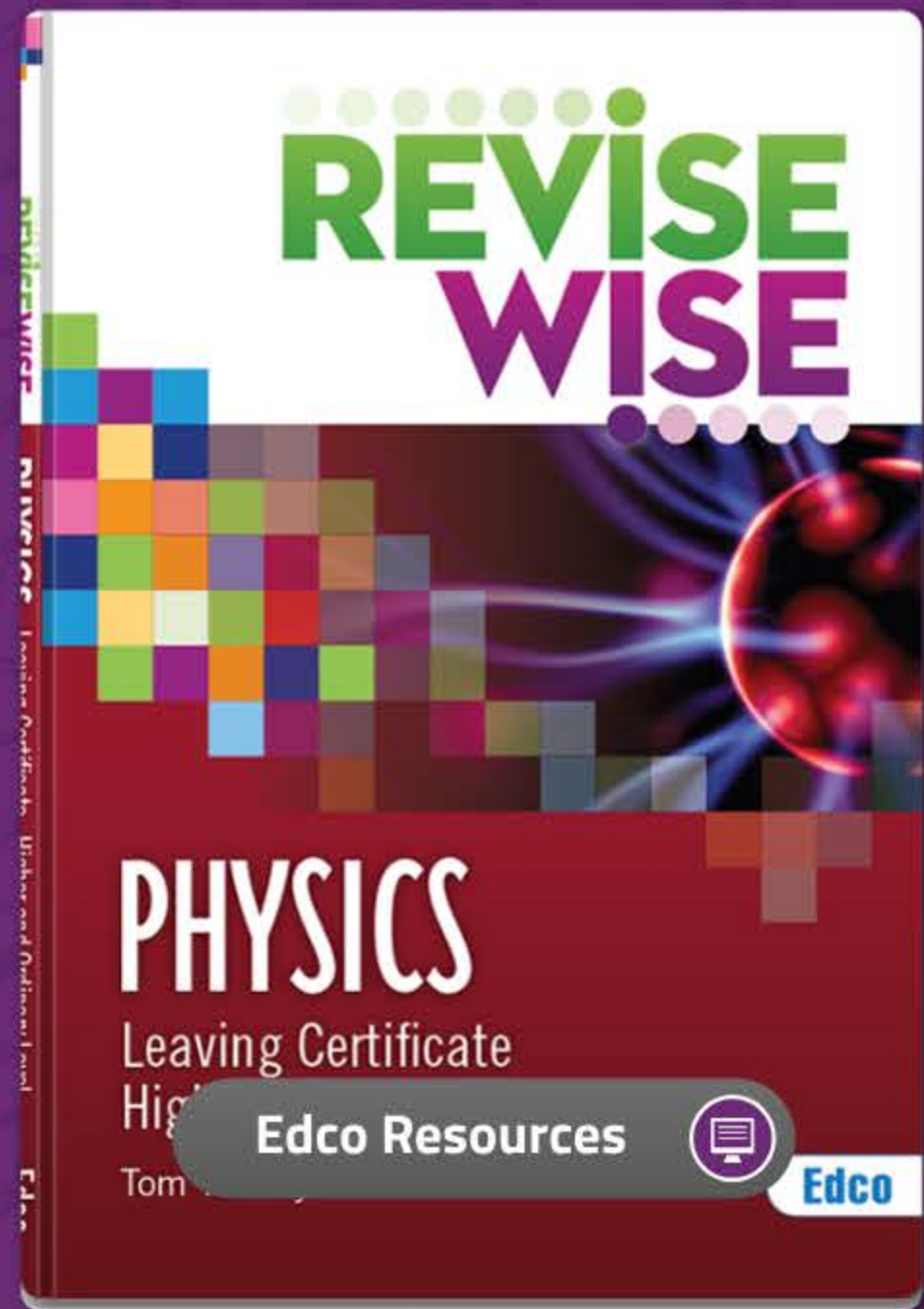




RW LC Physics



* Prelims



* Introduction

This revision guide will help you to prepare for the Leaving Certificate Physics examination at both higher and ordinary levels.



* Examination Section

The Leaving Certificate course essentially consists of six sections.



1 Mandatory Experiments

Section A in the examination focuses on these experiments and is worth 30% of the overall mark.



2 Demonstration Experiments

Section B in the examination may include questions on these experiments.



3 Key Definitions

There is no specific list of definitions that must be learned for the examination, but some are highlighted in the Leaving Certificate Physics syllabus.



4 Formulae and Derivations

Even without taking Section A into account, in the region of 40% of your grade will depend on your ability to carry out calculations.



5 Mechanics

Work is done when a force moves an object through a distance.



6 Light, Sound and Waves

Light reflects off a surface in much the same way that a ball will bounce off a solid surface.



7 Heat and Temperature

The temperature of a body is a measure of how hot it is.



8 Electricity

Nearly all electric charge comes from the charges on protons (positive) and electrons (negative).



9 Modern Physics

Thermionic emission is the emission of electrons from the surface of a hot metal.



10 Option 1: Particle Physics

The Cockcroft–Walton experiment was the first splitting of the nucleus, using artificially accelerated particles.



* Study Guide



First published 2014

The Educational Company of Ireland
Ballymount Road
Walkinstown
Dublin 12

www.edco.ie

A member of the Smurfit Kappa Group plc

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ISBN: 978-1-84536-629-2

Design and layout: Liz White Designs

Editor: Life Lines Editorial Services

Cover photograph: iStock

Cover design: Identikit

Illustrations: Keith Barrett, Design Image

Acknowledgements:

'Radioactive decay helps to determine exact dates', courtesy of the *Irish Times*.

Passage adapted from *Ernest Thomas Sinton Walton 1903–1995: The Irish Scientist* by Vincent J. McBrierty, courtesy of Dr Vincent J. McBrierty.

'The Miracle Year: 1905'. Adapted from *Einstein: His Life and Universe*; Isaacson; 2007, Simon & Schuster.

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Introduction

This revision guide will help you to prepare for the Leaving Certificate Physics examination at both higher and ordinary levels. The main purpose of the book is to reinforce what you have learned from your detailed standard textbook and to enhance your understanding and skills so that you perform at your optimum level on the day. It contains:

- All material central to the Higher and Ordinary Level syllabus
- A clear outline of the examination layout
- Advice on the skills used in the examination
- Examination questions and answers with guidelines on how the questions should be answered.

As always, the best preparation for any examination is to study hard for a long period of time but it is also important to study smart. Long before the examination you should know how the examination is structured, how it is broken down into sections and which material is likely to feature in each section. Understanding the examination should determine how you prepare for it. This book is designed to help.

Throughout the book, material that is higher level only is denoted by a grey line down the side of the page, e.g.

HL Simple Harmonic Motion

Your study guide

Some aspects of the Leaving Certificate Physics course are very challenging. Others are not. It is important in preparing for an examination not to become overly concerned with the difficult material and neglect some of the more straightforward topics where you will gain most of your marks. In organising your study you should make use of the study guide to help you plan your work coming up to the examination. Break the course into sections. Concentrate on first attempting to master the key material outlined in the examination section, and then on more complex material. Set yourself tasks and deadlines and record your progress as you go along.

How to use your study guide

- Plan your work schedule. Do not plan more than you think you will achieve.
- Keep to a daily work timetable.
- Fill in the study guide for each day between now and the examination.
- Think positively – remind yourself of the progress you have made and the fact that examiners want students to be successful.
- Study in small bursts interspersed with short breaks.
- As you complete each task that you have set yourself, tick it off. This will make you feel you have made progress.
- If you fall behind in your plan, don't give up! Start again!



Preparation for the examination day

You should practise as many past Leaving Certificate questions as you can. Check your answers against the marking schemes. All of these are available for download at www.examinations.ie

Get an early night before the examination. You will not perform well if you are tired.

On the day:

- 1 Follow the instructions in the examination paper.
- 2 Spend some time deciding which questions you can answer best. It is time well spent.
- 3 Highlight the key words in the question.
- 4 Make quick notes on the paper in an effort to structure your answer. This also informs you on whether you are making the right choice.
- 5 Ensure that you answer the question asked and that your answer stays relevant.
- 6 Time yourself throughout the examination.
- 7 Answer first the questions you know most about. Leave until last the ones you are least happy with.
- 8 Leave enough time at the end to read through your answers and make minor corrections if needed.
- 9 Remember, presentation, including handwriting, is important. Take care with both.

Examination Section

The examination paper

The Leaving Certificate course essentially consists of **six** sections:

- 1 Mechanics
- 2 Light, Sound and Waves
- 3 Electricity
- 4 Heat and Temperature
- 5 Modern Physics
- 6 Option (Particle Physics or Applied Electricity. Particle Physics is covered in this text.)

Chapters 5–10 of this book will deal with each of these topics in turn. They are not all of equal importance in the examination, and their relative importance varies from year to year. In general, though, you can gauge their importance from the number of questions that have featured in the past, which has always been close to the numbers shown here:

Topic	Questions in Section A	Questions in Section B
Mechanics	1	1.5
Light, Sound and Waves	1	1
Electricity	1	2.5
Heat and Temperature	1	0.5
Modern Physics	–	1.5
Option	–	1

As you prepare for the examination, you should focus on the material that is relatively easy to master and that is central to the examination. Such material includes:

Topic	Percentage of marks
Mandatory experiments	30%
Demonstration experiments	Up to 6–7 %
Definitions	At least 15%
Derivations	2–3%
Applications/STS* covered in relevant sections	Up to 30%

* Science and Technology in Society

The examination paper

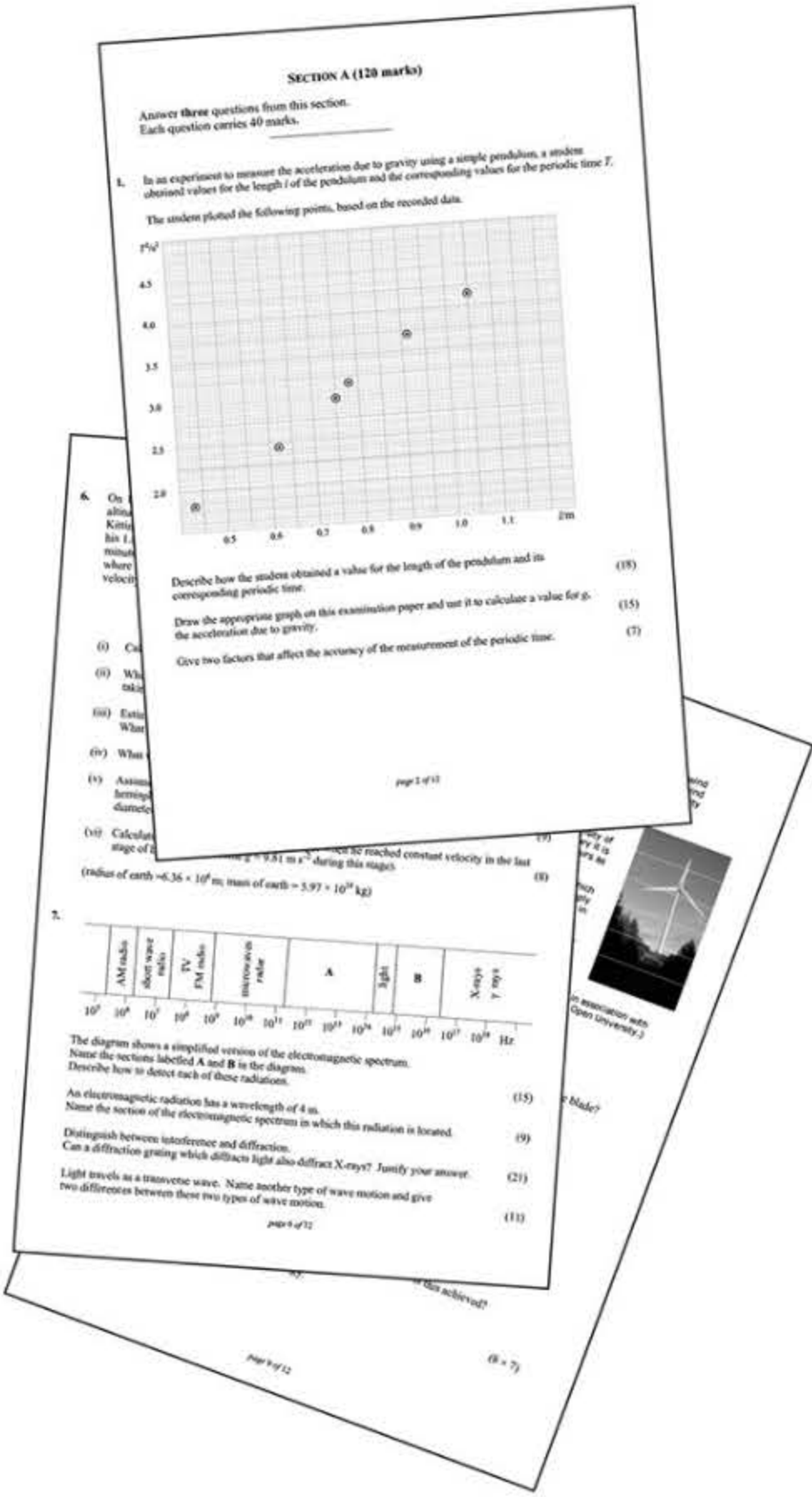
The paper is 400 marks in total, so 4 marks yield 1% of your overall grade. Remember as a rule of thumb that, generally, **one** piece of information will earn **three** marks. The examination is broken up into two sections.

Section A (120 marks, 30%)

- All questions are based on the mandatory experiments
- Answer **three** out of **four** questions

Section B (280 marks, 70%)

- Answer **five** out of **eight** questions
- **Question five** is a set of short questions
- **Question twelve** has **four** parts, of which any **two** must be answered
- **One** question will focus on STS (Science and Technology in Society) or real world applications



Examination strategy

In the examination, you have 3 hours, or 180 minutes. It is crucial that you are organised and that you have a plan as to how you will spend this time. One way this could be done is to allot the time as follows:

Activity	Time allowed
Read the paper and select your questions	10 minutes
Section A: 20 minutes on each of three questions	60 minutes
Section B: 20 minutes on each of five questions	100 minutes
Review answers	10 minutes

Alternatively you may wish to allow a little longer for the Section B questions, which are worth more. The important thing is that you have a plan and that you stick to it.

General preparation

- ✓ Be familiar with the different styles of question asked in each section of the examination.
- ✓ Practise each of the sections beforehand using past examination papers.
- ✓ Follow the instructions given at the beginning of each section on the examination paper with regard to the time you should spend on each section and the number of questions you are required to answer.
- ✓ Ensure that you have revised the key concepts for each section of the syllabus.

1 Mandatory Experiments

Learning objectives

In this chapter you will learn about:

The mandatory experiments, focusing on:

- 1 Method (including diagrams)
- 2 Maths
- 3 Accuracy

Section A in the examination focuses on these experiments and is worth 30% of the overall mark.

Remember

Experimental methods vary. If you are familiar with **one** method for an experiment, that is sufficient.

Remember

In measuring temperature, a thermometer may only be accurate to within $\pm 0.5^\circ\text{C}$

If we measure a change of temperature of 5°C , the percentage error is:

$$\text{Percentage error} = \frac{0.5}{5} \times 100 = 10\%$$

If, however, we had measured a change in temperature of 20°C , the percentage error is:

$$\text{Percentage error} = \frac{0.5}{20} \times 100 = 2.5\%$$

Clearly, the second situation is more accurate. This is why we always look for a lower percentage error.

Exam brief

Method

You should ensure that you can:

- Quickly draw a labelled diagram of the apparatus used.
- Briefly outline the **method** in bullet point format.

Maths

This is essentially the results and conclusion of each experiment.

- Make sure you know which **graphs** to draw and which **formulae** are relevant.
- Recall in particular that in order to show that **two** items are directly proportional to each other, we graph one against the other and look for a straight line through the origin.

Accuracy

For each experiment:

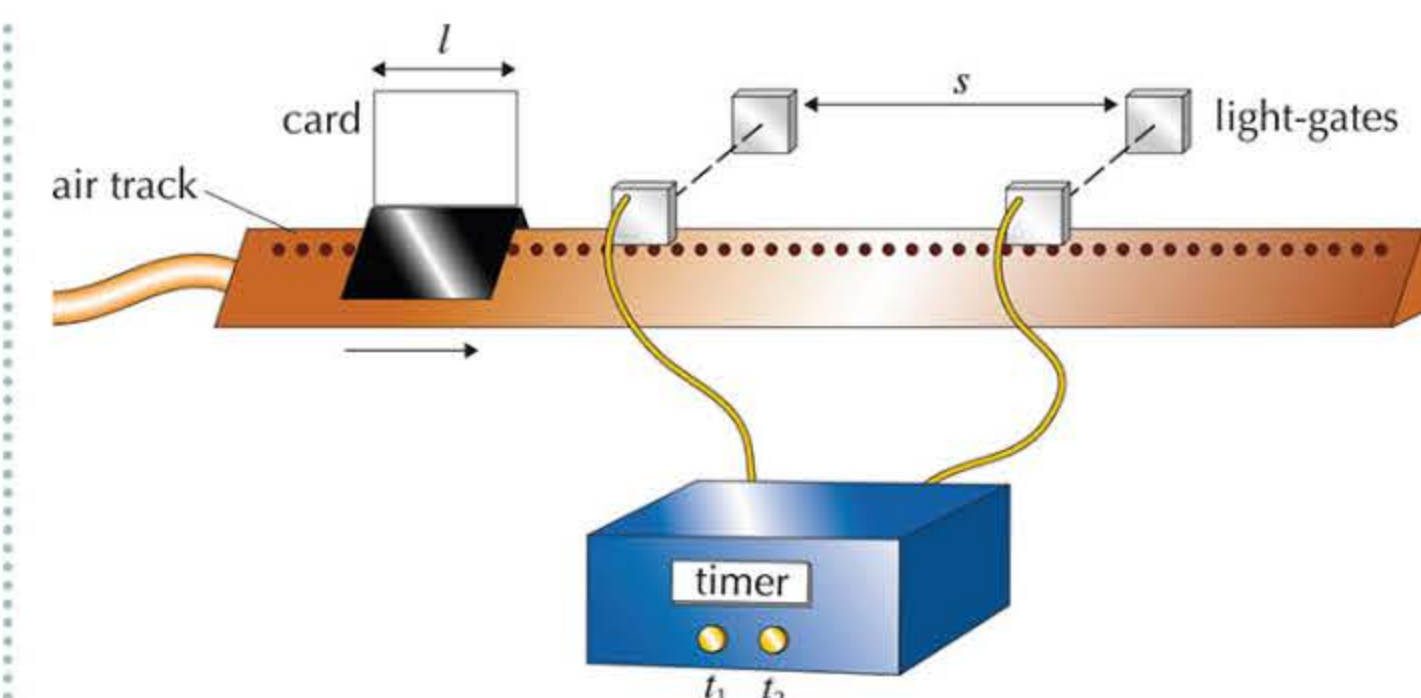
- Memorise the **two** or **three** factors most likely to undermine accuracy, and how to deal with these.
- In particular, look for instances where **percentage error** is affected. As a general rule, we try to take large measurements to keep the percentage error low.



Mechanics mandatory experiments

1 To measure velocity and acceleration

Apparatus



Method

- 1 The rider can be pushed along so that it passes through each of the light-gates.
- 2 As it passes through one, the light is blocked by the card. The time that it takes to pass is recorded electronically by the timer.
- 3 As we know the length of the card, and the time it takes to pass the light-gate, we can calculate the velocity, u , using the formula: $u = \frac{l}{t_1}$
- 4 This procedure can be repeated to measure the velocity at the second gate, v .
- 5 The acceleration can be calculated using the formula: $a = \frac{v^2 - u^2}{2s}$

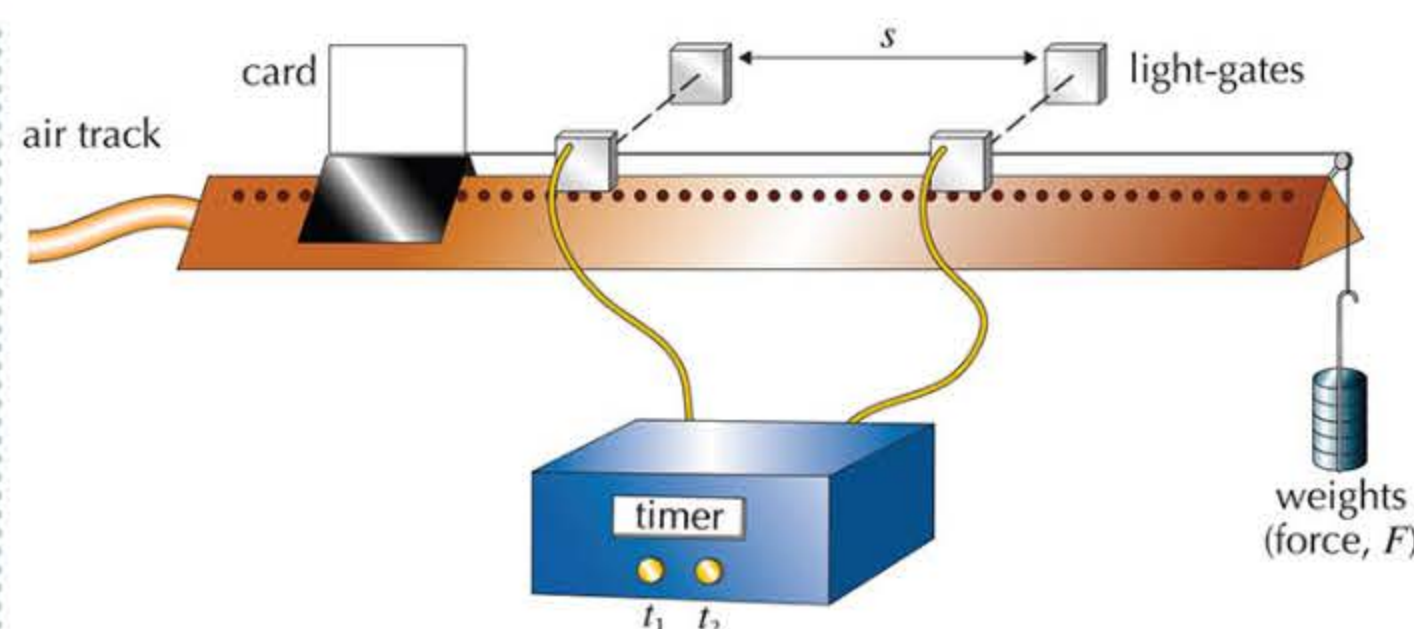
Conclusion The velocity and acceleration have been measured.

Remember

The method shown on the previous page depends on the use of light gates. You may have used a ticker tape timer, which is equally good and is described on page 71. It is best that you describe experiments exactly as you carried them out, as this will allow you to have a clearer understanding of that particular method.

2 To show that acceleration is proportional to force ($a \propto F$)

Apparatus

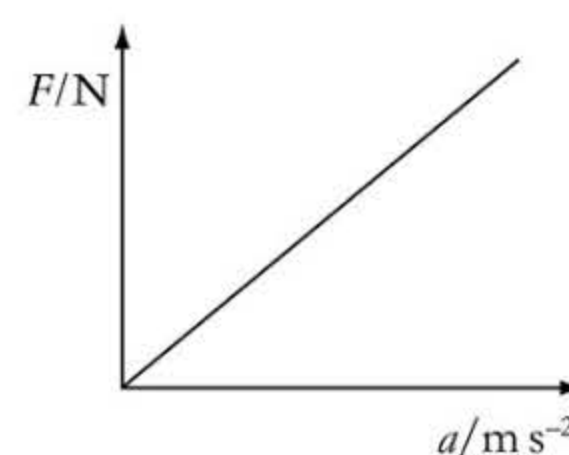


Method

- 1 Set up the apparatus as shown in the diagram.
- 2 Set the weights (F). Release the card from rest.
- 3 Calculate the initial velocity, u and the final velocity, v .
- 4 Find the acceleration using the equation: $a = \frac{v^2 - u^2}{2s}$
- 5 Remove one 1 N disc from the pan, attach this to the vehicle, and repeat.
- 6 Continue for a number of values of F . Record the results.
- 7 Draw a graph of a against F .

Conclusion

A straight line through the origin shows that, for a constant mass, the acceleration is proportional to the applied force.



Remember

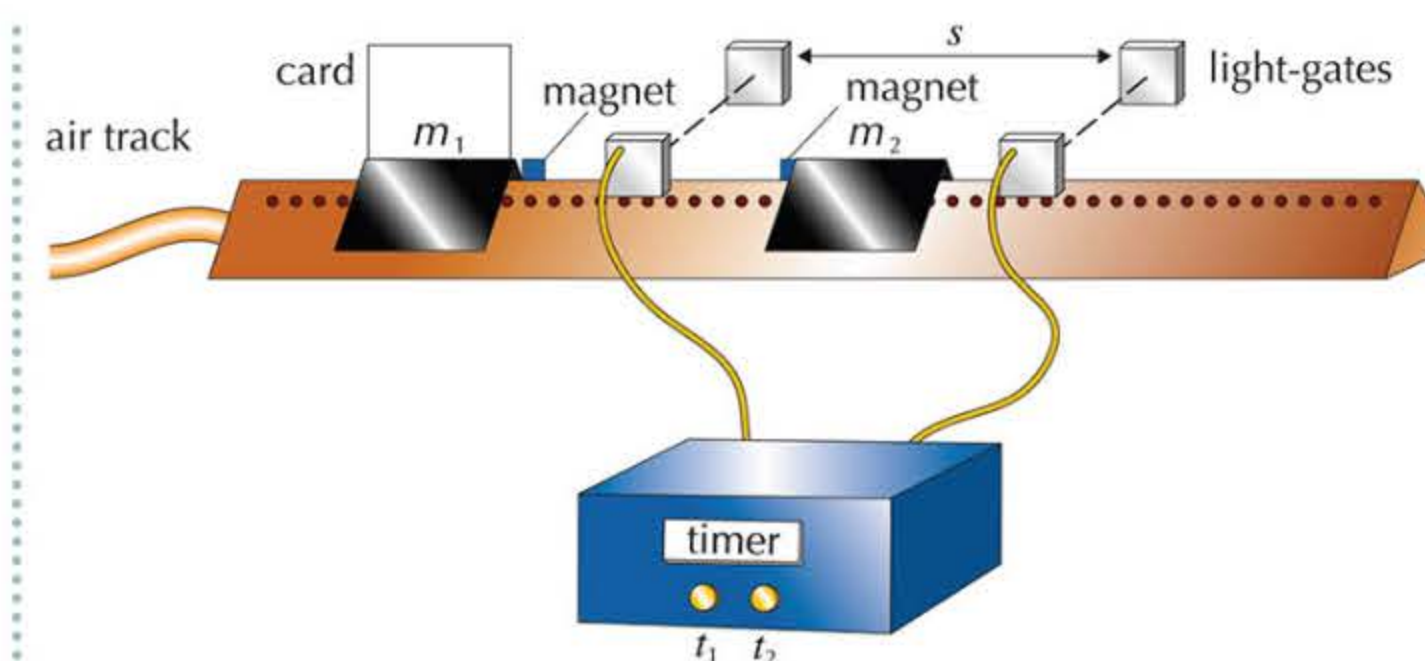
The mass of the system is given by the slope of the line.

Accuracy

- The weights are transferred between the string and the trolley to keep the total mass constant.
- The air track reduces friction, improving accuracy.

3 To verify the principle of conservation of momentum

Apparatus



Method

- 1 Set up apparatus as in the diagram.
- 2 With the second vehicle (m_2) stationary, give the first (m_1) a gentle push. After collision the two vehicles combine, using magnets, and move off together.
- 3 Note the times t_1 and t_2 . From these find the initial velocity u and the final velocity v .
- 4 Calculate the momentum before the collision, using the equation: $P_{\text{before}} = m_1 u$; and the momentum after the collision, using the equation: $P_{\text{after}} = (m_1 + m_2) v$.
- 5 Repeat several times, with different velocities and different masses. Record the results.

Conclusion

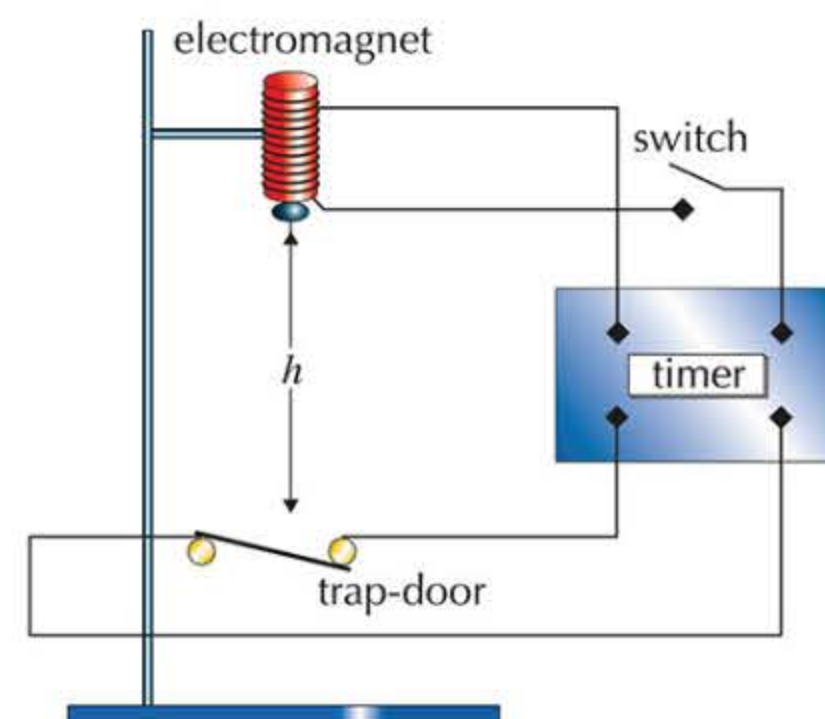
The results will consistently show that $P_{\text{before}} = P_{\text{after}}$, thus confirming the conservation of momentum.

Accuracy

- The air track reduces the effect of friction.
- It is important to measure the velocities immediately before and after the collision, to offset the slowing down due to friction.

4 Measurement of g (by freefall)

Apparatus



Method

- 1 Set up the apparatus. 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 in the diagram, 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 .

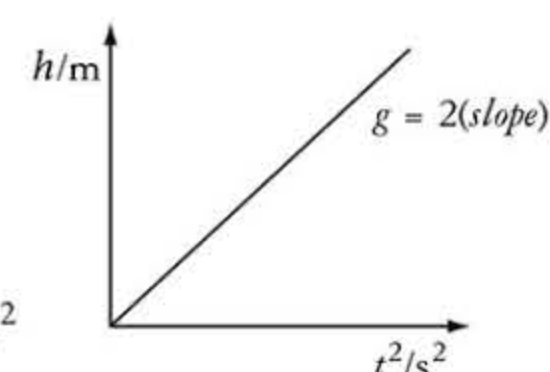
Remember
A piece of paper between the ball bearing and the electromagnet will help ensure a quick release.

Conclusion

Calculate the values for g using the equation: $h = \frac{1}{2}gt^2$.

Obtain an average value for g .

Alternatively draw a graph of h against t^2 and use the slope to find g .



Accuracy

The shortest of the three times is taken as t , because various factors can delay the falling of the ball, but nothing should speed it up.

Remember

Larger values of h will decrease the percentage error.

Exam question

2004, HL, Section A, Q1

In an experiment to measure the acceleration due to gravity g by a freefall method, a student measured the time t for an object to fall from rest through a distance s . This procedure was repeated for a series of values of the distance s .

The table shows the data recorded by the student.

s/cm	30	40	50	60	70	80	90
t/ms	244	291	325	342	371	409	420

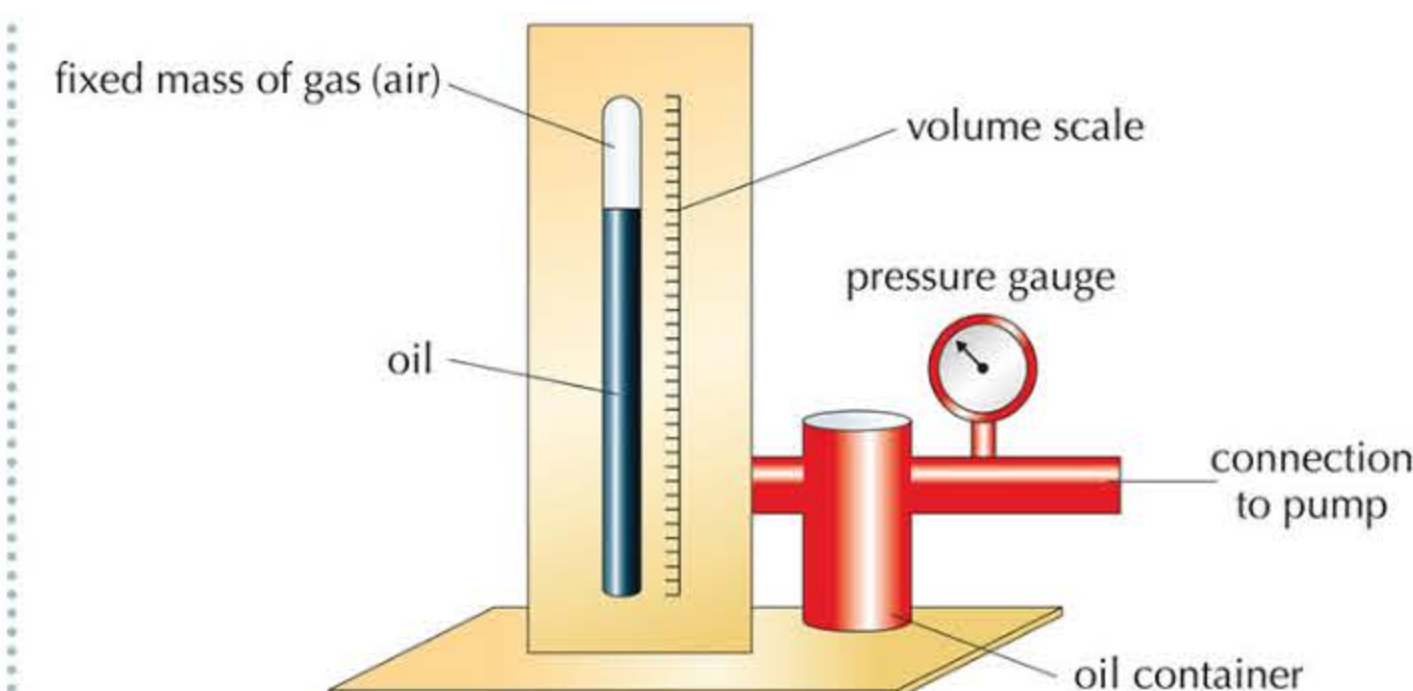
Describe, with the aid of a diagram, how the student obtained the data. (12 marks)

Calculate a value for the acceleration due to gravity g by drawing a suitable graph based on the recorded data. (21 marks)

Give two precautions that should be taken to ensure a more accurate result. (7 marks)

5 Verification of Boyle's law

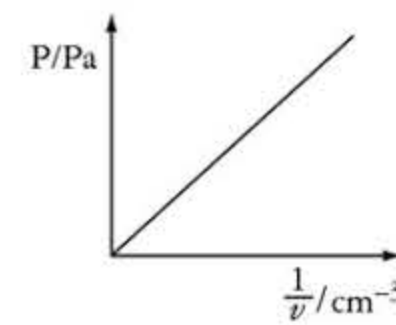
Apparatus



Method

- 1 Using the pump, increase the pressure on the air in the tube.
- 2 Record the volume v and the corresponding pressure P .
- 3 Repeat for several values of P and v .
- 4 Record the results.
- 5 Plot a graph of P against $\frac{1}{v}$.

Conclusion 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.



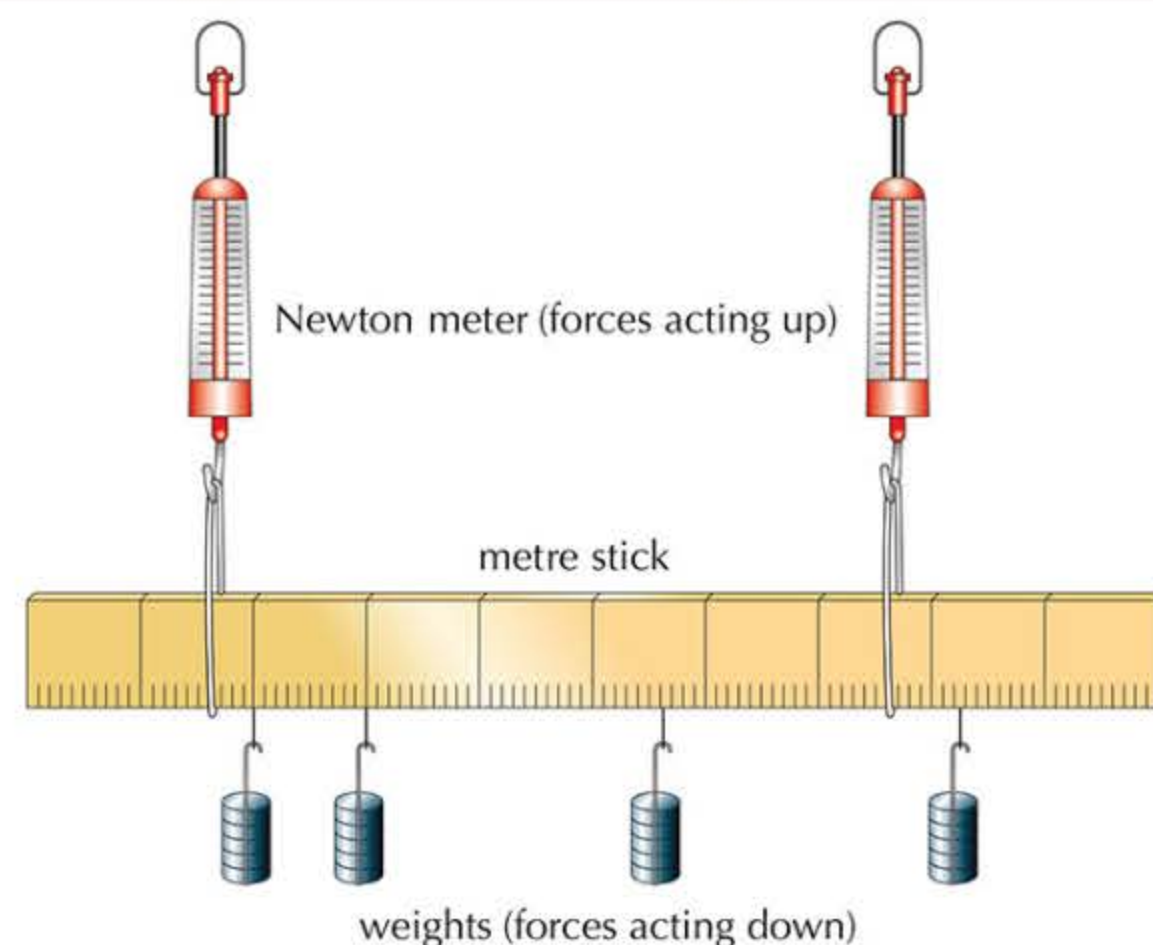
Accuracy

Remember

- 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.

6 Investigation of the laws of equilibrium for a set of co-planar forces

Apparatus



Method

- 1 Use a balance to find the centre of gravity of the metre stick and its weight.
- 2 Set up the apparatus as shown in the diagram.
- 3 Record the positions on the metre stick of each weight, each Newton meter and the reading on each balance.

Conclusion

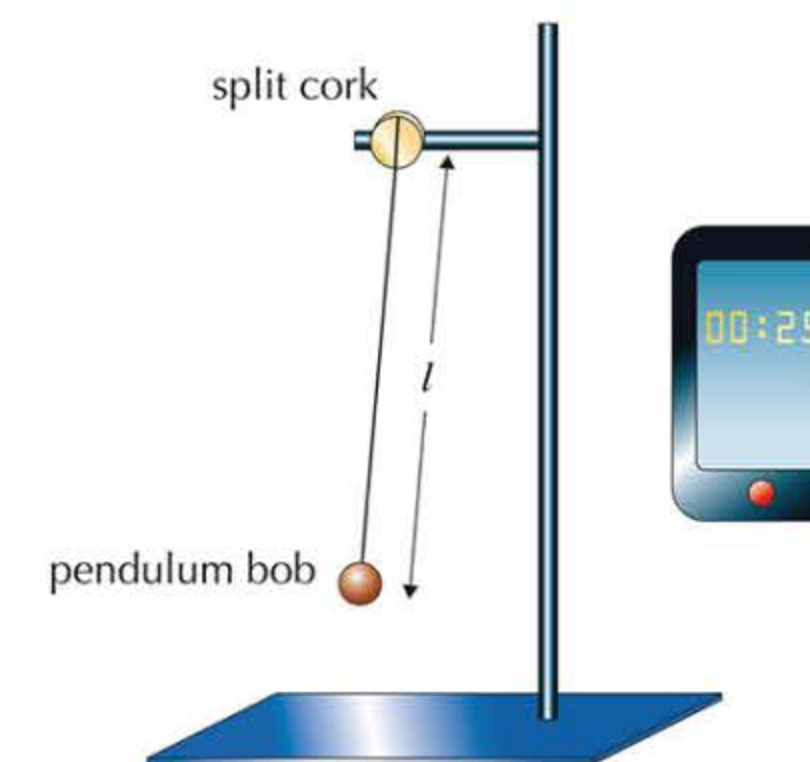
- 1 Calculate the total upward force and the total downward force on the stick. They should be equal, confirming the **First law of equilibrium**.
- 2 Calculate the total clockwise and anti-clockwise moments about the 0 cm mark, the 50 cm mark and one other mark on the stick. In all instances the total of the clockwise moments should equal the total of the anti-clockwise moments, confirming the **Second law of equilibrium**.

