a current of 1.5 A and passes through a magnetic field of length 2 cm and of magnetic flux density 2 T. What force does it experience?
4. An electrical wire of length 25 cm carries a current through a magnetic field of magnetic flux density 1.8 T and experiences a force of 5 N. What is the current?
5. If a wire carrying a current of 3 A experiences a force of 15 N when flowing through a magnetic field of length 15 cm, what is the magnetic flux density of the field?
6. Figure 9.14 shows the path that a number of particles follow when passing through a magnetic field. Which of the particles are positively charged, which are negative and which are uncharged?



9.14 *Question 6*

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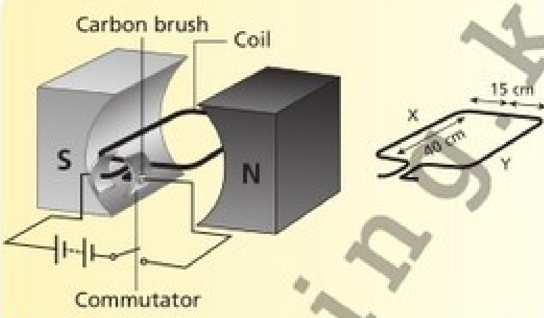
7 Figure 9.15 shows a basic design of a d.c. motor. The magnetic flux density is 4 T and the current is 2.5 A.
   (a) What is the magnitude of the force on the wire labelled X, and in what direction would it act?
   (b) What is the magnitude of the force on the wire labelled Y?
   (c) What is the total moment of the turning force on the wire?
   (d) Why do you think the magnets are curved in design?
   (e) Name two other devices based on the same principle.



9.15 *Question 7*

Electromagnetic induction

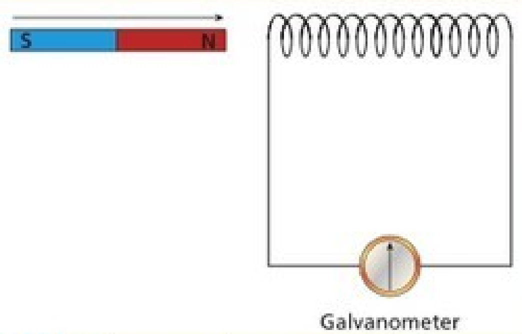
In the preceding section we showed how we can create movement by passing an electric current through a magnetic field. In this section we will see that the opposite is also true: we can create an electric current by moving a magnetic field through a coil of wire. This is known as **electromagnetic induction**.

When the magnetic field passing through a coil changes, a voltage is induced in the coil.

Experiment 9.5: To demonstrate electromagnetic induction

Method

1 Set up the apparatus as shown in figure 9.16.
2 Move the magnet towards the coil. Note that the needle on the galvanometer indicates that a current is flowing (a galvanometer is a device that measures electric current).
3 Try varying the speed with which you move the magnet, and observe what happens.



9.16 *To demonstrate electromagnetic induction*

Observations

You should see that the faster the magnet moves, the larger the current created.
Also, you should notice that the current flows in one direction as the magnet approaches and in the opposite direction as it moves away.

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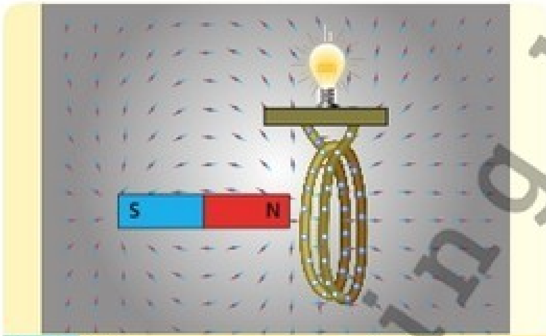
GrS PHYS Gr 10 Ss Mod 9.indd 166 5/9/19 4:48 PM

If you recall that each individual electron can be thought of as a sort of miniature magnet, it is hardly surprising that this effect occurs. In figure 9.17, we can see that the magnetic field from the bar magnet passes through the coil. In doing so, its effect can be felt by each of the electrons indicated (not to scale) in the wires that go to make up the coil.



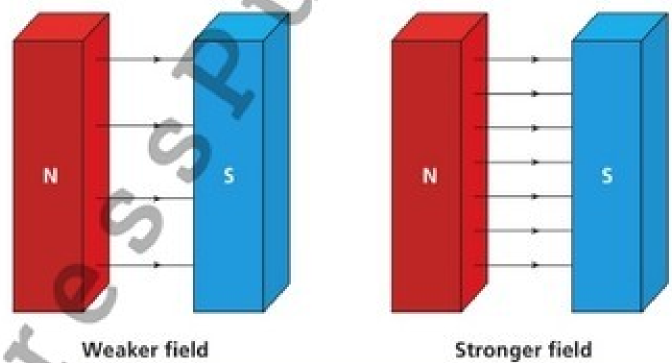
9.17 *If the magnet moves, it causes the electrons to move and the bulb to light up*

When the bar magnet is moved it will, like any moving magnet, create forces on any other magnets nearby, such as the electrons. This causes them to move. An electric current is the flow of electric charge, and so an electric current is created.

Electromagnetic induction was studied in detail by English scientist Michael Faraday (1791–1867), who was very important in the development of studies of electricity. It was Faraday who noted that the voltage created is directly proportional to the rate of change of the magnetic field. To make this mathematical connection, you have to be familiar with the concept of magnetic flux.

Magnetic flux

We often represent the presence and direction of magnetic fields by drawing magnetic field lines. Around a bar magnet, for example, you have been taught to draw the field lines as curving from the north to the south pole. We usually indicate the presence of stronger or weaker magnets by drawing these lines either closer together or further apart: the greater the density of the lines, the greater the strength of the magnet (see figure 9.18).

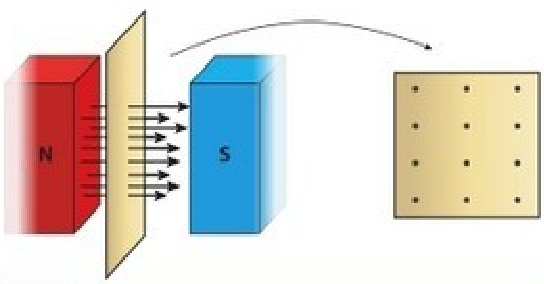


9.18 *The closer the lines, the stronger the magnet*

We have already come across the concept of magnetic flux density. Although formally defined according to the formula $B = \frac{F}{Il}$,

it is a useful shorthand to think of magnetic flux density as representing the number of field lines passing through a flat surface placed in a magnetic field, per unit area.

If you imagine a pair of magnets of comparable strength to those shown in figure 9.19, but ones that are much bigger, and again imagine the number of lines that would pass through a flat surface placed between the magnets, you can see that the field lines would be equally spaced in both cases, but that with the larger magnets, the total number of field lines would be increased.



9.19 *B is represented by the number of field lines per square metre; Φ is represented by the total number of lines*

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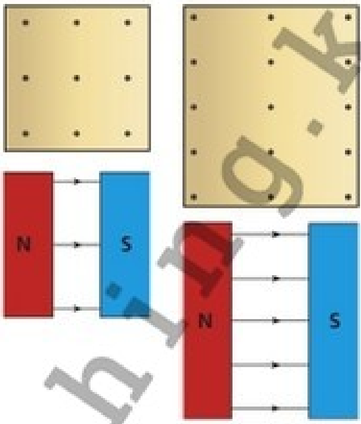
This is comparable to the distinction between the concepts of magnetic flux density (*B*) and magnetic flux, represented by the Greek letter phi (Φ), and it is in keeping with the definition of magnetic flux.

In simple terms, if *B* is represented by the number of field lines per square metre, Φ is represented by the total number of field lines (see figure 9.20).

More formally:

The magnetic flux, Φ, is a measure of the strength of a magnetic field over a given area perpendicular to it, A, and it is equal to the product of the area and the magnetic flux density, B, through it. The unit of magnetic flux is the weber (Wb).

$$\Phi = BA$$



9.20 *Both magnets have equal values of B. The magnet to the right has a larger value of Φ*

Faraday's laws

Faraday realised that the key measurement needed to predict the voltage that would be created during electromagnetic induction is the rate at which the magnetic flux passing through the coil changes.

When there is a change in the magnetic flux passing through a coil, a voltage is induced in that coil. The strength of the voltage is proportional to the rate of change of the flux passing through the coil.