Accuracy

- It is crucial that the metre stick should be horizontal when the readings are taken, so that distances are perpendicular to forces.
- The most likely source of inaccuracy is in the Newton meters.

7 Investigation of the relationship between period and length for a simple pendulum and hence calculation of g

Apparatus

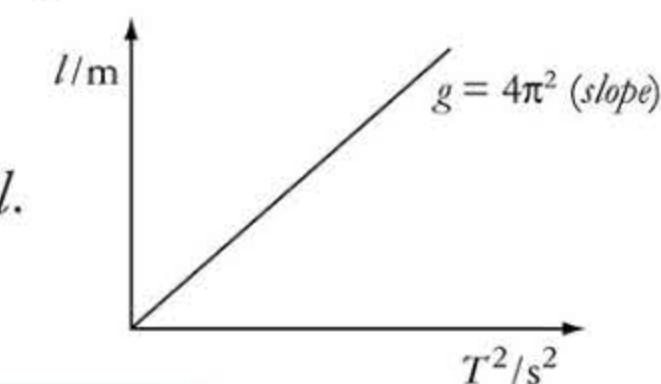


Method

- 1 Place the thread of the pendulum between two halves of a split cork.
- 2 Set the pendulum swinging through a small angle ($<10^\circ$). Measure the time t for thirty complete oscillations. Divide this time t by thirty to get the periodic time T .
- 3 Record both l and T .
- 4 Repeat for different lengths, l , of the pendulum.

Conclusion

Draw a graph of l against T^2 . The straight line through the origin will confirm that T^2 is proportional to l .



Remember

The experiment is based on the formula:

$$T^2 = 4\pi^2 \frac{l}{g}$$

Accuracy

- The split cork ensures that the pendulum swings evenly in all directions.
- Longer lengths will reduce the percentage error.

Exam questions

1 2007, HL, Section A, Q1

A student investigated the laws of equilibrium for a set of co-planar forces acting on a metre stick.

The student found that the centre of gravity of the metre stick was at the 50.4 cm mark and its weight was 1.2 N.

How did the student find (i) the centre of gravity, (ii) the weight, of the metre stick?

Why is the centre of gravity of the metre stick not at the 50.0 cm mark?

The student applied vertical forces to the metre stick and adjusted them until the metre stick was in equilibrium.

How did the student know that the metre stick was in equilibrium? (19 marks)

The student recorded the following data.

Position on metre stick/cm	11.5	26.2	38.3	70.4	80.2
Magnitude of force/N	2.0	4.5	3.0	5.7	4.0
Direction of force	down	up	down	up	down

Calculate:

- The net force acting on the metre stick
- The total clockwise moment about a vertical axis of the metre stick
- The total anti-clockwise moment about a vertical axis of the metre stick.
Use these results to verify the laws of equilibrium. (21 marks)

2 2006, HL, Section A, Q1

In investigating the relationship between the period and the length of a simple pendulum, a pendulum was set up so that it could swing freely about a fixed point. The length l of the pendulum and the time t taken for 25 oscillations were recorded. This procedure was repeated for different values of the length.

The table shows the recorded data.

l/cm	40.0	50.0	60.0	70.0	80.0	90.0	100.0
t/s	31.3	35.4	39.1	43.0	45.5	48.2	50.1

The pendulum used consisted of a small heavy bob attached to a length of inextensible string.

Explain

- Why a small heavy bob was used;
- Why the string was inextensible. (9 marks)

Describe how the pendulum was set up so that it swung freely about a fixed point. Give one other precaution taken when allowing the pendulum to swing. (7 marks)

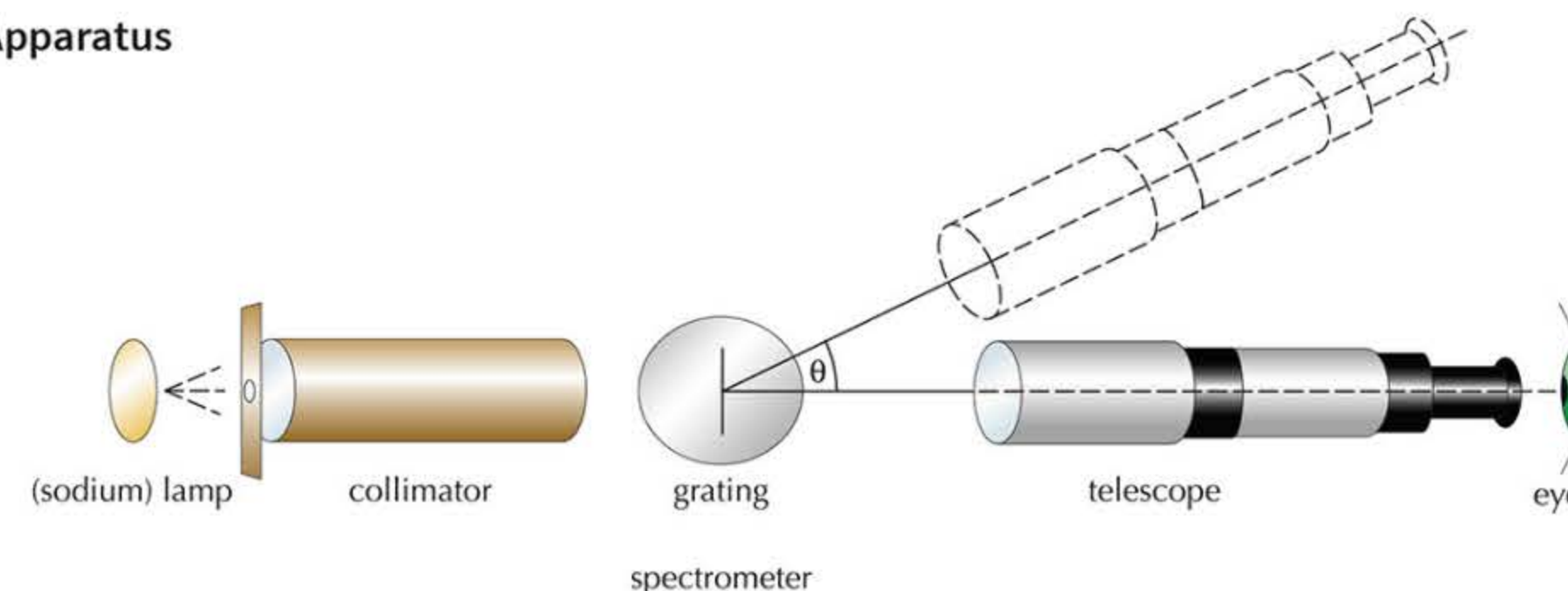
Draw a suitable graph to investigate the relationship between the period of the simple pendulum and its length. What is this relationship? Justify your answer. (24 marks)



Light, sound and waves mandatory experiments

1 Measurement of the wavelength of monochromatic light

Apparatus



Method

- Adjust the eyepiece of the telescope so that the crosswires are sharply focused.
- Focus the telescope for parallel light using a distant object.
- Set up the apparatus as shown in the diagram. Looking through the telescope, focus the collimator lens and adjust the width of the slit until a clear narrow image is seen.
- Place the diffraction grating on the turntable at right angles to the beam.
- Move the telescope to the right until the cross wires are centred on the first bright image. Take the reading θ from the scale on the turntable. Move the telescope back through the centre and then to the first bright image on the left. Take the reading for this position. The average of the two is the angle θ for the first order image ($n = 1$).
- Repeat for the second and third order images.

Remember

The first three steps describe how to set up the spectrometer.

Conclusion For each value of n , calculate the wavelength λ using $n\lambda = d \sin \theta$, and take an average.

d is the spacing between the slits on the diffraction grating, e.g. if there are 200 lines/mm, there are 200,000 lines/m, and d is given by:

$$d = \frac{1}{200,000} \text{ m} = 5 \times 10^{-6} \text{ m}$$

Accuracy

- If the grating is not perpendicular to the light beam, the angles to one side will be larger than to the other.
- The larger the value of θ , the smaller the percentage error. To achieve larger values of θ , the value of d can be reduced by using a grating with more lines per mm.

Exam questions

2006, HL, Section A, Q2

In an experiment to measure the wavelength of monochromatic light, a narrow beam of the light fell normally on a diffraction grating. The grating had 300 lines per millimetre. A diffraction pattern was produced. The angle between the second order image to the left and the second order image to the right of the central bright image in the pattern was measured.

The angle measured was 40.6° .

Describe, with the aid of a labelled diagram, how the data was obtained. (9 marks)

How was a narrow beam of light produced? (6 marks)

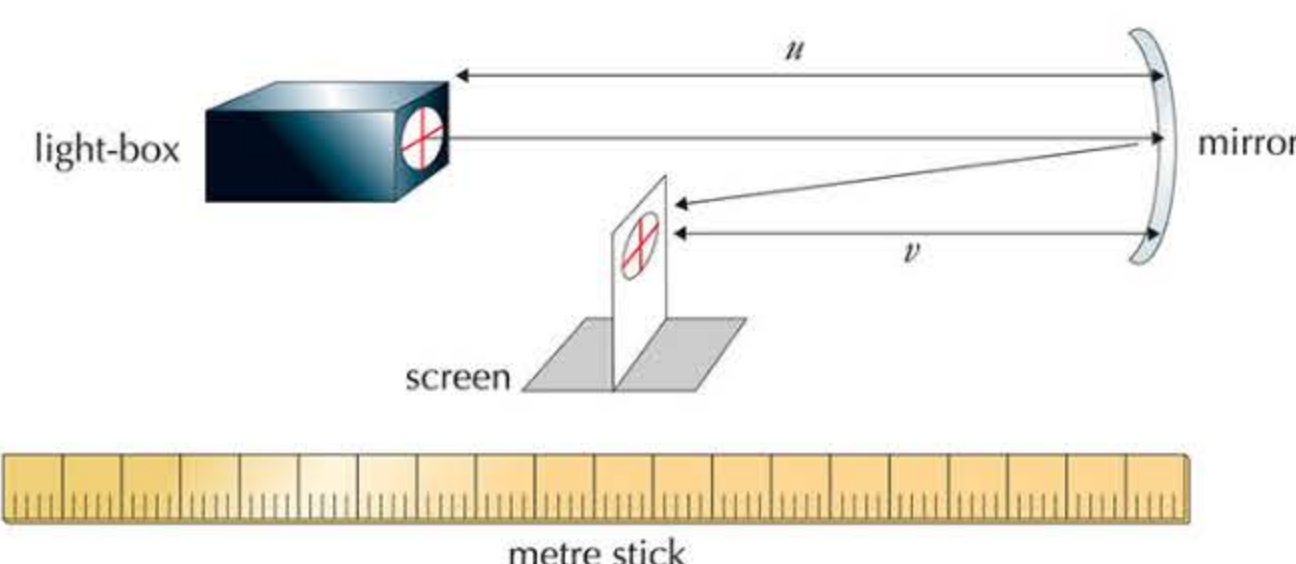
Use the data to calculate the wavelength of the monochromatic light. (15 marks)

Explain how using a diffraction grating of 500 lines per mm leads to a more accurate result. (6 marks)

Give another way of improving the accuracy of this experiment. (4 marks)

2 Measurement of the focal length of a concave mirror

Apparatus



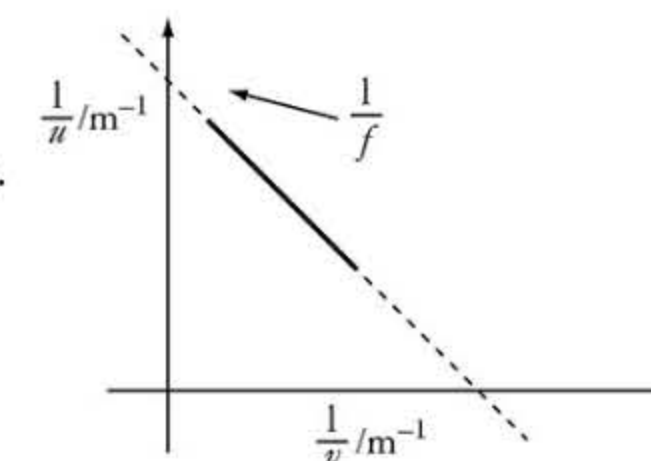
Method

- 1 Set up the apparatus as shown in the diagram.
- 2 Move the screen until a clear inverted image of the crosswire is obtained.
- 3 Measure the distances u and v , as shown in the diagram.
- 4 Repeat this procedure for different values of u .

Conclusion

For each set of results, find the focal length of the mirror using: $\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$.

Take an average value as the focal length. Alternatively, use the graph as shown.



Accuracy

- An approximate value can be found by locating the image of a distant object (through a window), which will be formed at the focal point.
- The difficulty in deciding in which position the image is most clear is the main source of inaccuracy.

Exam questions

2007, HL, Section A, Q3

In an experiment to measure the focal length of a concave mirror, an approximate value for the focal length was found. The image distance v was then found for a range of values of the object distance u . The following data was recorded.

u/cm	15.0	20.0	25.0	30.0	35.0	40.0
v/cm	60.5	30.0	23.0	20.5	18.0	16.5

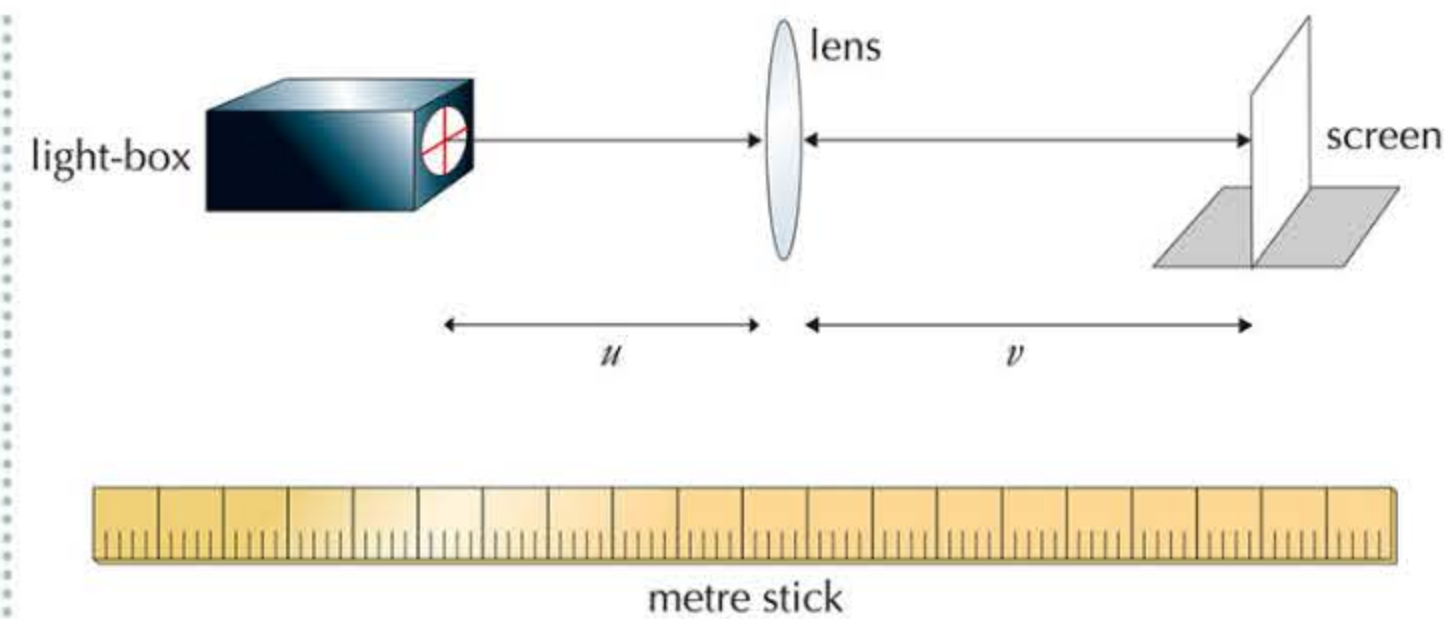
How was an approximate value for the focal length found? What was the advantage of finding the approximate value for the focal length? (10 marks)

Describe, with the aid of a labelled diagram, how the position of the image was found. (12 marks)

Calculate the focal length of the concave mirror by drawing a suitable graph based on the recorded data. (18 marks)

3 Measurement of the focal length of a converging lens

Apparatus



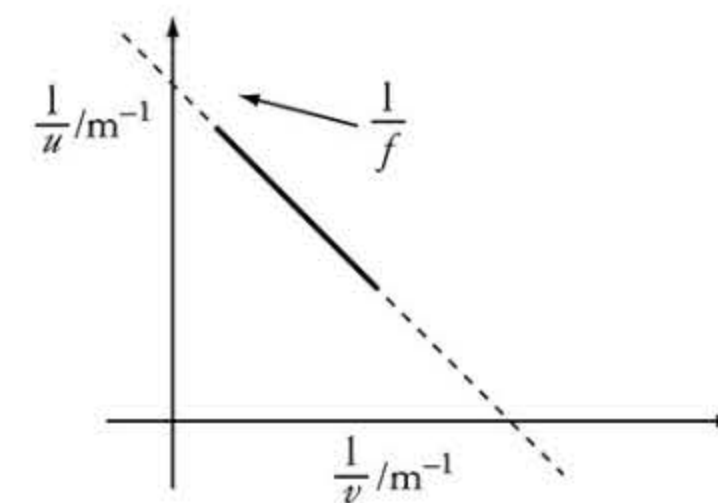
Method

- 1 Set up the apparatus as shown in the diagram.
- 2 Place the light-box well outside the approximate focal length.
- 3 Move the screen until a clear inverted image of the crosswire is obtained.
- 4 Measure the distances u and v , as shown in the diagram.
- 5 Repeat this procedure for different values of u .

Conclusion

For each set of results, find the focal length of the lens using: $\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$.

Take an average value as the focal length. Alternatively, use the graph as shown.

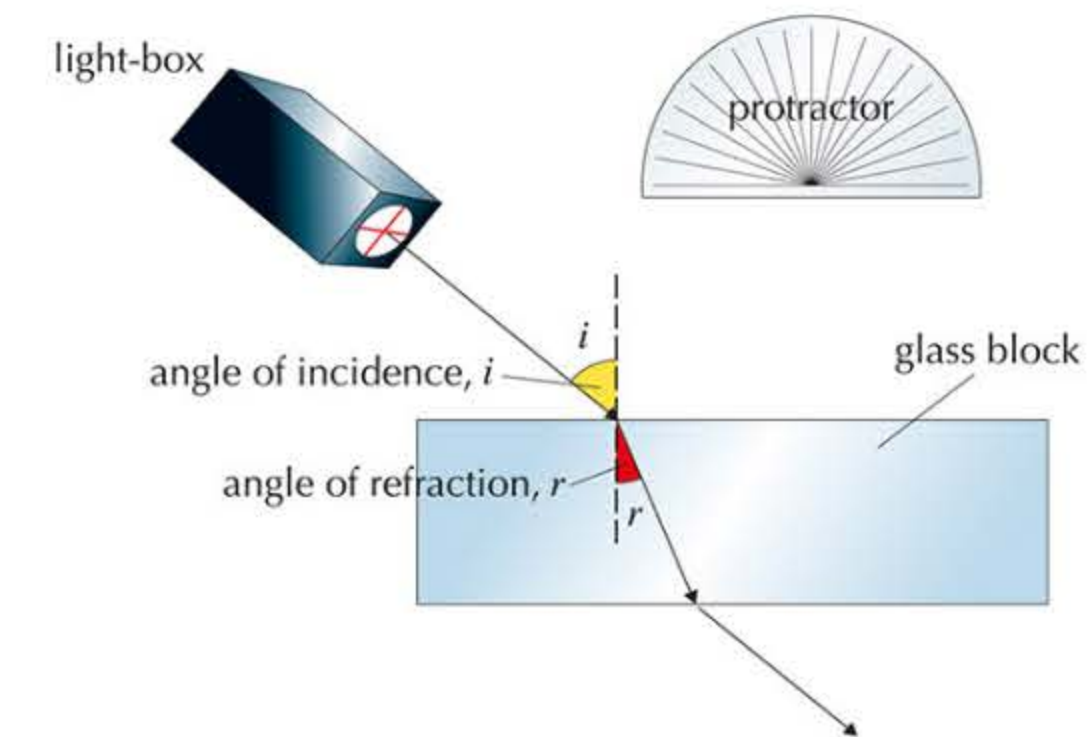


Accuracy

- An approximate value can be found by locating the image of a distant object (through a window), which will be formed at the focal point.
- The difficulty in deciding in which position the image is most clear is the main source of inaccuracy.

4 Verification of Snell's law of refraction (and hence finding the refractive index of glass)

Apparatus

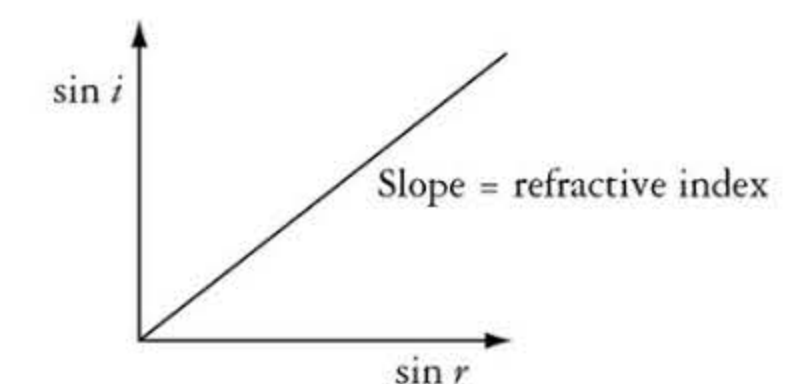


Method

- 1 Place a glass block as shown in the diagram and mark its outline.
- 2 Shine a ray of light from a light-box as shown in the diagram.
- 3 Mark the position of the light ray as it enters and leaves the block, and remove the block.
- 4 Draw in the normals and measure i and r , as shown in the diagram.

Conclusion

Plot a graph of $\sin i$ against $\sin r$. A straight line through the origin verifies Snell's law of refraction, i.e. $\sin i \propto \sin r$. The slope of the line is the refractive index.



Accuracy

- The light beam will spread out, or diverge, making it difficult to mark its position.
- Larger angles will lead to a smaller percentage error.

Exam question

2005, HL, Section A, Q3

In an experiment to verify Snell's law, a student measured the angle of incidence i and the angle of refraction r for a ray of light entering a substance. This was repeated for different values of the angle of incidence. The following data was recorded.

$i/\text{degrees}$	20	30	40	50	60	70
$r/\text{degrees}$	14	19	26	30	36	40

Describe, with the aid of a diagram, how the student obtained the angle of refraction. (9 marks)

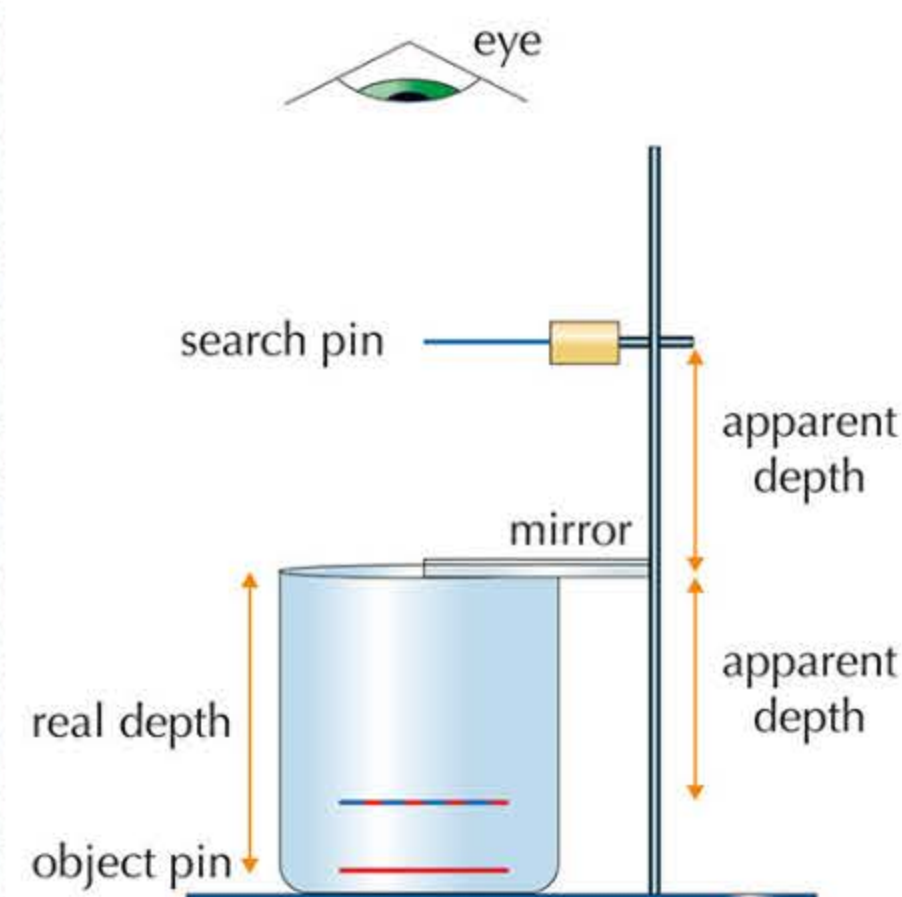
Draw a suitable graph on graph paper and explain how your graph verifies Snell's law. (18 marks)

From your graph, calculate the refractive index of the substance. (9 marks)

The smallest angle of incidence chosen was 20° . Why would smaller values lead to a less accurate result? (4 marks)

5 Measurement of the refractive index of a liquid

Apparatus



Note: Students are required to have carried out an experiment to find the refractive index of a solid **or** liquid. It is, however, helpful to be familiar with both experiments.

Method

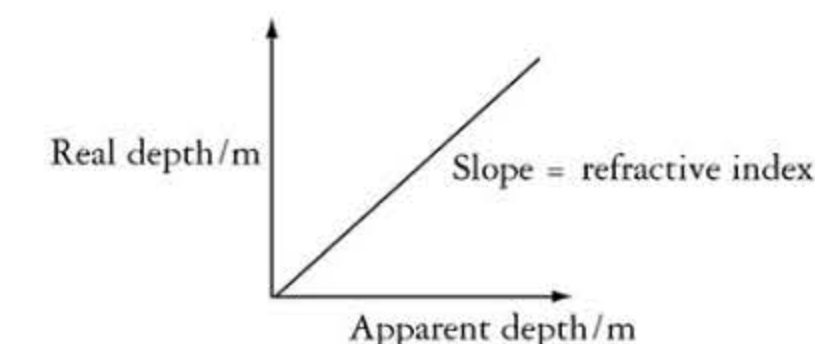
- 1 Set up the apparatus as shown in the diagram. Focus on the reflection of the search pin and the pin in the water.
- 2 Adjust the height of the search pin until there is no parallax between the two images, as shown in the diagram.

- 3 Measure the distance from the pin in the cork to the back of the mirror. This is the apparent depth. Measure the depth of the container. This is the real depth.
- 4 Repeat for different depths of water.

Conclusion

Plot a graph of real depth against apparent depth.

The slope of the line will be the refractive index.

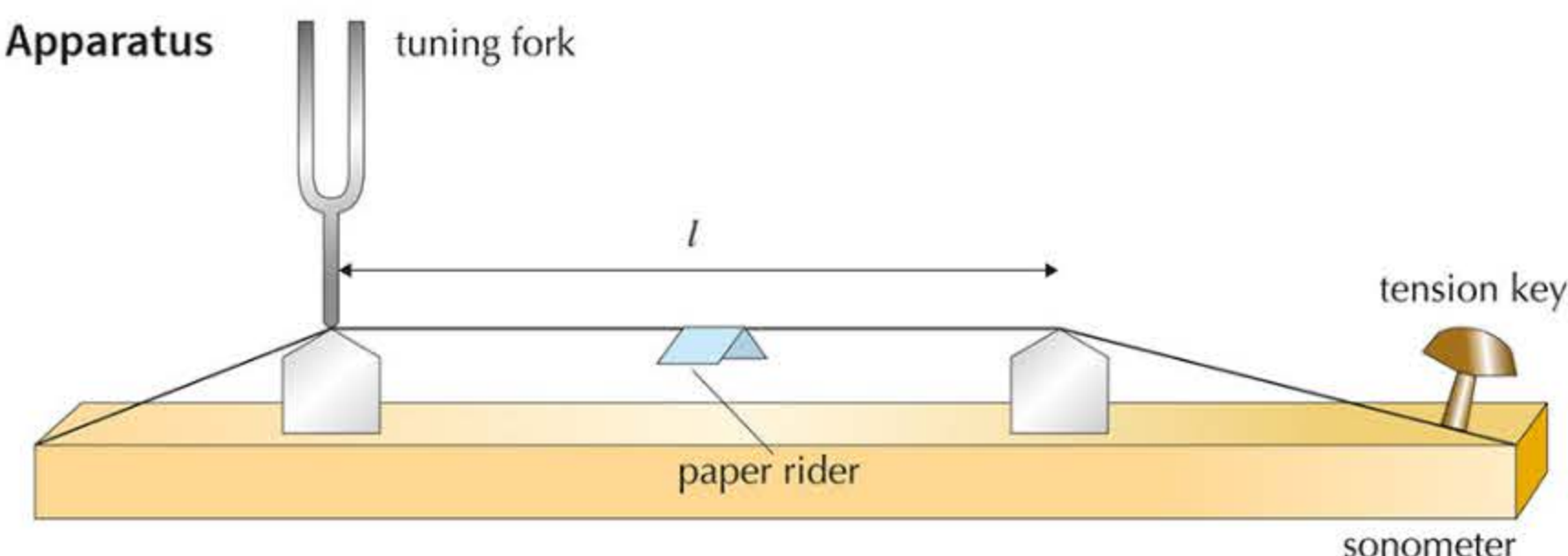


Accuracy

- It is very difficult to pinpoint the position of no parallax.
- Using larger values of the real depth will reduce percentage error.

6 Investigation of the variation of fundamental frequency of a stretched string with length

Apparatus

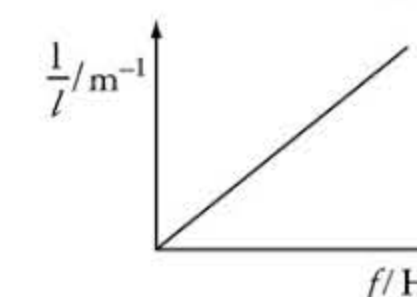


Method

- 1 Set up the apparatus as shown in the diagram. Set the tension at a fixed value.
- 2 Strike a tuning fork of known frequency f and place it on the sonometer.
- 3 Start with a small value for l and slowly increase it, until the paper rider moves, indicating that the string is vibrating.
- 4 Record l and f .
- 5 Repeat for various tuning forks, and record the measurements in a table.
- 6 Plot a graph of frequency f against inverse of length: $\frac{1}{l}$.

Conclusion

A straight line through the origin will verify that frequency f is proportional to $\frac{1}{l}$.



Accuracy

- It is difficult to determine when the string's vibrations are at their greatest. The paper rider helps with this.
- Tuning forks are easily damaged and may not vibrate at the labelled frequency.

Exam question

2002, HL, Section A, Q3

A student obtained the following data during an investigation of the variation of the fundamental frequency f of a stretched string with its tension T . The length of the string was kept constant.

T/N	15	20	25	30	35	40	45
f/Hz	264	304	342	371	402	431	456

Describe, with the aid of a diagram, how the student obtained the data. (12 marks)

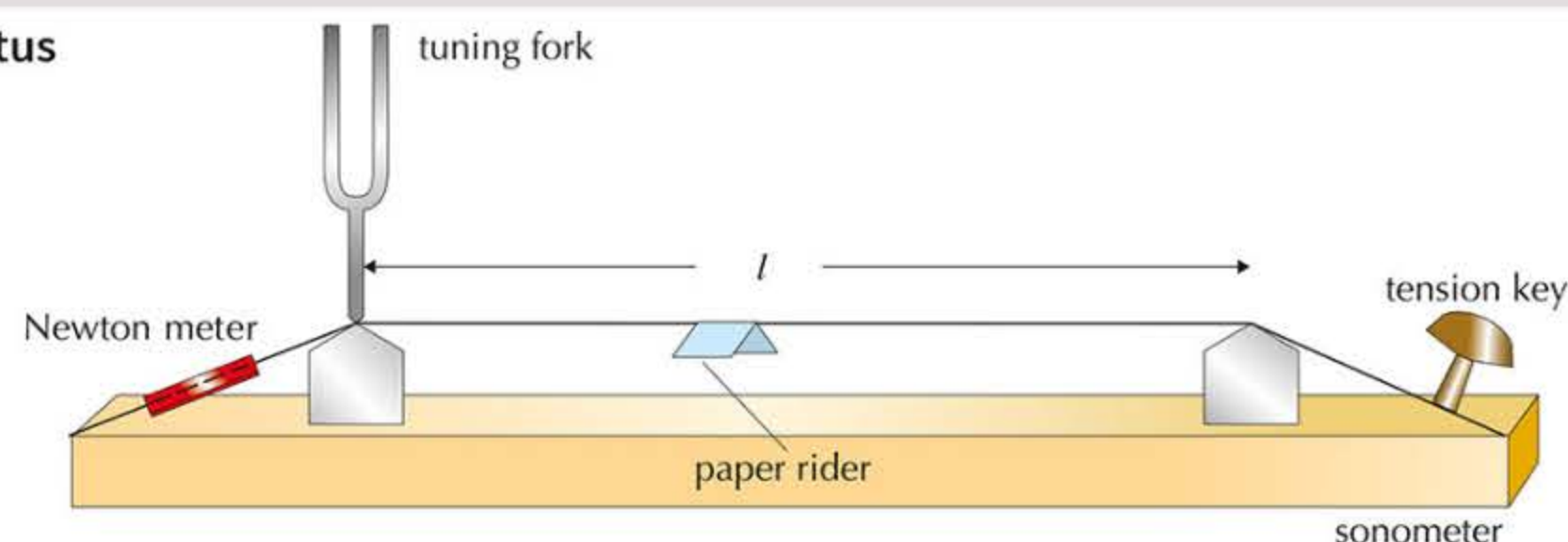
Why was the length of the string kept constant during the investigation? (6 marks)

Plot a suitable graph on graph paper to show the relationship between fundamental frequency and tension for the stretched string. (15 marks)

From your graph, estimate the tension in the string when its fundamental frequency is 380 Hz. (7 marks)

HL 7 Investigation of the variation of the fundamental frequency of a stretched string with tension

Apparatus



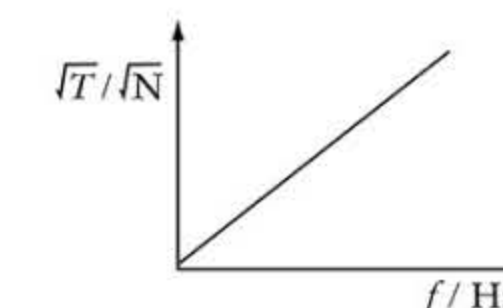
Method

- 1 Set up the apparatus as shown in the diagram.
- 2 Select a wire length l (e.g. 30 cm), by suitable placement of the bridges. Keep this length fixed throughout the experiment.
- 3 Strike a tuning fork and place it on the sonometer. Start at low tension and slowly increase it until the string begins to vibrate. Record f and T .

- 4 Repeat the procedure several times with different tuning forks.
- 5 Plot a graph of frequency f against the square root of tension: $\sqrt{T}$.

Conclusion

A straight line through the origin will verify a proportionality between the f and $\sqrt{T}$.

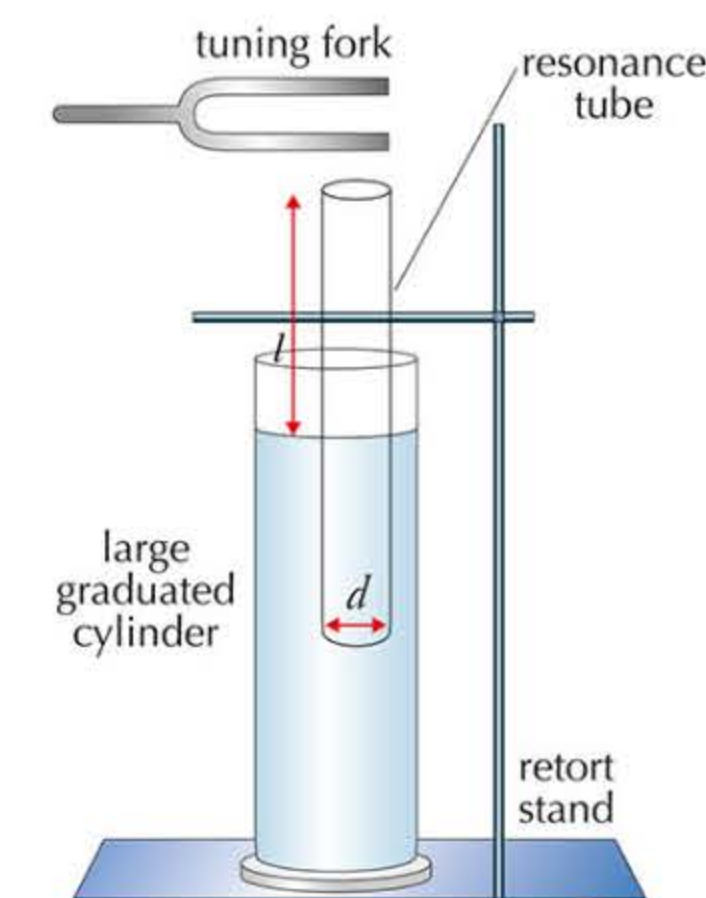


Accuracy

- It is difficult to determine when the string's vibrations are at their greatest. The paper rider helps with this.
- Tuning forks are easily damaged and may not vibrate at the labelled frequency.

8 Measurement of the speed of sound in air

Apparatus



Method

- 1 Clamp the tube so that the water in the graduated cylinder closes its lower end, as shown in the diagram. Using a vernier calipers, measure the diameter of the tube, d .
- 2 Strike the highest frequency, f , tuning fork on the wooden block, and hold it in a horizontal position just above the mouth of the tube.
- 3 Slide the tube slowly up until the note heard from the tube is at its loudest. Tighten the clamp in this position and measure the length of the air column (from the water level to the top of the tube) l with a metre stick.
- 4 Repeat this procedure to obtain the corresponding values of l for all the tuning forks in order of decreasing frequency. Record the measurements in a table.

Conclusion

- Calculate the wavelength using $\lambda = 4(l + 0.3d)$ in each case.
- Calculate the speed of sound from $c = f\lambda$, for each of the tuning forks.
- Find the average value for the speed of sound.

Accuracy

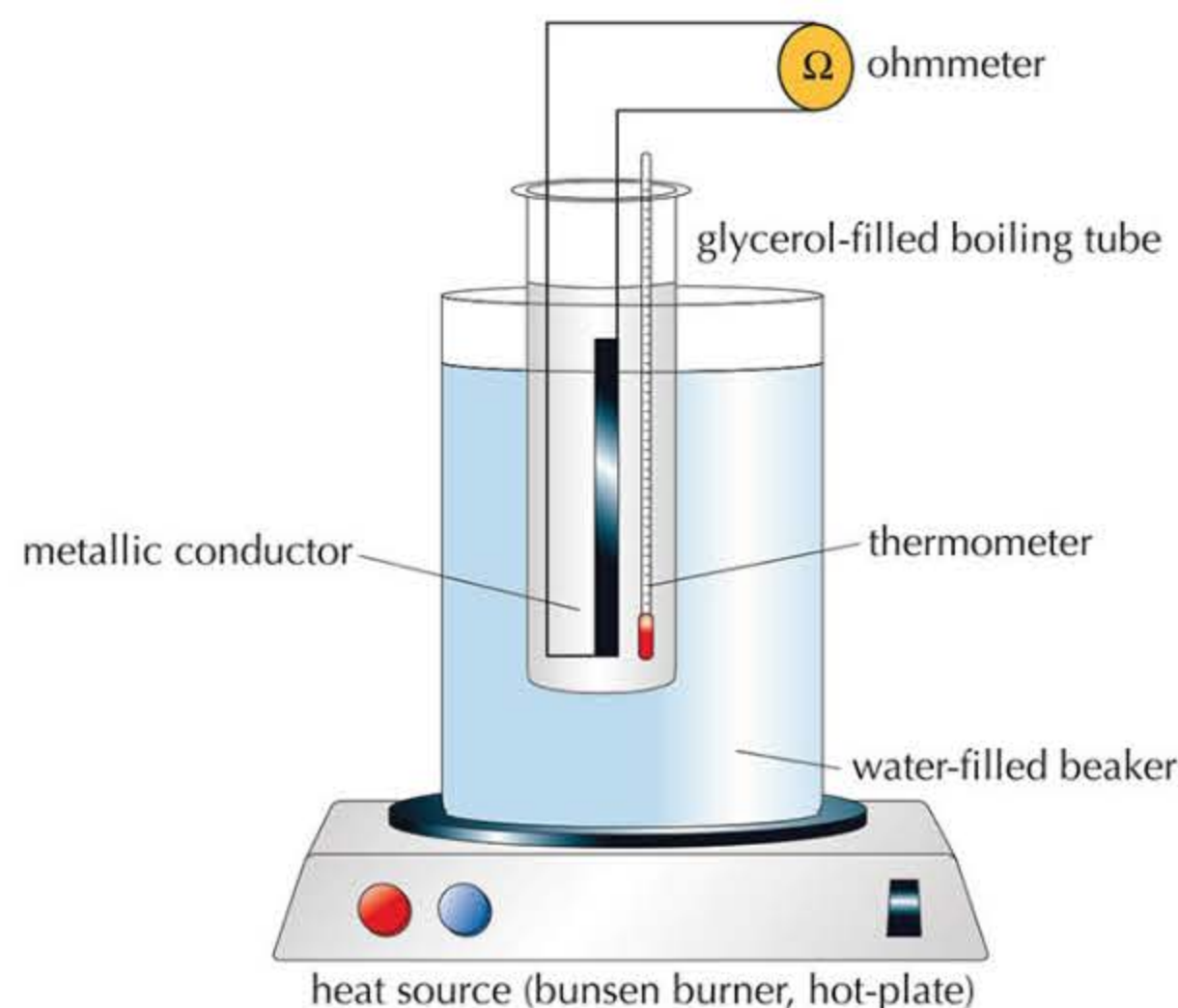
- It is difficult to determine when the resonance is at its peak.
- It helps to repeat the experiment several times.



Heat and temperature mandatory experiments

1 Calibration curve of a thermometer using the laboratory mercury thermometer as a standard

Apparatus

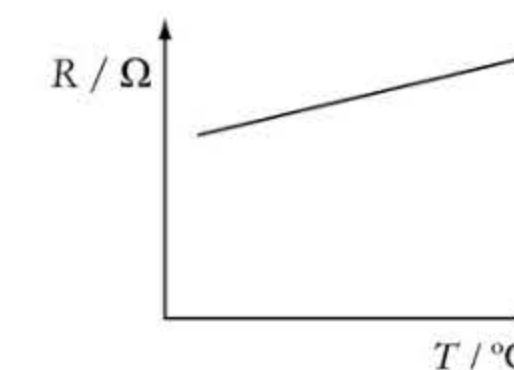


Method

- Set up apparatus as shown in the diagram.
- Record the temperature T , in $^{\circ}\text{C}$, from the mercury thermometer and the corresponding resistance R in ohms, from the ohmmeter.
- Allow the temperature of the glycerol to increase by about 10°C and again record the temperature and the corresponding resistance.
- Repeat the procedure several times.

Conclusion

Plot a graph of resistance R against temperature T . To measure temperature using the thermistor, measure the resistance and find the corresponding temperature from the calibration curve.



Remember

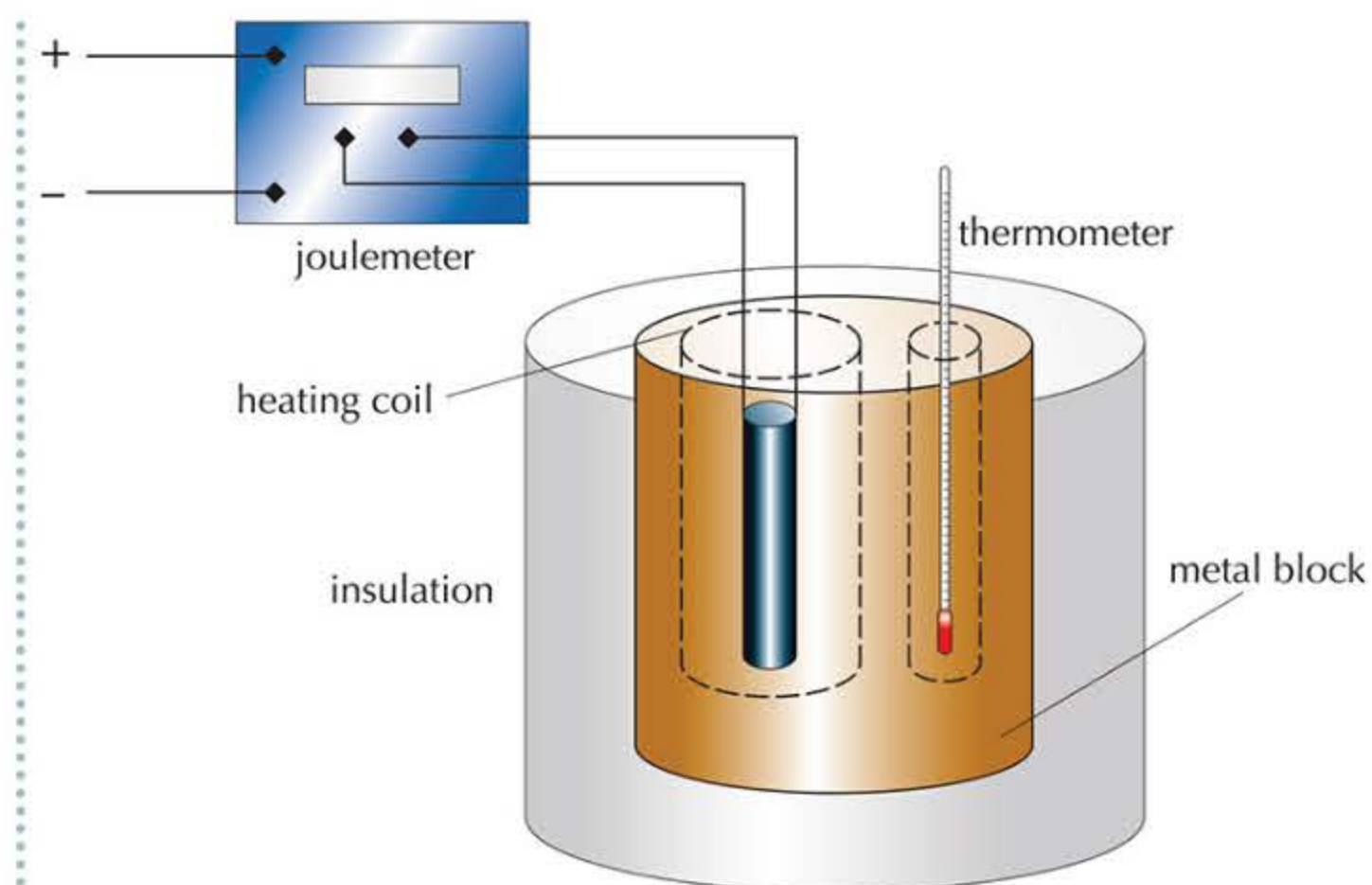
The same procedure can be followed to calibrate any thermometer.

Accuracy

The accuracy of the procedure is compromised by the relative inaccuracy of the mercury thermometer.

2 Measurement of the specific heat capacity of a metal by an electrical method

Apparatus



Method

- Find the mass of the metal block m .
- Set up the apparatus as shown in the diagram. Place the heater and thermometer in oil.
- Record the initial temperature of the metal block.
- Allow current to flow until there is a temperature rise of about 10°C .
- Switch off the power supply, allow time for the heat energy to spread throughout the metal block and record the highest temperature.
- Record the rise in temperature ΔT and the final joulemeter reading Q .

Conclusion Energy supplied electrically = energy gained by the metal block

$$Q = mc\Delta T \text{ where } c = \text{specific heat capacity}$$

$$c = \frac{Q}{m\Delta T}$$

Accuracy

Remember

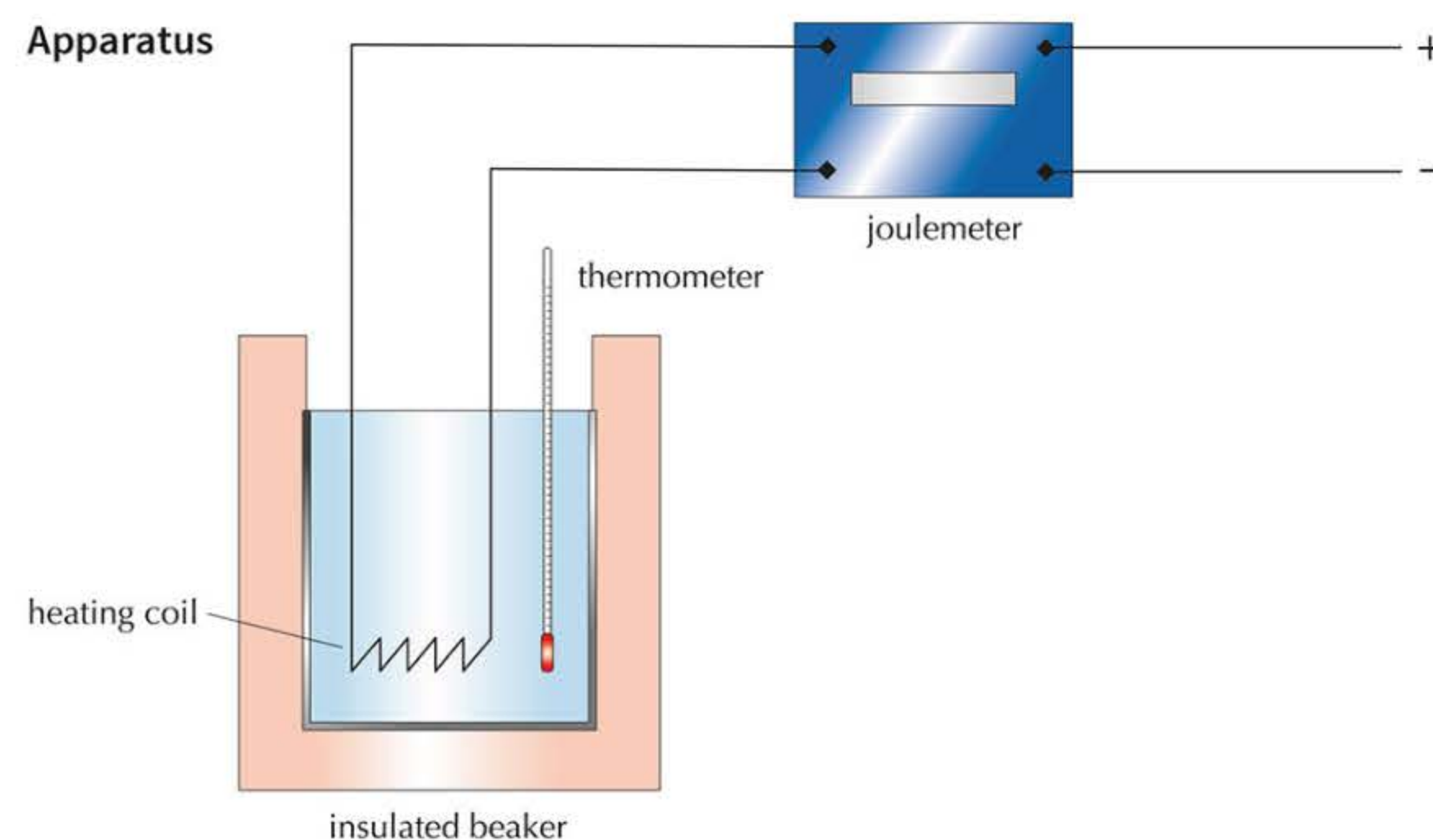
To improve accuracy we can begin by chilling the metal block.

Heat gained below room temperature will be cancelled by heat lost above room temperature.

A larger temperature change will reduce the percentage error.

3 Measurement of specific heat capacity of water by an electrical method

Apparatus



Method

- 1 Find the mass of the calorimeter.
- 2 Find the mass of the calorimeter plus the water, and use this to find the mass of the water. Note the initial temperature.
- 3 Allow current to flow until there is a temperature rise of about 10°C .
- 4 Switch off the power supply, stir the water and note the highest temperature.
- 5 Record the rise in temperature, ΔT , and the final joulemeter reading Q .

Conclusion Electrical energy supplied = energy gained by water + energy gained by calorimeter

$$\Rightarrow Q = (mc\Delta T)_{\text{water}} + (mc\Delta T)_{\text{calorimeter}}$$

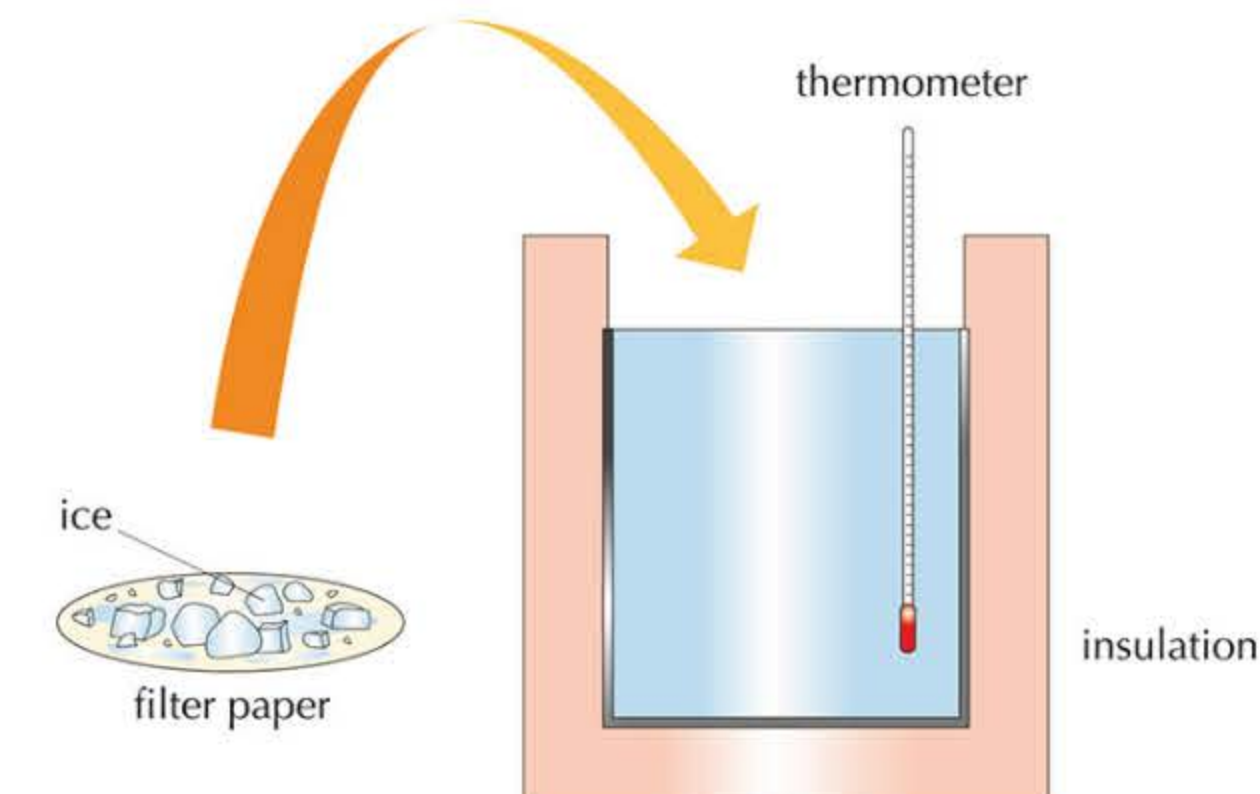
where c = specific heat capacity

Accuracy

- To improve accuracy we can begin by chilling the water. Heat gained below room temperature will be cancelled by heat lost above room temperature.
- A larger temperature change will reduce the percentage error.
- If a joulemeter is unavailable, the energy, Q , can be calculated using the formula: $Q = VIt$ where V = voltage I = current t = time.

4 Measurement of the specific latent heat of fusion of ice

Apparatus



Method

- 1 Place some ice cubes in a beaker of water and keep taking the temperature with the thermometer until the ice-water mixture reaches 0°C .
- 2 Find the mass of the calorimeter. Half fill the calorimeter with water warmed to approximately 10°C above room temperature. Find the combined mass of the calorimeter and water, and use this to find the mass of the water.
- 3 Record the initial temperature T_1 of the calorimeter plus water.

- 4 Surround the ice cubes with kitchen paper or a cloth and crush them between wooden blocks. Dry them with the kitchen paper and add the ice to the calorimeter until the temperature of the water has fallen by about 20°C .
- 5 Record the lowest temperature T_2 of the calorimeter plus water plus melted ice. The rise in temperature of the ice T_2 and the fall in temperature of the calorimeter plus water ΔT is $T_1 - T_2$.
- 6 Find the increase in mass of the calorimeter. This is the mass of the melted ice.

Conclusion Energy gained by ice = energy lost by calorimeter + energy lost by the water

$$(ml)_{\text{ice}} + (mcT_2)_{\text{ice/water}} = (mc\Delta T)_{\text{water}} + (mc\Delta T)_{\text{calorimeter}}$$

Accuracy

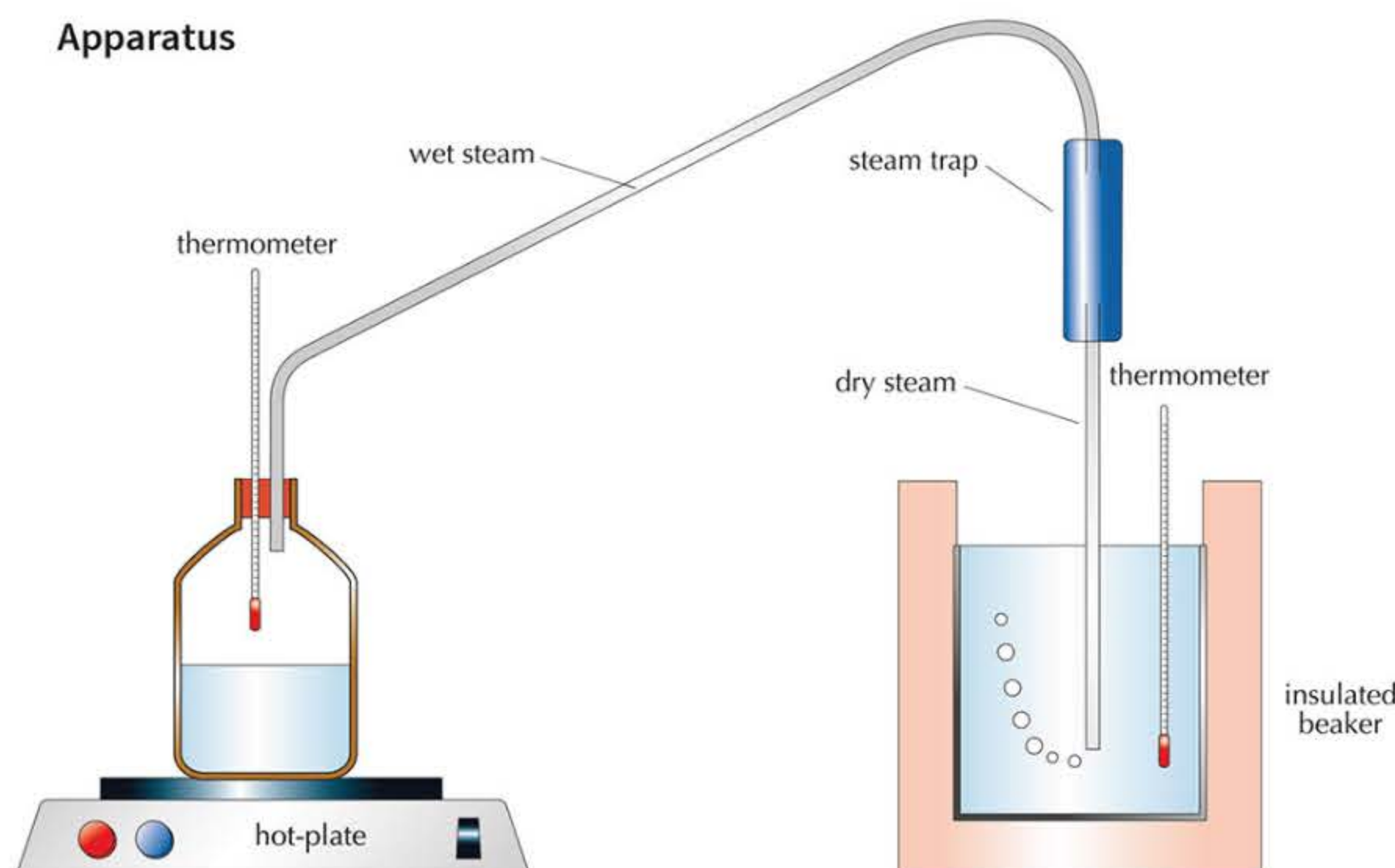
Remember

Warming the water beforehand ensures that heat lost above room temperature will be cancelled by heat gained below room temperature.

A large temperature change (such as 20°C) ensures a reduced percentage error.

5 Measurement of the specific latent heat of vaporisation of water

Apparatus



Method

- 1 Find the mass of the calorimeter.
- 2 Half fill the calorimeter with water cooled to approximately 10°C below room temperature. Find the mass of the water plus calorimeter, and hence the mass of the water. Record the temperature of the calorimeter plus water T_1 .
- 3 Allow dry steam to pass into the water in the calorimeter until the temperature has risen by about 20°C . Remove the steam delivery tube from the water, taking care not to remove any water from the calorimeter in the process.
- 4 Record the final temperature T_2 of the calorimeter plus water plus condensed steam. The fall in temperature of the steam ΔT_1 is $100 - T_2$.
- 5 The rise in the temperature of the calorimeter plus water ΔT is $T_2 - T_1$.
- 6 Find the mass of the calorimeter plus water plus condensed steam m_2 , and hence the mass of the condensed steam.

Conclusion Energy gained by steam = energy gained by calorimeter + energy gained by the water

$$(ml)_{\text{st}} + (mc\Delta T_1)_{\text{condensed steam}} = (mc\Delta T_2)_{\text{calorimeter}} + (mc\Delta T_2)_{\text{water}}$$

and l , the latent heat of vaporisation, can be calculated.

Accuracy

- Cooling the water beforehand ensures that heat lost above room temperature will be cancelled by heat gained below room temperature.
- A large temperature change (such as 20°C) ensures a reduced percentage error.

Exam questions

1 2007, HL, Section A, Q2

The specific heat capacity of water was found by adding hot copper to water in a copper calorimeter. The following data was recorded.

Mass of calorimeter	= 55.7 g
Mass of calorimeter + water	= 101.2 g
Mass of copper + calorimeter + water	= 131.4 g
Initial temperature of water	= 16.5°C
Temperature of hot copper	= 99.5°C
Final temperature of water	= 21.0°C

Describe how the copper was heated and how its temperature was measured. (9 marks)

Using the data, calculate:

- (i) the energy lost by the hot copper
- (ii) the specific heat capacity of water. (16 marks)

Give two precautions that were taken to minimise heat loss to the surroundings.

Explain why adding a larger mass of copper would improve the accuracy of the experiment. (15 marks)

(specific heat capacity of copper = $390 \text{ J kg}^{-1} \text{ K}^{-1}$)

2 2005, HL, Section A, Q2

In an experiment to measure the specific latent heat of vaporisation of water, cool water was placed in an insulated copper calorimeter. Dry steam was added to the calorimeter. The following data was recorded.

Mass of calorimeter	= 50.5 g
Mass of calorimeter + water	= 91.2 g
Initial temperature of water	= 10°C
Temperature of steam	= 100°C
Mass of calorimeter + water + steam	= 92.3 g
Final temperature of water	= 25°C

Calculate a value for the specific latent heat of vaporisation of water. The specific heat capacity of copper is $390 \text{ J kg}^{-1} \text{ K}^{-1}$ and the specific heat capacity of water is $4200 \text{ J kg}^{-1} \text{ K}^{-1}$. (24 marks)

Why was dry steam used? How was the steam dried? (10 marks)

A thermometer with a low heat capacity was used to ensure accuracy. Explain why. (6 marks)

3 2002, HL, Section A, Q2

In an experiment to measure the specific latent heat of fusion of ice, warm water was placed in an aluminium calorimeter. Crushed dried ice was added to the water. The following results were obtained.

Mass of calorimeter	= 77.2 g
Mass of water	= 92.5 g
Initial temperature of water	= 29.4°C
Temperature of ice	= 0°C
Mass of ice	= 19.2 g
Final temperature of water	= 13.2°C

Room temperature was 21°C. What was the advantage of having the room temperature approximately halfway between the initial temperature of the water and the final temperature of the water? (9 marks)

Describe how the mass of the ice was found. (9 marks)

Calculate a value for the specific latent heat of fusion of ice. The specific heat capacity of aluminium is $790 \text{ J kg}^{-1} \text{ K}^{-1}$ and the specific heat capacity of water is $4180 \text{ J kg}^{-1} \text{ K}^{-1}$. (15 marks)

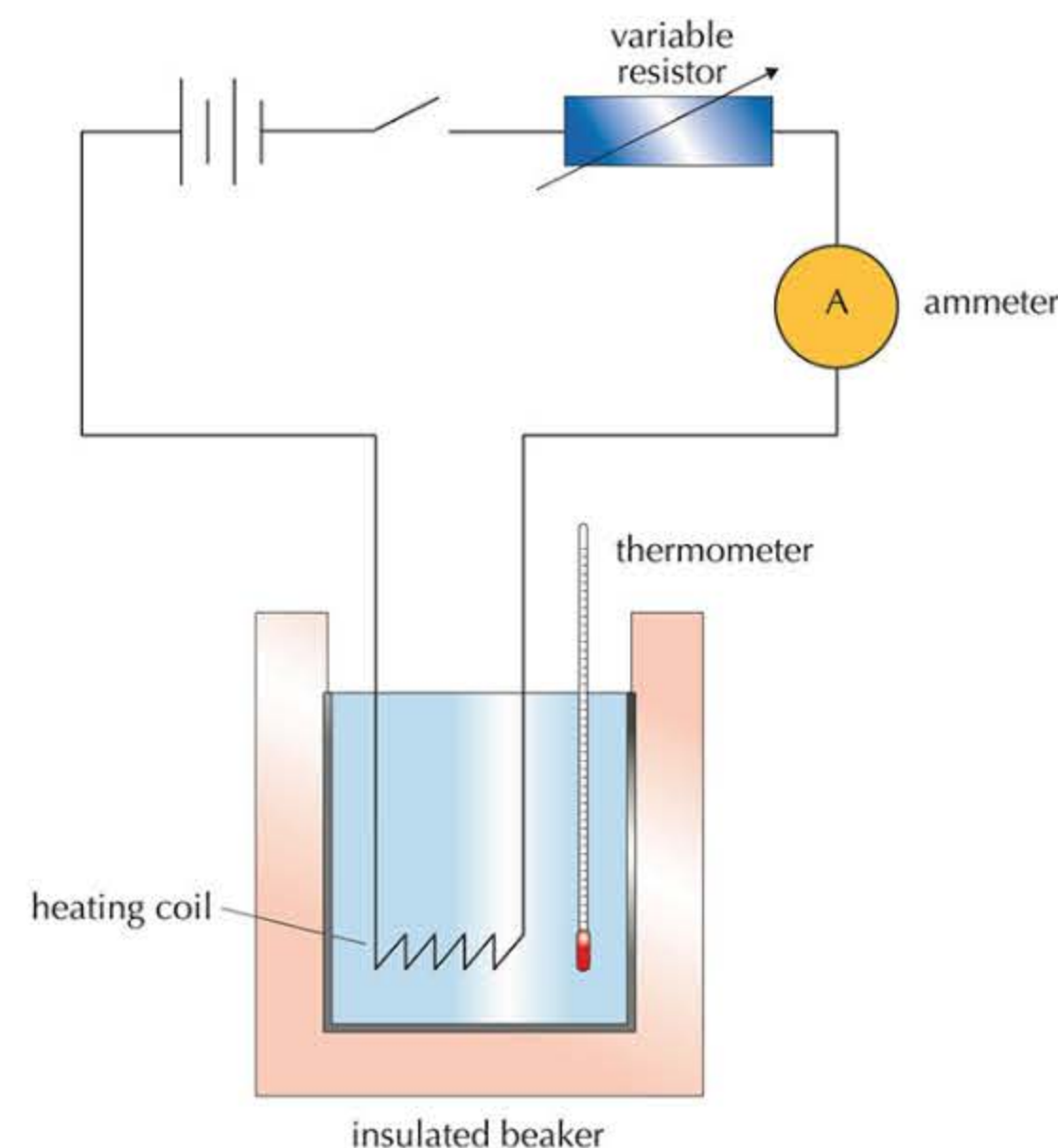
The accepted value for the specific latent heat of fusion of ice is $3.3 \times 10^5 \text{ J kg}^{-1}$. Suggest **two** reasons why your answer is not this value. (7 marks)



Electricity mandatory experiments

1 Verification of Joule's law (as $\Delta T \propto I^2$)

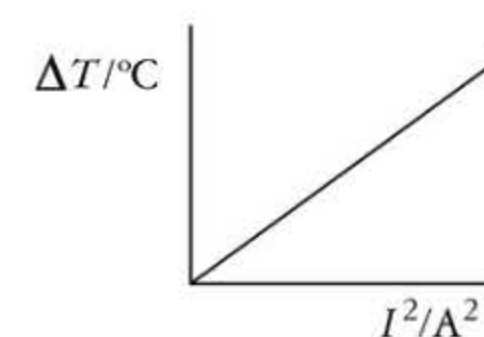
Apparatus



Method

- 1 Set up the apparatus as shown in the diagram. Note the initial temperature.
- 2 Switch on the power and simultaneously start the stopwatch. Allow a current of 0.5 A to flow for five minutes, adjusting the rheostat if necessary to keep the current constant.
- 3 Stir and note the highest temperature. Calculate the change in temperature ΔT .
- 4 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.

Conclusion Plot a graph of ΔT against I^2 .



Remember

Joule's law actually states that $P \propto I^2$, where P is the power, but: $P = \frac{\text{energy}}{\text{time}} = \frac{mc \Delta T}{t}$

If mass and time are kept constant, as is the case here, we can say that $P \propto \Delta T$

Therefore, if $\Delta T \propto I^2$, we can conclude that $P \propto I^2$

A straight-line graph through the origin verifies that $\Delta T \propto I^2$, i.e. Joule's law.

Accuracy

- 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.

Exam question

2006, HL, Section A, Q4

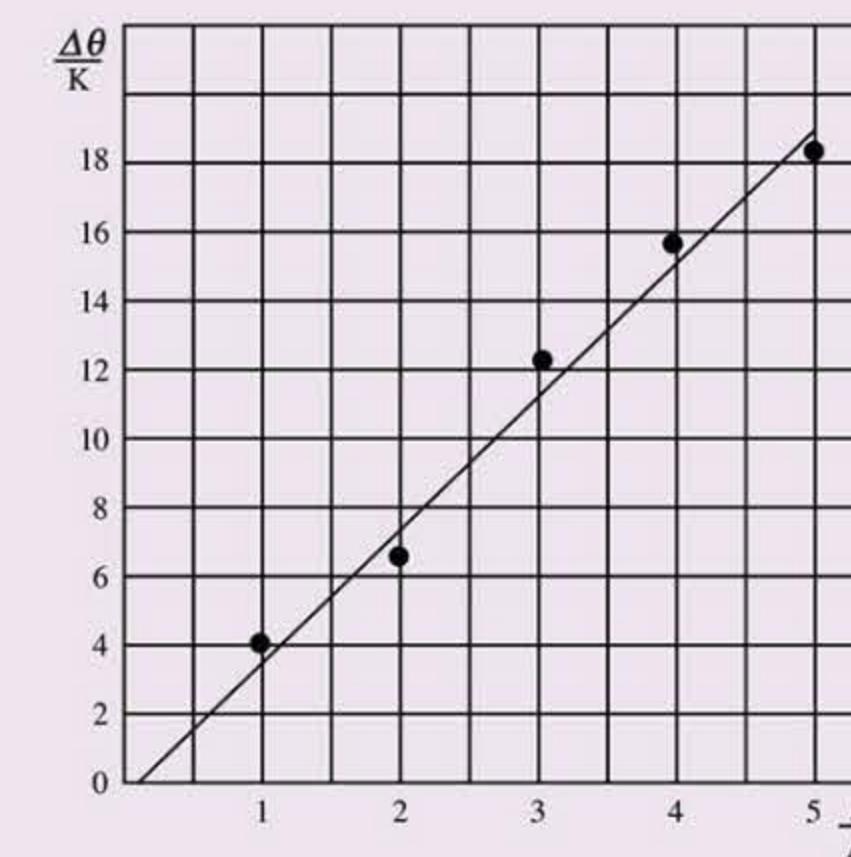
In an experiment to verify Joule's law a student passed a current through a heating coil in a calorimeter containing a fixed mass of water and measured the rise in temperature $\Delta\theta$ for a series of different values of the current I . The student allowed the current to flow for three minutes in each case.

Describe, with the aid of a labelled diagram, how the student arranged the apparatus. (12 marks)

Why was a fixed mass of water used throughout the experiment? (6 marks)

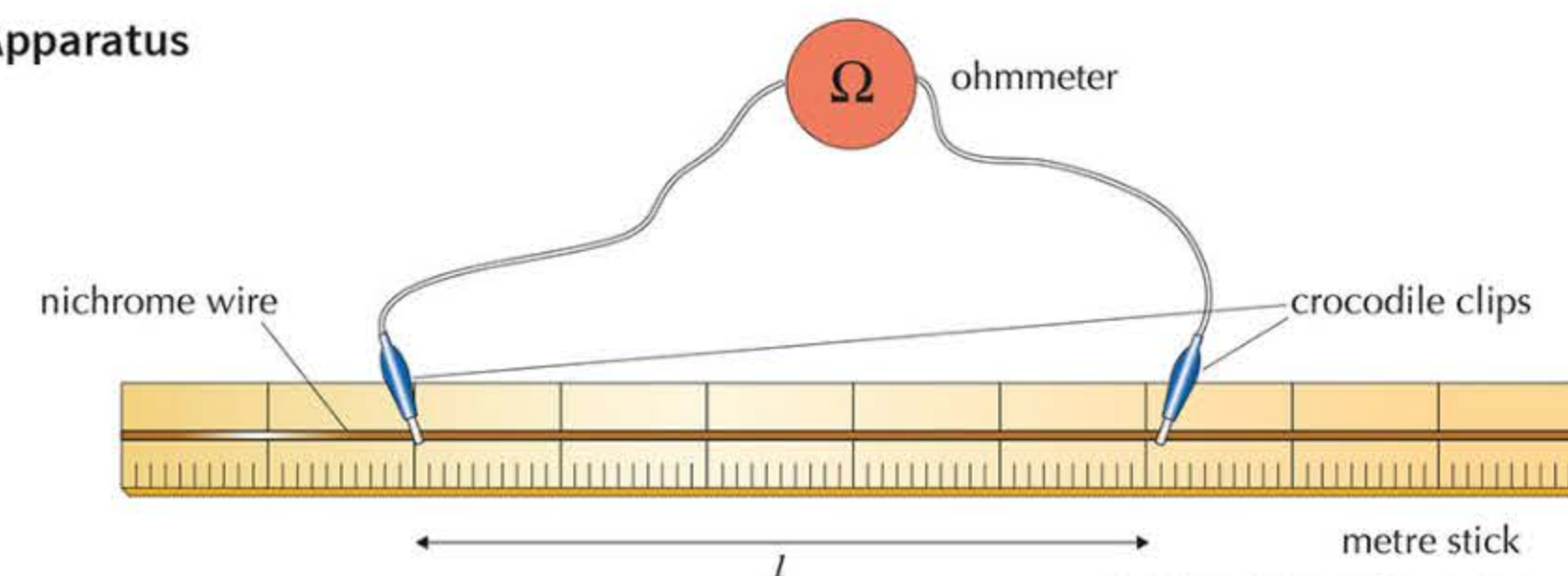
The student drew a graph, as shown. Explain how this graph verifies Joule's law. (7 marks)

Given that the mass of water in the calorimeter was 90 g in each case, and assuming that all of the electrical energy supplied was absorbed by the water, use the graph to determine the resistance of the heating coil. The specific heat capacity of water is $4200 \text{ J kg}^{-1} \text{ K}^{-1}$. (15 marks)



2 To measure the resistivity of the material of a wire

Apparatus



Method

- 1 Set up the apparatus as shown in the diagram. Ensure that the resistance of the leads when the crocodile clips are connected together is zero.
- 2 Note the resistance, R , for a particular length, l , of wire.
- 3 Increase the distance between the crocodile clips. Measure the new values of R and l .
- 4 Make a note of the zero error on the micrometer. 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 .
- 5 Repeat this procedure for a number of different lengths.

Conclusion

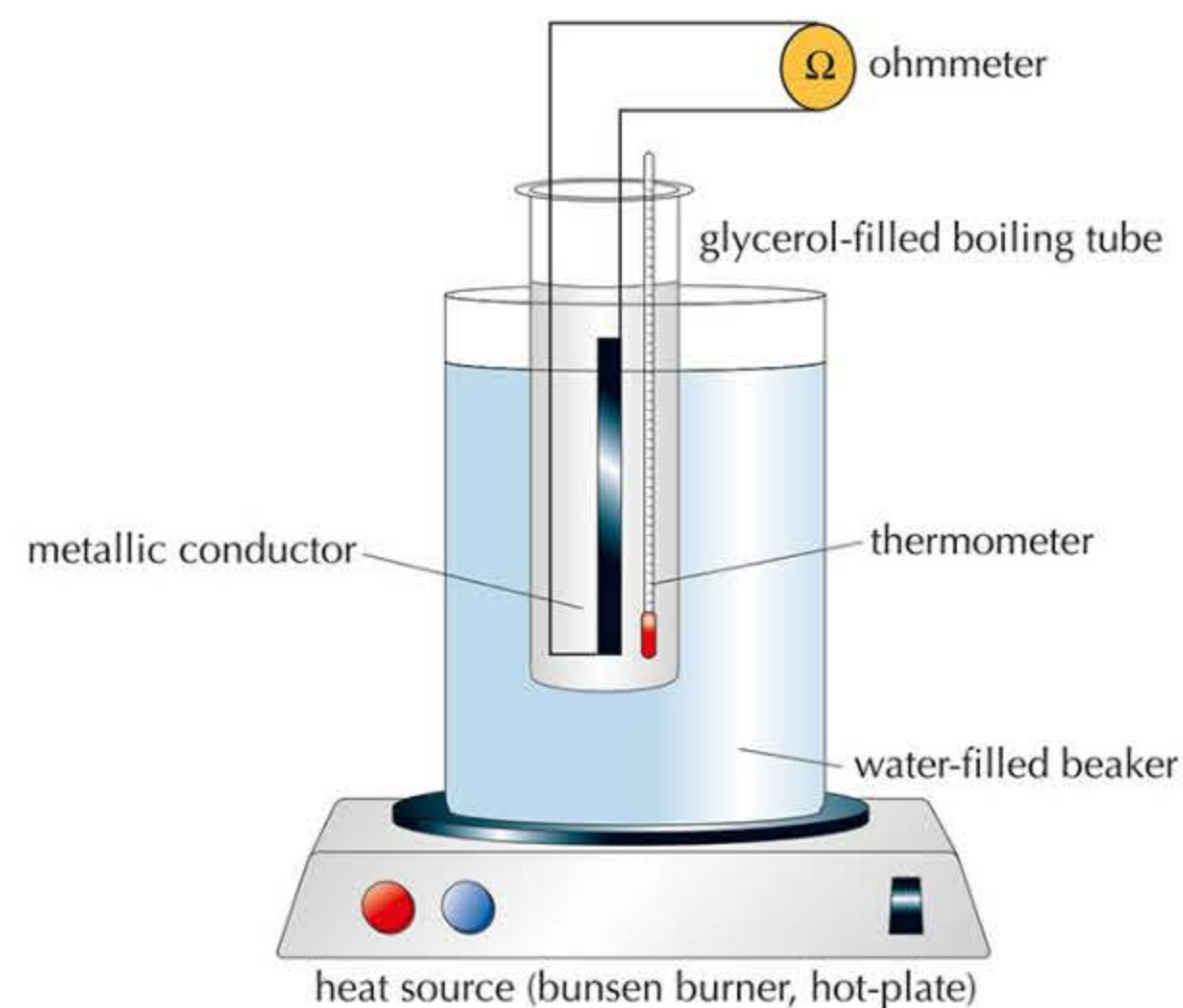
For each set of results, calculate the resistivity using the formula:

$$\rho = \left(\frac{R}{l} \right) A, \text{ (where } A = \pi r^2 \text{).}$$

Take the average value as the resistivity.

Accuracy

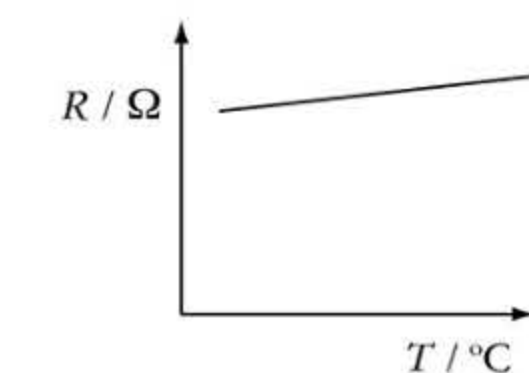
- Kinks in the wire will affect the measurement of both length and cross-sectional area.
- Greater lengths will reduce the percentage error.