Mathematically, induction can be described using the formula:

$$E = \frac{\text{Change in flux}}{\text{Time}}$$

where:

E – induced voltage

It is important to remember that this is the voltage created in each turn of the coil. If there are two turns on the coil, the voltage is doubled and – more typically – if there are several hundred turns in the coil, then the voltage will be several hundred times bigger.

A more useful version of the formula is:

$$E = n\,\frac{\text{Change in flux}}{\text{Time}}$$

where:

E – induced voltage

n – number of turns in a coil

9.5 Sample Question

If a magnetic field has a total flux of 3 Wb, and covers an area of 0.25 m², what is the magnetic flux density?

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Sample Answer

$$\Phi = BA$$

$$B = \frac{\Phi}{A} = \frac{3}{0.25} = 12\,\text{T}$$

9.6 Sample Question

If the magnetic flux passing through a coil changes from 5 Wb to 12 Wb in 2.5 s, what is the value of the induced emf?

Sample Answer

$$E = n\frac{\text{Change in flux}}{\text{Time}} = (1)\,\frac{12-5}{2.5} = 2.8\,V$$

9.7 Sample Question

The magnetic flux density of a magnetic field is 3.5 T. This field passes through a coil of area 0.15 m^2.

(a) What is the total magnetic flux passing through the coil?

(b) If the value of the magnetic flux density decreases to zero over a period of half a second, what will be the value of the average emf induced in the coil?

Sample Answer

(a) $\Phi = BA = (3.5)(0.15) = 0.525\,\text{Wb}$

(b) $E = n\frac{\text{Change in flux}}{\text{Time}} = (1)\,\frac{0.525-0}{0.5} = 1.05\,\text{V}$

Lenz's law

Heinrich Lenz (1804–1865) was a Russian scientist who in the 1830s studied electromagnetic induction and noted that the current induced in a coil will always flow in such a way that the associated magnetic field opposes the change.

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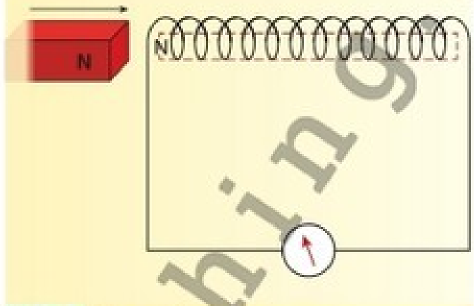
GrS PHYS Gr 10 Ss Mod 9.indd 169 5/9/19 4:48 PM

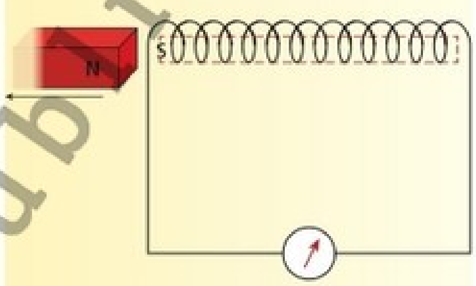
The direction of an induced current is such as to oppose the change causing it.

As we have learnt, in a situation like that shown in figure 9.21, in which the north pole of a bar magnet is approaching a coil, a current will be created in the coil. However, we have not learnt in which direction it will flow. Remember that any current through the coil will create a magnetic field and that the magnetic field around a coil is very similar to that of a bar magnet. Lenz realised that, in keeping with Newton's laws of motion, the magnetic field created here would have its north pole at the end closest to the approaching magnet. This has the effect of trying to push away, or at least, slow down the approaching north pole.

If, however, the bar magnet is then pulled away from the coil, as shown in figure 9.22, the current flowing in the coil will change direction. This will have the effect of changing the direction of the magnetic field. The south pole will now be closest to the bar magnet, trying again to slow down its motion.



9.21 The north pole of a magnet approaches a coil

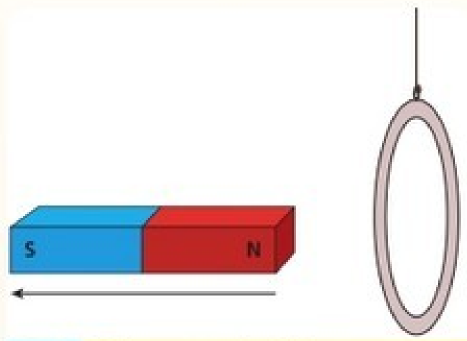


9.22 The north pole of a magnet moves away from a coil

Experiment 9.6: To demonstrate Lenz's law

Method

1 Suspend a light aluminium ring from a long thread hanging from a wooden retort stand, as shown in figure 9.23.
2 Hold a strong magnet up to the ring and then move it away from it, and observe what happens.



9.23 To demonstrate Lenz's law

Observations

You should find that when the magnet is moved away from the ring, the ring follows the magnet. Then, when the magnet moves towards the ring, the ring moves away from the magnet.
This is an example of Lenz's law, which states that the direction of an induced current is such as to oppose the change causing it. (The moving magnet creates a current in the ring. This in turn creates a magnetic field. In order to oppose the change, the ring follows the magnet.)

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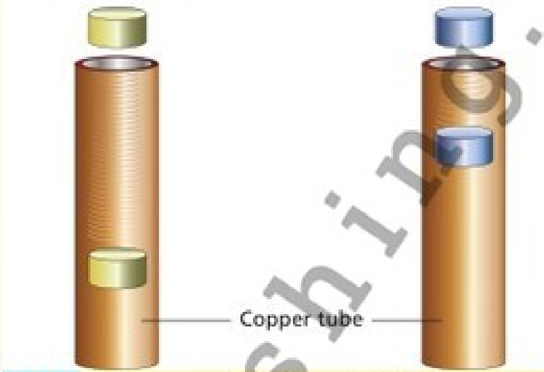
Experiment 9.7: To demonstrate Lenz's law and eddy currents

Method

1 Take two pieces of copper tube, as shown in figure 9.24.
2 Take two cylindrical pieces of metal, similar in mass and shape, but one of which is magnetised.
3 Drop each of the pieces of metal in turn through a copper tube, and observe what happens.



9.24 *To demonstrate Lenz's law and eddy currents*

Observations

You should find that the magnetised metal drops much more slowly through the tube than the non-magnetised metal.
This is due to electromagnetic induction, and Lenz's law. The moving magnet creates eddy currents in the tube, which oppose the change, slowing the fall of the magnet.

Michael Faraday

Michael Faraday (1791–1867) received little formal education but became one of the great scientists of the nineteenth century and contributed enormously to our understanding of electricity.
Growing up in London, Faraday served an apprenticeship with a bookbinder, and took advantage of the books surrounding him to become widely read. Later, he followed a growing interest in science by attending public lectures given in the Royal Society by a celebrated chemist, Humphry Davy (1778–1829). Faraday impressed Davy by producing a bound book summarising these lectures, and when Davy was later injured in a laboratory accident he summoned Faraday to work as his assistant.
Faraday's scientific career developed from there, and he became renowned as a great experimentalist and lecturer. In 1825 he organised for the Royal Institution to provide entertaining and informative lectures for the public at Christmas time, and over the following decades gave many of these lectures himself. The tradition continues today, and the lectures are usually televised and made available online.
Over his career, Faraday not only studied electromagnetic induction and electrolysis, but also discovered benzene and invented early versions of the electric motor and the Bunsen burner. Building on Faraday's work and analysing it mathematically, James Clerk Maxwell (1831–1879) later developed his electromagnetic theory, which linked the study of electricity, magnetism and optics and opened up the study of the electromagnetic spectrum.
It is interesting to know that Albert Einstein (1879–1955) always kept photographs on his study wall of Newton, Maxwell and Faraday.

9.25 *Michael Faraday holding a heavy glass bar, which he used to show that, in certain circumstances, magnetism can affect light*

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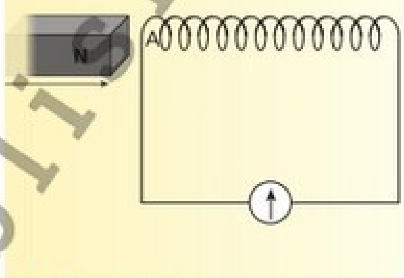
GrS PHYS Gr 10 Ss Mod 9.indd 171 5/9/19 4:48 PM

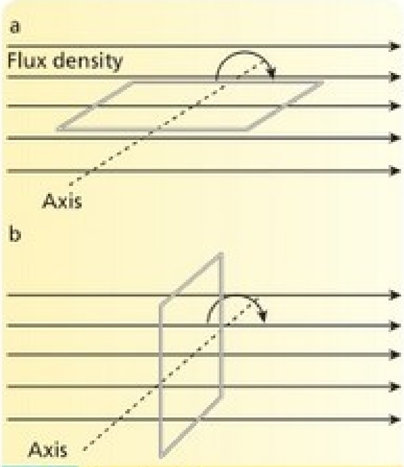
For you to try

1 State Faraday's law of electromagnetic induction.
2 State Lenz's law.
3 What is meant by the term 'magnetic flux'? In what unit is it measured?
4 If a magnetic field has a total flux of 4 Wb, and covers an area of 15 cm^2, what is the magnetic flux density?
5 Two magnetic fields each have magnetic flux density of 3.5 T.
(a) The area of the first is 1.5 m^2. What is its magnetic flux?
(b) The area of the second is 150 cm^2. What is its magnetic flux?
6 Figure 9.26 shows a magnet approaching a coil. As it does so a current will be induced in the coil and this will create a magnetic field. Will the end of the coil marked with the letter A be a north or a south pole?



9.26 Question 6

7 A sheet of copper is placed between the poles of an electromagnet so that it is perpendicular to the magnetic field. It is then pulled out of the magnetic field, but a considerable force is required to do so. The faster the sheet moves, the greater the force required to move it. Why would this happen?
8 There are 100 turns in a solenoid. The magnetic flux passing through it changes from 0 Wb to 30 Wb over a period of 10 s. What is the total emf induced in the coil?
9 The magnetic flux density of a magnetic field is 4 T. This field passes through a coil of area 0.5 m^2.
(a) What is the total magnetic flux passing through the coil?
(b) If the value of the magnetic flux density decreases to zero, what will be the value of the magnetic flux?
(c) If this change happens over a period of 2 s, what will be the value of the average emf induced in the coil?
10 A solenoid with 250 turns passes through a magnetic field of magnetic flux density 5 T. A cross section of the coil has an area of 0.05 m^2.
(a) What is the total magnetic flux passing though the coil?
(b) If the magnetic flux density is reduced to zero over a period of 1.5 s, what is the change in the magnetic flux?
(c) What is the average emf induced in the solenoid in this time?
11 Figure 9.27 shows a rectangular coil with dimensions 5 cm x 12 cm, positioned at right angles to a magnetic field of magnetic flux density 5 T.
(a) What is the value of the magnetic flux passing through the coil?
(b) If it rotates through 90° as shown, in a period of 0.5 s, what is the value of the induced emf in the coil?
(c) If the wire in the coil has a resistance of 2.5 Ω, what is the induced current in the coil?
(d) What total charge moves through the coil over the 0.5 s when this current is flowing?



9.27 Question 11

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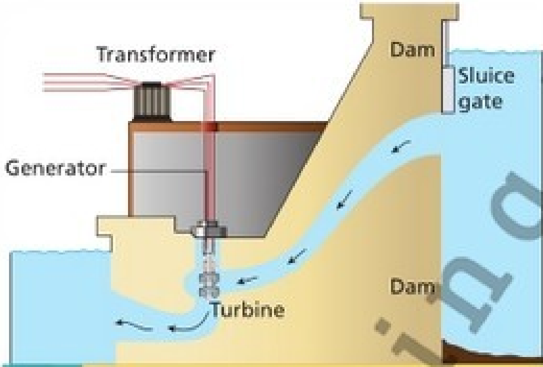
Power stations

The basic design of the power stations we use to generate electricity is based on electromagnetic induction. Essentially, the power station consists of a large coil between magnets. When the coil turns, a voltage is created. As long as the coil keeps rotating, a voltage is constantly maintained.



9.28 *The flow of water turns the turbine*

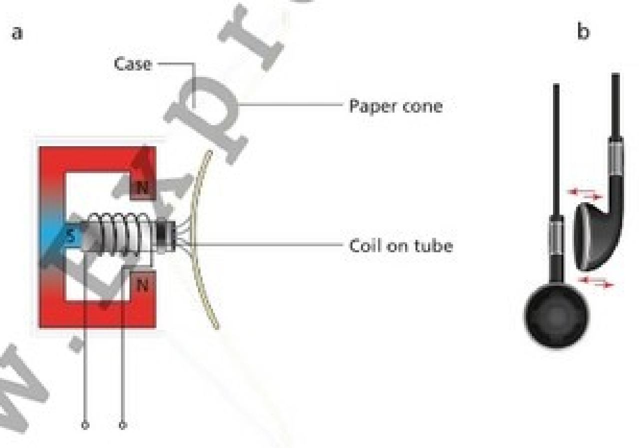
Applications of Electromagnetism

Many novel and interesting applications using electromagnetism have been invented. You will have many of them in your home without even realising it: radio, television, speakers, headphones, phone chargers, mobile phone applications that have a compass ... and there are many more that are used industrially: generators, transformers, seismographs ... Some of these applications go from electrical currents to motion, and others go from motion to electrical currents. We will limit our study to the ones where the operating principle is more readily understood.

Speakers

Speakers are another example of a device that makes use of the fact that a current carrying conductor in a magnetic field will experience a force. In these a coil is wound around a magnet, as shown in the diagram below. When a current flows through the coil it creates a force. The coil is usually held tightly in place, so it is the magnet that moves instead. This is connected to the cone of the speaker, often simply made of paper.

A constantly changing current in the coil creates a constantly changing force on the magnet. This causes it to move backwards and forwards and creates vibration in the cone, which in turn creates the sound waves we hear coming from the speaker.



9.29 *Applications of electromagnets: two types of speaker, (a) Design of a standard speaker. (b) Earphones. Allow one earphone to hang loosely by its connecting wires and move the other earphone close to it. You will notice either a slight attraction or repulsion between the two, created by the magnets that are a key part of their design*

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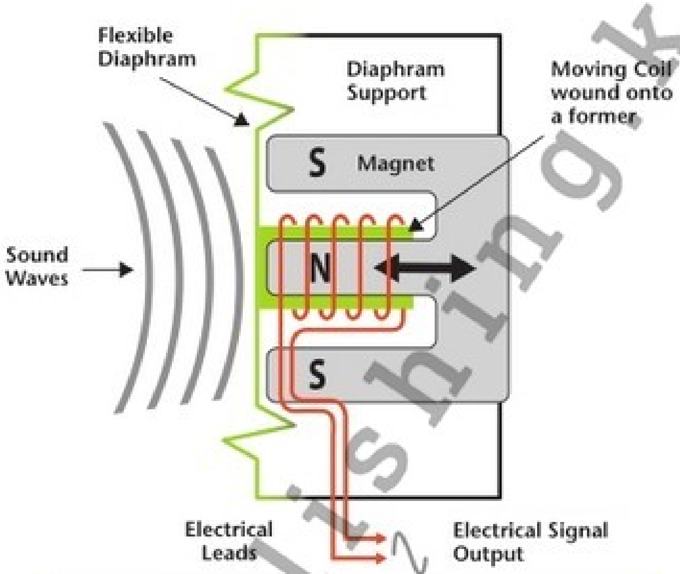
The microphone

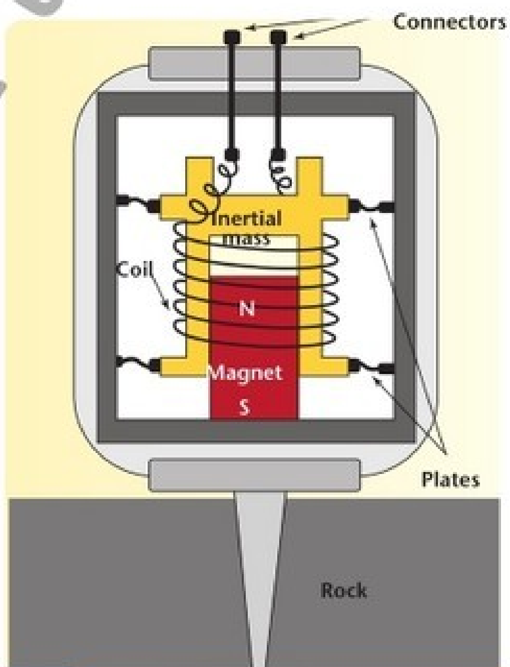
A microphone does the exact opposite of an earphone: it converts movement (from the pressure waves coming from sound) into very small electrical currents which must then be amplified in order to be used. Interestingly, it is possible to use a loudspeaker as a microphone, but because the cone and the coils are so large you need to shout into the speaker very loudly in order to produce a small electrical current.