3 To investigate the variation of the resistance of a metallic conductor with temperature**Apparatus****Method**

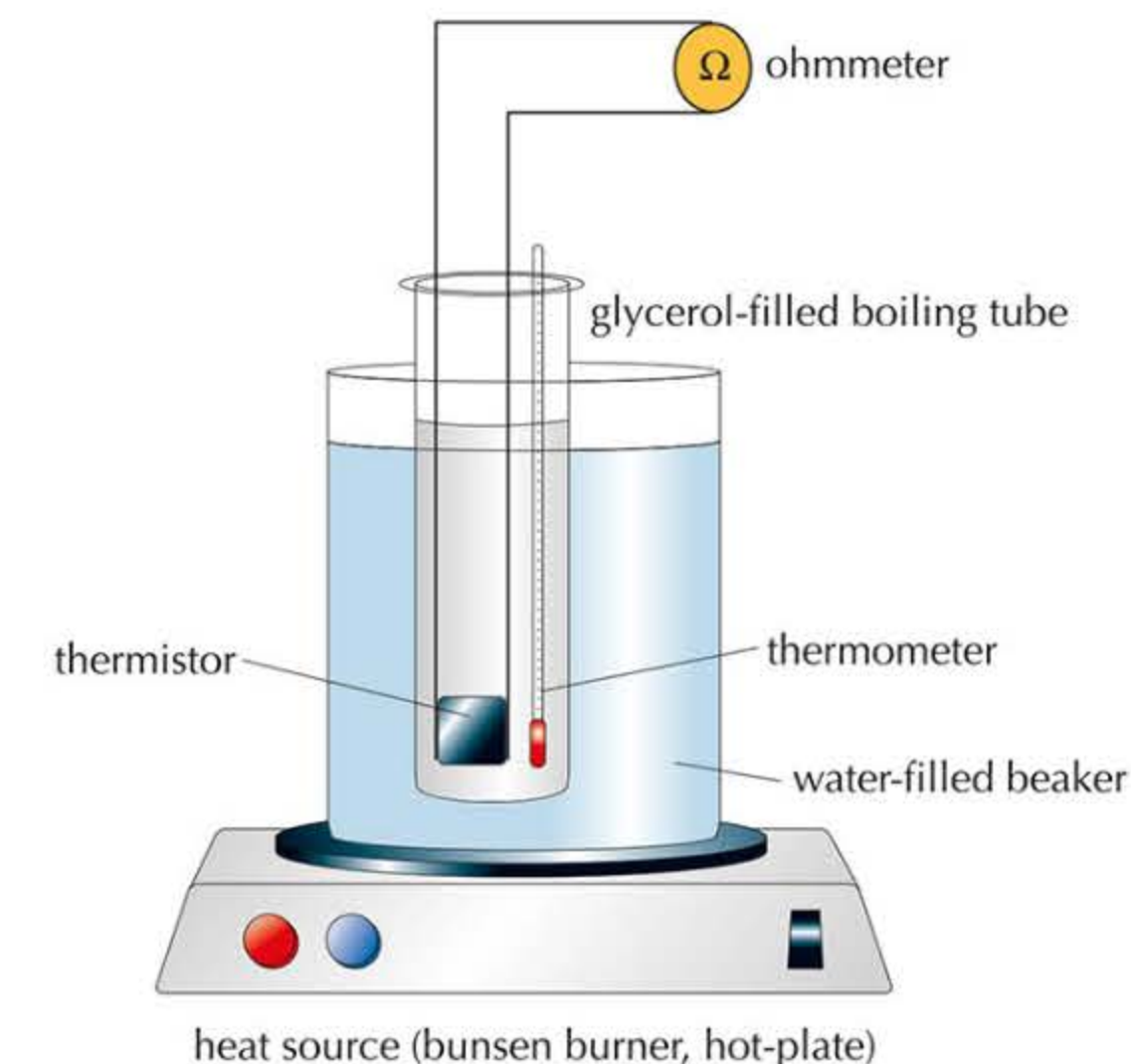
- 1 Set up the apparatus as shown in the diagram.
- 2 Use the thermometer to note the temperature of the glycerol, which is also the temperature of the coil.
- 3 Record the resistance of the coil of wire using the ohmmeter.
- 4 Slowly heat the beaker.
- 5 For each 10°C rise in temperature record the resistance and temperature using the ohmmeter and the thermometer.

Conclusion

Plot a graph of resistance against temperature.

**Accuracy**

- It is important to slowly heat the water, to avoid a situation where the liquid will be much hotter than the wire.
- It is important to use as accurate a thermometer as possible.

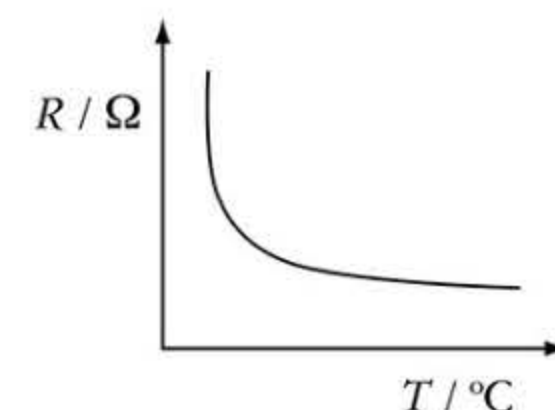
4 To investigate the variation of the resistance of a thermistor with temperature**Apparatus**

Method

- 1 Set up the apparatus as shown in the diagram.
- 2 Use the thermometer to note the temperature of the glycerol, and therefore of the thermistor.
- 3 Record the resistance of the thermistor using the ohmmeter.
- 4 Heat the beaker.
- 5 For each 10°C rise in temperature, record the resistance and the temperature using the ohmmeter and the thermometer.

Conclusion

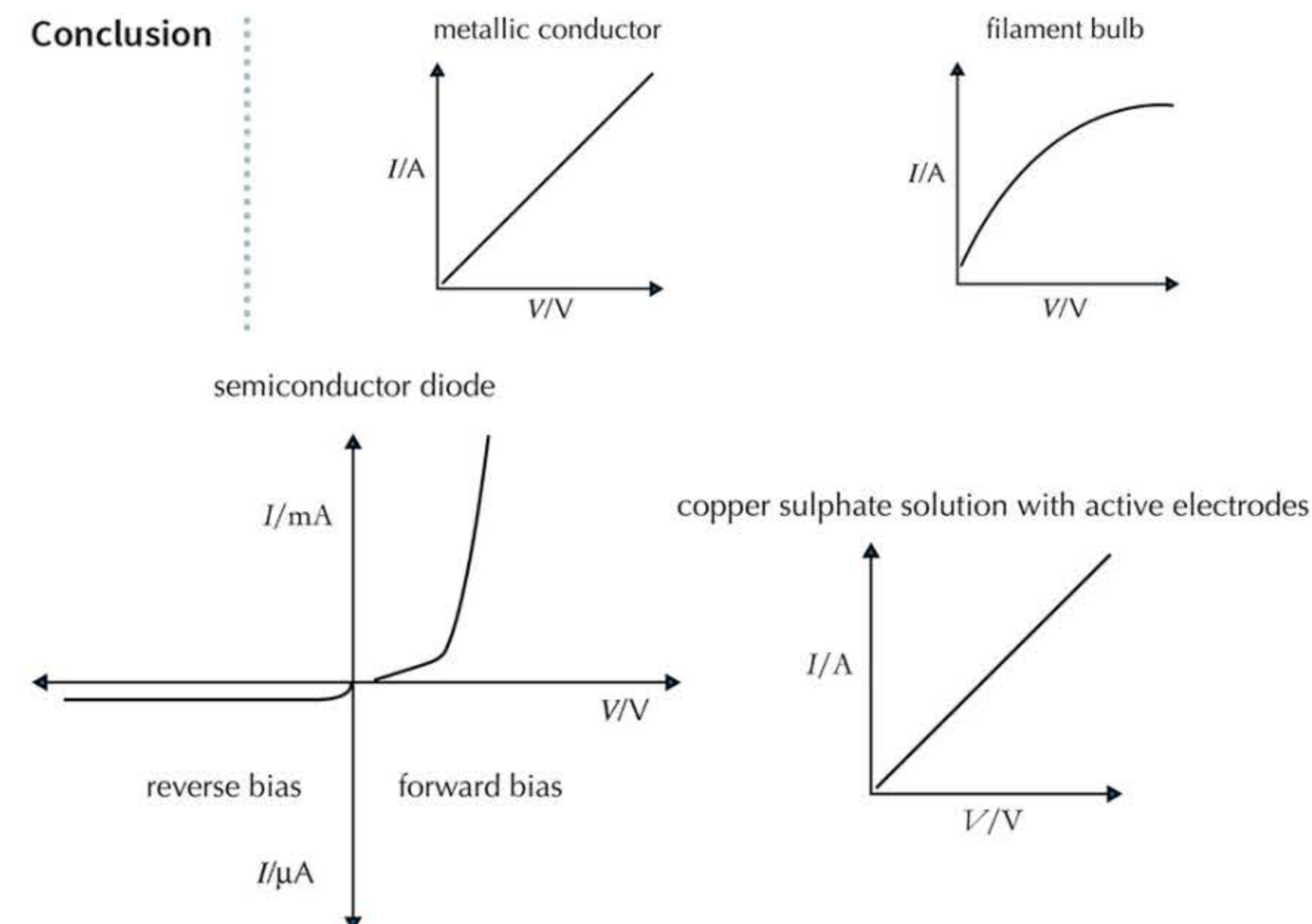
Plot a graph of resistance against temperature.



Accuracy

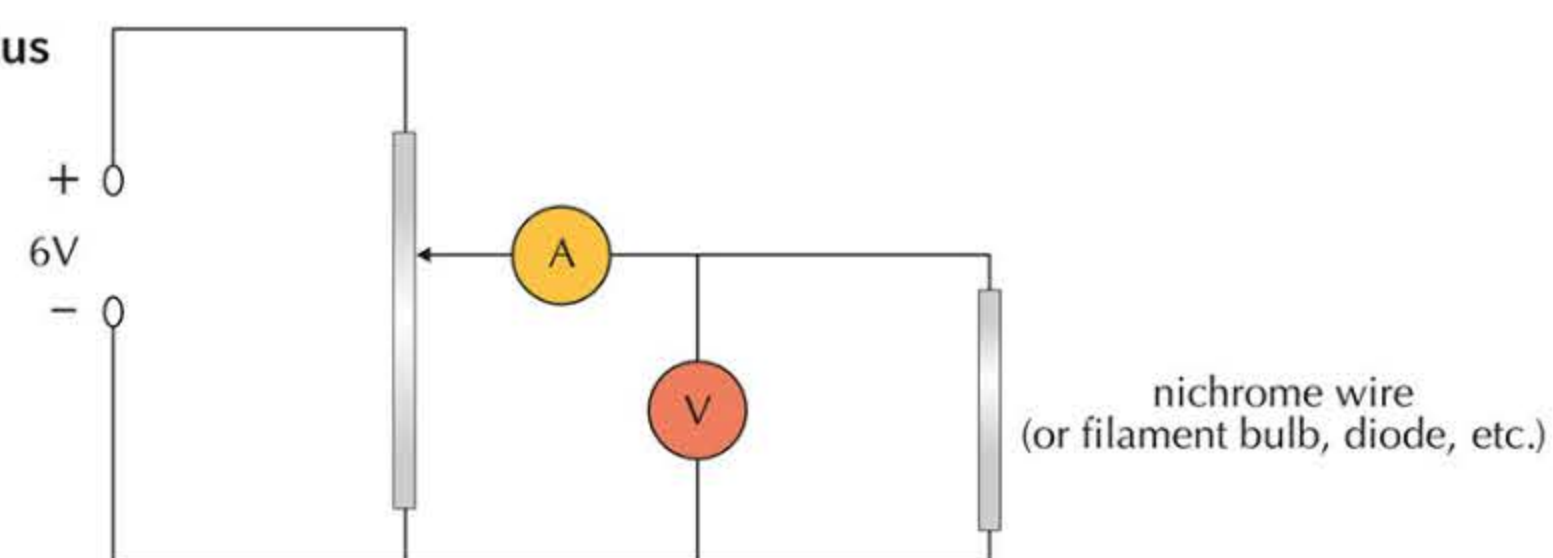
- It is important to slowly heat the water, to avoid a situation where the water will be much hotter than the wire.
- It is important to use as accurate a thermometer as possible.

Conclusion



5 To investigate the variation of current (I) with p.d. (V) for a metallic conductor, etc.

Apparatus



Method

- 1 Set up the circuit as shown in the diagram and set the voltage supply at, say, 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 these various devices.

Exam questions

1 2007, HL, Section A, Q4

The following is part of a student's report of an experiment to investigate the variation of current I with potential difference V for a semiconductor diode.

I put the diode in forward bias as shown in the circuit diagram. I increased the potential difference across the diode until a current flowed. I measured the current flowing for different values of the potential difference. I recorded the following data.

V/V	0.60	0.64	0.68	0.72	0.76	0.80
I/mA	2	4	10	18	35	120

Draw a circuit diagram used by the student.

How did the student vary and measure the potential difference? (15 marks)

Draw a graph to show how the current varies with the potential difference.

Estimate from your graph the junction voltage of the diode. (12 marks)

The student then put the diode in reverse bias and repeated the experiment.

What changes did the student make to the initial circuit?

Draw a sketch of the graph obtained for the diode in reverse bias. (13 marks)

2 2008, HL, Section A, Q4

A student investigated the variation of the resistance R of a metallic conductor with its temperature θ .

The student recorded the following data.

$\theta/^{\circ}\text{C}$	20	30	40	50	60	70	80
R/Ω	4.6	4.9	5.1	5.4	5.6	5.9	6.1

Describe, with the aid of a labelled diagram, how the data was obtained. (9 marks)

Draw a suitable graph to show the relationship between the resistance of the metal conductor and its temperature. (12 marks)

Use your graph to:

- estimate the resistance of the metal conductor at a temperature of -20°C ;
- estimate the change in resistance for a temperature increase of 80°C ;
- explain why the relationship between the resistance of a metallic conductor and its temperature is **not** linear. (19 marks)

3 2013, HL, Section A, Q4

A student was asked to investigate the variation of current with potential difference for a thin metallic conductor. The student set up a circuit using appropriate equipment. The student recorded the values of the current I passing through the conductor for the corresponding values of potential difference V . The recorded data are shown in the table.

V/V	1.0	2.0	3.0	4.0	5.0	6.0
I/A	0.17	0.34	0.50	0.64	0.77	0.88

Draw and label the circuit diagram used by the student.

Name the device in the circuit that is used to vary the potential difference across the conductor.

Explain how the student used this device to vary the potential difference. (18 marks)

Use the data in the table to draw a graph on graph paper to show the variation of current with potential difference. Use your graph to find the value of the resistance of the conductor when the current is 0.7 A . (15 marks)

Explain the shape of your graph. (7 marks)

Demonstration Experiments 2

Learning objectives

In this chapter you will learn about:

The demonstration experiments, focusing on:

- 1 Method (including diagrams)
- 2 Observations
- 3 Conclusions

Section B in the examination may include questions on these experiments.



Exam brief

In **Section B** of the examination paper, the questions may ask you to briefly describe some experiments that you have not performed yourself, but that you might have seen carried out in the classroom and should have read about. In answering these you should lay out the description in a formal manner, including **aim, method, observations, conclusions** and a good **labelled diagram**.

There is no definitive list of the experiments that you could be asked to describe, but those shown here are mentioned in the syllabus and should cover most questions of this nature.



Mechanics demonstration experiments

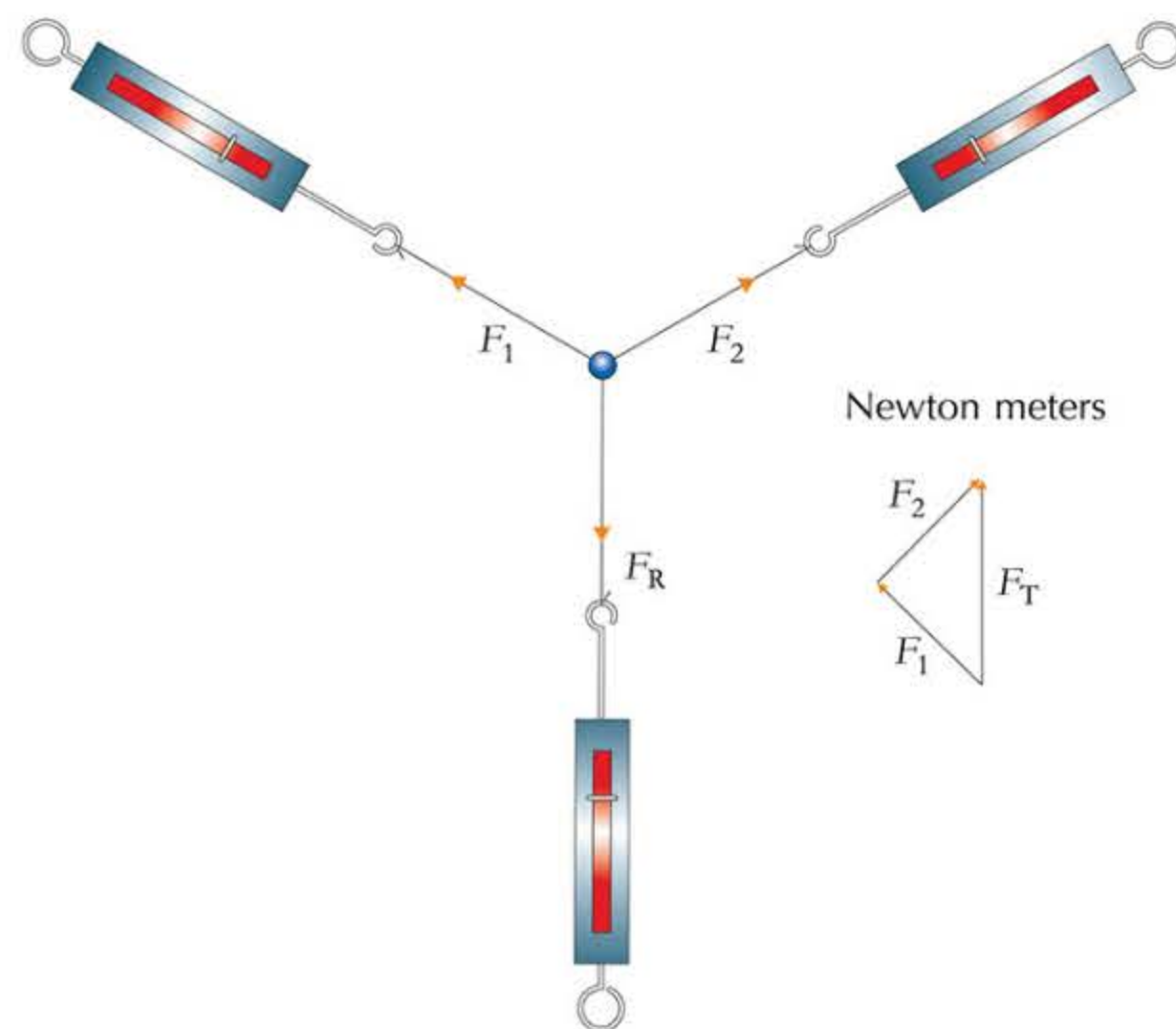
1 To find the resultant of vectors

Method

- Set up apparatus as shown on page 40. Ensure that the point at which the strings meet is stationary.
- Note the readings on the first two Newton meters.
- The resultant, F_1 , could be calculated using vector addition.

Observation

- According to Newton's third law, this should be equal in magnitude but opposite in direction to F_R .
- This demonstrates that our method of adding vectors is valid.
- We can therefore use either vector addition or this experimental method to find the resultant of two vectors.



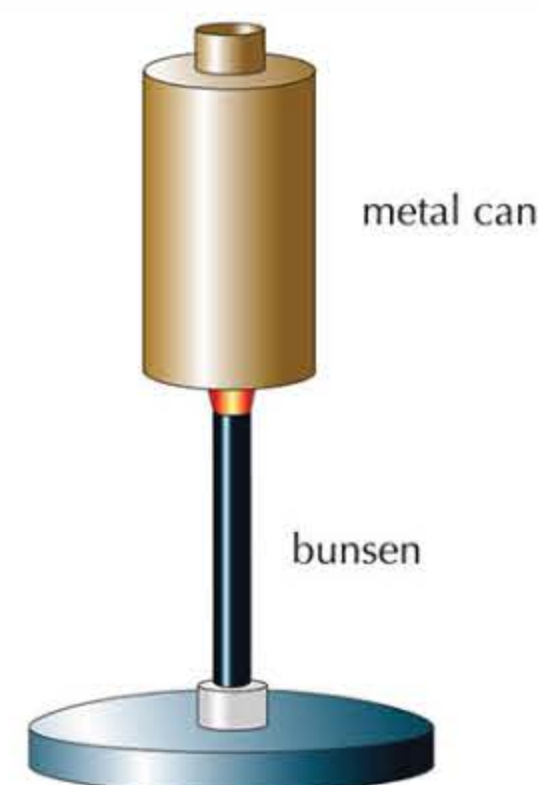
2 To demonstrate atmospheric pressure

Method

- 1 Set up apparatus as shown in the diagram.
- 2 Heat the can for a period with the lid removed, so that the water inside boils.
- 3 Remove the can from the heat and tightly replace the lid.
- 4 Let the can cool.

Observation The can becomes crushed as the air cools.

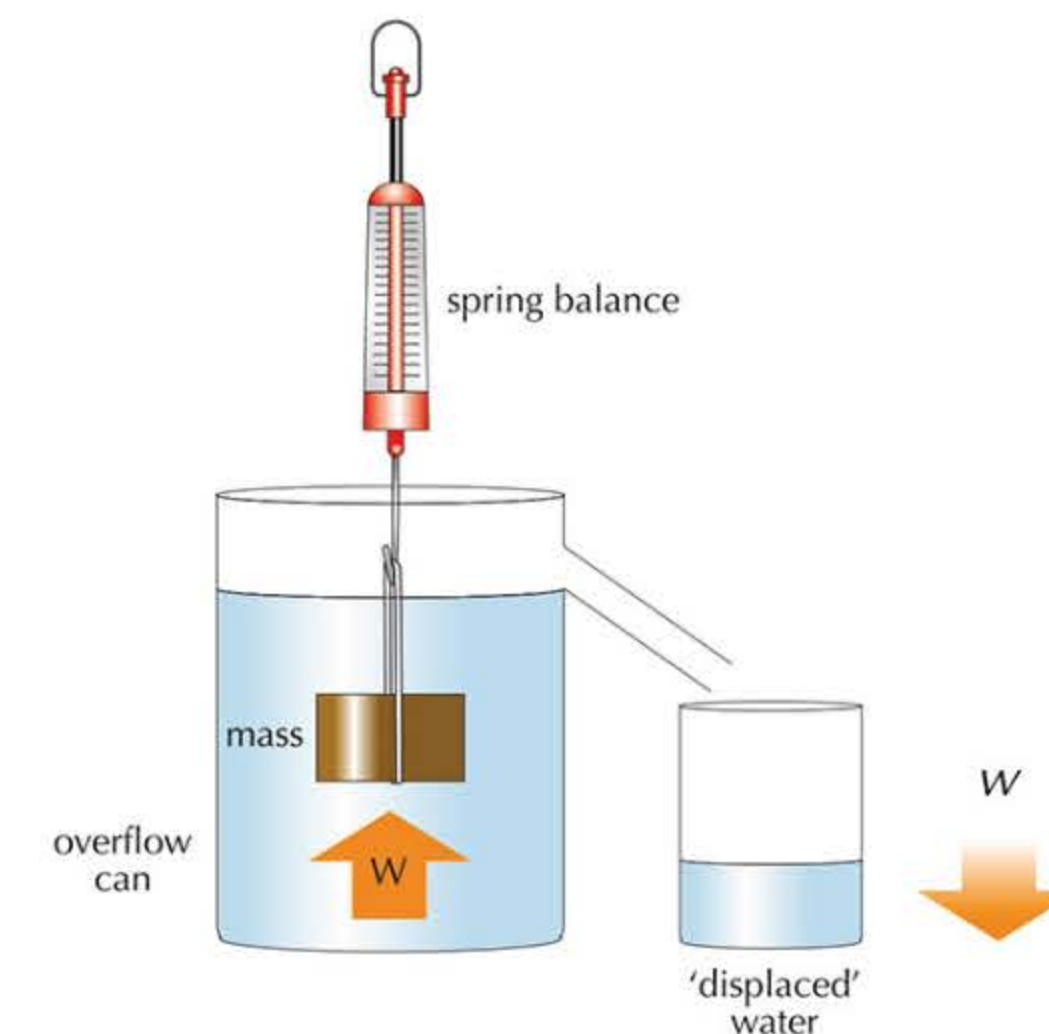
Conclusion This demonstrates the effect of atmospheric pressure, which is acting on the outside of the can, but is no longer balanced by an equal pressure from within.



3 To demonstrate Archimedes' principle

Method

- 1 Set up apparatus as shown in the diagram at the top of the opposite page.
- 2 Hang the mass from the spring balance and note the reading.
- 3 Lower the mass into the water and again note the reading.
- 4 Find the weight of the displaced water.



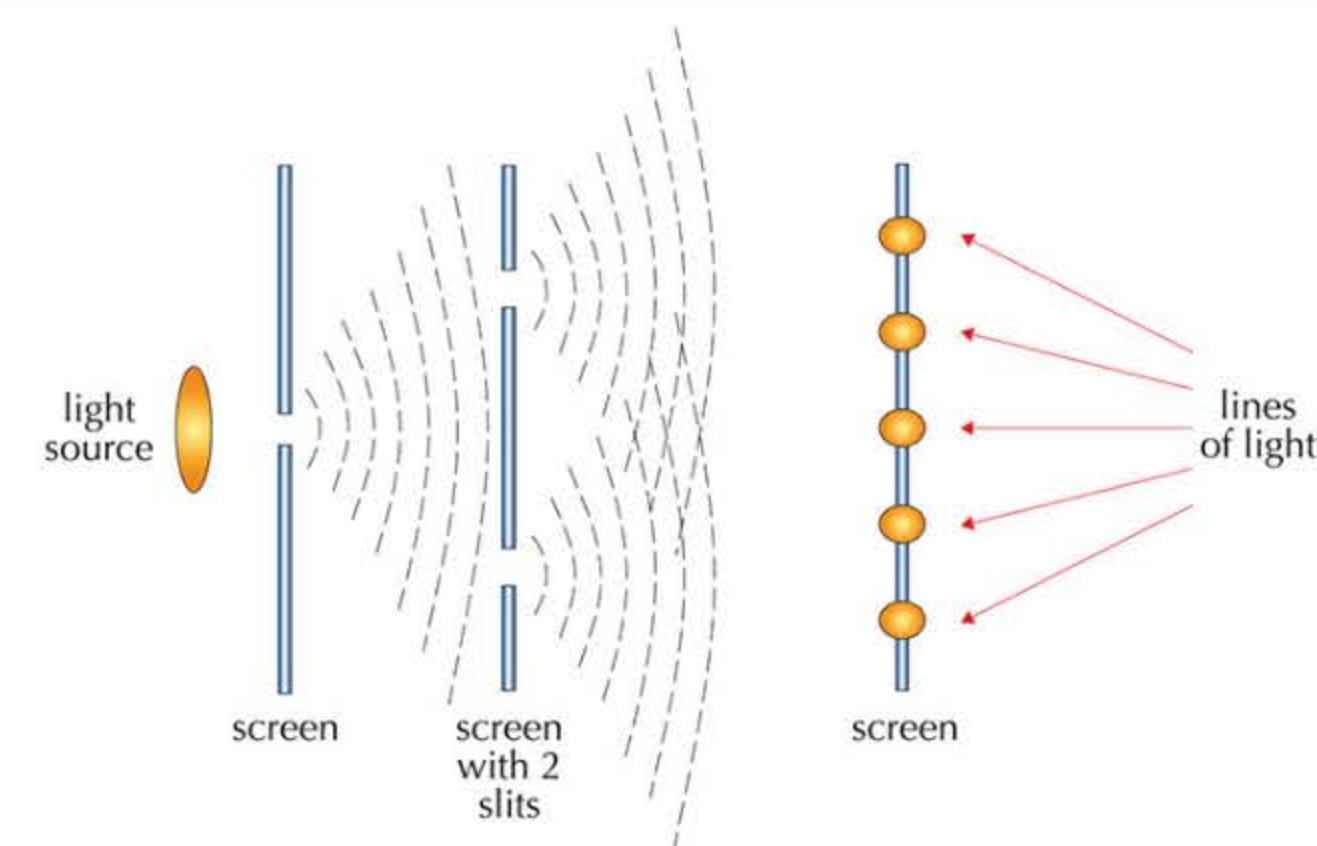
Observation When the mass is lowered into the water, the reading on the spring balance is reduced by ' W ' newtons. This is the upwards force experienced by the mass.

Conclusion The weight of the displaced water will also be equal to ' W ', indicating that an object immersed in a fluid will experience an upthrust equal in magnitude to the weight of the fluid displaced.



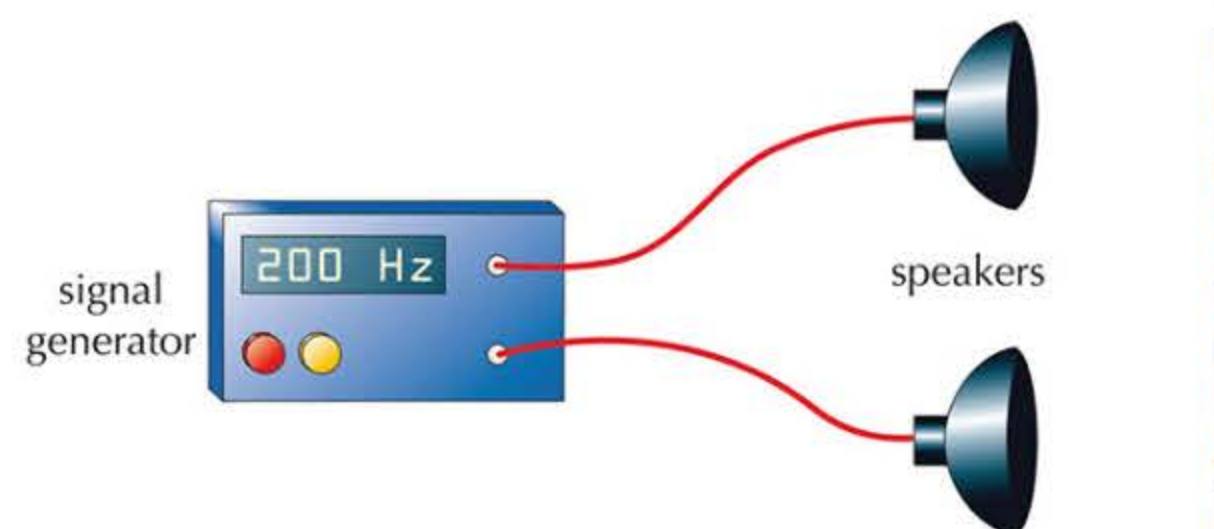
Light, sound and waves demonstration experiments

1 To show that light is a wave (Young's double slit experiment)



- Method**
- 1 A single light source is placed behind a screen.
 - 2 The light passes through this screen and encounters another, with two slits, thus creating coherent sources.
 - 3 A third and final screen is found beyond this one.
- Observation** A pattern is found on the screen as shown in the diagram. The pattern can only be explained if light is a wave, which diffracts at each of the two slits, and creates an interference pattern as the resulting waves meet.
- Conclusion** As diffraction and interference are wave characteristics, this demonstrates that light is a wave.

2 To show that sound is a wave



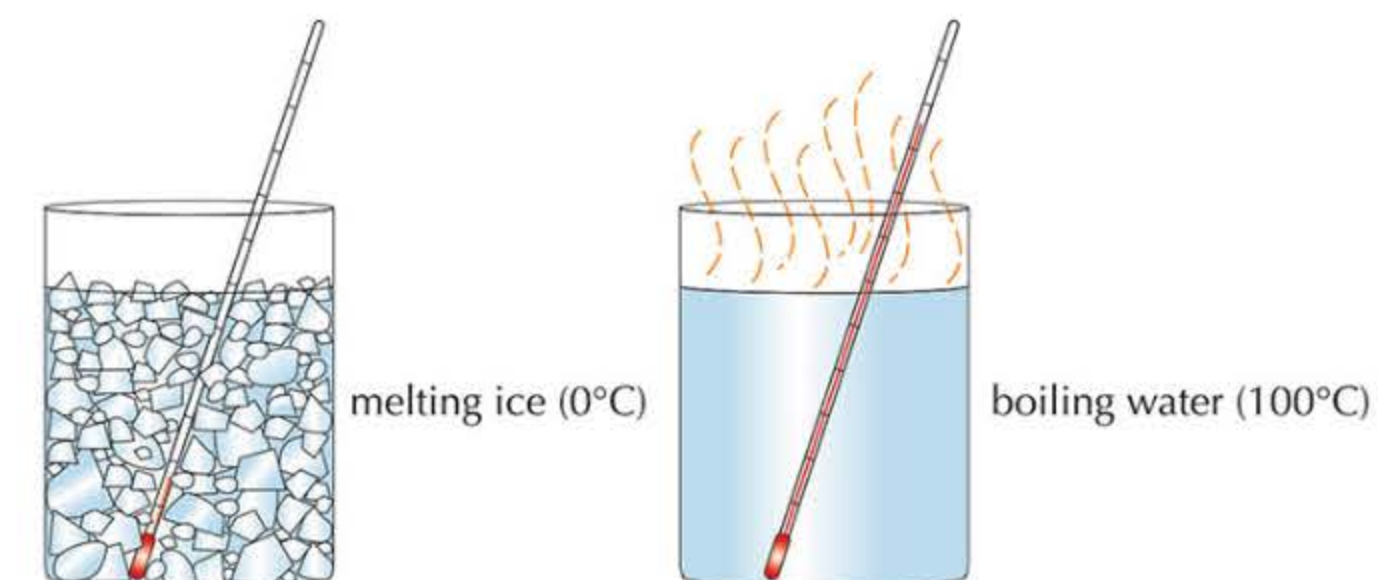
- Method** A single signal generator is connected to two speakers, thus creating coherent waves.
- Observation** Walking along the dotted line shown in the diagram, we would hear the sound repetitively grow and fall in volume.
- Conclusion** This can only be explained if the sound is creating an interference pattern, thus demonstrating that sound is a wave.



Heat and temperature demonstration experiment

Using the ice and steam points to calibrate a thermometer

- Method**
- 1 Place a thermometer in melting ice, as shown in the diagram at the top of the opposite page; wait until the line in the thermometer is stationary.
 - 2 Mark the length of the column of mercury.
 - 3 Place the thermometer in boiling water.
 - 4 Again mark the length of the column of mercury.



- Conclusion** You can then either:
- Divide the length between the marks on the thermometer into 100 even units, each representing 1°C .
 - or
 - Graph the results, and use the graph to find the value of any unknown temperature.

Remember

The length of a column of mercury is only one possible thermometric property. The experiment could also be carried out using any other such property, e.g.

- The resistance of a metal
- The emf of a thermocouple.

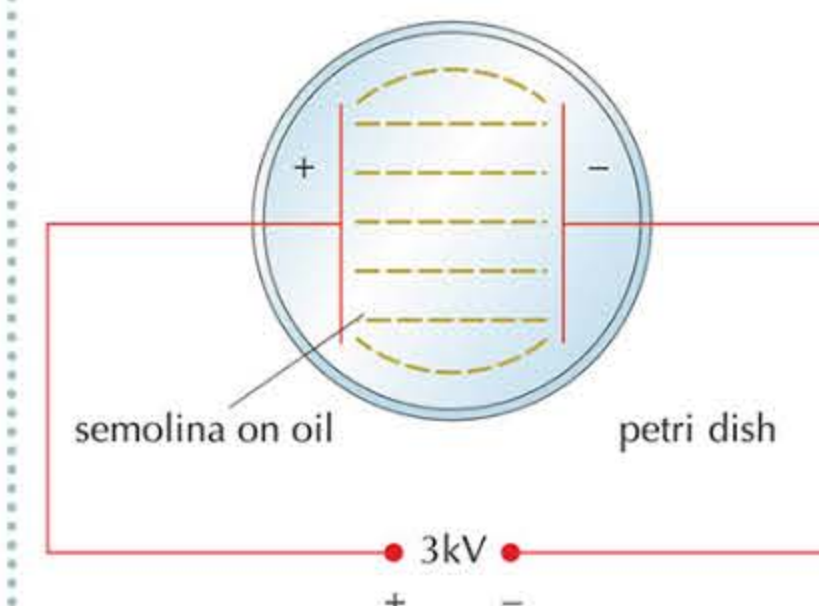


Electricity demonstration experiments

1 To demonstrate an electric field

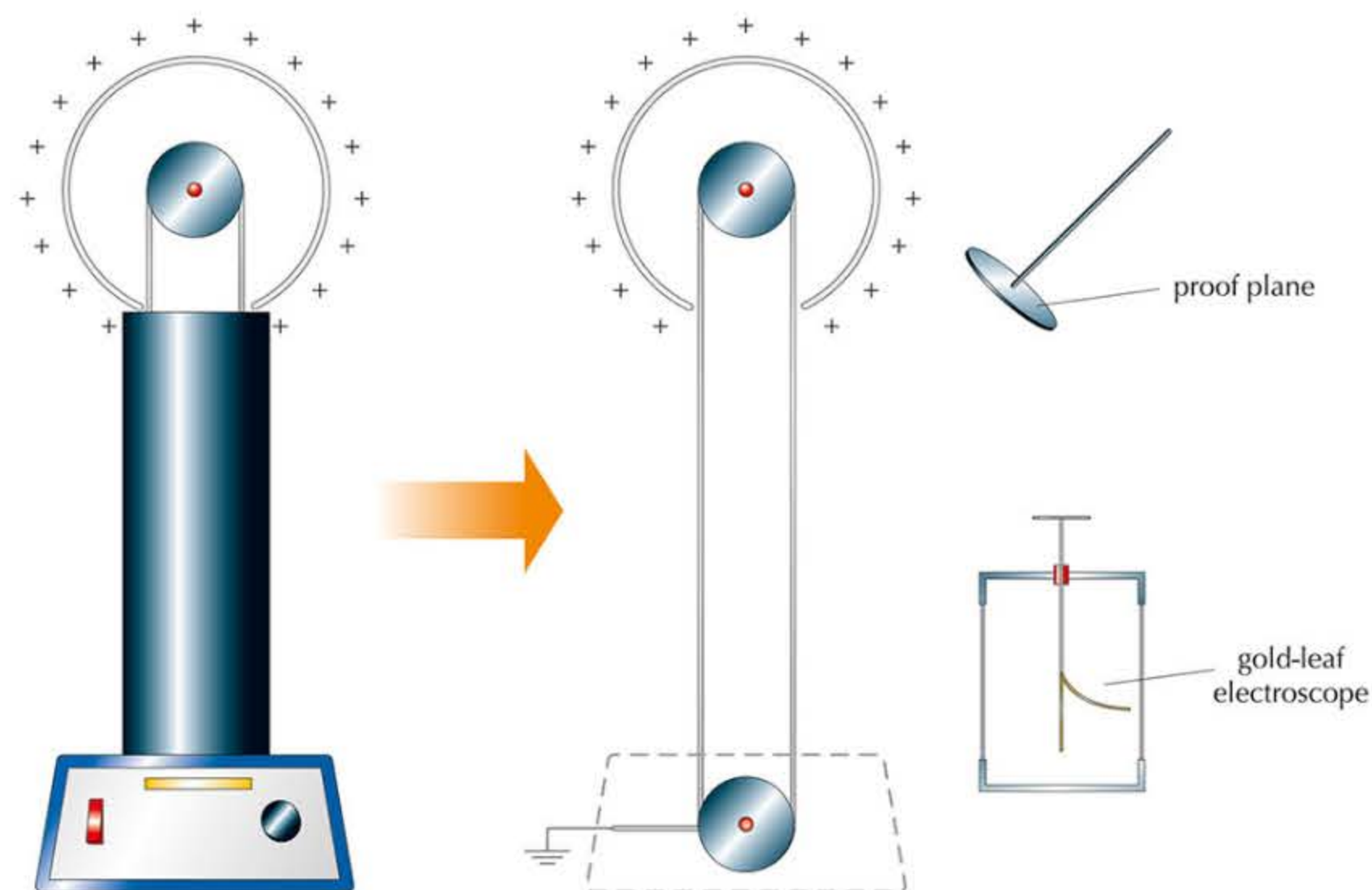
- Method**
- 1 Add some semolina to a shallow dish of oil.
 - 2 Attach electrodes as shown in the diagram.

- Observation** The semolina (rice) particles become slightly charged at each end, and line up along the lines of force, showing the shape of the electric field.



See section on the electroscope, p. 137.

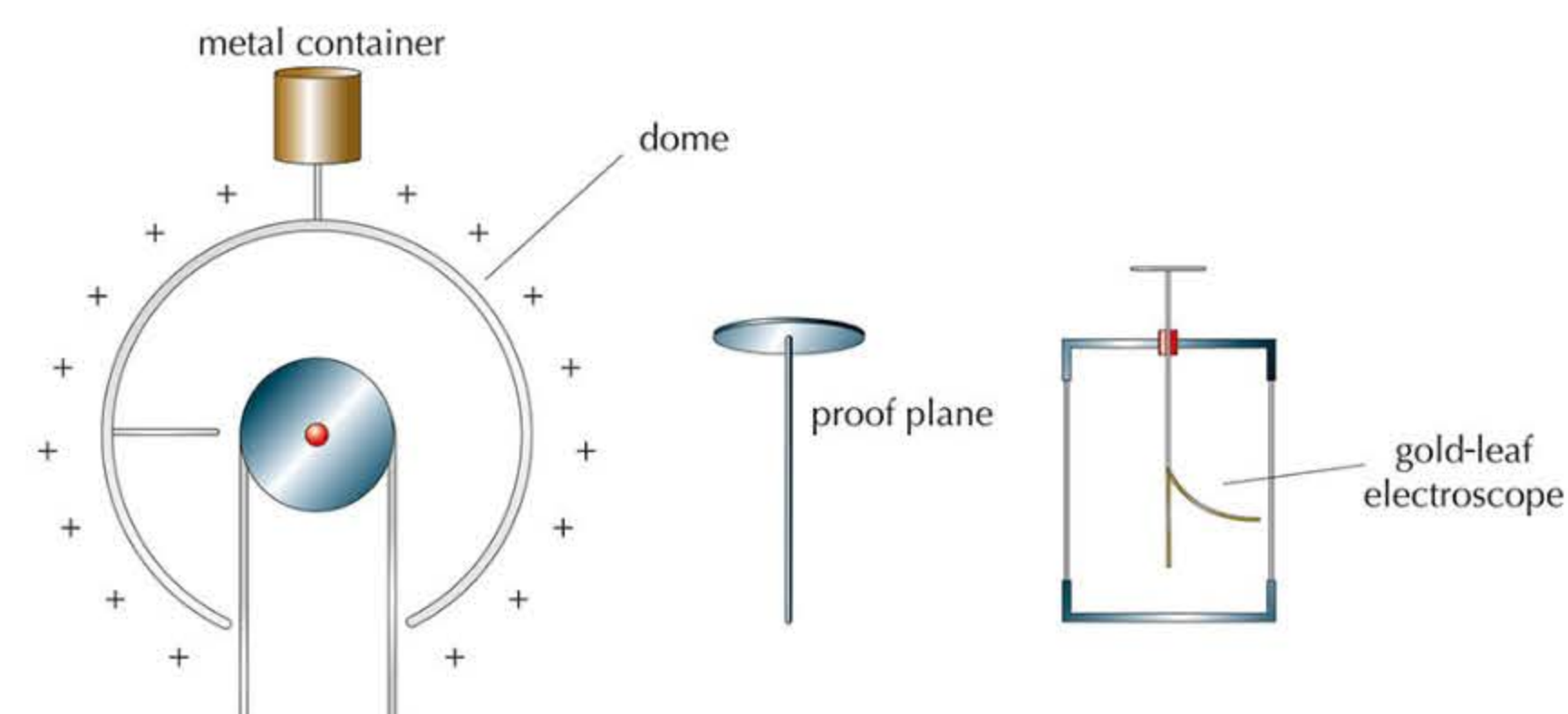
2 To show the distribution of charge on an object



- Method 1**
- 1 Bring a proof plane near to the dome of a charged Van de Graaff generator as shown in the diagram.
 - 2 Earth the side furthest from the dome (i.e. touch it).
 - 3 Remove the connection to earth.
 - 4 Bring the proof plane to a gold-leaf electroscope, and check for charge.
 - 5 Repeat at different points on the dome.