9.30 *A microphone converts movement into small electrical currents.*

The seismograph

A seismograph is an instrument specially designed to measure tremors of the Earth's surface. They need to be situated on a large rock well away from traffic and man-made sources of vibration. At the core of the instrument is a large inertial mass suspended from some very flexible springs. If the rock below the seismograph shakes up and down, the instrument will move up and down, but the inertial mass will hardly move. A coil is attached to the inertial mass, and a strong permanent magnet is attached to the outer body of the seismograph. The relative movement between the body and the inertial mass causes the coil to move within the magnetic field of the magnet, and that is enough to produce a small electrical current. That small current is amplified and used to move a chart recorder. Because earthquakes are not only up and down movements, but also include lateral movements, it is necessary to have 3 of these, each orientated at 90 degrees to the other, so that all possible movements of the Earth can be recorded.



9.31 *A seismograph is used to measure any movements in the Earth's crust.*

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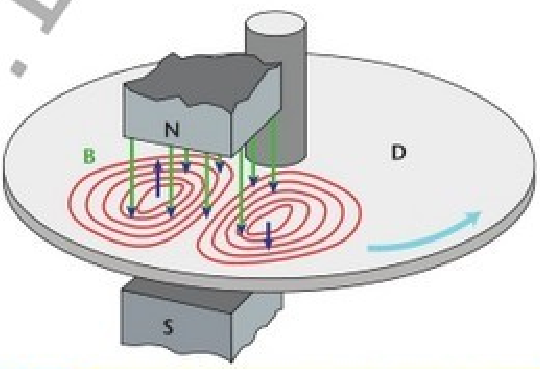
Metal detectors

The principle of a metal detector is a little like that of a single coil transformer. A pulse is sent to a large coil at the base of the instrument which is held just above the ground. This will create a magnetic field which reaches some distance into the ground. If there are any electrical metallic objects within the reach of the magnetic field, this increasing magnetic field will cause eddy currents to be induced in them. When the pulse to the search coil is shut off, the magnetic field will collapse, and the small eddy currents produced in the metal object will produce a small decaying magnetic field which the large search coils can detect as a small induced voltage. A special circuit is designed to amplify this small voltage and alert the user that there is some metal present within the search distance of the detector.

9.32 *Metal detectors detect the small magnetic fields produced by eddy currents induced in sub-surface conducting objects.*

Induction braking

This is another modern application of electromagnetism designed to slow large vehicles such as buses and trucks when they are descending a long hill. It is not possible for the driver to simply use the brake pedal, because there is so much energy being liberated that the breaks will overheat and then they will fail. So normally the driver has to put the vehicle into a low gear so that the gravitational potential energy liberated by the descent can be wasted as heat through friction in the gearbox and engine. This puts a lot of additional wear on the engine, and creates a lot of noise too. A modern innovation is called inductive braking. An electromagnet close to the brake disc is energised, and then the movement of the disc in the magnetic field of the electromagnet caused eddy currents to flow in the disc. These eddy currents convert the kinetic energy into heat energy in the disc without any friction or wear.



9.33 *Induction braking converts kinetic energy into heat without friction or wear*

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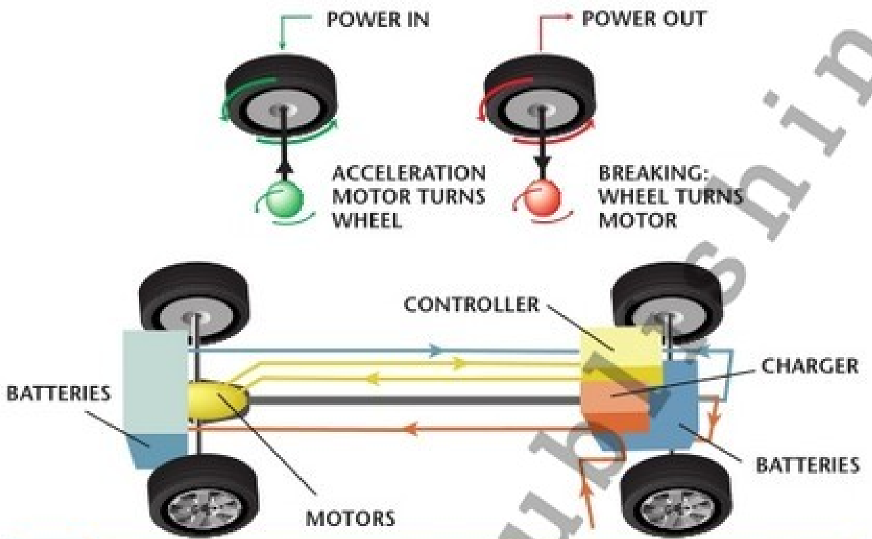
Regenerative braking

This technique can be used in electrically powered cars. Normally the battery supplies the energy that drives the electric motors to propel the car, but when the car is being braked, it is possible to use the motors as generators, and so convert kinetic energy back into electrical energy stored in the batteries. In this way the range of electrical vehicles can be increased.

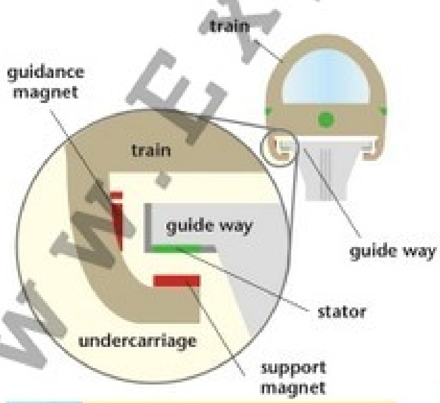


9.34 *Electrically powered cars can generate some electric charge when they are being slowed down*

Regenerative braking is better than induction braking, because the energy is not wasted, however, regenerative braking is only possible in electric or hybrid cars; conventional cars and trucks are not driven by electric motors.

Magnetically levitating trains

In Japan there is a train system which is not only driven by a linear array of magnets, but is also propelled forwards by rapidly alternating electromagnets. The precise detail of the operation is quite advanced, but the principle used is the repulsion between like poles and the attraction of opposite poles.



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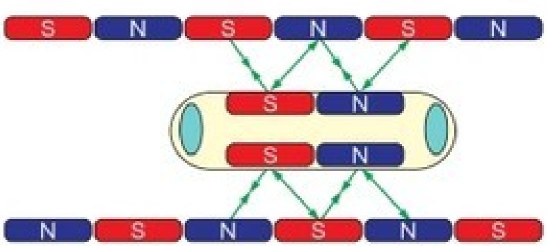

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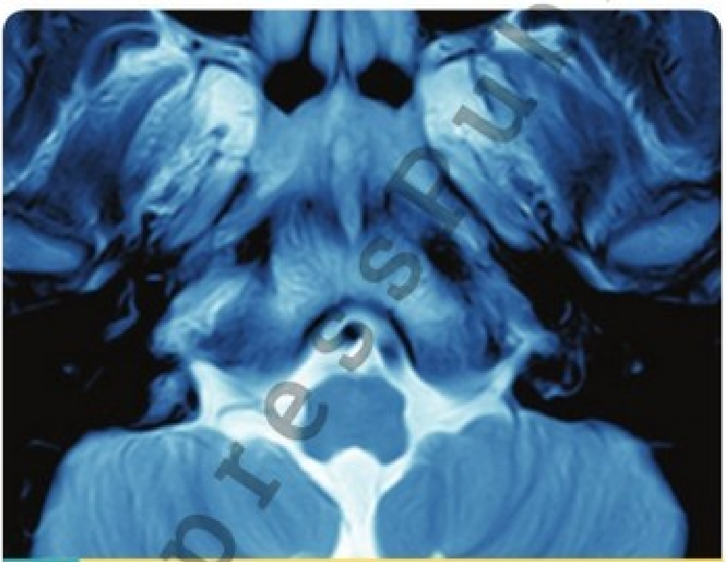
Magnetically levitated trains use the attraction of opposite poles and the repulsion of like poles to drive the train forwards. The polarity of the electromagnets is controlled very precisely in order to achieve this.

Magnetic Resonance Tomography (MRT)

Magnetic Resonance Tomography (MRT), is a technique that uses the magnetic properties of hydrogen nuclei present in all water molecules which has revolutionised the way in which medical doctors can image soft tissue in the human body. It a non-invasive imaging technology that produces detailed three-dimensional anatomical images without the use of damaging radiation from X-Rays or invasive and potentially life-threatening biopsies.

A patient is placed inside a large magnet. The concentration and position of the hydrogen nuclei within the water molecules in tissues excitated by the magnet is encoded in the signal from responding electro-magnetic waves and this is computed into images. MRT technology is particularly useful for imaging the non-bony parts or softer tissues of the body. It allows specialists to analyse tissue alterations, diagnose a range of conditions such as tumours and cerebral inflammations and to plan minimally invasive operations.



9.37 *Magnetic Resonance Imaging*

Effect of electromagnetic fields on charged particles in a vacuum

Charges in magnetic fields

Stationary charges do not experience any forces in magnetic fields, because there is no current flowing. However, as soon as they start moving, they will experience a force determined by Flemming's left-hand rule. In electric fields, however, charges will experience forces whether they are moving or stationary. The figure below shows the forces acting on two opposite polarity charges when entering a magnetic field.

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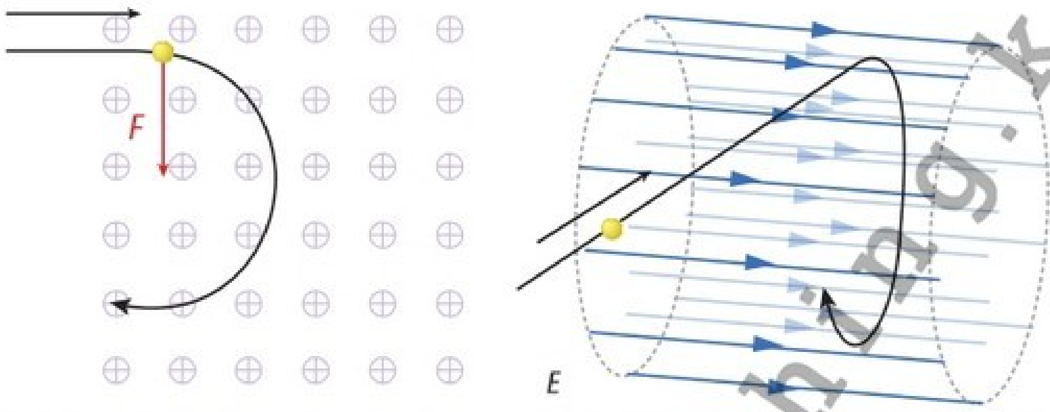


9.38 *Forces on charged particles in a magnetic field*

On the left, the magnetic field direction is into the paper, and the particle is negatively charged. The perpendicular force determined by Fleming's left-hand rule forces the particle downwards initially, and as its trajectory changes the direction of the force also changes.

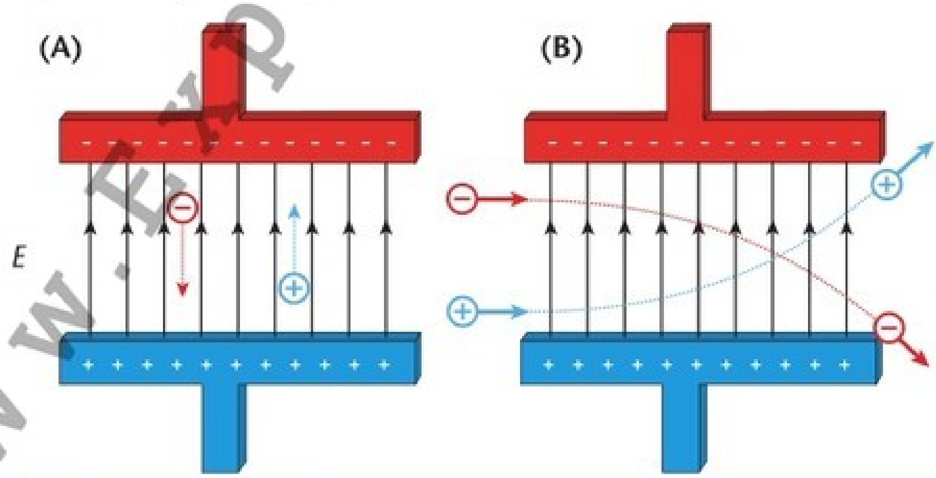
On the right-hand side, a positively charged particle enters a magnetic field and is also initially forced downwards, but notice that this is because the magnetic field direction has also changed.

It should be noted that a magnetic field will not increase or decrease the speed of a charged particle, because the direction of the force will always be perpendicular to the velocity vector.

Notice also that a magnetic field can be used to trap a charged particle without needing walls to contain it.

Charges in electric fields

By contrast, charges in an electric field will always experience a change in velocity (direction as well as magnitude). The figure below shows how the electrostatic charge will affect the trajectory of charged particles which were initially stationary (on the left) or moving to the right (on the right-hand side). The magnitude of the force is determined by the electric field strength and the amount of charge on the particle, and the direction of the force is governed by the polarity of the charge.



9.39 *Charges in electric fields*

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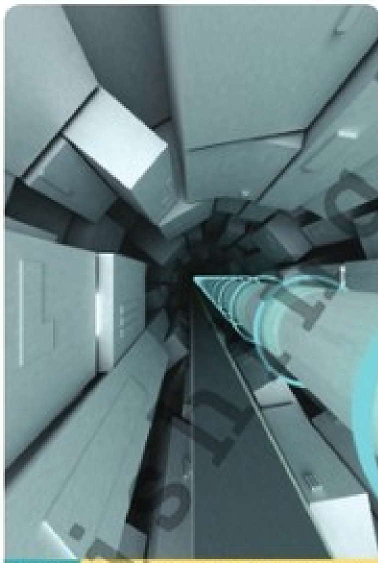
Effect of magnetic fields on materials

Some materials are magnetic, and some are not. Those that respond to magnetic effects are said to be in the family of 'ferro-magnetic' materials: iron, steel, nickel, and cobalt are the most common ones.

Magnetically 'soft' materials

Iron is the most obvious one. It is attracted to a magnet and becomes magnetised itself when in contact with the magnet, but quickly loses its magnetism when it is separated from the magnet. One might think this is not a very useful property, but for some applications this is exactly how we need them to behave. Electromagnets and transformers are the main application of magnetically soft materials.



9.40 *Large Hadron Collider in CERN*

Magnetically 'hard' materials

Steel is the most common magnetically hard material. It does not magnetise quite as easily as iron, but once magnetised it retains its magnetism. Other magnetically hard materials which can be strongly magnetised are neodymium based. These make it possible to have strong magnetic fields from relatively light magnets.

For you to try

1. Explain why magnetic fields do not change the speed of charged particles.
2. Explain why magnetically soft materials can still be useful, and list some of the applications.
3. Explain how a speaker works.
4. How does regenerative braking work?
5. Describe some differences between gravitational, electrostatic and magnetic fields.

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Module 10 Applied electricity

Learning objectives

- To become familiar with the operating principles and practical application of the following devices:
  - A d.c. motor
  - A speaker
  - A galvanometer as voltmeter, ammeter, ohmmeter
  - An induction coil

The electric motor

The electric motor is a device absolutely central to modern technology. It is the basis of a large number of big household items such as washing machines, driers and dishwashers, as well as power tools, blenders, vacuum cleaners, clocks, turntables and smaller items such as disk drives. In all situations the basics of the design are the same, and the key part of that design is based on the fact that an electric current in a magnetic field will experience a force.

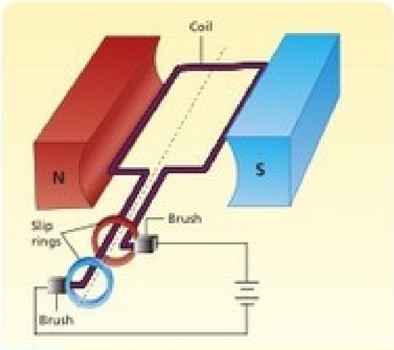
10.1 *An X-ray of a washing machine, which depends on the use of an electric motor*

A current-carrying conductor in a magnetic field experiences a force

We have seen how if we let a current flow in a piece of tinfoil and pass that current through a magnetic field, a force is created. This demonstrates a principle that is central to the design of many electrical devices:

> A current-carrying conductor in a magnetic field experiences a force.