Conclusion : The charge is evenly distributed over the dome.

- Method 2** : Repeat the above procedure holding the proof plane inside the metal pot, before transferring it to the electroscope.



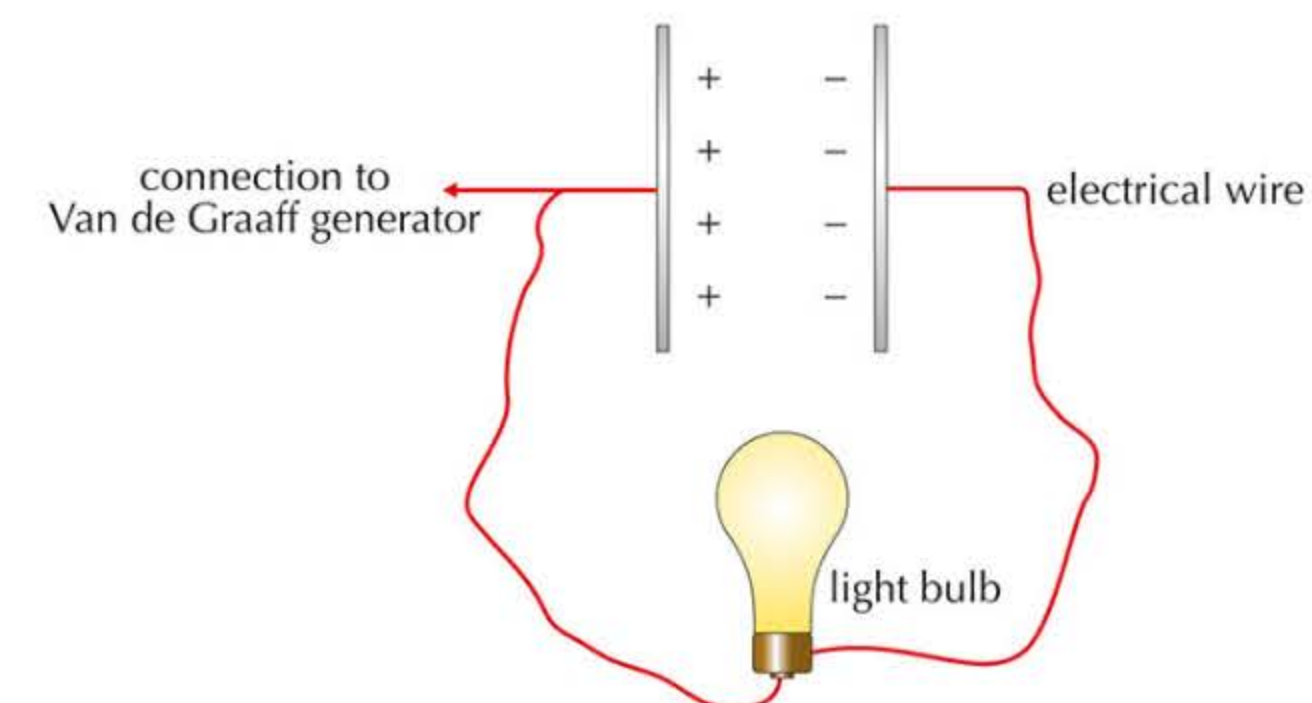
Conclusion : There is no charge (and no electric field) inside a metal conductor.

- Method 3** : Repeat the above procedure using a proof plane to investigate at various points on a pear-shaped conductor.



Conclusion : Charge builds up at a point on a metal conductor.

3 To demonstrate that a capacitor stores energy

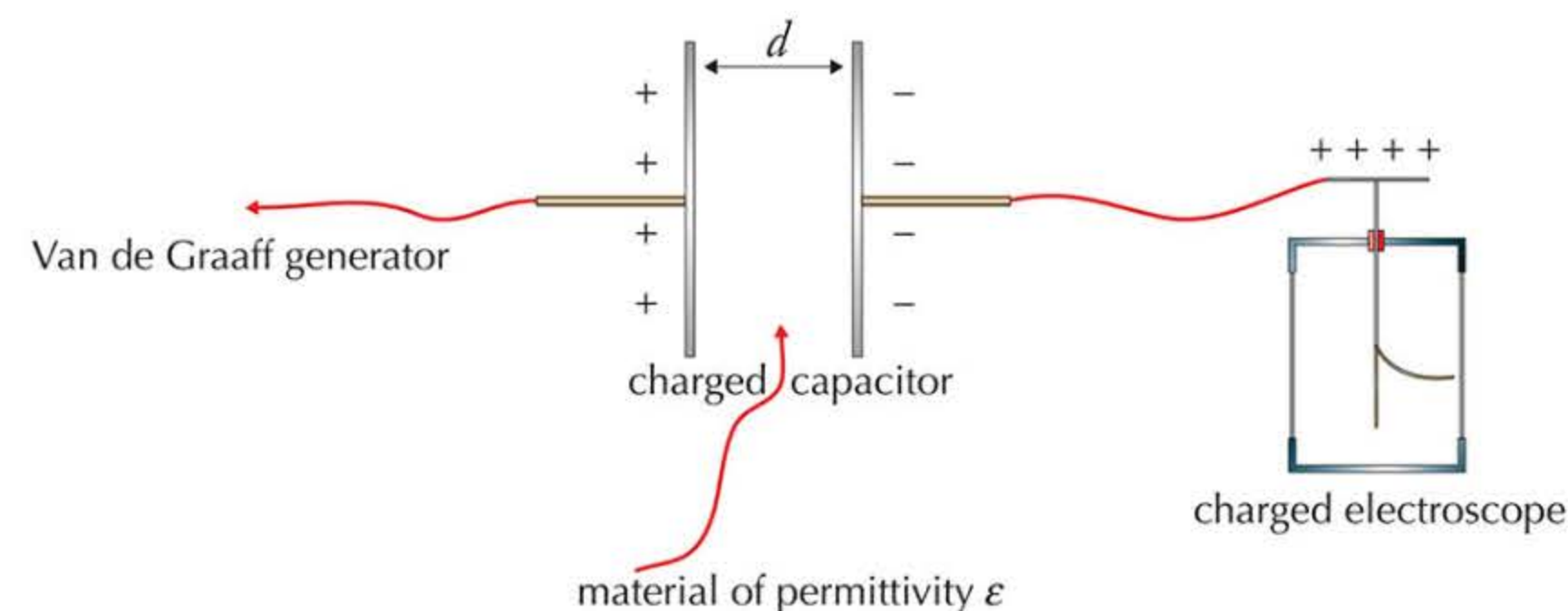


- Method**
- 1 Set up the apparatus as shown in the diagram.
 - 2 Allow the capacitor to build up a charge.
 - 3 Disconnect it from the generator and bring a conducting wire from each plate to the bulb.

Observation : The bulb flashes.

Conclusion : The presence of light energy indicates that energy had been stored on the capacitor.

HL 4 To demonstrate the factors on which the capacitance of a capacitor depends



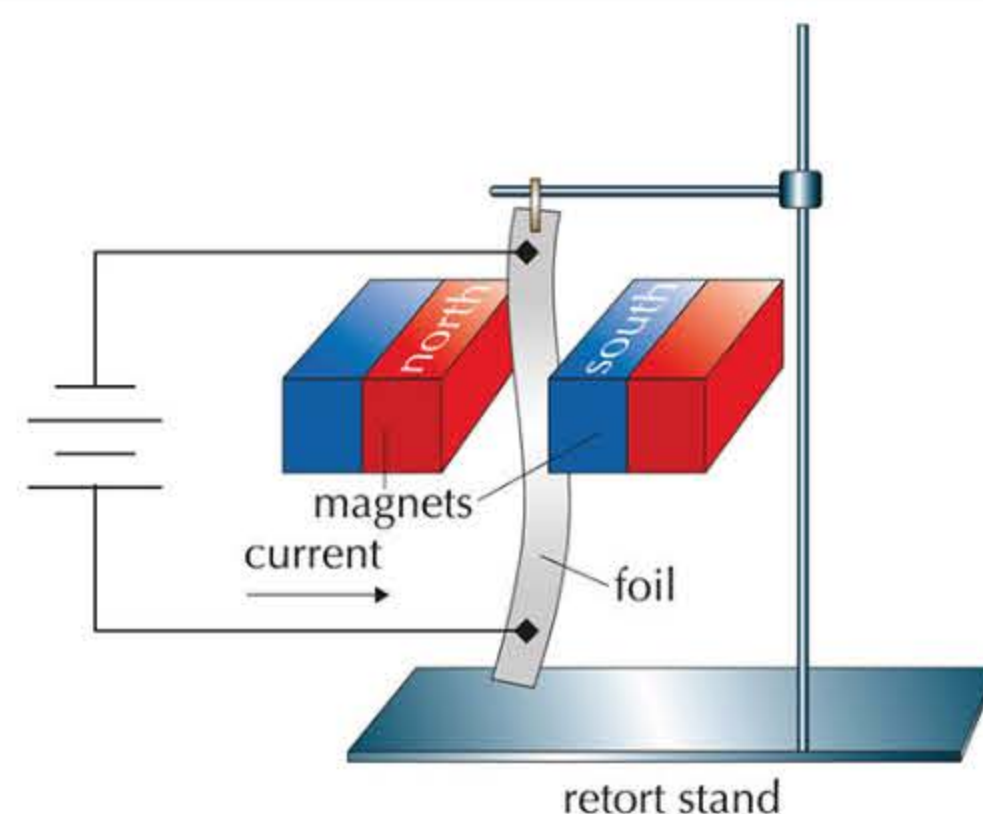
Method Set up the apparatus as shown in the diagram.

Observation When the plates are drawn apart, the leaves slowly collapse, indicating that the stored charge, and therefore the capacitance, is inversely proportional to d . Changing the material between the plates also affects the capacitance. As does any change to the common area of the plates.

Conclusion Similarly we can show that reducing A , the common area, reduces the capacitance, and varying the material between the plates affects the capacitance according to the formula:

$$C = \frac{\epsilon A}{d}$$

5 To demonstrate that a current-carrying conductor in a magnetic field experiences a force



Method Set up a circuit as shown in the diagram, supporting the foil with a retort stand.

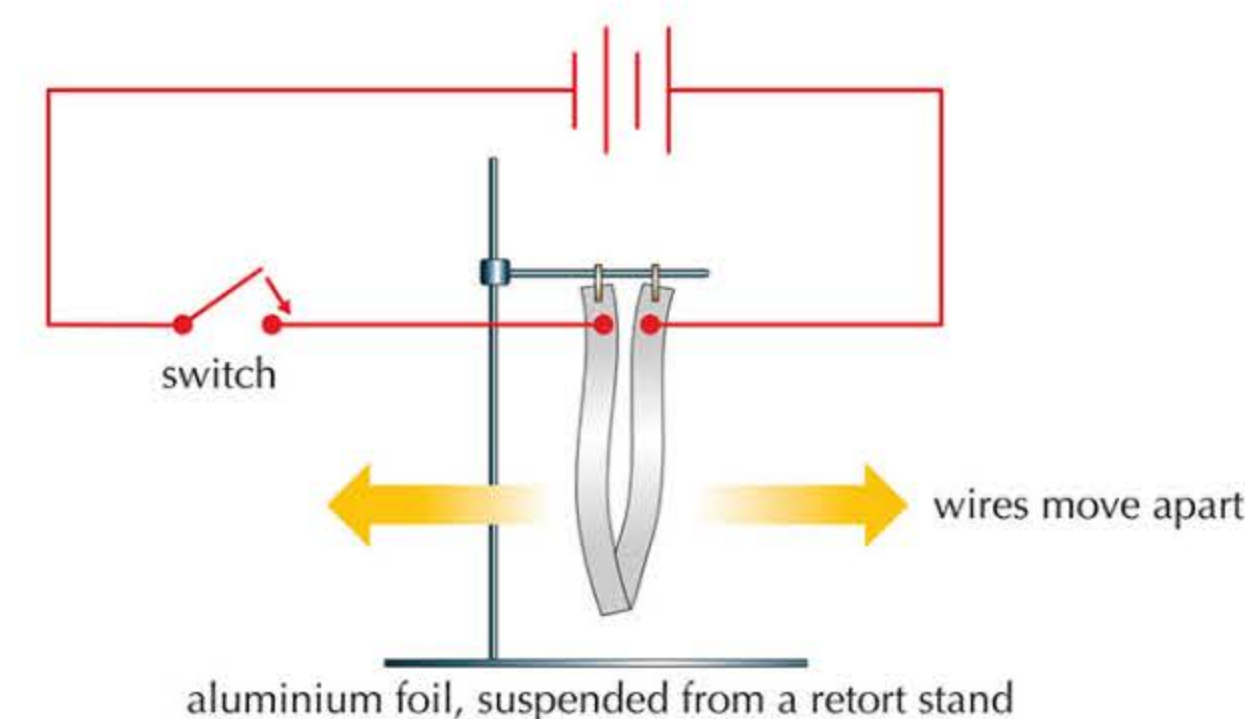
Observation When the current flows, the strip of foil moves, indicating that a current-carrying conductor in a magnetic field experiences a force.

Conclusion The direction of the force can be determined by the left hand rule, and its magnitude is given by the formula: $F = BIL$.

6 To demonstrate the principle on which the definition of the ampere is based

Remember

The ampere is the current that, if maintained in two infinitely long parallel wires of negligible cross section placed one metre apart in a vacuum, would produce between the wires a force of 2×10^{-7} newtons per metre length of the wire.



Method

- 1 Set up a circuit as shown in the diagram, supporting the foil with a retort stand.
- 2 Switch on the current and observe what happens.

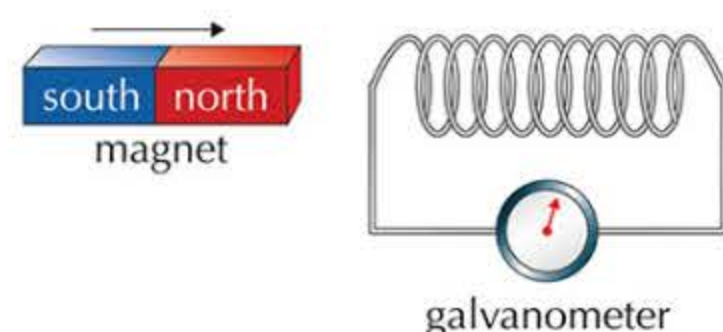
Observation The wires move apart.

Conclusion This indicates that parallel wires conducting a current will experience a force. This is the principle on which the definition of the ampere is based.

7 To demonstrate electromagnetic induction

Remember

Faraday's law of electromagnetic induction states that when there is a change in the magnetic flux linking a coil, an emf is induced in that coil. The strength of the emf is proportional to the rate of change of the flux linking the coil.

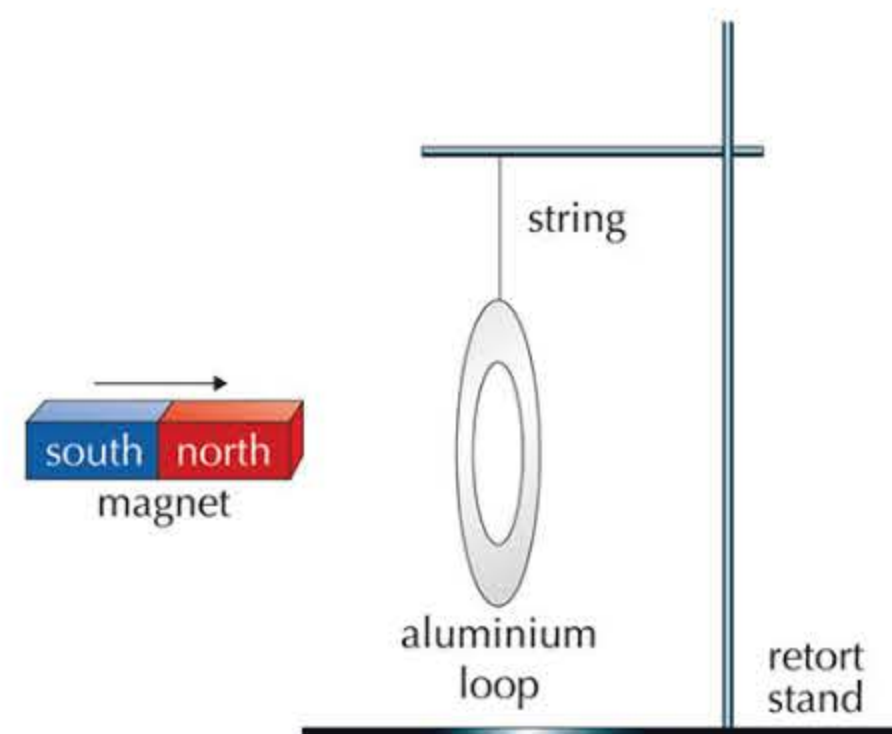


- Method**
- 1 Set up a circuit as shown in the diagram.
 - 2 Move the magnet towards the coil at varying speed.
- Observation** When the magnet is in motion, a current is shown on the galvanometer.
- Conclusion** The existence of the current on the galvanometer indicates that the changing magnetic field is creating an emf as stated in Faraday's law. The faster the magnet moves, the greater the current registered on the galvanometer.

8 To demonstrate Lenz's law

Remember

Lenz's law states that the direction of an induced current is such as to oppose the change causing it.

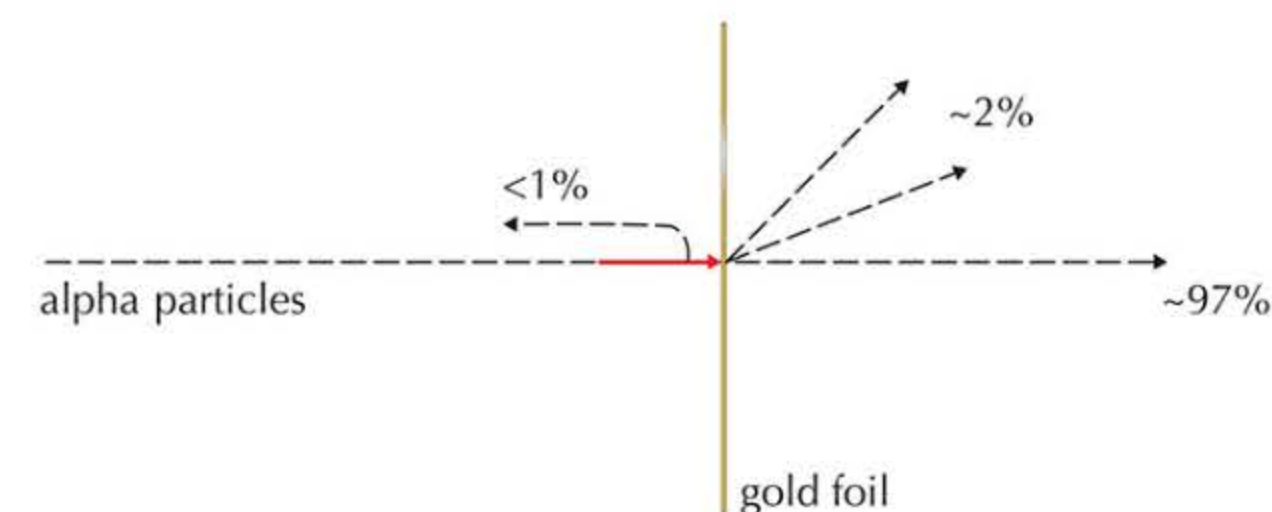


- Method**
- 1 Set up the apparatus as shown in the diagram.
 - 2 Move the magnet towards the loop and then away from it.
- Observation** The loop always moves in the same direction as the magnet.
- Conclusion** The movement of the loop in the same direction as the magnet indicates that a current is flowing in the loop that opposes the change, as stated in Lenz's law.



Modern physics demonstration experiments

1 Rutherford's gold foil experiment



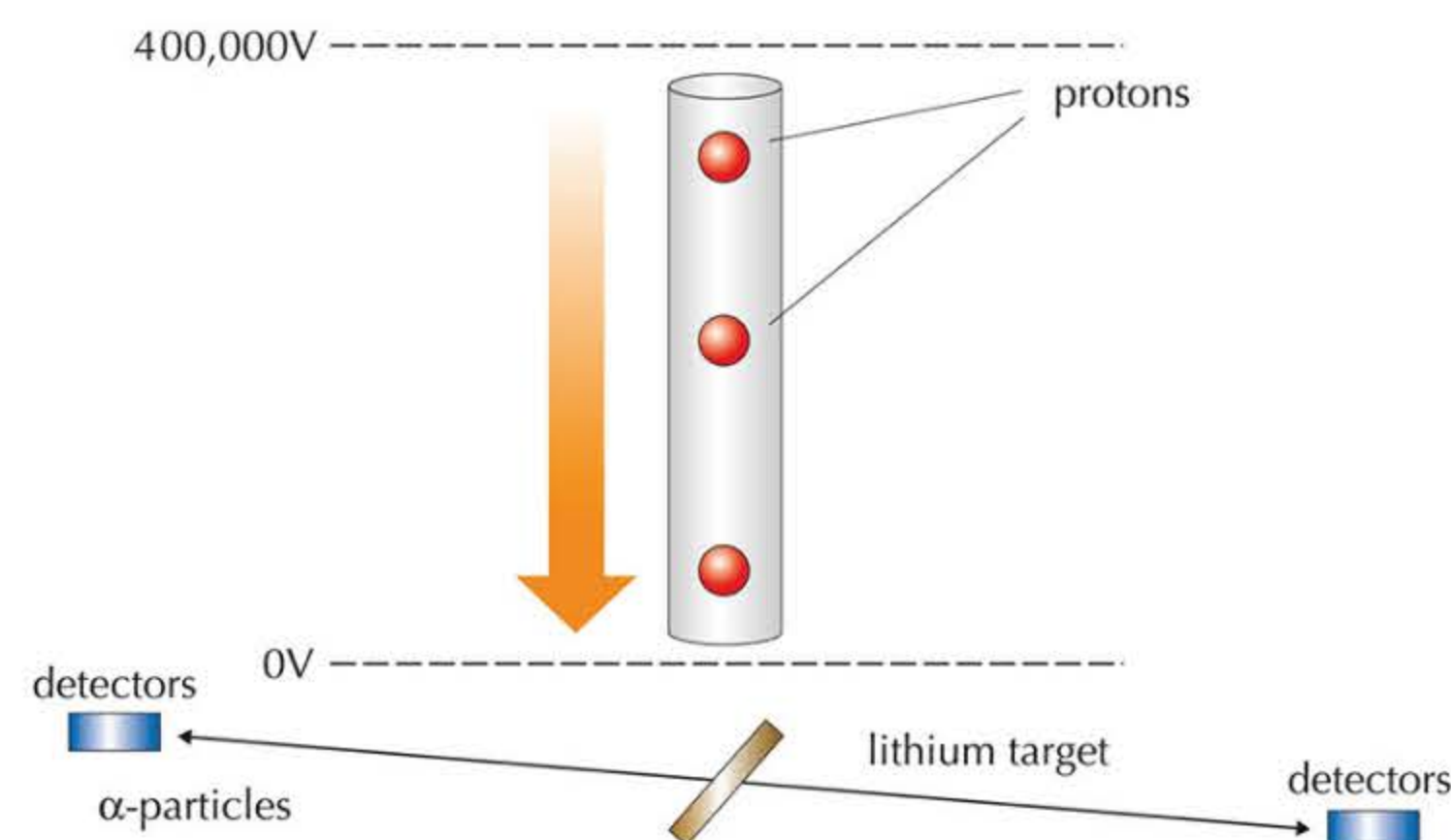
- Method** **Rutherford** fired a beam of alpha particles towards a thin sheet of gold. A detector indicated where the alpha particle went.
- Observation** What Rutherford found was that most particles went through the foil, without causing damage to the foil. A small percentage was diverted through various angles as shown, while an even smaller percentage was repelled back towards the source.
- Conclusion** This experiment gave rise to the idea of the **Rutherford-Bohr** model of the atom, which is now the standard view of the atom. In this model:
- Most of the atom is empty space
 - There is a positively charged nucleus, which contains the protons and neutrons
 - The nucleus is surrounded by several 'shells' of negatively charged electrons.

Remember

Alpha particles are small, positively charged particles.

2 The Cockcroft-Walton experiment

HL



Method

Remember

The Cockcroft-Walton experiment demonstrated for the first time that the splitting of a nucleus was possible by the use of artificially accelerated particles.

To carry out the experiment, Cockcroft and Walton fired protons at a lithium target.

Protons are the nucleus of a hydrogen atom.

Observation

Two alpha particles were created by the experiment, as shown in the diagram.

Conclusion

After the reaction, Cockcroft and Walton noted that some mass had 'disappeared' but energy had 'appeared'.

- The loss in energy and gain in mass fitted perfectly with Einstein's equation: $E = mc^2$.

Remember

This was the first experiment carried out that verified Einstein's equation.

Exam questions

The following are extracts from past exam questions.

1 2013, HL, Section B, Q10(a)

In 1932 J.D. Cockcroft and E.T.S. Walton accelerated protons to energies of up to 700 keV and used them to bombard a lithium target. They observed the production of alpha-particles from the collisions between the accelerated protons and the lithium nuclei.

How did Cockcroft and Walton accelerate the protons?

How did they detect the alpha-particles?

(12 marks)

Write the nuclear equation for the reaction that occurred and indicate the historical significance of their observation.

(12 marks)

2 2007, HL, Section B, Q8

(i) Describe how an electric field pattern may be demonstrated in the laboratory.

(12 marks)

(ii) Describe an experiment to demonstrate that total charge resides on the outside of a conductor. Give an application of this effect.

(20 marks)

3 2007, HL, Section B, Q12

Describe an experiment to demonstrate Faraday's law.

(12 marks)

4 2006, HL, Section B, Q9

Describe an experiment to demonstrate the principle on which the definition of the ampere is based.

(15 marks)

5 2005, HL, Section B, Q7

Describe an experiment to demonstrate that sound is also a wave motion.

(12 marks)

6 2005, HL, Section B, Q10

Describe an experiment to show an electric field pattern.

(12 marks)

7 2004, HL, Section B, Q12

What is electromagnetic induction? Describe an experiment to demonstrate electromagnetic induction.

(15 marks)

3 Key Definitions

Learning objectives

In this chapter you will learn about:

The key definitions relevant to the Leaving Certificate Physics course.



Exam brief

There is no specific list of definitions that must be learned for the examination, but some are highlighted in the Leaving Certificate Physics syllabus. There are also other terms that are not specifically mentioned in the syllabus but have appeared in past examination papers. To be certain of getting all the marks available for definitions (which amounts to 15% or more of the overall marks available), it would be necessary to learn a few hundred terms. However, for ease of learning, this chapter includes the vast majority of terms that are likely to be asked.

Remember

It may be possible to get full marks for a definition question by giving a formula, as long as all terms are explained. The best policy, however, is to give both the formula and a definition.

Mechanics definitions

- **Energy** is the ability to do work.
- **Work** is done when a force moves an object through a distance.
- **Power** is:
 - 1 The rate at which work is done
 - 2 The rate at which energy is converted from one form into another.

Newton's laws of motion

- (i) A body will continue in a state of rest or of uniform velocity unless an unbalanced external force acts upon it.
- (ii) 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. ($F = ma$)
- (iii) If body A exerts a force on body B, then body B exerts an equal but opposite force on body A.

- A **force** is anything that causes or tends to cause an acceleration.
- The **momentum** of a body is the product of a body's mass and velocity.
- **Friction** is a force that tends to oppose motion.
- The **principle of conservation of momentum** states that in any interaction between bodies, the total momentum before the interaction will equal the total momentum after the interaction, provided no external forces act upon the bodies.
- **Centripetal acceleration** is the acceleration of a body in circular motion. Its direction is towards the centre of the circle.
- **Centripetal force** is the force on a body in circular motion. Its direction is towards the centre of the circle.

Newton's law of gravitation

This law 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.

$$F = \frac{GM_1M_2}{d^2}$$

- **Simple harmonic motion:** Any motion where the acceleration (a) of a particle is proportional to its distance (s) from an equilibrium position is simple harmonic motion: $a \propto -s$.

Hooke's law

This law states that the restoring force on a spring is proportional to the extension of the spring.

- The **density** of an object is its mass per unit volume, i.e. $\rho = m/V$.
- **Pressure** is defined as force per unit area, i.e. $P = F/A$. It is measured in Pascal (Pa).

Boyle's law

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

Archimedes' principle

This principle states that a body immersed in a fluid will experience an upthrust equal to the weight of fluid it has displaced.

- The law of flotation states that when a body floats it is displacing exactly its own weight of fluid.

The conditions for equilibrium

- 1 The sum of the forces in any direction equals the sum of the forces in the opposite direction.
- 2 The sum of the moments about any point is zero.

Light, sound and waves definitions

The laws of reflection

The angle of incidence equals the angle of reflection.

The incident ray, the normal at the point of incidence, and the reflected ray are all in the same plane.

Laws of refraction

The incident ray, the normal at the point of incidence, and the refracted ray are all in the same plane.

For any pair of media, the sin of i , the angle of incidence, is proportional to the sin of r , the angle of refraction, i.e. $n = \frac{\sin i}{\sin r}$ (Snell's law).

- A **real image** is formed by the actual intersection of light rays. It can be formed on a screen.
- A **virtual image** is formed by the apparent intersection of light rays. It cannot be formed on a screen.
- The **refractive index** of a medium is the ratio of the sine of the angle of incidence to the sine of the angle of refraction when light travels from a vacuum into that medium.
- The **critical angle** is the angle of incidence for which the corresponding angle of refraction is 90° .
- **Total internal reflection** occurs when the angle of incidence in a dense material is greater than the critical angle. Light is reflected at the meeting of the two materials.
- A **wave** is a means of transferring energy through a medium, without any net movement of that medium.
- In a **transverse wave**, the movement of the particles is perpendicular to the movement of the wave.
- In a **longitudinal wave**, the movement of the particles is parallel to the movement of the wave.

- **Diffraction** is the ability of a wave to spread out after meeting an obstacle or passing through a small gap.
- **Interference** occurs when two waves meet. When this happens, the total displacement will be equal to the algebraic sum of the individual displacements.
- **Coherent waves** are two or more waves that have the same frequency and wavelength, and that are in phase or maintain a constant phase difference.
- **Polarisation** is the restriction of a wave to vibrations in one plane.
- A **standing wave** is produced when two waves of the same frequency and wavelength meet, moving in opposite directions.
- **Harmonics** are multiples of the natural frequency of vibration of a body.
- **Resonance** is the transfer of energy between two bodies of the same natural frequency.
- The **intensity of sound** at a point is defined as the rate at which energy is crossing a unit area perpendicular to the direction in which the sound is travelling. Sound is measured in Bels or deciBels (dB).
- The **threshold of hearing** is the lowest sound intensity to which an average human ear can respond. Its value is taken as 10^{-12} Wm^{-2} , at 1 KHz.
- The **frequency limits of audibility** are the highest and lowest frequency sound waves that the average human can hear.
- **Doppler effect**: The apparent change in the frequency of a wave due to the relative motion of the source of the wave or an observer is known as the Doppler effect.

Heat and temperature definitions

- The **temperature** of a body is a measure of how hot it is.
- A **thermometric property** is any measurable property of a body that changes with temperature.
- **Heat** is a form of energy that causes a rise in temperature when added to a body, or a fall in temperature when withdrawn.
- The **heat capacity** of a body is the amount of energy needed to raise the temperature of the body by 1 K.

The **specific heat capacity**, c , of a substance is the amount of energy required to raise the temperature of 1 kg of the substance by 1 K.

- The **latent heat** of a body is the energy required to change the state of the body without changing its temperature.

The **specific latent heat**, l , of a substance is the amount of energy required to change the state of 1 kg of that substance.

- **Conduction** is the transfer of heat within a body without any net movement of the particles of that body.
- **Convection** is the transfer of heat within a body accompanied by the movement of the particles of that body.
- **Radiation** is the transfer of energy across empty space. This is how the heat and light from the sun reach earth.
- The **U-value** of a structure is the amount of heat energy conducted per second through 1 m^2 of that structure when a temperature difference of 1 K is maintained between its ends.
- The **solar constant** is the average amount of energy from the sun falling per second perpendicularly on 1 m^2 of the earth's atmosphere.

Electricity definitions

- A **conductor** is a material that tends to allow a flow of electrons.
- An **insulator** is a material that tends to restrict the flow of electrons.

Coulomb's law

This 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.

$$F = \frac{1}{4\pi\epsilon} \frac{Q_1 Q_2}{d^2}$$

HL

- **Electric field strength** is the force per unit positive charge at a point in an electric field, i.e. $E = \frac{F}{Q}$ (also known as electric field intensity).
- The **potential difference** between two points is the work done in moving a unit positive charge from one point to the other.
- The **volt**: The potential difference between two points is 1 volt if the work done in moving a charge of 1 coulomb from one point to the other is 1 joule.
- The **capacitance** of a body is defined as the ratio of the charge (Q) on the body to its potential (V): $C = \frac{Q}{V}$.
- The **farad**: A body has a capacitance of 1 farad if the addition to the body of 1 coulomb raises the potential of the body by 1 volt.

Ohm's law

This law states that for a metallic conductor at constant temperature the current will be proportional to the voltage.

- The **resistance** of an object within an electrical circuit is defined as the ratio of the voltage across it to the current flowing through it, i.e. $R = \frac{V}{I}$.
- The **ohm**: A conductor has a resistance of 1 ohm (1Ω), if a current of 1 amp (1A) flows when a voltage of 1 volt (1V) is applied.
- The **resistivity**, ρ , of a material is the resistance of an object of that material, with unit area and unit length,

$$\text{or: } \rho = \frac{RA}{l}$$

where: R = resistance, A = cross-sectional area, l = length.

Joule's law

This law states that the rate at which heat is produced by an electric current is proportional to the square of the current, or

$$P \propto I^2$$

where: P = power, I = current.

- A **semiconductor** is a material whose resistivity lies between that of a conductor and an insulator.
- A **current-carrying conductor** in a magnetic field experiences a force.
- **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 field.
The direction of the force is the direction of the magnetic field lines
 $B = \frac{F}{Il}$.
- The **ampere** is that current which, if maintained in two parallel, infinitely long wires of negligible cross-section placed one metre apart in a vacuum, would produce between the wires force of 2×10^{-7} newtons per metre length of the wire.

HL

Faraday's laws

These laws state that when there is a change in the magnetic flux linking a coil, an emf is induced in that coil. The strength of the emf is proportional to the rate of change of the flux linking the coil.

Lenz's law

This law states that the direction of an induced current is such as to oppose the change causing it.

Modern physics definitions

Thermionic emission is the emission of electrons from the surface of a hot metal.

- The **photoelectric effect** is the emission of electrons from a metal, caused by the incidence of electromagnetic radiation of suitable frequency.
- The **threshold frequency** of a metal is the minimum frequency of electromagnetic radiation that will cause photoemission from that metal.
- **Pair production** is the creation of a subatomic particle and its anti-particle from another form of energy.
- **Pair annihilation** is the transformation of a particle and anti-particle into 2 photons of electromagnetic energy.
- The **electronvolt** is the amount of energy gained or lost by a single electron when it moves through a potential difference of one volt.
- **Radioactivity** is the emission of either particles or electromagnetic radiation from the nucleus of an atom.
- **X-rays** are high-energy electromagnetic radiation.

Law of radioactive decay

This law states that the number of disintegrations per second is proportional to the number of nuclei present: activity = λN .

- **The half-life** of an element is the time taken for half of the nuclei in any given sample to decay or the time taken for the activity of any given sample to decrease to half its original value.
- **One becquerel** is defined as the disintegration of one nucleus per second.
- **Nuclear fission** is the breaking up of a large nucleus into two smaller nuclei of similar size with the release of energy.
- **Nuclear fusion** occurs when two small atomic nuclei join together to form a larger nucleus, accompanied by the release of large amounts of energy.

Formulae and Derivations 4

Learning objectives

In this chapter you will learn about:

- 1 All the formulae required for the Leaving Certificate Physics examination
- 2 The derivations of some of those formulae



Exam brief

Even without taking Section A into account, in the region of 40% of your grade will depend on your ability to carry out calculations. The formulae are now available in tables; but there are so many, you will still need to do a lot of practice to be able to quickly select the correct formula and use it properly in the exam. It is important to:

- Practise the use of formulae constantly, by attempting past questions
- Write out the formula in full every time you use it. This will help you to keep track of your own work and helps the examiner to understand your thinking.

The formulae that are included in this chapter cover those that are mentioned in the Leaving Certificate Physics syllabus.

Formulae

Mechanics formulae

Linear motion:

$$v = u + at; s = ut + \frac{1}{2}at^2; v^2 = u^2 + 2as$$

Momentum: $p = mv$

Force: $F = ma$

Conservation of momentum:

$$P_{\text{before}} = P_{\text{after}}$$

Angle in radians: $\theta = \frac{s}{r}$

Angular velocity: $\omega = \frac{\theta}{t}$

Angular/linear velocity: $v = r\omega$

Centripetal acceleration: $a = r\omega^2 = \frac{v^2}{r}$

Centripetal force: $F = mr\omega^2 = m\frac{v^2}{r}$

Newton's law of gravitation: $F = \frac{Gm_1m_2}{d^2}$

Weight: $W = mg$

Acceleration due to gravity: $g = \frac{GM}{R^2}$

Period of a satellite: $T^2 = \frac{4\pi^2 r^3}{GM}$

Density: $\rho = \frac{m}{V}$

Pressure: $P = \frac{F}{A}$

Pressure in a liquid: $P = \rho gh$

Boyle's law: $PV = \text{constant}$

Moments: $M = Fd$

Couple: $T = Fd (d = 2s)$

HL **Hooke's law:** $F = -ks$

Simple harmonic motion: $a = -\omega^2 s$

Period of SHM: $T = \frac{2\pi}{\omega}$

HL Period of a pendulum: $T = 2\pi\sqrt{\frac{l}{g}}$

Work: $W = Fs$

Potential energy: $E_p = mgh$

Kinetic energy: $E_k = \frac{1}{2}mv^2$

Mass-energy equivalence: $E = mc^2$

Power: $P = \frac{W}{t}$

Percentage efficiency: $= \frac{\text{output}}{\text{input}} \times 100$

Light, sound and waves formulae

Velocity of a wave: $c = f\lambda$

Doppler effect: $f' = \frac{fc}{c \pm u}$

HL Frequency of a stretched string:

$$f = \frac{1}{2l} \sqrt{\frac{T}{\mu}}$$

Mirror and lens formula: $\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$

Magnification: $m = \frac{v}{u}$

Power of a lens: $P = \frac{1}{f}$

Two lenses in contact: $P = P_1 + P_2$

Refractive index:

$$n = \frac{\sin i}{\sin r} = \frac{\text{real depth}}{\text{apparent depth}} = \frac{1}{\sin c} = \frac{c_1}{c_2}$$

Diffraction grating/spectrometer:

$$n\lambda = d \sin \theta$$

Heat and temperature formulae

Celsius temperature: $T/^{\circ}\text{C} = T/\text{K} - 273.15$

Energy to change temperature: $Q = mc\Delta\theta$; $Q = C\Delta\theta$

Energy to change state: $Q = ml$ or $Q = L$

Electricity formulae

Coulomb's law: $F = \frac{1}{4\pi\epsilon} \frac{Q_1 Q_2}{d^2}$

HL Electric field strength: $E = \frac{F}{Q}$

Potential difference: $V = \frac{W}{Q}$

Ohm's law: $V = IR$

Resistors in series: $R = R_1 + R_2$

Resistors in parallel: $\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$

HL Wheatstone bridge: $\frac{R_1}{R_2} = \frac{R_3}{R_4}$

Resistivity: $\rho = \frac{RA}{l}$

Joule's law: $W = I^2 R t$

Force on a conductor: $F = IlB$

HL Force on a moving charge: $F = qvB$

Induced emf: $E = n \frac{\text{change in flux}}{\text{time}}$

HL Rms voltage: $V_{\text{rms}} = \frac{V_0}{\sqrt{2}}$

Rms current: $I_{\text{rms}} = \frac{I_0}{\sqrt{2}}$

Capacitance: $C = \frac{Q}{V}$

Capacitor: $C = \frac{A\epsilon_0}{d}$

HL Energy in a capacitor: $W = \frac{1}{2} CV^2$

Power: $P = VI$

Magnetic flux: $\phi = BA$

Transformer: $\frac{V_{\text{in}}}{V_{\text{out}}} = \frac{N_{\text{p}}}{N_{\text{s}}}$

Modern physics formulae

Energy of a photon: $E = hf$

HL Einstein's photoelectric law: $hf = \Phi + \frac{1}{2}mv^2$

Law of radioactive decay: rate of decay $= \lambda N$

Half life: $T_{\frac{1}{2}} = \frac{\ln 2}{\lambda}$

Mass-energy equivalence: $E = mc^2$

Derivations

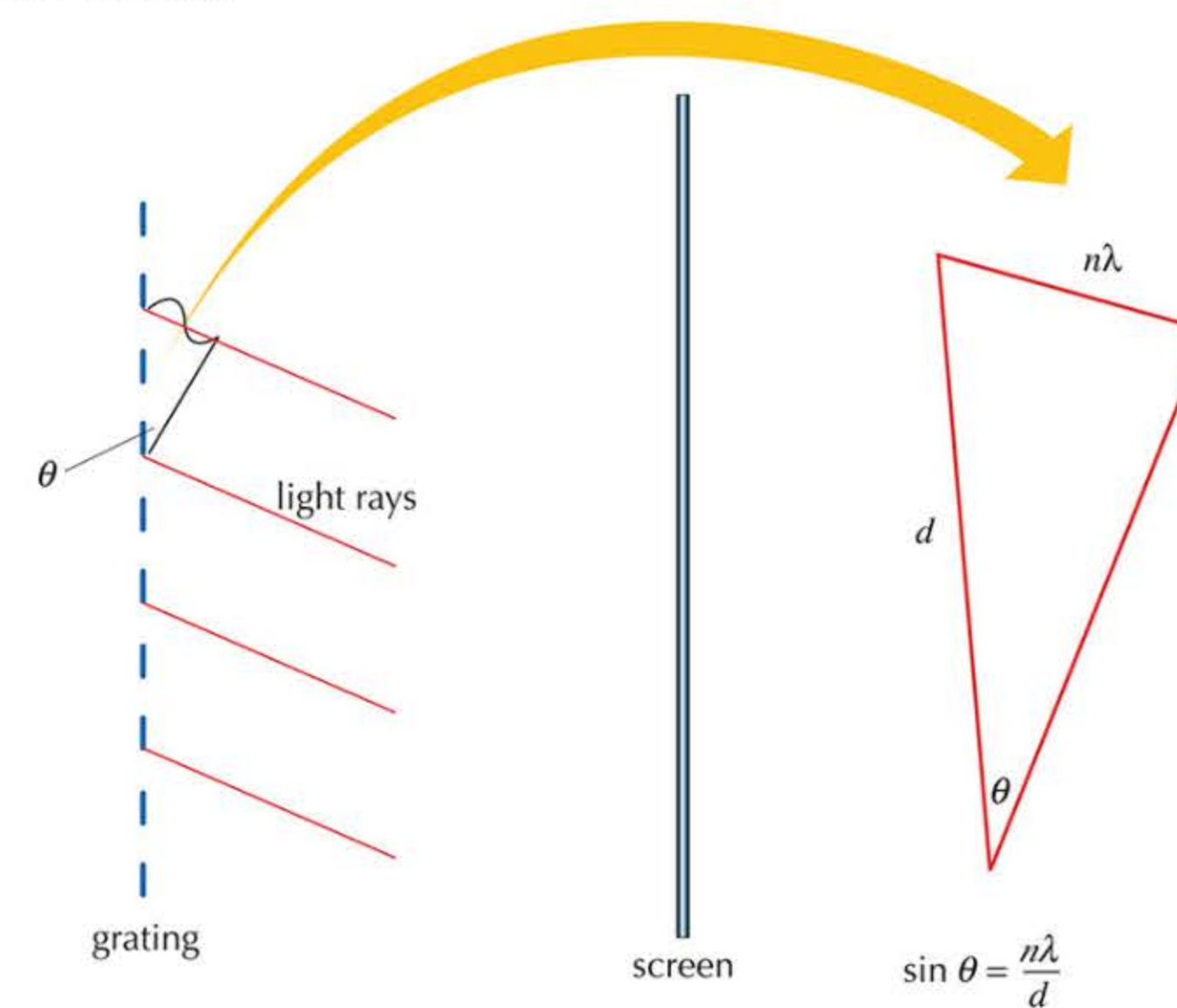
Remember

In addition to being familiar with these formulae, you may be required to show the derivation of some of them. This would typically amount to about 3% of your overall examination marks. This may not seem like much, but it is worth the trouble of learning them properly.

Light, sound and waves derivations

$$n\lambda = d \sin \theta$$

- Consider a light beam shining through a diffraction grating. It is 'split' into many different waves, as shown in the diagram.
- For constructive interference to occur, two of these light rays must meet.
- This tells us that one has travelled further than the other, by a distance equal to $n\lambda$.
- From this we can look at the triangle shown below, and derive the above formula.



$$n\lambda = d \sin \theta$$

Remember

In all these equations u = initial velocity; v = velocity after time t ;
 a = acceleration; s = displacement; t = time.

The equations of motion

Acceleration is the rate of change of velocity:

$$\text{i.e. } a = \frac{v - u}{t}$$

We can rearrange this to give: $at = v - u$

$$v = u + at$$

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

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

$$\text{Also, by definition:} = \frac{\text{displacement}}{\text{time}}$$

$$\begin{aligned} \text{Therefore displacement} &= (\text{average velocity})(\text{time}) \\ &= \frac{u + v}{2} t \\ &= \frac{u + u + at}{2} t \end{aligned}$$

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

Take the equation:

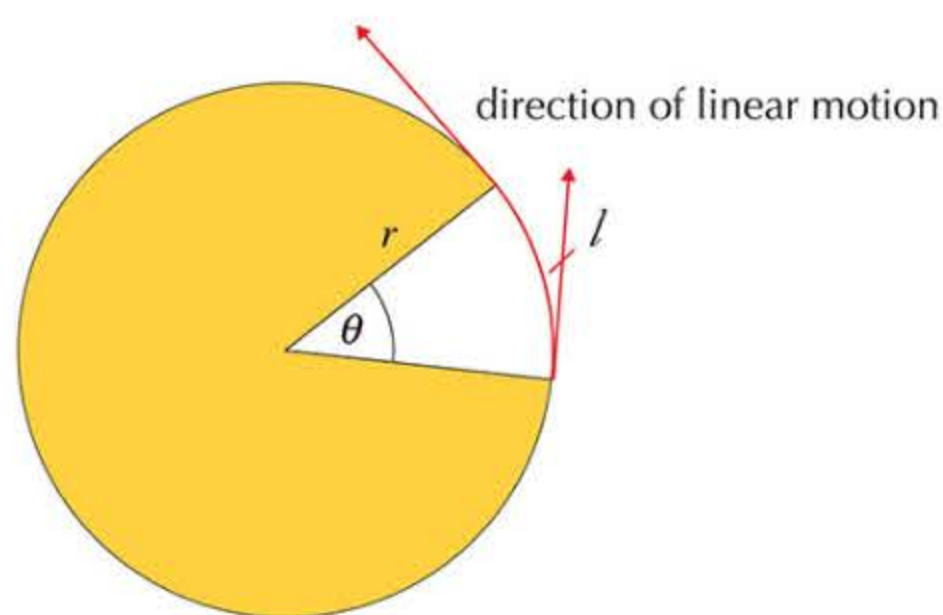
$$v = u + at$$

Square both sides:

$$\begin{aligned} v^2 &= u^2 + 2uat + a^2t^2 \\ &= u^2 + 2a\left(ut + \frac{1}{2}at^2\right) \end{aligned}$$

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

Circular motion



An object in circular motion has a **linear velocity** v and an **angular velocity** ω .

The angular velocity ω is given by: $\omega = \frac{\theta}{t}$

The direction of the linear motion is at a tangent to the circle and is constantly changing. Its magnitude is given by:

$$\begin{aligned} v &= \frac{l}{t} \\ \Rightarrow v &= \frac{r\theta}{t} \quad (\text{as } l = r\theta) \\ \Rightarrow v &= r \frac{\theta}{t} \end{aligned}$$

And substituting, we find: $v = r\omega$

Gravity

Consider a body on the surface of the earth. The force acting on the body is given by Newton's law of gravitation to be:

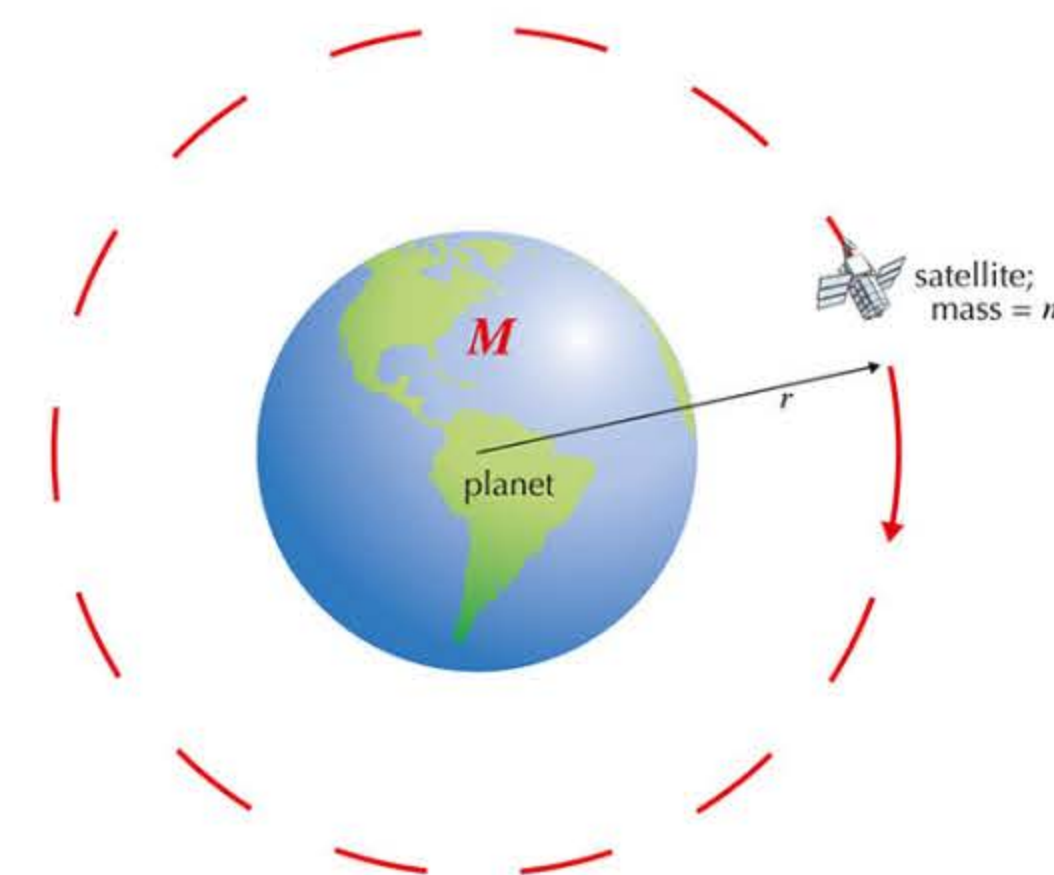
$$F = \frac{GMm}{r^2}$$

And by $F = ma$, to be:

$$F = mg$$

Equating these two, we can see that: $g = \frac{GM}{r^2}$

Satellites

Period (T) of a satellite

For satellites in orbit about a planet of mass M the centripetal force is equal to the gravitational force: i.e.

$$\begin{aligned} \frac{GMm}{r^2} &= mr\omega^2 \\ \Rightarrow \omega^2 &= \frac{GM}{r^3} \end{aligned}$$

HL But, in terms of the period T of a motion:

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

$$\Rightarrow \left(\frac{2\pi}{T}\right)^2 = \frac{GM}{r^3}$$

$$T^2 = \frac{4\pi^2 r^3}{GM} \quad (\text{i.e. Kepler's third law of planetary motion})$$

The speed (v) of the satellite:

By the same logic: $\frac{GMm}{r^2} = m \frac{v^2}{r}$

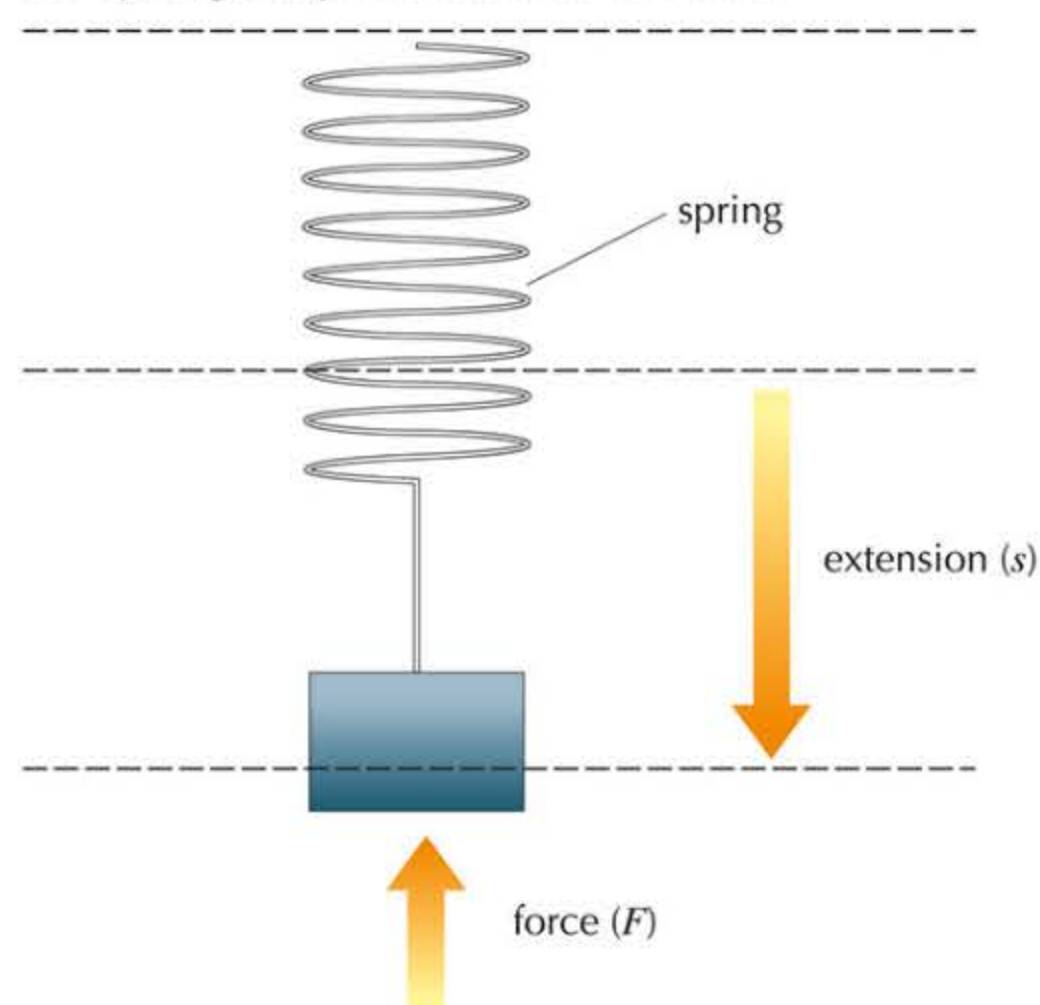
Gives:

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

Simple harmonic motion

Hooke's law states that the force on a spring is proportional to the extension of the spring.

Is the motion of the spring simple harmonic motion?



If: $F = -ks$ (Hooke's law)

$$\Rightarrow ma = -ks$$

$$\Rightarrow a = -\frac{k}{m}s$$

$$\Rightarrow a \propto s$$

$$\text{or: } a = -\omega^2 s$$

i.e. the spring is exhibiting simple harmonic motion.

Electricity

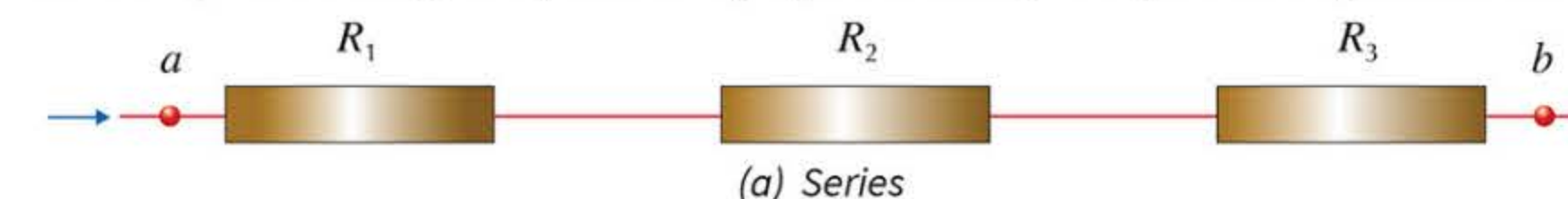
Resistors in series

This is an example of three resistors connected in series as seen in the diagram below.

For this set-up, 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 , V_2 is the voltage drop across R_2 , and so on.



Following **Ohm's law** we can say:

$$IR_T = IR_1 + IR_2 + IR_3$$

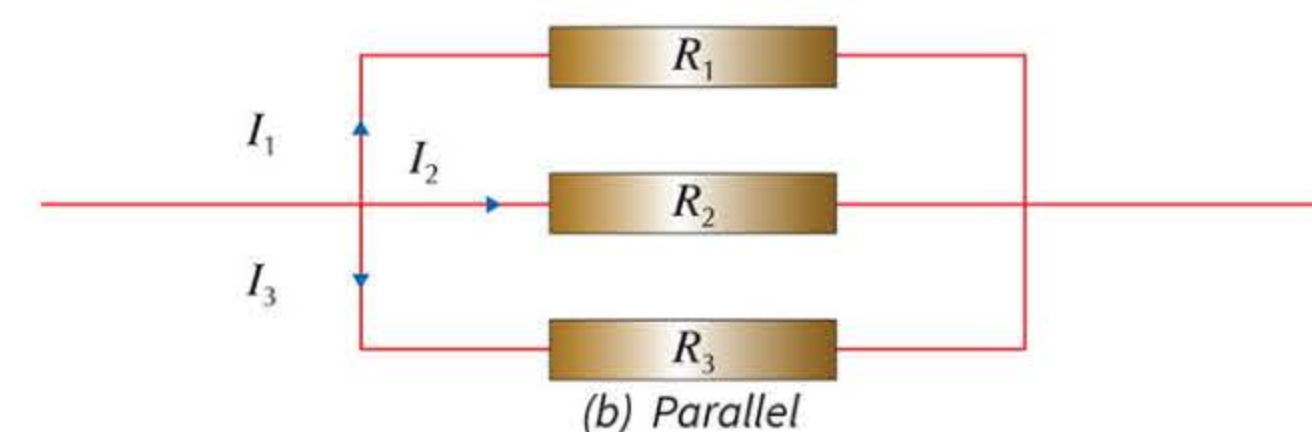
And, dividing the equation by I :

$$R_T = R_1 + R_2 + R_3$$

Resistors in parallel

See the diagram below. The total current is given by:

$$I = I_1 + I_2 + I_3$$



Using **Ohm's law**: $\frac{V}{R_T} = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3}$

And dividing across by V gives:

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

$$F = qvB$$

A force exists on a current-carrying conductor in a magnetic field. It is described by the formula:

$$F = BIl$$

where F = force, B = magnetic flux density, I = current, l = length of conductor.

Point to note

The voltage between two points is the same regardless of the path followed, so V is common to all terms.

HL A similar force exists on a charge, q , moving through a magnetic field at velocity v .
We can say that the current in this case is the quantity of charge passing any point per second ($I = \frac{q}{t}$), and the effective length of the charge in the magnetic field is given by $l = vt$.

Substituting into: $F = BIl$

Gives: $F = B \frac{q}{t} vt$

$$F = qvB$$

Exam questions

1 2012, HL, Section B, Q9 (i)

Two resistors of resistance R_1 and R_2 are connected in series. Derive an expression for the effective resistance of the two resistors in terms of R_1 and R_2 . (18 marks)

2 2013, HL, Section B, Q6 (ii)

Explain what is meant by angular velocity. Derive an equation for the angular velocity of an object in terms of its linear velocity when the object moves in a circle. (9 marks)

Mechanics 5

Learning objectives

In this chapter you will learn about:

- 1 Work, energy and power
- 2 Linear motion
- 3 Vectors and scalars
- 4 Newton's laws of motion
- 5 Conservation of momentum
- 6 Circular motion
- 7 Planets and gravity
- 8 Satellites
- 9 Simple harmonic motion
- 10 Density and pressure
- 11 Moments

Key definitions relevant to this chapter

Work/Energy/Power
Newton's laws of motion
Newton's law of gravitation
Friction
Momentum
Conservation of momentum
Density/Pressure
Boyle's law
Archimedes' principle/Law of flotation
Angular velocity
Centripetal acceleration
Laws of equilibrium/Moments
Hooke's law

Key formulae

Linear motion $v = u + at$

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

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

Momentum $p = mv$

Force $F = ma$

Conservation of momentum

$$P_{\text{before}} = P_{\text{after}}$$

Angle in radians $\theta = \frac{s}{r}$

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

Angular/linear velocity $v = r\omega$

Centripetal acceleration $a = r\omega^2 = \frac{v^2}{r}$

Centripetal force $F = mr\omega^2 = \frac{mv^2}{r}$

Newton's law of gravitation

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

Weight $W = mg$

Acceleration due to gravity $g = \frac{GM}{R^2}$

Period of a satellite $T^2 = \frac{4\pi^2 r^3}{GM}$

Density $\rho = \frac{m}{V}$

Pressure $P = \frac{F}{A}$

Pressure in a liquid $P = \rho gh$

Boyle's law $PV = \text{constant}$

Moments $M = Fd$

Couple $T = Fd$ ($d = 2s$)

Hooke's law $F = -ks$

Simple harmonic motion (SHM)

$$a = -\omega^2 s$$

Period of SHM $T = \frac{2\pi}{\omega}$

Period of a pendulum $T = 2\pi\sqrt{\frac{l}{g}}$

Work $W = Fs$

Potential energy $E_p = mgh$

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

Mass-energy equivalence $E = mc^2$

Power $P = \frac{W}{t}$

Percentage efficiency $= \frac{\text{output}}{\text{input}} \times 100$

Common forms of energy are kinetic energy (E_k), the energy a body has due to its motion, and potential energy, (E_p), the energy a body has due to its height, or position. Useful equations are:

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

$$E_p = mgh$$

It is important to remember that mass should be treated as a form of energy. The energy contained within a mass m is given by:

$$E = mc^2$$

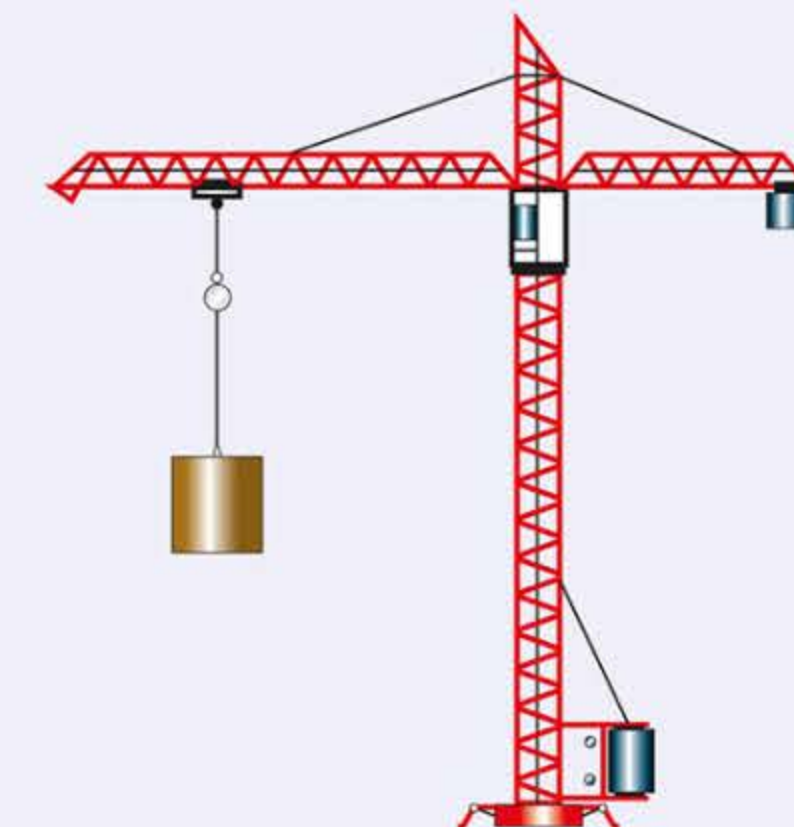
Power is:

- 1 The rate at which work is done
- 2 The rate at which energy is converted from one form into another.

$$\text{Power} = \frac{\text{energy}}{\text{time}}$$

Example:

A crane lifts a weight of 1000 kg through 30 m in 100 seconds. Find the work done, the power of the crane, and, if it uses 500 000 J doing this work, the efficiency of the crane.



$$\begin{aligned} \text{Work done} \quad E_p &= mgh \\ &= 1000 \times 9.8 \times 30 \\ &= 294\,000 \text{ J} \end{aligned}$$

$$\begin{aligned} \text{Efficiency} &= \frac{\text{output}}{\text{input}} \times 100 \\ &= \frac{294\,000}{500\,000} \times 100 \\ &= 58.8\% \end{aligned}$$

$$\begin{aligned} \text{Power of crane} \quad P &= \frac{294\,000}{100} \\ &= 2940 \text{ W} \end{aligned}$$

Work, energy and power

Work is done when a force moves an object through a distance.

Work = force $\times$ distance, or $W = Fd$

Energy is the ability to do work.

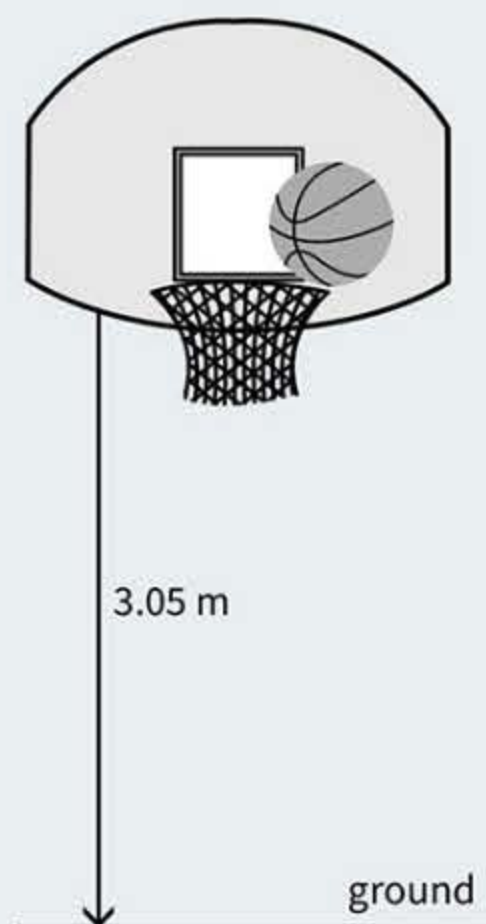
Remember

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

Sample answer

Leaving Certificate 2005, Higher Level, Section B, Q12 (a)

A basketball of mass 600 g which was resting on a hoop falls to the ground 3.05 m below. What is its maximum kinetic energy as it falls? (9 marks)



Maximum $E_k = E_p$ (at height of 3.05 m)

$$E_p = mgh \quad (3)$$

$$= (0.6)(9.8)(3.05) \quad (3)$$

$$= 17.9 \text{ J} \quad (3)$$

On bouncing from the ground the ball loses 6 joules of energy. What happens to the energy lost by the ball? (4 marks)

It changes into sound, heat, or other forms of energy. (4)

Calculate the height of the first bounce of the ball. (9 marks)

$$\text{Retained energy} = E = 17.9 - 6 = 11.9 \text{ J} \quad (3)$$

$$h = E / mg \quad (E = mgh)$$

$$= 11.9 / (0.600)(9.8) \quad (3)$$

$$= 2.02 \text{ m} \quad (3)$$

Exam question

2005, HL, Section B, Q12

State the principle of conservation of energy. (6 marks)

Linear motion

HL The equations of motion

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

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

We can rearrange to give:

$$at = v - u$$

$$v = u + at$$

Remember

In all these equations:

u = initial velocity

v = velocity after time t

a = acceleration

s = displacement

t = time

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

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

$$\text{Also, by definition:} = \frac{\text{displacement}}{2}$$

$$\text{Therefore, displacement} = (\text{average velocity})(\text{time})$$

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

$$= \frac{u + u + at}{2} t$$

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

$$v = u + at$$

$$\text{Square both sides: } v^2 = u^2 + 2uat + a^2t^2$$

$$= u^2 + 2a\left(ut + \frac{1}{2}at^2\right)$$

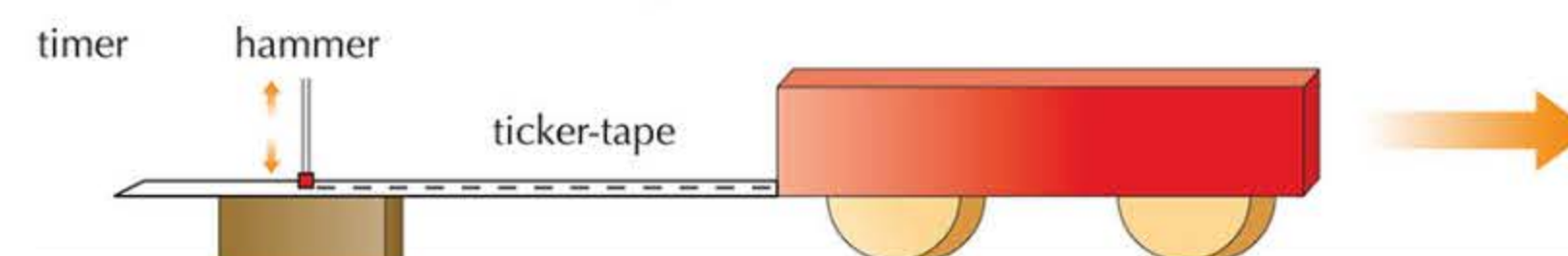
$$v^2 = u^2 + 2as$$

Vectors and scalars

Measurement of velocity and acceleration

You should be familiar with at least **one** method of measuring **velocity** and **acceleration**.

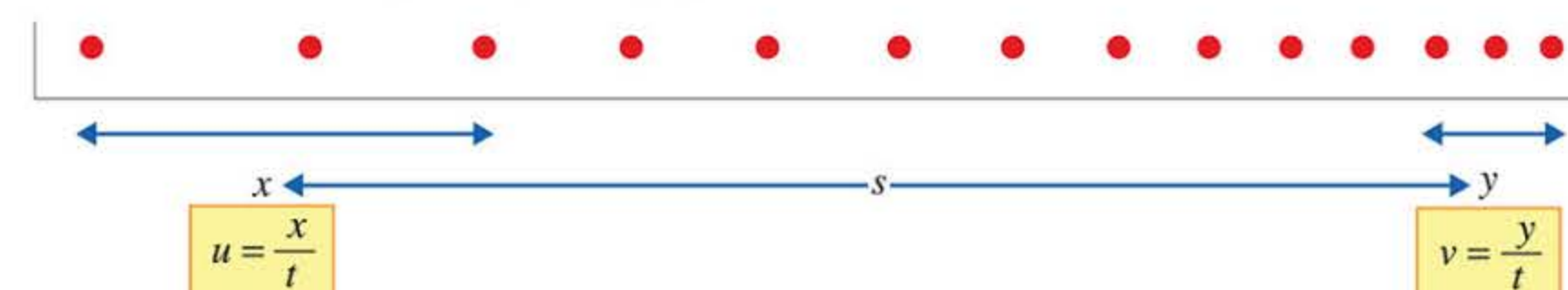
The operation of the ticker-tape timer is shown below. You may alternatively focus on the use of light-gates (see pp. 7–9).



As the trolley moves along the track, the tape is pulled through the timer.

Every 0.02 seconds a mark is made on the paper by the hammer.

For an accelerating trolley, the paper looks like this:

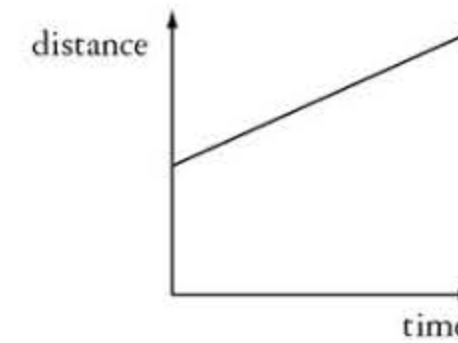


The value of t , the time, is (the number of spaces between dots) $\times (0.02)$.

To find the acceleration, we use the formula: $a = \frac{v^2 - u^2}{2s}$ (derived from $v^2 = u^2 + 2as$).

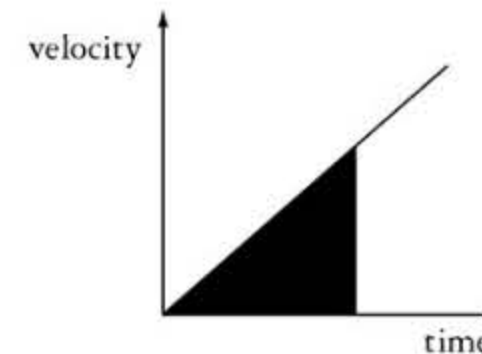
Distance-time graphs

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



Velocity-time graphs

This represents the motion of an accelerating body. The **slope** is the **acceleration**. The **area under the graph** is the **distance travelled**.



In mechanics we make use of both **vector** and **scalar quantities**.

Scalar quantities are those that only have a magnitude: e.g. mass (measured in kilograms), length (measured in **metres**) and time (measured in seconds).

Vector quantities have both magnitude and direction: e.g. velocity (speed in a given direction), acceleration and displacement (distance in a given direction).

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 obviously be replaced with a single force of 15 N, pushing in the same direction: i.e.

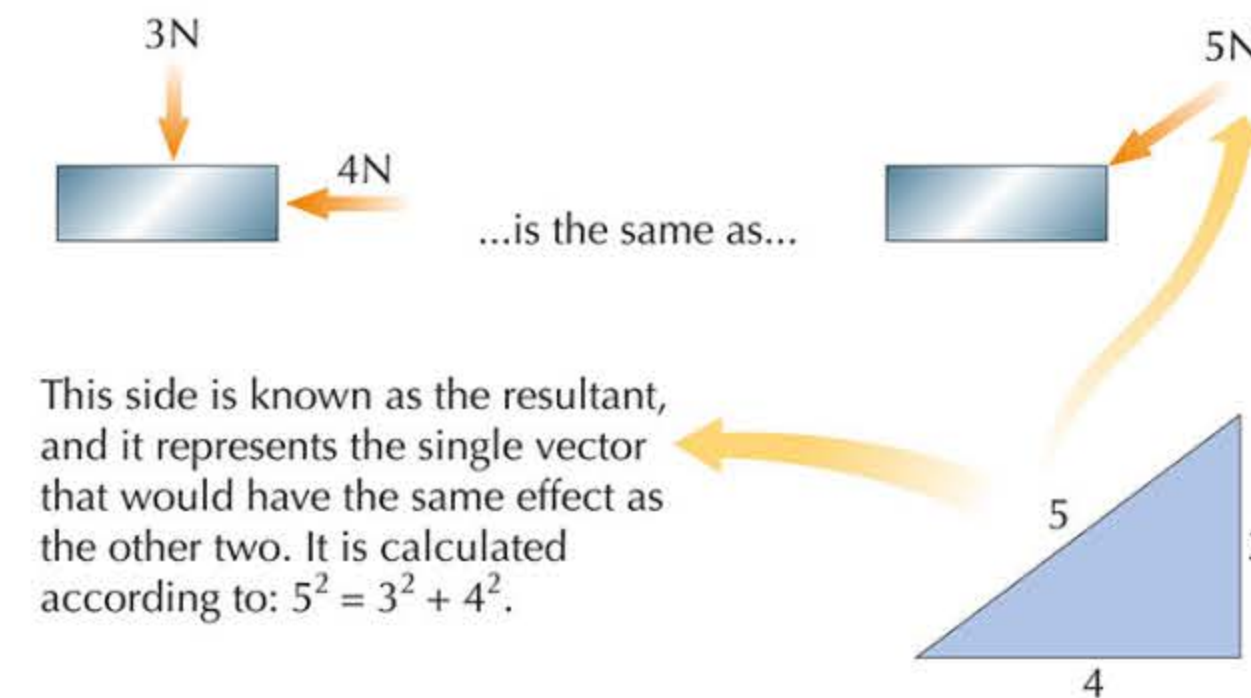


If two forces, one of 5 N and one of 10 N, push in opposite directions, they could obviously be replaced with a single force of 5 N, pushing as shown: i.e.



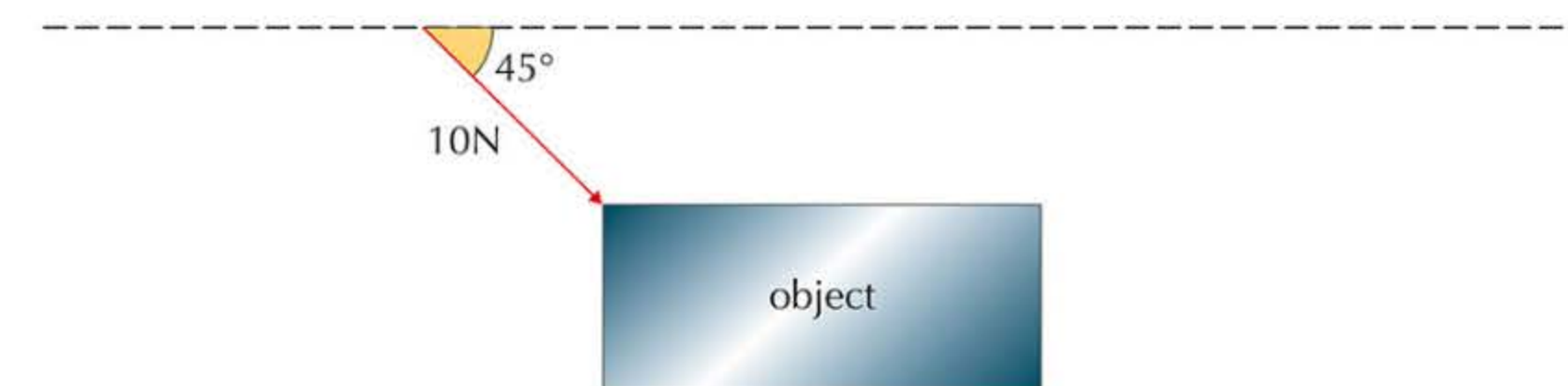
HL If **forces are at an angle to each other**, we add them according to what is known as the **triangle law**:

The 5 N is found using a right-angled triangle and Pythagoras' theorem:



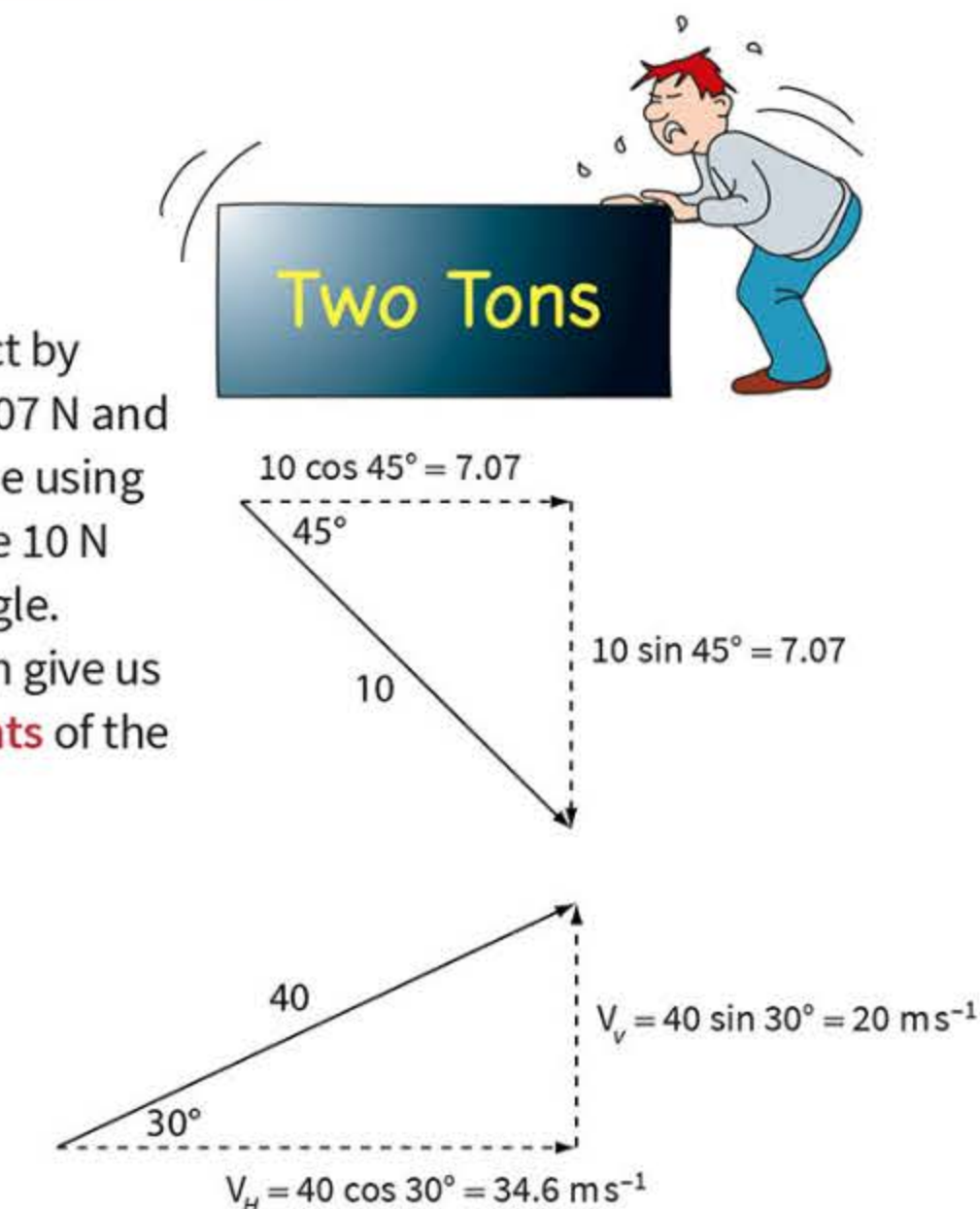
Vector resolution

Every vector (forces, velocities, acceleration etc.) can be **resolved** into two perpendicular vectors. For example, imagine we are pushing an object with a force of 10 newtons at an angle of 45° to the horizontal, as shown.