The tinfoil would move forwards or backwards. This shows us how motion can be created using electricity, but the movement is very slight and quickly reaches the limits imposed on it by the manner in which the tinfoil is suspended from the retort stand. The key to creating an electric motor was to find a way in which the motion could be maintained indefinitely. That can be done using a setup like that shown in figure 10.2.



10.2 *A d.c. motor*

When a current flows through the coil, as indicated in figure 10.2, a pair of forces is created. One side of the coil is pushed upwards while the other is pushed downwards. The curved face of the magnets ensures that, as the coil turns, the direction of the force turns with it. This means that the coil can turn easily through 90°.

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GrS PHYS Gr 10 Ss Mod 10.indd 180 5/9/19 4:49 PM

The use of **metallic brushes** as connectors ensures that the motion will continue past this point. There can be sparking caused at these brushes, though, which is a problem with the use of direct current (d.c.) motors. The problem is avoided with induction motors, which are covered later in this module. As the coil continues to turn, the connections ensure that the side of the coil that was being pushed downwards will now be pushed upwards, and vice versa.

As long as the current flows, the motion will continue.

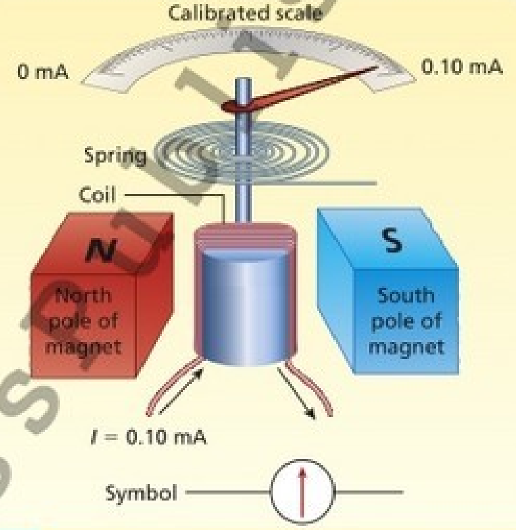
Speakers

Speakers are an example of a device that is based on the fact that a current-carrying conductor in a magnetic field experiences a force.

The galvanometer

Another device based on the fact that a current-carrying conductor in a magnetic field experiences a force is the moving coil galvanometer, which can be used to measure small currents and, with adaptations, large current as well as voltage and resistance.

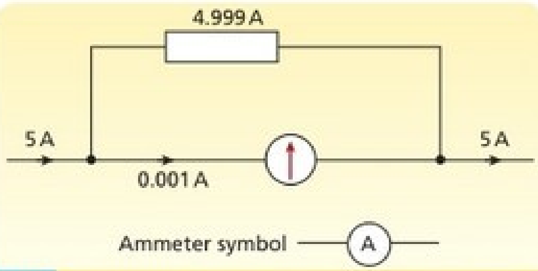
The device contains a coil of wire that is free to rotate between the poles of a cylindrical magnet. When a current flows through the coil, the resulting force causes it to twist – the larger the current, the greater the angle through which it moves. An attached needle moving along a calibrated face allows the user to measure what current is flowing.



10.3 *A galvanometer*

The galvanometer as ammeter

The above arrangement is very sensitive. This means that even very small currents can be measured very accurately, but it also means that the galvanometer is best used as a device to measure currents in the micro-amp range. To adapt it for use as an ammeter, a low-resistance resistor is connected, as shown in figure 10.4.



10.4 *An ammeter designed to measure current up to 5 A*

The low-resistance resistor takes a large proportion of the current, but the galvanometer still has a small current. The value of the galvanometer current is proportional to the total current and is therefore a measure of the full current.

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10.1 Sample Question

What resistance should be used in parallel with a galvanometer of resistance 100 Ω and designed to take a maximum of 1 mA to create a 5 A ammeter?

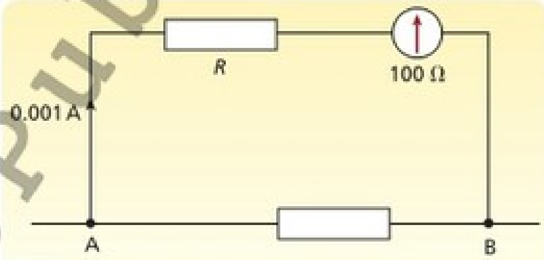
Sample Answer

$$V = RI$$
$$V = R \times 4.999$$
$$\text{and } V = (100)(0.001)$$
$$\text{so } (100)(0.001) = 4.999R$$
$$R = 0.020004\,\Omega$$

The galvanometer as voltmeter

If the galvanometer is placed in series with a high-resistance resistor, it can be used as a voltmeter.

Figure 10.5 shows a circuit in which a galvanometer is used as a voltmeter. Remember that the voltage between A and B is the same regardless of the path followed. To measure the voltage across the resistor shown, then, the galvanometer is connected to A and B. The current that flows through it is proportional to the voltage. As long as the galvanometer is suitably calibrated, it can give a reading for the voltage V_{AB}.



10.5 *A galvanometer adapted to work as a voltmeter*

10.2 Sample Question

What resistance should be connected in series with a galvanometer, of resistance 100 Ω and designed to measure up to 1 mA, to create a voltmeter capable of reading up to 10 V?

Sample Answer

$$V = RI$$
$$10 = (R + 100) \times 0.001$$
$$= 0.001R + 0.1$$
$$R = \frac{9.9}{0.001} = 9900\,\Omega$$

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The galvanometer as ohmmeter

Resistance is inversely proportional to current, so this allows a galvanometer to be used to measure resistance as well. To measure the resistance of a resistor as shown, the galvanometer needs to be connected to a battery or power supply and a variable resistor.

Basically, once connected, the ohmmeter measures the current flowing and the larger this current, the lower the resistance. Again, the scale on the galvanometer has to be suitably calibrated.

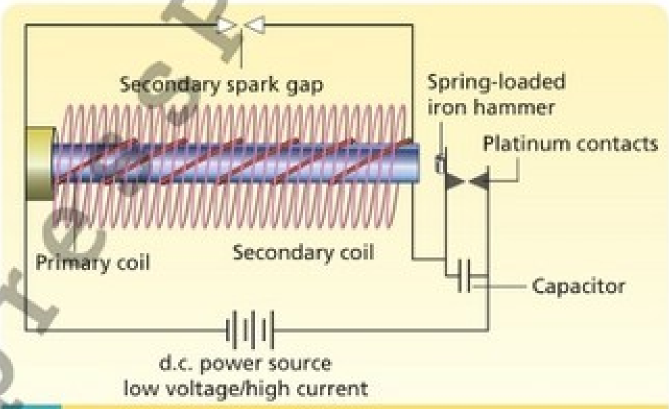
10.6 *Multimeters are electronic measuring instruments that contain both an ammeter and voltmeter, enabling them to measure current, voltage and resistance*

The induction coil

The induction coil is a device invented by Father Nicholas Callan (1799–1864), an Irish priest and scientist teaching at St Patrick's College, Maynooth, in 1836. It was in many ways a precursor to the transformer, but it is also a key part of the design of many modern technologies – most notably the ignition of a car's engine.

The induction coil contains a primary and secondary coil, just like a transformer. In this design, though, the two are usually wrapped around a single iron core. The number of turns in the secondary is always much greater than that in the primary, meaning that the output voltage is always greater than the input.

There are two more significant differences between this design and the design of a transformer. Firstly, the output is not used to drive an alternating current (a.c.) through some other device. Instead, a small gap is left between two wires in the output, as shown in figure 10.7, and the large voltage created causes sparks to jump across this gap. It is such a spark that is used, for example, to ignite the fuel in a car's engine to begin its operation.



10.7 *An induction coil*

Secondly, the input into the induction coil is always from a d.c. source. The spring-loaded iron 'hammer' is attracted to the magnetised core of the coil when a current flows through the primary and creates a magnetic field. However, in a way that is similar to the operation of the electromagnetic relay, the movement of the hammer breaks the circuit, causing the current to stop flowing. When the hammer falls back into place, the current can flow again and the process repeats.

In this way, the current in the primary is constantly being switched on and off, and the associated magnetic field is constantly varying. This changing magnetic field induces a large voltage in the secondary coil, which causes the sparks to jump across the gap.