We could create exactly the same effect by simultaneously pushing it across by 7.07 N and down by 7.07 N. The calculation is done using trigonometry, as shown here. Make the 10 N the hypotenuse of a right angled triangle. The lengths of the other two sides then give us the **horizontal** and **vertical components** of the 10 N force.

Similarly, a velocity of say, 40 m s^{-1} at an angle of 30° to the horizontal would have the same effect as a horizontal velocity of 34.6 m s^{-1} and a vertical velocity of 20 m s^{-1} .



Newton's laws of motion

- 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 ($F = ma$).
- 3 If body A exerts a force on body B , then body B exerts an equal but opposite force on body A .

Newton's first law is demonstrated by space travel. In the absence of air resistance, a spacecraft travelling at several thousand metres per second can be left to do so without using the engines. It will continue to travel until a force is applied to stop it.

Newton's second law is seen in effect by the use of seat belts. When a person is thrown forwards, the belt expands slightly. This extends the time over which the person is slowing 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 see that force is proportional to the change in a body's momentum, i.e. for a body of mass m , changing from a velocity v to one of u :

$$\begin{aligned} F &\propto \frac{mv - mu}{t} \\ \Rightarrow F &\propto \frac{m(v - u)}{t} \\ \Rightarrow F &\propto ma \quad \left(\text{as } a = \frac{v - u}{t} \right) \\ \Rightarrow F &= kma \end{aligned}$$

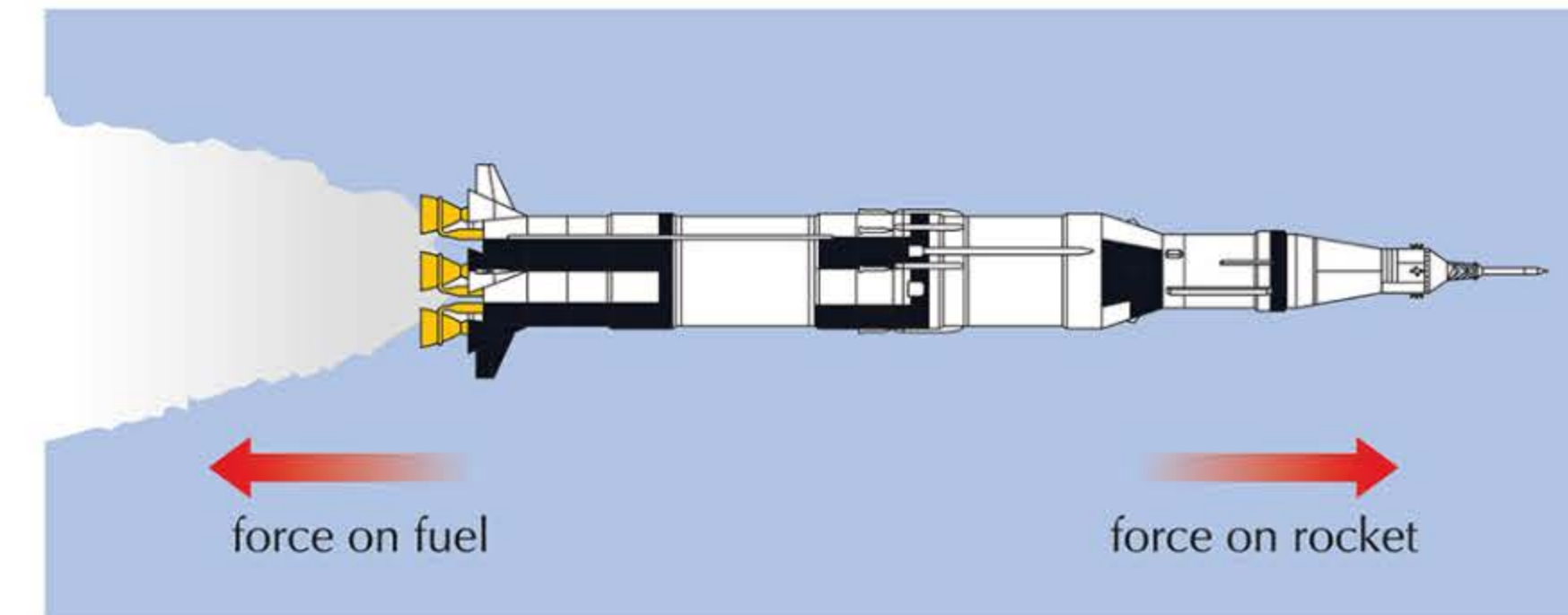
As this is the formula that is used to define the unit of force, the **newton**, we can choose a value for k , and choose the value of 1.

$$\Rightarrow F = ma$$

A **force** is anything that causes or tends to cause acceleration. The **momentum** of a body is the product of a body's **mass** and **velocity**, i.e.

$$F = ma \quad \text{and} \quad p = mv$$

Newton's third law is seen in rocket propulsion. The large force created towards the rear of the rocket creates an equal, but opposite, force forwards. Therefore the rocket moves forwards.



Friction is a **force that tends to oppose motion**. It is encountered whenever one body slides, or attempts to slide, across the surface of another. It is both beneficial and problematic. Without friction we could not walk or drive. Instead, we would slide about when attempting either activity. On the other hand friction reduces efficiency and increases wear in machinery.

Conservation of momentum

The **principle of conservation of momentum** states that in any interaction between bodies, the total momentum before the interaction will equal the total momentum after the interaction provided no external forces act upon the bodies.

Point to note

The **momentum** of a body is the product of the mass of the body and its velocity ($p = mv$).

STS

Conservation of momentum applies to situations where, for example, balls collide. It also applies in situations such as the take-off of a rocket. Before the take-off, the total momentum is zero. Afterwards the momentum of the rocket forwards is matched by the momentum of the exhaust gases backwards. It does not apply if the system is not **closed**, i.e. it does not apply in the case of games such as tennis, where some momentum is 'absorbed' by the player's arms.

Sample answer

Leaving Certificate 2004, Higher Level, Section B, Q6

Define (i) force, (ii) momentum. (12 marks)

Force is anything that causes, or tends to cause, an acceleration. (6)

The momentum, p , of a body is the product of a body's mass, m , and velocity, v .

$$p = mv \quad (6)$$

State Newton's second law of motion. Hence, establish the relationship: force = mass $\times$ acceleration. (15 marks)

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, 3)

$$F \propto \frac{mv - mu}{t} \quad (3)$$

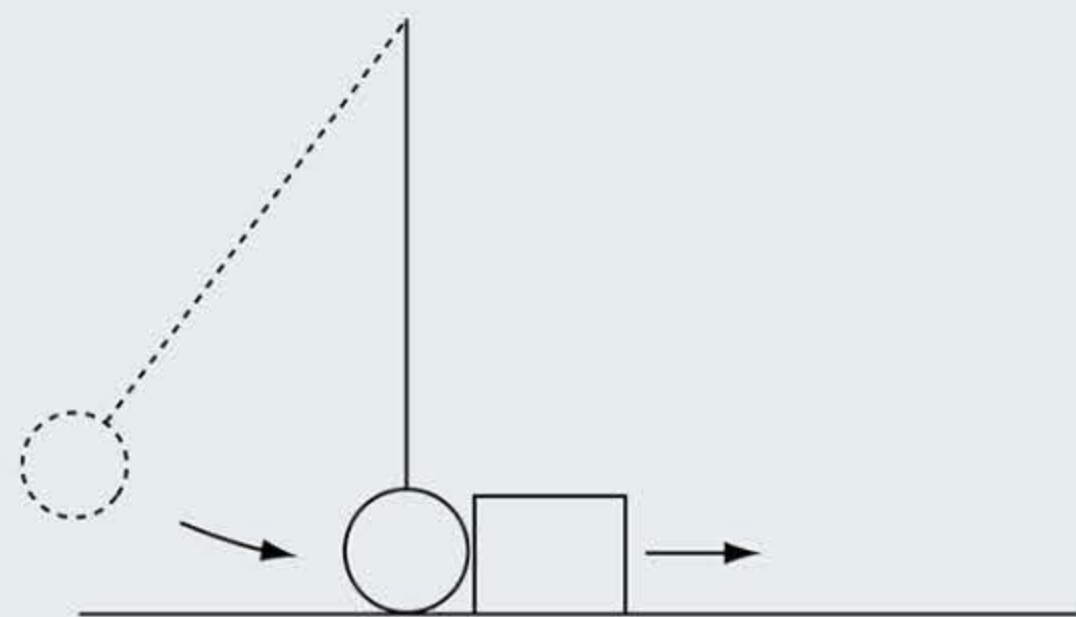
$$F \propto \frac{m(v - u)}{t} \quad (3)$$

$$F = kma \quad (3)$$

$$\text{Let } k = 1$$

$$F = ma \quad (3)$$

A pendulum bob of mass 10 g was raised to a height of 20 cm and allowed to swing so that it collided with a block of mass 8.0 g at rest on a bench, as shown. The bob stopped on impact and the block subsequently moved along the bench.



Calculate

(i) the velocity of the bob just before the collision; (ii) the velocity of the block immediately after the collision. (18 marks)

Velocity of the block just before the collision:

$$E_k = E_p \quad (3)$$

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

$$v^2 = 2gh \quad (3)$$

$$= 2(9.8)(0.2)$$

$$= 3.92$$

$$v = 1.98 \text{ ms}^{-1} \quad (3)$$

Velocity of the block immediately after the collision:

$$P_{\text{after}} = P_{\text{before}} \text{ (because of the conservation of momentum)} \quad (3)$$

$$(mv)_{\text{after}} = (mv)_{\text{before}} \quad (3)$$

$$(0.008)v = (0.01)(1.98)$$

$$v = 2.475 \text{ ms}^{-1} \quad (3)$$

The block moved 2.0 m along the bench before stopping. What was the average horizontal force exerted on the block while travelling this distance?

(acceleration due to gravity = 9.8 ms^{-2}) (11 marks)

$$F = ma$$

$$= (0.008)(1.53)$$

$$= 0.012 \text{ N}$$

$$u = 2.475$$

$$v = 0$$

$$a = a$$

$$s = 2$$

$$t = ?$$

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

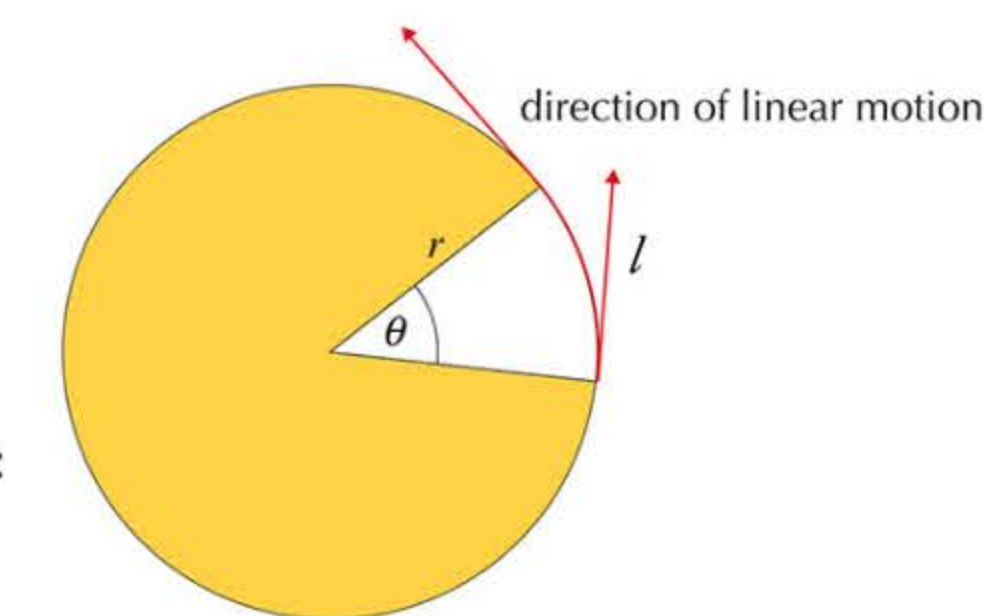
$$0^2 = 2.475^2 + 2a(2)$$

$$a = 1.53 \text{ ms}^{-2} \quad (11)$$

Circular motion

An object in circular motion has a **linear velocity**, v , and an **angular velocity**, ω . The angular velocity, ω , represents the angle passed through each second. It is given by:

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



HL The direction of the linear motion is at a tangent to the circle and is constantly changing. Its magnitude is given by:

$$v = \frac{l}{t} \text{ (speed = distance/time)}$$

$$\Rightarrow v = \frac{r\theta}{t} \text{ (as } l = r\theta)$$

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

and substituting, we find:

$$v = r\omega$$

Period

The period T of a particle in circular motion is given by:

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

Acceleration

As the object is changing its direction, its velocity is changing and therefore there is **acceleration**. This is known as the **centripetal acceleration**, and its direction is towards the centre of the circle. It gives rise to the **centripetal force**. The reaction to this force is away from the centre of the circle and is known as the **centrifugal force**.

Point to note

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

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

The value of the acceleration is given by:

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

As $F = ma$, we can say that:

$$F = mr\omega^2 \quad \text{or} \quad F = \frac{mv^2}{r}$$

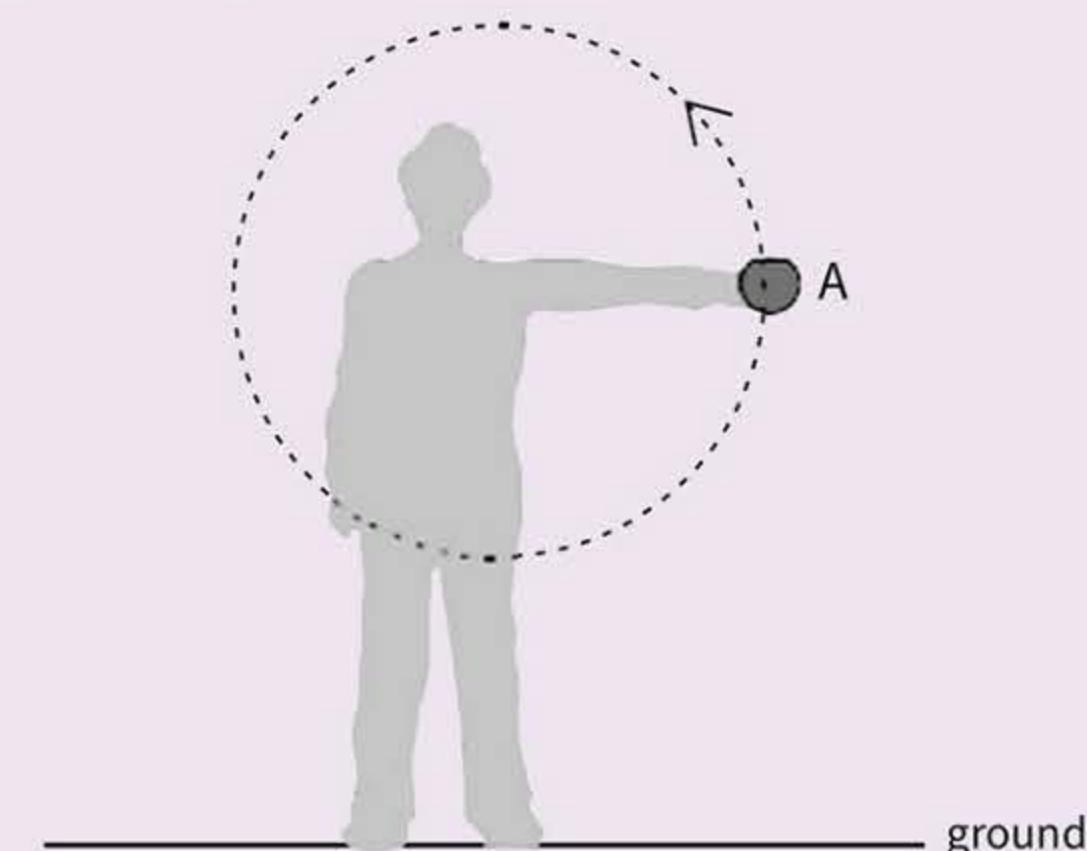
Exam question

2006, HL, Section B, Q6

Define (i) velocity, (ii) angular velocity. (12 marks)

Derive the relationship between the velocity of a particle travelling in uniform circular motion and its angular velocity. (12 marks)

A student swings a ball in a circle of radius 70 cm in the vertical plane as shown. The angular velocity of the ball is 10 rad s^{-1} .



What is the velocity of the ball? How long does the ball take to complete one revolution? (9 marks)

Draw a diagram to show the forces acting on the ball when it is at position A. (6 marks)

The student releases the ball when it is at A, which is 130 cm above the ground, and the ball travels vertically upwards.

Calculate

- (i) The maximum height, above the ground, the ball will reach
- (ii) The time taken for the ball to hit the ground after its release from A. (acceleration due to gravity = 9.8 ms^{-2}) (17 marks)

Planets and gravity

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.

$$F = \frac{Gm_1 m_2}{d^2}$$

Weight

The weight (w) of a body is the gravitational force on that body. From Newton's second law we can say that the weight is given by:

$$W = mg$$

Consider a body on the surface of the earth:



The force acting on the body is given by Newton's law of gravitation to be:

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

and by $F = ma$, to be:

$$F = mg$$

Equating these two, we can see that

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

STS

This equation shows that the acceleration of a falling body does not depend on the mass of the body, i.e. where air resistance can be ignored, large and small bodies fall at the same rate. As the weight of a body is given by $W = mg$, we can also see that the weight of a body decreases as it moves away from the earth, or from any planet.

Also, you can see from the equation that a body is never truly weightless. Though it might be far from any planet the value of g , and therefore the weight, may be very small but will never be zero.

In a space shuttle in orbit, both astronauts and shuttle are caught in what is essentially perpetual freefall. In comparison to the shuttle, then, the astronauts appear weightless.

Satellites

For satellites in orbit, the centripetal force is equal to the gravitational force:

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

But, in terms of the period T of a motion:

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

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

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

$$T^2 = \frac{4\pi^2 r^3}{GM} \quad (\text{which is Kepler's third law})$$

Also we can get a value for v , the speed of the satellite:

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

gives:

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

Exam question

2012, HL, Section B, Q6

On 16 August, 1960, Joseph Kittinger established a record for the highest altitude parachute jump. This record remains unbroken. Kittinger jumped from a height of 31 km. He fell for 13 seconds and then his 1.8-metre canopy parachute opened. This stabilised his fall. Only four minutes and 36 seconds more were needed to bring him down to 5 km, where his 8.5-metre parachute opened, allowing him to fall at constant velocity, until he reached the surface of the earth.

(Adapted from <http://www.centennialofflight.gov>)

- Calculate the acceleration due to gravity at a height of 31 km above the surface of the earth. (12 marks)
- What was the downward force exerted on Kittinger and his equipment at 31 km, taking their total mass to be 180 kg? (6 marks)
- Estimate how far he fell during the first 13 seconds. What assumptions did you take in this calculation? (12 marks)
- What was his average speed during the next 4 minutes and 36 seconds? (9 marks)

STS

Both equations 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.

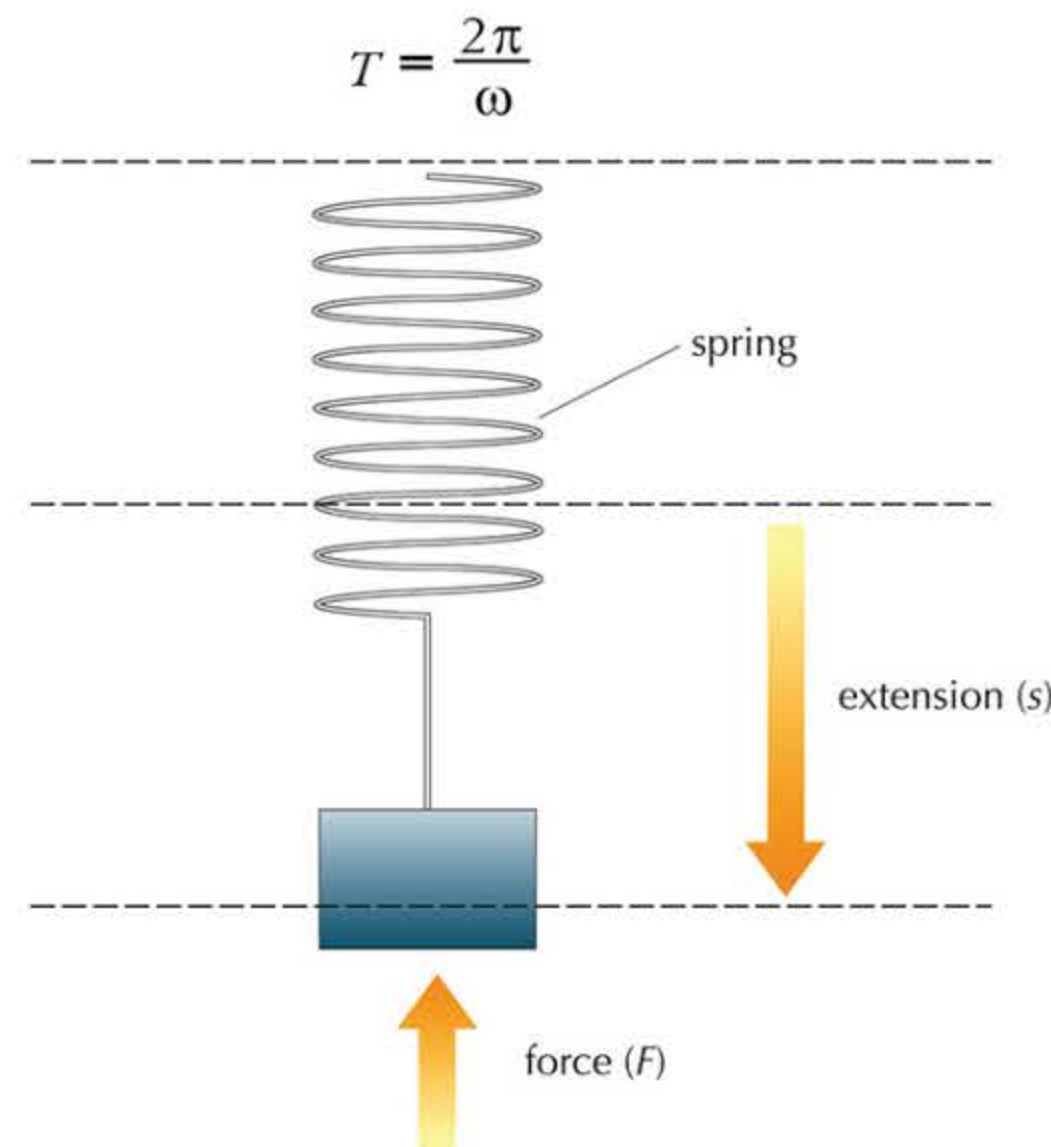
HL

Simple harmonic motion

Any motion where the acceleration (a) of a particle is proportional to its distance (s) from an equilibrium position is called **simple harmonic motion**:

$$a = -\omega^2 s \quad (-\omega^2 \text{ is a constant})$$

The period of a particle in simple harmonic motion is the same as that of a particle in circular motion, i.e.



We can show that a spring that obeys Hooke's law must also exhibit simple harmonic motion:

If $F = -ks$ (Hooke's law)

$$\Rightarrow ma = -ks$$

$$\Rightarrow a = -\frac{k}{m}s$$

$$\Rightarrow a \propto s$$

or $a = -\omega^2 s$

i.e. the spring is exhibiting simple harmonic motion.

Point to note

Hooke's law states that the restoring force on a spring is proportional to the extension of the spring.

Sample answer

HL

Leaving Certificate 2012, Higher Level, Section B, Q12 (a)

An Olympic hammer thrower swings a mass of 7.26 kg at the end of a light inextensible wire in a circular motion. In the final complete swing, the hammer moves at a constant speed and takes 0.8 s to complete a circle of radius 2.0 m.

- (i) What is the angular velocity of the hammer during its final swing? (6 marks)

$$\omega = \frac{\theta}{t} = \frac{2\pi}{0.8} = 7.85 \text{ rad s}^{-1} \quad (3, 3)$$

- (ii) Even though the hammer moves at a constant speed, it accelerates. Explain. (4 marks)

Acceleration is the rate of change of velocity.

Velocity is a vector quantity, having both a magnitude and a direction.

Therefore, if the direction of movement changes the velocity changes, even when the speed is constant.

A changing velocity means that there is an acceleration. (4)

Calculate

- (iii) the acceleration of the hammer during its final swing. (9 marks)

$$a = r\omega^2 = (2)(7.85)^2 = 123.25 \text{ m s}^{-2} \quad (3, 6)$$

- (iv) the kinetic energy of the hammer as it is released. (9 marks)

$$E_k = \frac{1}{2}mv^2 \quad (3)$$

to find v :

$$v = r\omega \quad (3)$$

$$v = (2)(7.85) = 15.7$$

$$E_k = \frac{1}{2}(7.26)(15.7)^2 = 894.76 \text{ J} \quad (3)$$

Exam question

2007, HL, Section B, Q6

State Hooke's law. (6 marks)

A stretched spring obeys Hooke's law. When a small sphere of mass 300 g is attached to a spring of length 200 mm, its length increases to 285 mm.

Calculate its spring constant. (9 marks)

The sphere is pulled down until the length of the spring is 310 mm. The sphere is then released and oscillates about a fixed point.

Derive the relationship between the acceleration of the sphere and its displacement from the fixed point.

Why does the sphere oscillate with simple harmonic motion? (18 marks)

Calculate

- (i) The period of oscillation of the sphere.
- (ii) The maximum acceleration of the sphere.
- (iii) The length of the spring when the acceleration of the sphere is zero. (Acceleration due to gravity = 9.8 m s^{-2}) (23 marks)

Density and pressure

The **density** of an object is its **mass per unit volume**, i.e. $\rho = m/v$

Pressure is defined as **force per unit area**, i.e. $P = F/A$. Pressure is measured in pascals (Pa).

STS

Atmospheric pressure can be demonstrated by an experiment in which the air inside a can is heated and the can then sealed. As it cools, the walls are drawn in. This is because there is less air inside pushing out than there is air outside pushing in (see page 40).

The **bends** is an illness that can be experienced by scuba divers. It is caused by the fact that, as a diver moves down through the water, the water pressure increases. This increase is sufficient to 'push' more nitrogen into the blood stream where it is dissolved. As the diver rises and the pressure lessens, this nitrogen will come back out of the blood as small bubbles – very like the bubbles forming in a soft drink when the bottle is opened. These bubbles in the blood can cause great damage as they pass through the brain.

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.

$$\text{i.e. } P \propto \frac{1}{V}$$

This 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.

Exam question

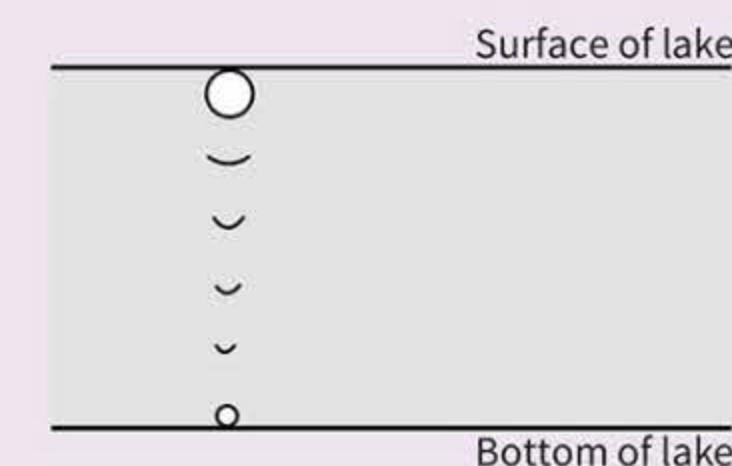
2006, HL, Section B, Q12

Define pressure. (6 marks)

Is pressure a vector quantity or a scalar quantity? Justify your answer. (6 marks)

State Boyle's law. (6 marks)

A small bubble of gas rises from the bottom of a lake. The volume of the bubble increases threefold when it reaches the surface of the lake where the atmospheric pressure is $1.01 \times 10^5 \text{ Pa}$. The temperature of the lake is 4°C .

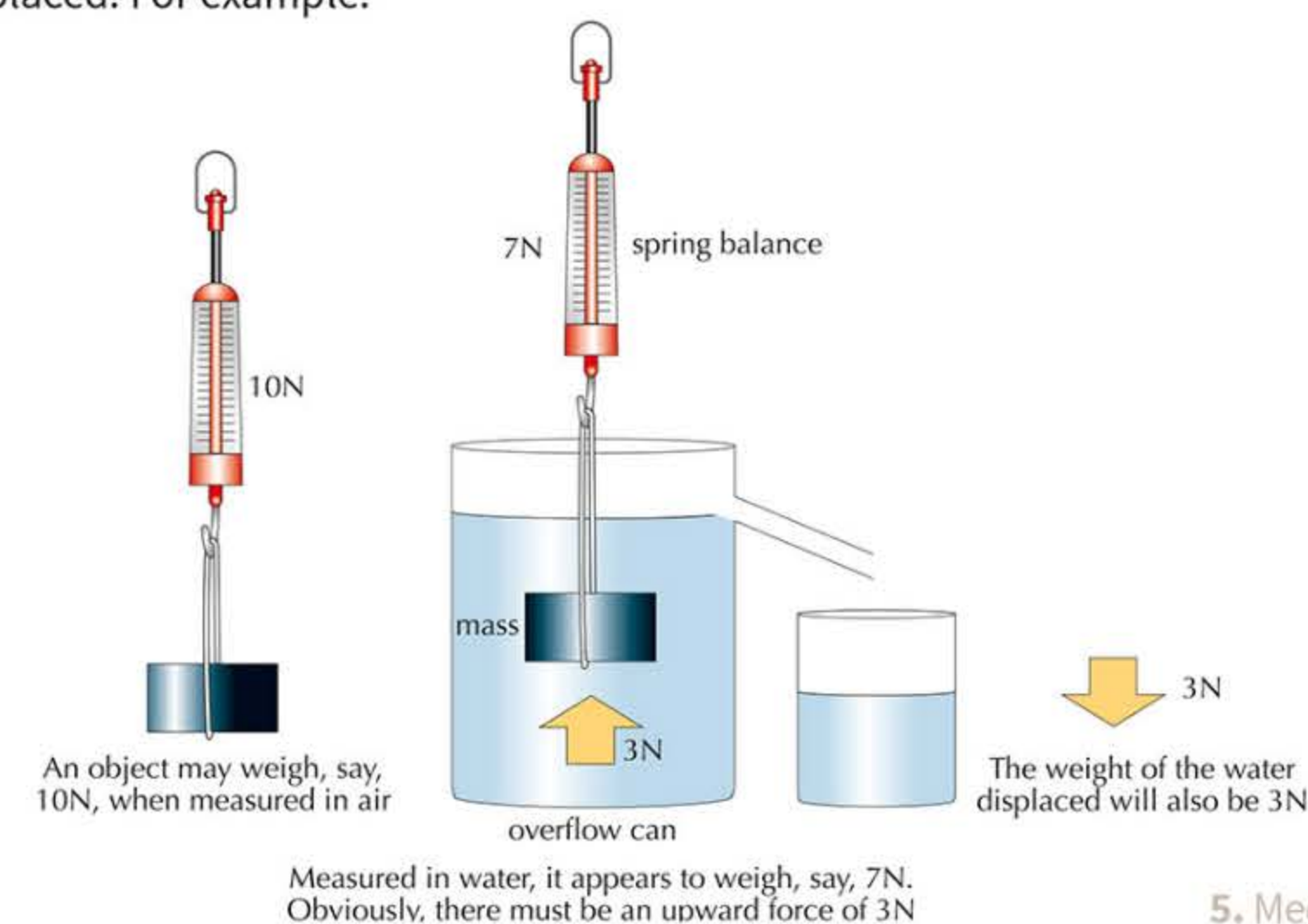


Calculate

- (i) The pressure at the bottom of the lake; (ii) The depth of the lake. (Acceleration due to gravity = 9.8 m s^{-2} ; density of water = $1.0 \times 10^3 \text{ kg m}^{-3}$) (10 marks)

Archimedes' principle states that a body immersed in a fluid will experience an upthrust equal to the weight of fluid it has displaced.

A body immersed in a fluid appears to become lighter. This is because it is experiencing an upward force, equal in size to the weight of the fluid it has displaced. For example:



The **law of flotation** states that when a body floats, it is displacing exactly its own weight of fluid.

STS

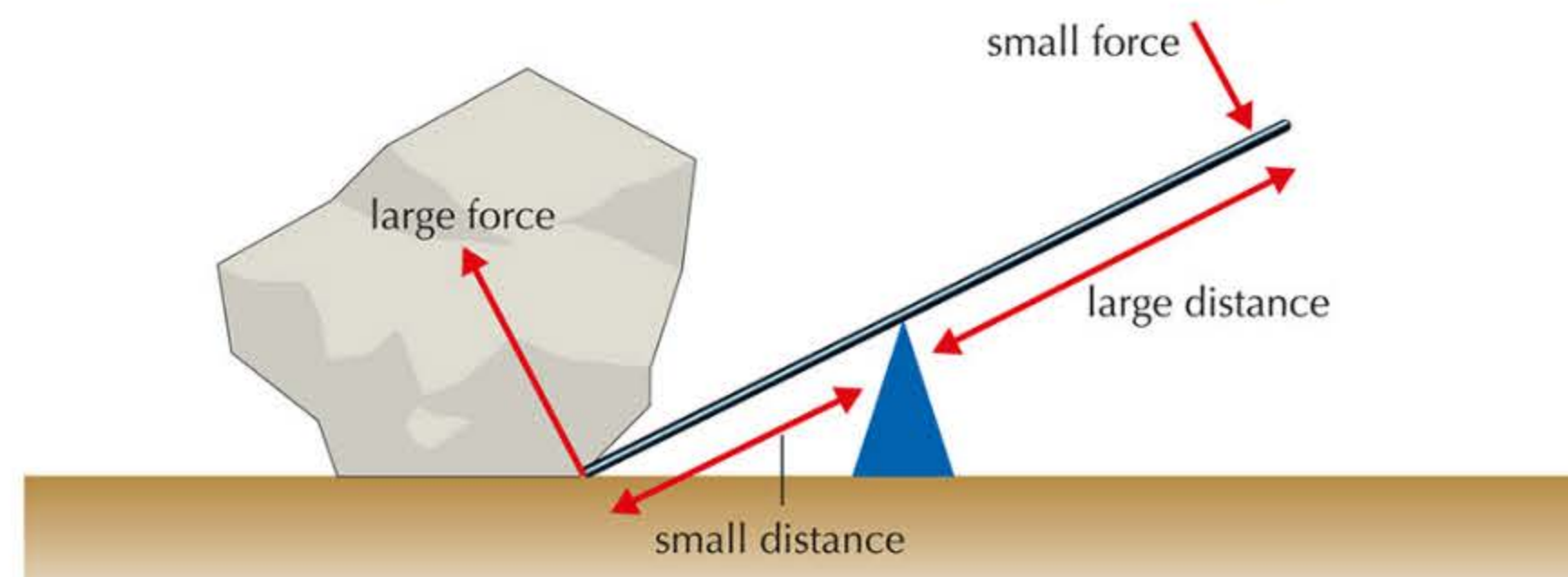
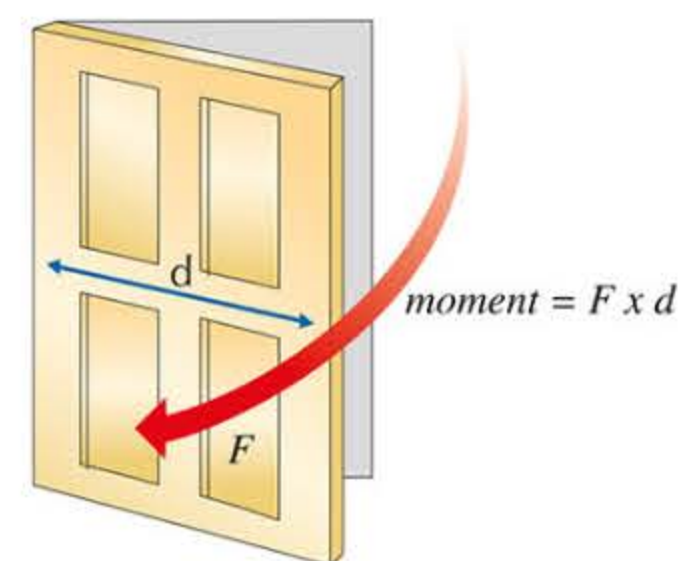
Archimedes' principle underlies the use of hydrometers. These are devices for measuring the density of a liquid. In a dense liquid, the hydrometer can displace its own weight by displacing only a small quantity of liquid. In a less dense liquid, it must sink deeper in order to displace the same weight.

Moments

The **moment of a force** about an axis is equal to the magnitude of the force multiplied by the perpendicular distance from the axis to the line of action of the force.

The moment of a force tells us about its ability to make something turn. For example, when we open or close a door we use a handle located as far from the hinges as is reasonable. For a small force, this creates a large moment, or turning effect.

A crow bar is an example of a lever that makes maximum use of a force to move a heavy object.



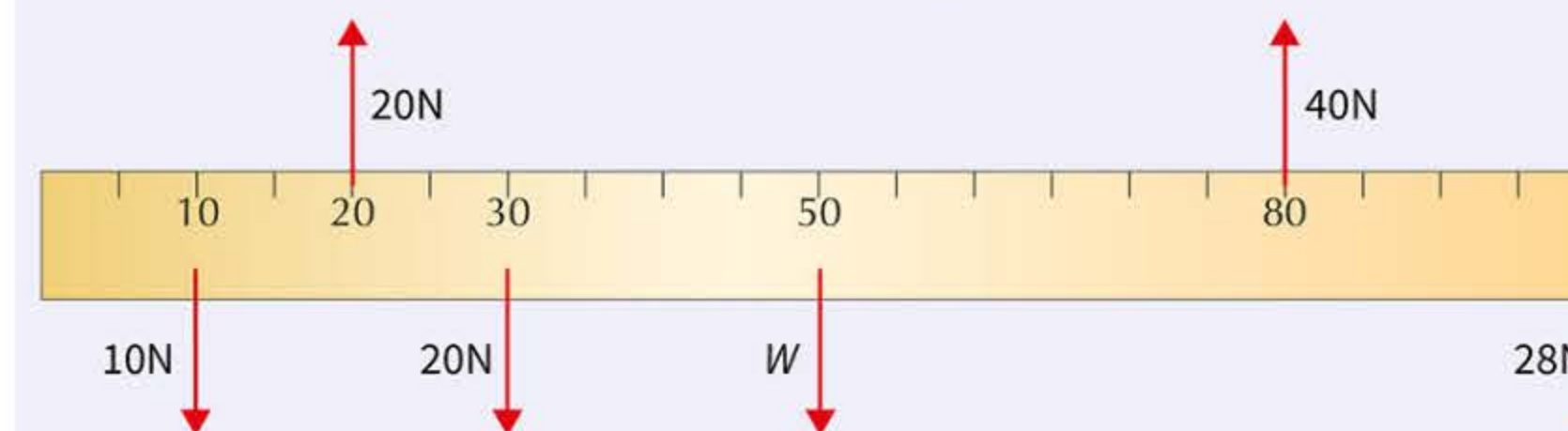
A **couple** is created by two parallel forces with the same magnitude acting in opposite directions.

An example of a couple is the handlebars of a bike. One hand moves forward, the other back, and the couple created turns the handlebar, and with it the bike.

The conditions for equilibrium

- 1 The sum of the forces in any direction equals the sum of the forces in the opposite direction.
- 2 The sum of the moments about any point is zero.

Consider a situation as shown here, consisting of a metre stick in equilibrium.



As the stick is in equilibrium, we know that the total forces up must equal the total forces down. We can use this to find W , the weight of the stick.

$$\begin{aligned}10 + 20 + 28 + W &= 20 + 40 \\ \Rightarrow W &= 60 - 58 \\ \Rightarrow W &= 2\text{N}\end{aligned}$$

Also, we can see that the moments about any point are zero.