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GrS PHYS Gr 10 Ss Mod 10.indd 183 5/9/19 4:49 PM

For you to try

1 Briefly, with a diagram, outline the operation of a d.c. motor.
2 Briefly outline the design of a galvanometer.
3 Draw a circuit diagram to show how a galvanometer can be used to operate as an ammeter.
4 What resistor would you need to create an ammeter capable of reading up to 10 A from a galvanometer with a resistance of 100 Ω capable of reading up to 1 mA?
5 Draw a circuit diagram to show how a galvanometer can be used to operate as a voltmeter.
6 What resistor would you need to create an voltmeter capable of reading up to 10 V from a galvanometer with a resistance of 100 Ω capable of reading up to 1 mA?
7 Outline the operation of an induction coil.
8 Name the Irish physicist who invented the induction coil.

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GrS PHYS Gr 10 Ss Mod 10.indd 184 5/9/19 4:49 PM

Glossary

A

Acceleration:

$$Acceleration = \frac{Change\ in\ Velocity}{Time} \text{ or}$$

$$a = \frac{v - u}{t},$$

where a is acceleration, v is final velocity, u is initial velocity and t is time.

Acceleration due to gravity: In the absence of air resistance, objects near Earth's surface fall with constant acceleration due to gravity, $g = 9.8$ m s^{-2}.

Active electrodes: Electrodes that take part in the chemical reaction during electrolysis.

Air track: A tube with a row of holes through which air is blown from an air blower. The air lifts a rider slightly off the track thus creating very low friction between the rider and the air track.

Ammeter: An instrument used to measure the size of an electric current.

Angular displacement: θ is the angle subtended at centre of a circle by an arc of equal length to the radius.

Angular velocity: ω is the rate of change of angular displacement with respect to time.

Anode: The electrode that is connected to the positive terminal of the power supply.

Average speed: The distance travelled divided by the time taken to travel that distance (scalar).

B

Boolean: Of, relating to, or being a logical combinatorial system (such as Boolean algebra) that represents symbolically relationships (such as those implied by the logical operators AND, OR, and NOT) between entities (such as sets, propositions, or on-off computer circuit elements) Boolean expression.

Boundary: The portion of a fluid flowing past a body that is in the immediate vicinity of the body and that has a reduced flow due to the forces of adhesion and viscosity.

Boyle's law: Boyle's law states that at constant temperature, the volume of a fixed mass of gas is inversely proportional to its pressure.

C

Calorimeter: A device used for measuring heat transfer.

Capacitance: Charge stored per unit of potential difference across a capacitor C = Q/V.

Cathode: The electrode that is connected to the negative terminal of the power supply.

Centre of gravity: The point on an object through which the entire weight of the object may be considered to act.

Centripetal acceleration: The rate of change of tangential velocity.

Centripetal force: A force which acts on a body moving in a circular path and is directed towards the centre around which the body is moving.

Charge carriers: Particles that are free to move and carry electrical charge, e.g. electrons or ions.

Conductor (electrical): A substance that allows electric charge to flow freely through it.

Conductor (thermal): A substance that allows heat to transfer through it.

Conventional current: Moves in the same direction as the positive charge flow. So, in metals where the charge carriers (electrons) are negative, conventional current is in the opposite direction to the electrons.

Coulomb's Law: States that the electrostatic force between two point charges is proportional to the product of their charges and inversely proportional to the square of the distance between them.

Couple: Two equal, opposite and parallel forces which create rotational force.

Cross-sectional area: The area that is exposed when an object is cut at right angles to its length.

Current: The flow of electric charge.

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D

Data-logger: A device that collects and stores information. Information is usually transmitted to the data-logger from a motion sensor.

Density: Density is the mass of a body per unit volume.

Diode: A semiconductor device that allows current to flow through it in one direction only.

Displacement: A vector quantity, the distance of an object from its initial position, in a given direction.

E

Electric charge: The amount or type of electrical force that something has. The protons in an atom have a positive charge, and the electrons have a negative charge.

Electric field strength: The point in an electric field where the electrostatic force per unit charge experienced by a small positive test charge placed at that point.

Electric potential: The energy that a unit charge would have at a specified point. Measured in Volts.

Electrodes: Conductors that are in contact with the electrolyte.

Electrolysis: A process in which a chemical reaction takes place when an electric current is passed between two electrodes in an electrolyte.

Electrolyte: An ionic conductor (usually a solution) through which an electric current is passed.

Electromagnet: A soft iron core inside a solenoid. When current is passed through the solenoid, the core becomes magnetised.

Electromagnetic induction: The induction of an electromotive force by the motion of a conductor across a magnetic field or by a change in magnetic flux in a magnetic field.

Electromotive force: The energy converted from other forms to electrical per unit charge delivered round a complete circuit.

Electroscope: An instrument for detecting and measuring electricity, especially as an indication of the ionization of air by radioactivity.

Emergent light ray: A light ray that leaves a medium.

Energy: The ability to do work.

F

Farad: A unit of capacitance defined as one coulomb per volt.

Faraday's Law: States that the induced e.m.f. is directly proportional to the rate of change of magnetic flux linkage or rate of cutting of magnetic flux linkage.

Force: Anything that causes the velocity of an object to change. Force = Mass × Acceleration.

Forward-biased diode: If the positive terminal of the power supply is connected to the p-type part of the diode and the negative terminal of the power supply is connected to the n-type part of the diode, then current will flow and the diode is said to be forward-biased.

Frequency: The number of cycles (or oscillations) passing a point in one second.

Friction: A force that opposes motion.

G

Geostationary satellites: Being or having an equatorial orbit at an altitude of about 22,300 miles (35,900 kilometres) requiring an angular velocity the same as that of the earth, so that the position of a satellite in such an orbit is fixed with respect to the earth.

Gravitational field strength: The force that a unit mass would experience at a specified point. Measured in metres per second or Newtons per kilogramme.

Gravitational potential: The energy that a unit mass would have at a specified point. Measured in Joules per kilogramme.

Gravitational potential energy: The energy an object has due to its relative position above the ground. Found by mass x gravity (or gravitational field strength) x height or force per unit mass at a set point in a gravitational field.

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H

Harmonics: Frequencies that are multiples of a certain frequency, *f*.

Heat capacity: The heat energy needed to change its temperature by one kelvin (1 K).

Heat transfer: The non-mechanical transfer of energy from the environment to the system or from the system to the environment because of a temperature difference between the two.

I

Instantaneous acceleration: The change of velocity over an instance of time.

Instantaneous position: Position of an object at a specific time.

Instantaneous velocity: The velocity of an object at any given instant (especially that of an accelerating object).

Inactive electrodes: Electrodes that do not take part in the chemical reaction during electrolysis.

Insulator (electrical): A substance that does not allow electric charge to flow through it easily.

Insulator (thermal): A substance that does not allow heat to transfer through it easily.

Interference: Interference occurs when two waves meet and a new wave is formed. The displacement produced at any point by this wave is the algebraic sum of the displacements that each wave would produce on its own.

Internal combustion: An engine, such as an automotive gasoline piston engine or a diesel, in which fuel is burned within the engine proper rather than in an external furnace, as in a steam engine.

Internal energy: Sum of potential energy and kinetic energy with random motion.

Inverse square laws: The principle in physics that the effect of certain forces on an object varies by the inverse square of the distance between the object and the source of the force. The magnitude of light, sound, and gravity obey this law, as do other quantities.

J

Joulemeter: An instrument that measures the electrical energy supplied to a circuit.

Joule: The SI unit of work done, or energy. One joule is the work done when a force of one newton moves an object one metre.

Joule's law: Joule's law states that the rate at which heat is produced in a conductor is directly proportional to the square of the current provided its resistance is constant.

Junction voltage: The potential difference that exists across a p-n junction caused by holes and electrons moving across the junction when it was formed.

K

Kilowatt-hour: A unit of energy defined as 1000 watts for 3600 seconds, or kW x h (kWh).

Kinetic energy: The energy an object possesses due to its motion, given by KE = 0.5 x mass x velocity^2.

L

Laminar flow: The flow of a viscous fluid in which particles of the fluid move in parallel layers, each of which has a constant velocity but is in motion relative to its neighboring layers.

Laws of equilibrium: The sum of the forces acting upwards must be equal to the sum of the forces acting downwards and the sum of the clockwise moments must be equal to the sum of the anticlockwise moments.

Left-hand rule: When a wire carrying an electric current is moved in a magnetic field of a magnet, the magnetic field induced by the wire reacts with the magnetic field of the magnet causing the wire to move outwards. Fleming's left-hand rule helps you to predict the movement. First finger - direction of magnetic field (N-S).

Lenz's Law: States that the induced e.m.f. will be directed such that the current which it causes to flow opposes the change that is produced.

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GrS PHYS Gr 10 Ss Gloss.indd 187 5/9/19 4:51 PM

Light-dependent resistor (LDR): A photoresistor (or light-dependent resistor, LDR, or photo-conductive cell) is a light-controlled variable resistor. The resistance of a photoresistor decreases with increasing incident light intensity; in other words, it exhibits photoconductivity.

Lightning conductor: A metal strip terminating in a series of sharp points, usually attached to the highest part of a building, to discharge the electric field before it can reach a dangerous level and cause a lightning strike.

Light gate: A device with a light beam that goes across it. When an object passes through a light gate, a timer records the time that the light beam is interrupted by an object.

Linear momentum: A vector product of Mass and Velocity (= m x).

M

Magnetic declination: The angle that a compass needle makes with the direction of the geographical north pole at any given point on the earth's surface.

Magnetic flux density: The force acting per unit current per unit length on a wire placed at right angles to the magnetic field.

Magnification: Magnification = $\frac{v}{u}$ or $\frac{h_i}{h_o}$.

Magnified image: An image that is larger than the object.

Mass: The amount of matter in any solid object or in any volume of liquid or gas. The acceleration of a body equals the force exerted on it divided by its mass – measured in kg.

Micrometer: An instrument used to measure small distances accurately.

Moment of a force: The force multiplied by the perpendicular distance between the force and the fulcrum.

Momentum: Momentum = Mass × Velocity

Motion sensor: A sensor detects the movement of an object and transmits this information to a data-logger and a computer.

Multimeter: An instrument that can be used to measure various electrical quantities, e.g. voltage, current or resistance.

N

Newton balance: An instrument that measures force (also known as a force-meter).

No parallax: No parallax means that an observer will observe no relative motion between two objects.

Normal: An imaginary line perpendicular to the surface.

n-type doping: Extrinsic semiconductors doped with donor impurities are called n-type semiconductors because they donate an excess of negative charge.

O

Ohmmeter: An instrument used to measure resistance.

Ohm's law: Ohm's law states that the current flowing through a conductor is directly proportional to the potential difference across it, assuming constant temperature. This leads to the equation $V = IR$, where V is voltage, I is current and R is resistance.

Origin (of a graph): (0,0) point on a graph.

Oscillation: The movement back and forth in a regular rhythm.

P

Parallel plate capacitor: An electric circuit element used to store charge temporarily, consisting in general of two metallic plates separated and insulated from each other by a dielectric. Also called condenser.

Period of motion: The period T of an object in circular motion is the time taken for the object to make one complete revolution.

Periodic time (period) of a particle executing simple harmonic motion: The time taken for one complete oscillation.

Permittivity: The ability of a material to store electrical potential energy under the influence of an electric field, measured by the ratio of the capacitance of a capacitor with the material as dielectric to its capacitance with vacuum as dielectric – also called dielectric constant dielectric constant.

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Perpetual freefall: The motion of an object where gravity is the only force acting upon it. A skydiver may be pulled towards earth by gravity, but they are also affected by air resistance, a force opposing their downward movement.

Piston: A sliding piece moved by or moving against fluid pressure which usually consists of a short cylindrical body fitting within a cylindrical chamber or vessel along which it moves back and forth.

Point discharge: Loss of charge through a point on an object.

Point effect: The build-up of charge at corners if an object is less curved than a sphere.

Potential difference: The potential difference between two points is the work done when a charge of 1 coulomb moves from one point to the other.

Power: The rate at which work is done.

Pressure: Force per unit area. $P = \frac{F}{A}$ where P is pressure, F is force and A is area.

Pressure gauge: An instrument used to measure pressure.

Principle of conservation of momentum: The principle of conservation of momentum states that in any interaction between two or more bodies, the total momentum of the bodies before the interaction is equal to the total momentum of the bodies after the interaction provided no external forces act on the system.

p-type doping: (of a semiconductor) having a density of mobile holes in excess of that of conduction electrons associated with or resulting from the movement of holes in a semiconductor p-type conductivity.

R

Radian: A radian is the angle subtended at the centre of the circle when the arc length is equal in length to the radius.

Rectification: The process in which an alternating current is forced to only flow in one direction.

Regenerative braking: A form of braking in electric vehicles in which the loss of kinetic energy from braking is stored and then fed back later to provide power to the electric motor. The system uses regenerative braking to recharge the battery.

Resistance: The ratio of the potential difference across to the current flowing through, i.e. $R = \frac{V}{I}$ where R is resistance, V is voltage and I is current.

Resistivity: If a conductor of length ℓ and cross-sectional area A has a resistance R, the constant ρ given by $R = \frac{RA}{\ell}$ is called the resistivity of the material in the conductor.

Resonance: The transfer of energy between two objects of the same natural frequency.

Reverse-biased diode: If the positive terminal of the power supply is connected to the n-type part of the diode and the negative terminal of the power supply is connected to the p-type part of the diode, then current will not flow and the diode is said to be reverse biased.

Rheostat: A variable resistor with resistance that can be changed by moving a sliding contact.

S

Scalar: A quantity with magnitude but no direction.

Seismograph: An instrument designed to measure tremors of the Earth's surface.

Semiconductor: A substance with resistivity that is between that of a conductor and an insulator. It is neither a good conductor nor a good insulator.

Simple harmonic motion: A body is said to be moving with simple harmonic motion if its acceleration is directly proportional to its distance from a fixed point on its path and its acceleration is always directed towards that point.

Simple pendulum: A mass at the end of a string. For a small angle of swing, a simple pendulum can be considered to be undergoing simple harmonic motion.

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Sink: To displace part of the volume of a supporting substance or object and become totally or partially submerged or enveloped.

Solenoid: A coil of wire that acts like a magnet when a flow of electricity passes through it. An example of a solenoid is the part of a car's starting system that transfers the electric current from the ignition to the motor.

Sonometer: A device consisting of a hollow wooden box with a wire stretched between two movable bridges.

Spark: A spectrum formed from the light produced by an electric spark, characteristic of the gas or vapour through which the spark passes.

Speed: A scalar quantity, speed = distance / time.

Superconductivity: The property of certain substances that have no electrical resistance. In metals it occurs at very low temperatures, but higher temperature superconductivity occurs in some ceramic materials.

T

Temperature: The measure of the hotness or coldness of a body.

Thermal equilibrium: Thermal equilibrium occurs when all parts of a system are at the same temperature.

Thermionic emission: An electrically charged particle or ion that is emitted by a heated conducting material. The electrons emitted from the cathodes of electron tubes (such as cathode ray tubes) are thermions.

Thermistor: A semiconductor with resistance that decreases rapidly as temperature increases.

Thermometer: An instrument used to measure temperature.

Thermometric property: A physical property that changes measurably with temperature.

Threshold frequency: The lowest frequency of electromagnetic radiation that will result in the emission of photoelectrons from a specified metal surface.

Thrust: A type of force due to an engine (usually forward force).

Ticker timer and ticker tape: A standard ticker timer has frequency of 50 Hz and makes 50 dots per second on ticker tape.

Time interval: An SI quantity, measured in seconds (s).

Torque/moment: Moment = force x perpendicular distance from the pivot to the line of action of the force.

Torque: Torque = one of the forces x the distance between them.

Turning forces: More than one force that if unbalanced will cause a rotation.

V

Variable resistor: A device with resistance that can be adjusted.

Vector: A quantity with magnitude and direction.

Velocity-time graph: A motion graph which shows velocity against time for a given body.

Velocity: $Velocity = \frac{Displacement}{Time}$ or $v = \frac{s}{t}$ where v is velocity, s is displacement and t is time.

Volt: The unit of potential difference (p.d.) or electromotive force (e.m.f.) potential difference = energy/charge.

Voltage: See potential difference.

Voltmeter: An instrument used to measure voltage.

Volume: A physical quantity representing how much 3D space an object occupies, measured in cubic metres(m^3).

W

Wavelength: The distance between any point on one cycle of a wave to the corresponding point on the next cycle of the wave.

Weight: The weight of an object is the force of Earth's gravity acting on it. The gravitational force acting on a body is measured in newtons (N). Weight = mass x gravitational force.

Z

Zero error: Zero error occurs when a measuring instrument registers a reading when there should be no reading.

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GrS PHYS Gr 10 Ss Gloss.indd 191 5/9/19 4:51 PM

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