Consider two points:

- 1 about 0 cm:

$$\begin{aligned}(10)(0.1) + (20)(0.3) + (2)(0.5) + (28)(1) &= (20)(0.2) + (40)(0.8) \\ 1 + 6 + 1 + 28 &= 4 + 32 \\ 36\text{ Nm} &= 36\text{ Nm}\end{aligned}$$

clockwise moments = anti-clockwise moments

- 2 about 50 cm:

$$\begin{aligned}(28)(0.5) + (20)(0.3) &= (10)(0.4) + (20)(0.2) + (40)(0.3) \\ 14 + 6 &= 4 + 4 + 12 \\ 20\text{ Nm} &= 20\text{ Nm}\end{aligned}$$

clockwise moments = anti-clockwise moments

Sample answer

Leaving Certificate 2013, Higher Level, Section B, Q6

- (i) State Newton's law of universal gravitation. (6 marks)

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. (3)

$$F = \frac{Gm_1m_2}{d^2} \quad (3)$$

- (ii) Explain what is meant by angular velocity. Derive an equation for the angular velocity of an object in terms of its linear velocity when the object moves in a circle. (9 marks)

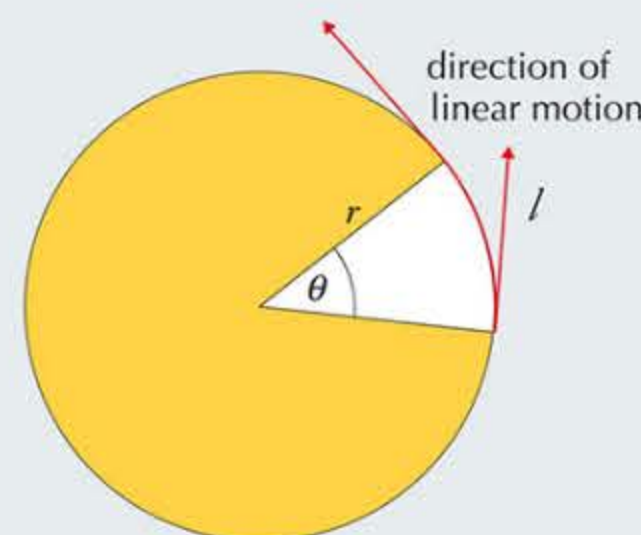
An object in circular motion has a linear velocity v and an angular velocity ω .

The angular velocity is the angle moved through each second by an object undergoing circular motion. (3)

The angular velocity ω is given by: $\omega = \frac{\theta}{t}$ (3)

The direction of the linear motion is at a tangent to the circle and is constantly changing. Its magnitude is given by:

$$\begin{aligned} V &= \frac{l}{t} \\ \Rightarrow V &= \frac{r\theta}{t} \quad (\text{as } l = r\theta) \\ \Rightarrow V &= r \frac{\theta}{t} \end{aligned}$$



and substituting, we find: $v = r \omega$ (3)

The International Space Station (ISS) functions as a research laboratory and a location for testing of equipment required for trips to the moon and to Mars. The ISS orbits the earth at an altitude of 4.13×10^5 m every 92 minutes 50 seconds.

- (iii) Calculate (a) the angular velocity, (b) the linear velocity, of the ISS. (12 marks)

$$T = \frac{2\pi}{\omega} \quad (3)$$

$$\omega = \frac{2\pi}{T} = \frac{2\pi}{(92 \times 60 + 52)} = 1.127 \times 10^{-3} \text{ rad s}^{-1} \quad (3)$$

$$v = r\omega = (6.37 \times 10^6 + 4.13 \times 10^5)(1.127 \times 10^{-3})^2 = 7644 \text{ ms}^{-1} \quad (6)$$

- (iv) Name the type of acceleration that the ISS experiences as it travels in a circular orbit around the earth. What force provides this acceleration? (6 marks)

The ISS is experiencing a centripetal acceleration, as does every object in circular motion. Here, the centripetal acceleration is created by the gravitational attraction between the ISS and the earth. (3, 3)

- (v) Calculate the attractive force between the earth and the ISS. Hence or otherwise, calculate the mass of the earth. (15 marks)

Following the formula for centripetal force:

$$F = \frac{mv^2}{r} = \frac{(5.4 \times 10^5)(7644)^2}{(6.37 \times 10^6 + 4.13 \times 10^5)} = 3.876 \times 10^6 \text{ N} \quad (3, 3)$$

Following the formula for gravitational force:

$$F = \frac{GM_1M_2}{d^2} \quad (3)$$

$$F = \frac{GM_eM_{ISS}}{d^2} = \frac{6.7 \times 10^{-11}M_e \times 4.5 \times 10^5}{(6.783 \times 10^6)^2}$$

This is the same as the force found above, and therefore:

$$\frac{6.7 \times 10^{-11}M_e \times 4.5 \times 10^5}{(6.783 \times 10^6)^2} = 3.876 \times 10^6 \quad (3)$$

Solving this for M gives the mass of the earth:

$$M_e = \frac{3.876 \times 10^6 \times (6.783 \times 10^6)^2}{6.7 \times 10^{-11} \times 4.5 \times 10^5} = 5.91 \times 10^{24} \text{ kg} \quad (3)$$

- (vi) If the value of the acceleration due to gravity on the ISS is 8.63 ms^{-2} , why do occupants of the ISS experience apparent weightlessness? (3 marks)

They experience apparent weightlessness because they are in a state often referred to as perpetual freefall. Generally, we experience our own weight indirectly via the normal reaction from the floor. In freefall and therefore in the ISS, there is generally no such normal reaction and the occupants experience something akin to weightlessness. (3)

- (vii) A geostationary communications satellite orbits the earth at a much higher altitude than the ISS. What is the period of a geostationary communications satellite? (mass of ISS = 4.5×10^5 kg; radius of the earth = 6.37×10^6 m) (5 marks)

The period of a geostationary satellite is the same as that of the earth – one day, i.e.

$$T = 1 \text{ day} = 86400 \text{ s} \quad (5)$$

Exam questions

1 2013, HL, Section B, Q12 (a)

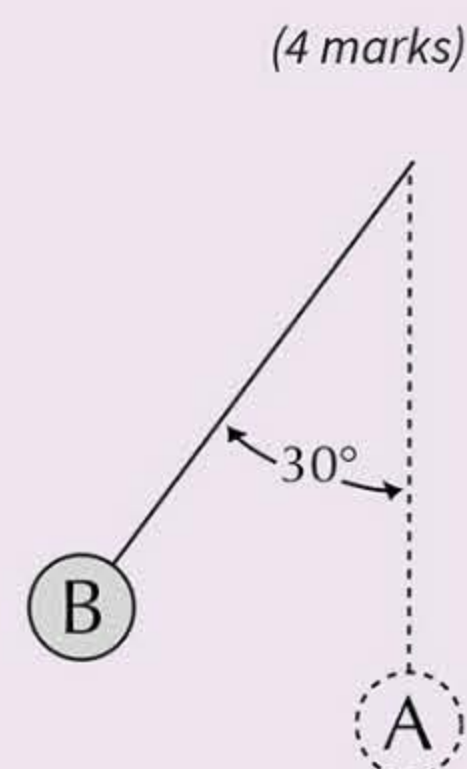
State the law of conservation of energy.

The pendulum in the diagram is 8 m long with a small bob of mass 6 kg at its end. It is displaced through an angle of 30° from the vertical (position A) and is then held in position B, as shown. Calculate the height through which the bob has been raised and the potential energy that it has gained. (9 marks)

The bob is then released and allowed to swing freely. What is the maximum velocity it attains? (9 marks)

When the moving bob is at position A, a force is applied which brings the bob to a stop in a distance of 5 mm. Calculate the force applied. (6 marks)

(acceleration due to gravity, $g = 9.8 \text{ m s}^{-2}$)



2 2006, HL, Section B, Q5

State Newton's third law of motion.

3 2005, HL, Section B, Q6

Define (i) angular velocity, (ii) centripetal force. State Newton's Universal Law of Gravitation. (18 marks)

A satellite is in a circular orbit around the planet Saturn. Derive the relationship between the period of the satellite, the mass of Saturn and the radius of the orbit. (15 marks)

4 2005, OL, Section B, Q6

Define pressure and give the unit of pressure. (12 marks)

Name an instrument used to measure pressure. (5 marks)

The earth is covered with a layer of air called the atmosphere. What holds this layer of air close to the earth? (6 marks)

Describe an experiment to show that the atmosphere exerts pressure. (12 marks)

The type of weather we get depends on the atmospheric pressure. Describe the kind of weather we get when the atmospheric pressure is high. (6 marks)

The African elephant is the largest land animal. An elephant weighs 40 000 N and is standing on all four feet each of area 0.2 m^2 . Calculate the pressure exerted on the ground by the elephant. (9 marks)

Why would the pressure on the ground be greater if the elephant stood up on just two feet? ($P = F/A$) (6 marks)

5 2004, HL, Section B, Q12 (a)

State Newton's universal law of gravitation. (6 marks)

Centripetal force is required to keep the earth moving around the sun.

- (i) What provides this centripetal force?
- (ii) In what direction does this centripetal force act?
- (iii) Give an expression for centripetal force. (10 marks)

6 2004, OL, Section B, Q6

Define (i) velocity, (ii) acceleration. (12 marks)

Describe an experiment to measure the velocity of a moving object. (12 marks)

The cheetah is one of the fastest land animals. A cheetah can go from rest up to a velocity of 28 ms^{-1} in just 4 seconds and stay running at this velocity for a further 10 seconds. Sketch a velocity-time graph to show the variation of velocity with time for the cheetah during these 14 seconds. (11 marks)

Calculate the acceleration of the cheetah during the first 4 seconds. (9 marks)

Calculate the resultant force acting on the cheetah while it is accelerating. The mass of the cheetah is 150 kg. (6 marks)

Name two forces acting on the cheetah while it is running. ($v = u + at$, $F = ma$) (6 marks)

6 Light, Sound and Waves

Learning objectives

In this chapter you will learn about:

- 1 Reflection
- 2 Refraction
- 3 Total internal reflection
- 4 Lenses
- 5 The eye
- 6 Waves
- 7 The wave nature of light
- 8 Colour
- 9 Dispersion
- 10 Polarisation
- 11 Electromagnetic spectrum
- 12 Sound

Key definitions relevant to this chapter

Laws of reflection	Diffraction
Laws of refraction	Interference
Refractive index	Doppler effect
Critical angle	Resonance
Total internal reflection	Harmonics
Longitudinal / transverse waves	Threshold of hearing
Stationary wave	Frequency limits

Key formulae

Velocity of a wave $c = f\lambda$

Doppler effect $f' = \frac{fc}{c \pm u}$

Frequency of a stretched string $f = \frac{1}{2l} \sqrt{\frac{T}{\mu}}$

Mirror and lens formula $\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$

Magnification $m = \frac{v}{u}$

Power of a lens $P = \frac{1}{f}$

Two lenses in contact $P = P_1 + P_2$

Refractive index $n = \frac{\sin i}{\sin r} = \frac{\text{real depth}}{\text{apparent depth}} = \frac{1}{\sin c} = \frac{c_1}{c_2}$

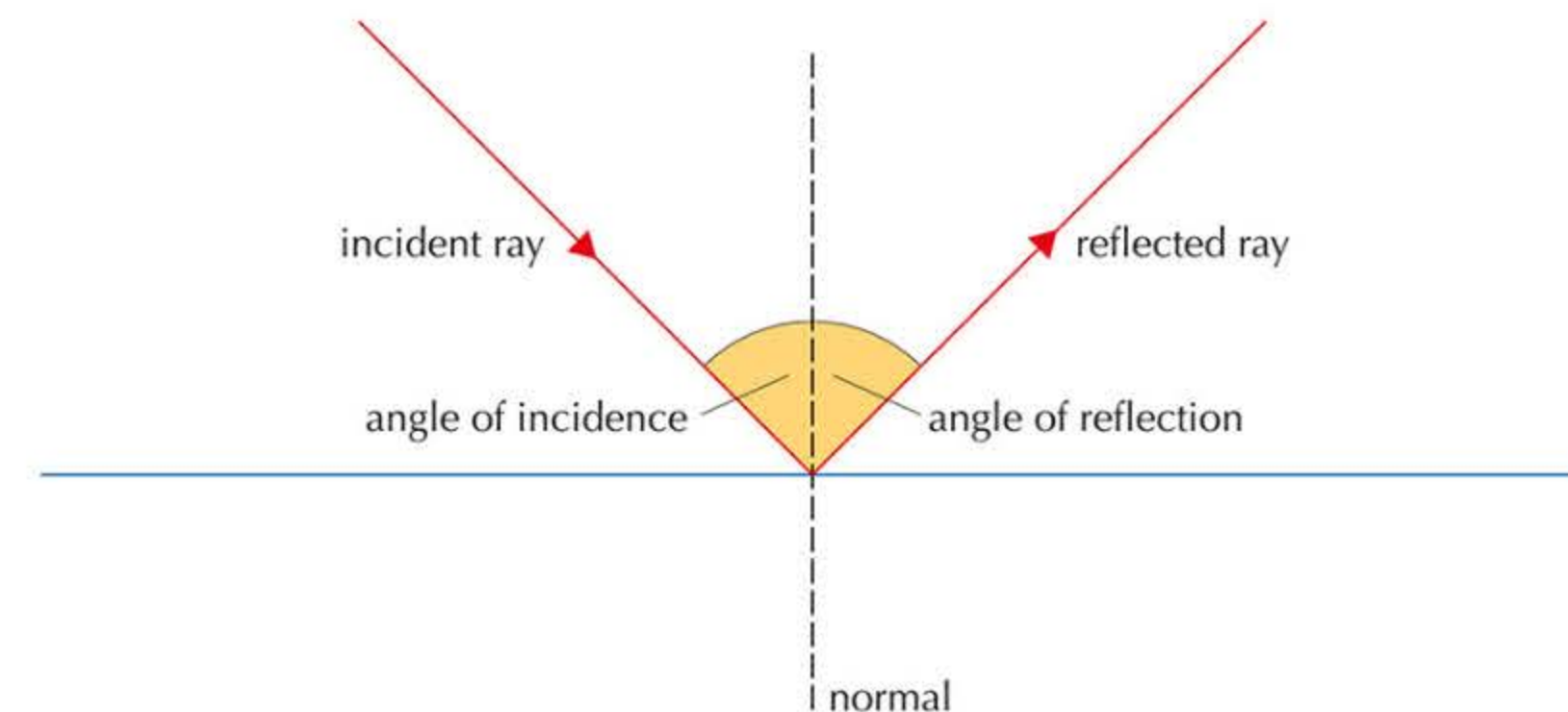
Diffraction grating/spectrometer $n\lambda = d \sin \theta$

Reflection

Light reflects off a surface in much the same way that a ball will bounce off a solid surface. The laws of reflection set out to describe this as precisely as possible:

The angle of incidence equals the angle of reflection.

The incident ray, the normal, and the reflected ray are all in the same plane.



The laws of reflection apply to all cases where there is reflection. Though they can be easily demonstrated using a laser or light box and a plane (or flat) mirror, the same laws apply to curved mirrors and to comparatively rough surfaces such as a table top or a page of a book.

Image formation

There are two kinds of images, real and virtual. We cannot tell the difference between them when we look into a mirror, but the differences are important.

A real image is formed by the actual intersection of light rays. It can be formed on a screen.

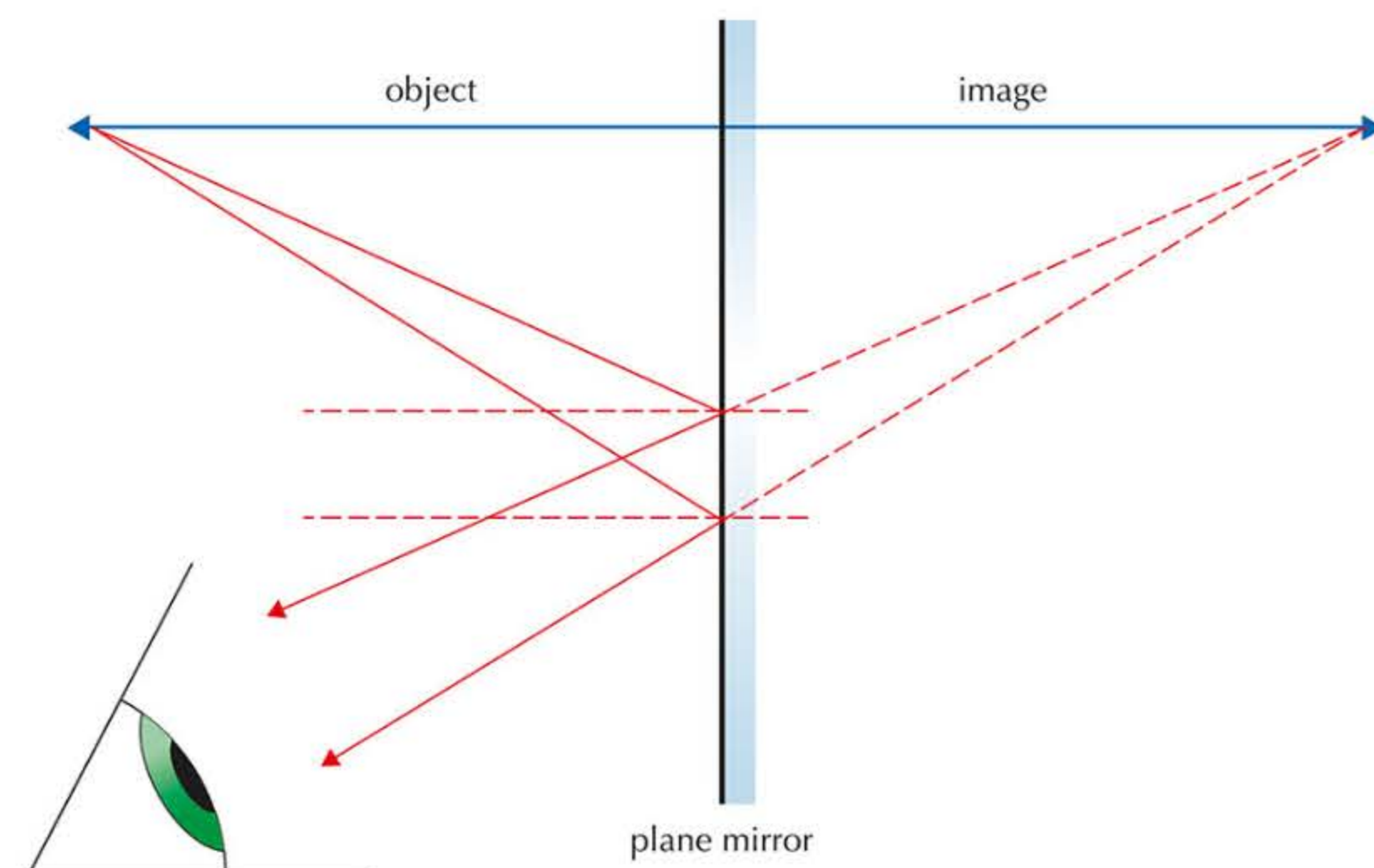
A virtual image is formed by the apparent intersection of light rays. It cannot be formed on a screen.

On the next few pages we will see examples of both.

Plane mirrors

The image formed with a **plane mirror** is a virtual image. It is formed according to the ray diagram shown at the top of the opposite page. The light rays entering the eye are diverging, or moving away from each other. But our eyes and our brains assume that all light rays travel in a straight line, and so we believe the light entering our eye has come from a point behind the mirror, as shown. This is where we 'see' the image.

The image is always the same size as the object, and the same distance behind the mirror as the object is in front of it.



Curved mirrors

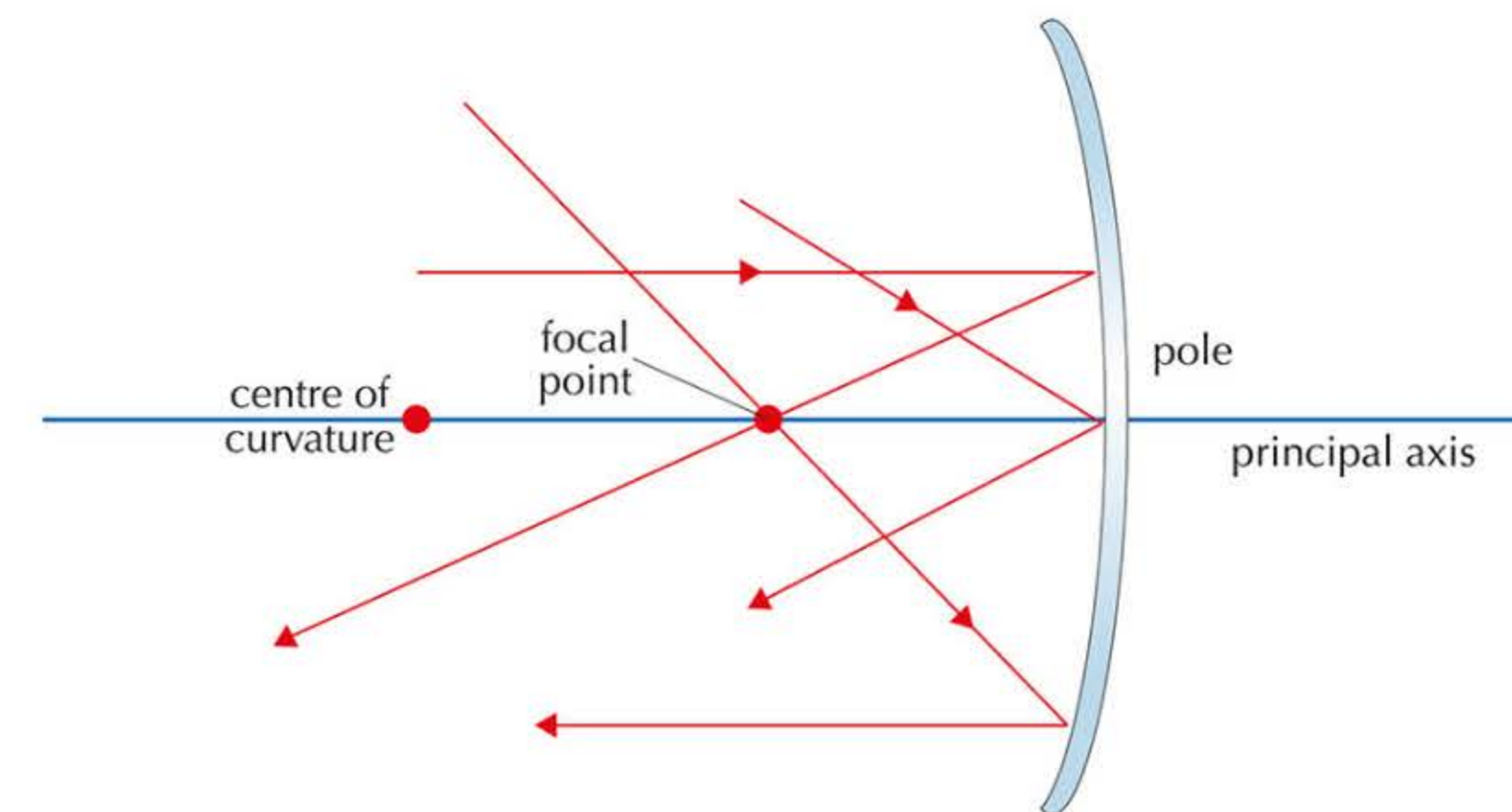
Concave mirrors

Though usually a lot smaller, a **concave mirror** is a similar shape to a satellite dish. In order to find how images are formed, we can usually follow these light rays:

A light ray parallel to the principal axis reflects through the focal point.

A light ray through the focal point reflects parallel to the axis.

A light ray incident at the pole clearly reflects according to the laws of reflection.



The **centre of curvature** is the 'centre' around which the mirror is formed. The focal point (f) is half way between the mirror and the centre of curvature (C).

The following diagrams show how the position of the object with respect to the mirror affects the type of image that is formed.

Object outside C

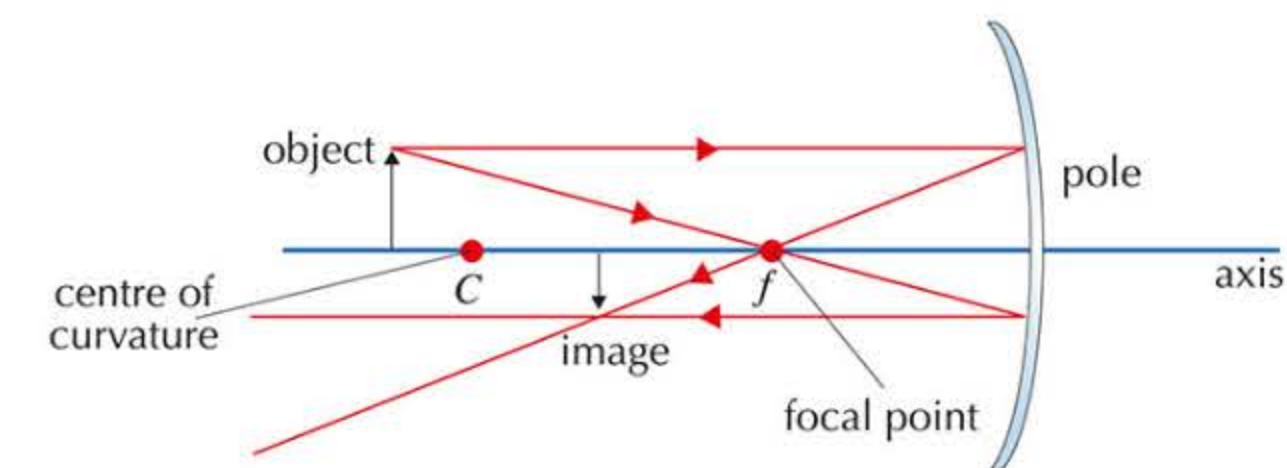


Image is real, inverted and diminished

Object at C

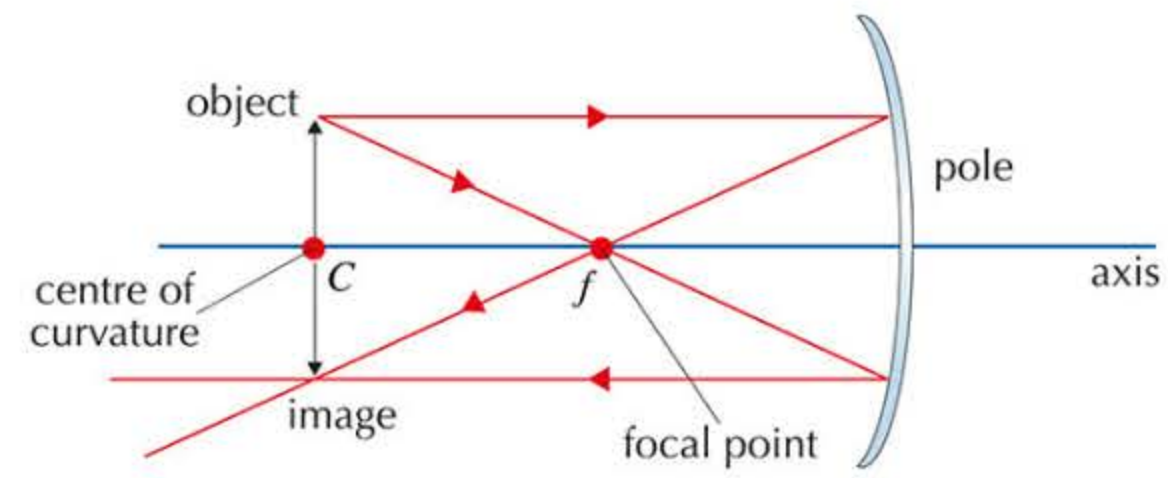


Image is real, inverted and same size

Object between C and f

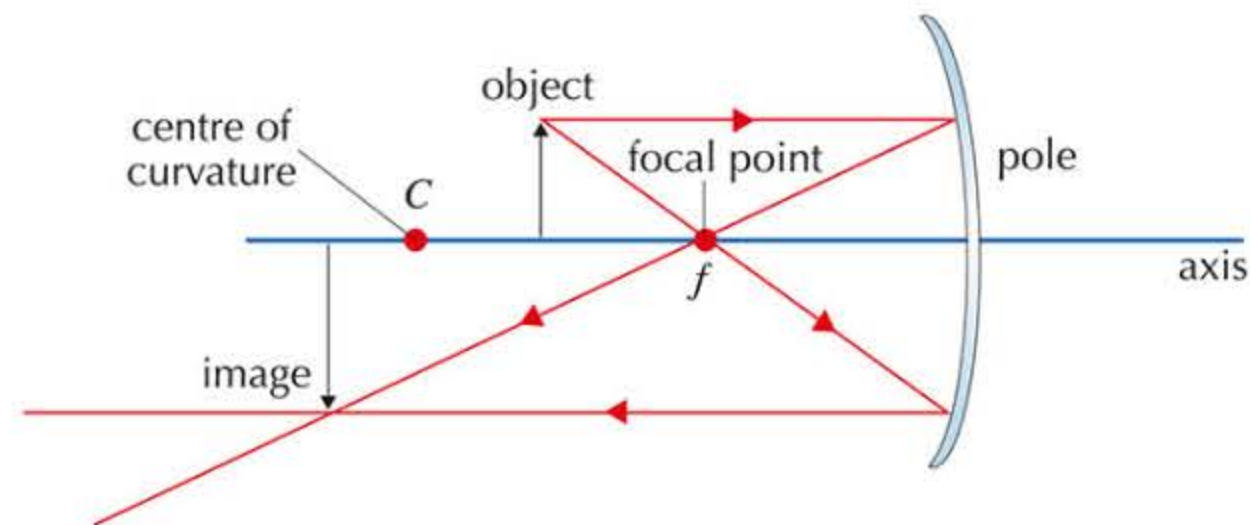


Image is real, inverted and magnified

Object at f

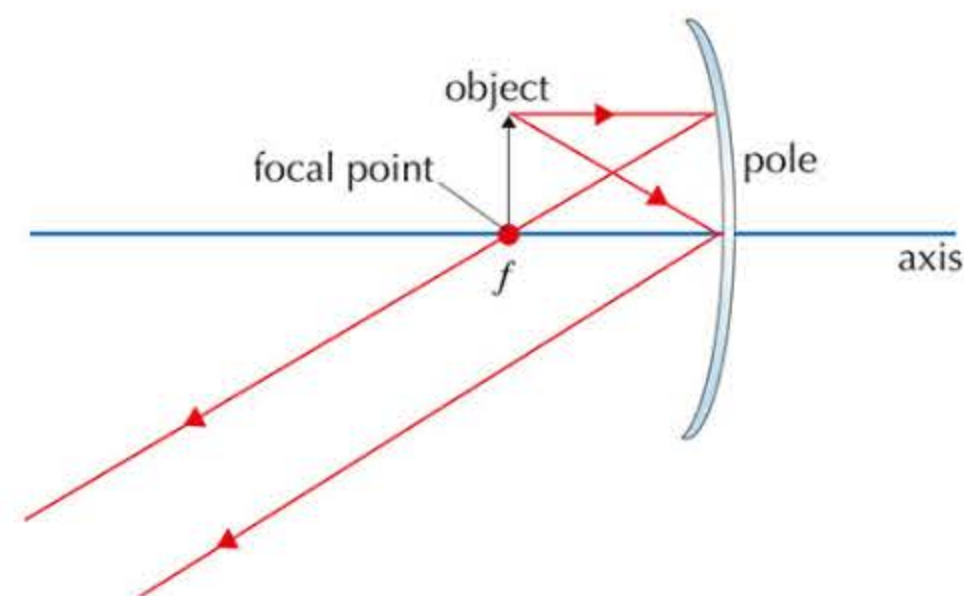


Image is at infinity

Object inside f

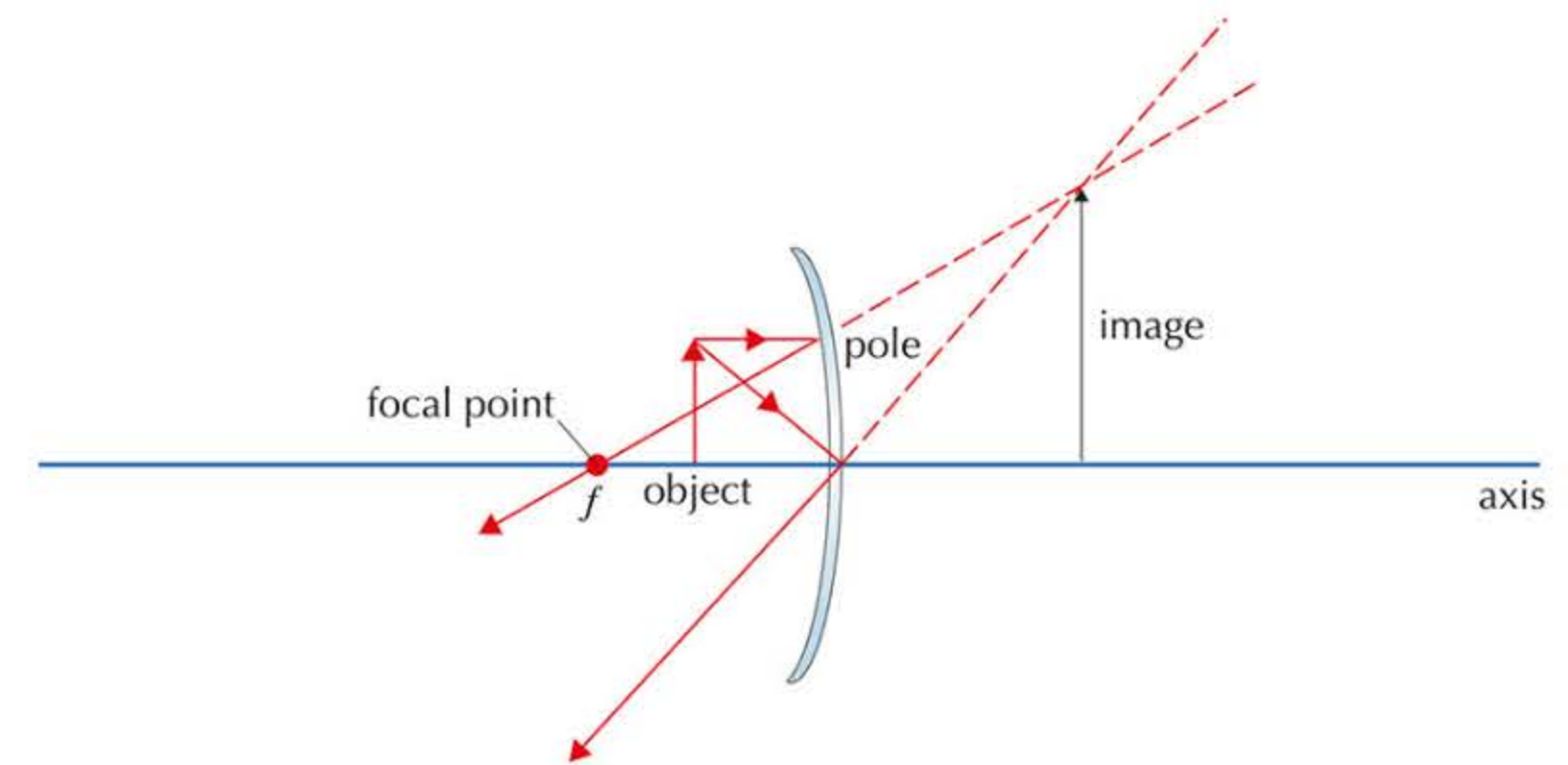
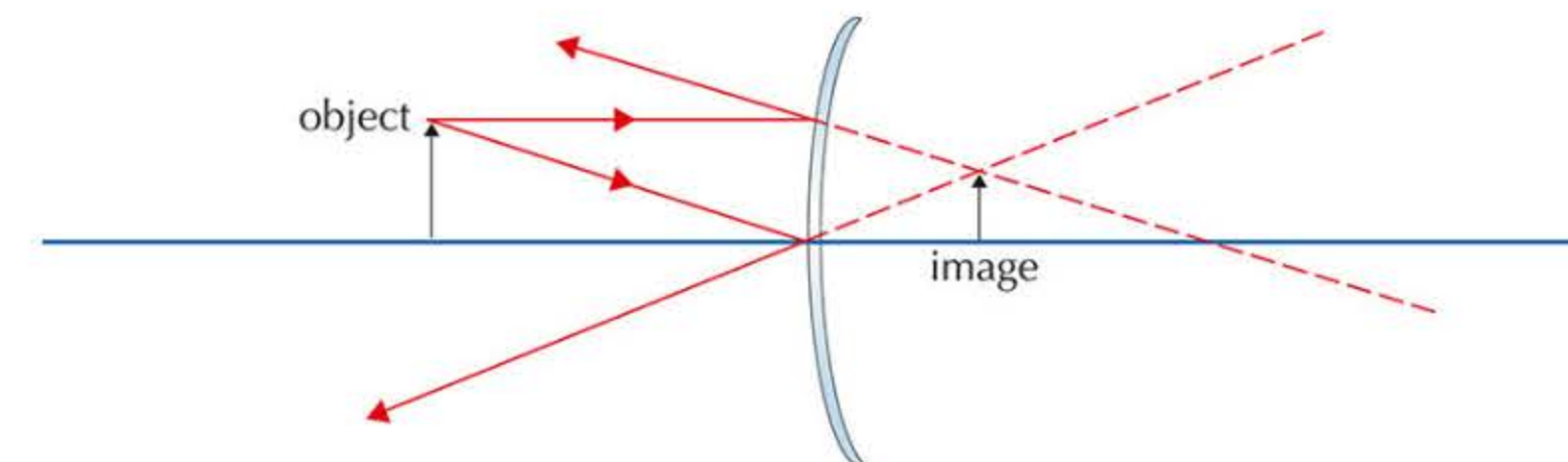


Image is virtual, upright and magnified

Convex mirrors

In **convex mirrors**, the focal point still exists, but is now *behind* the mirror. Incident beams parallel to the axis are not reflected through it, but seem to originate there instead.



The image formed is always virtual, upright and diminished.

The formula still applies but it is important to remember that with a convex mirror, the image is always virtual, so v is always negative, and that as no light passes through the focal point, it is also virtual, and f is also always negative.

Maths

For all curved mirrors, this formula applies:

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$

Also the magnification is given by both:

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

and

$$m = \frac{\text{height of image}}{\text{height of object}}$$

Remember

For virtual images,
 v is always negative.

For a convex mirror,
 f is always negative.

STS

Common uses of **concave** mirrors include:

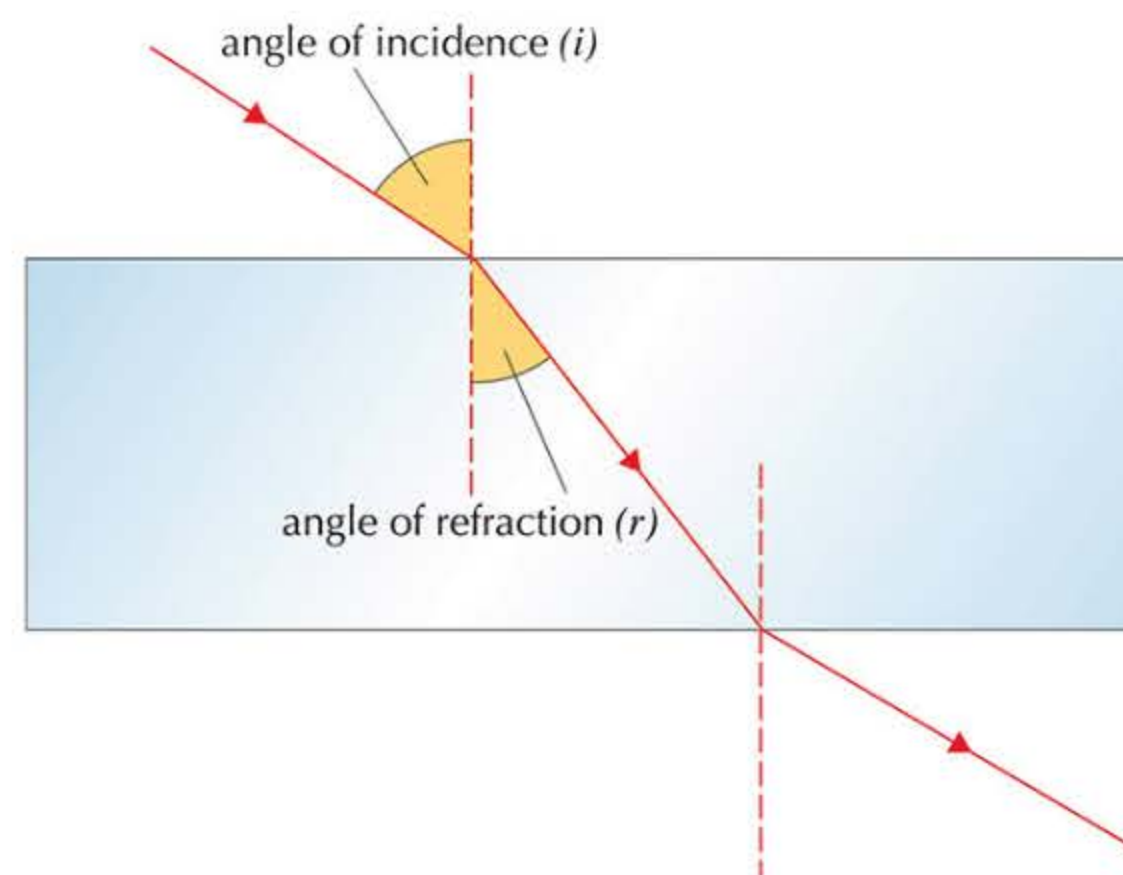
- Dentist's mirrors: by placing a mirror close to teeth, they are positioned inside the focal length, and a magnified image is formed.
- Shaving or make-up mirrors: These are often found in bathrooms. If you stand close to them, you get an enlarged image of your face.

Common uses of **convex** mirrors include:

- In shops as security devices, so that a large area can be easily seen.
- On country roads, to aid vision on dangerous corners.
- As the wing mirrors in a car, giving a large field of vision (but with the problem that the image is diminished and can lead a driver to feel another car is further away than it really is).

Refraction

When a car drives from a hard surface, such as tarmac, onto a soft surface, such as sand, it tends to change direction. This is because one wheel hits the sand first and slows down while the others do not. Something similar happens with light when it goes from one material, such as air, into a more dense material, such as glass or water.



We can describe exactly what happens by the laws of refraction:

- The incident ray, the normal, and the refracted ray are all in the same plane.
- For any pair of media, the sin of i , the angle of incidence, is proportional to the sin of r , the angle of refraction, i.e. $\frac{\sin i}{\sin r} = \text{constant}$ (i.e. Snell's law)

The value of the constant is known as the refractive index, n , of the material, i.e.

$$n = \frac{\sin i}{\sin r}$$

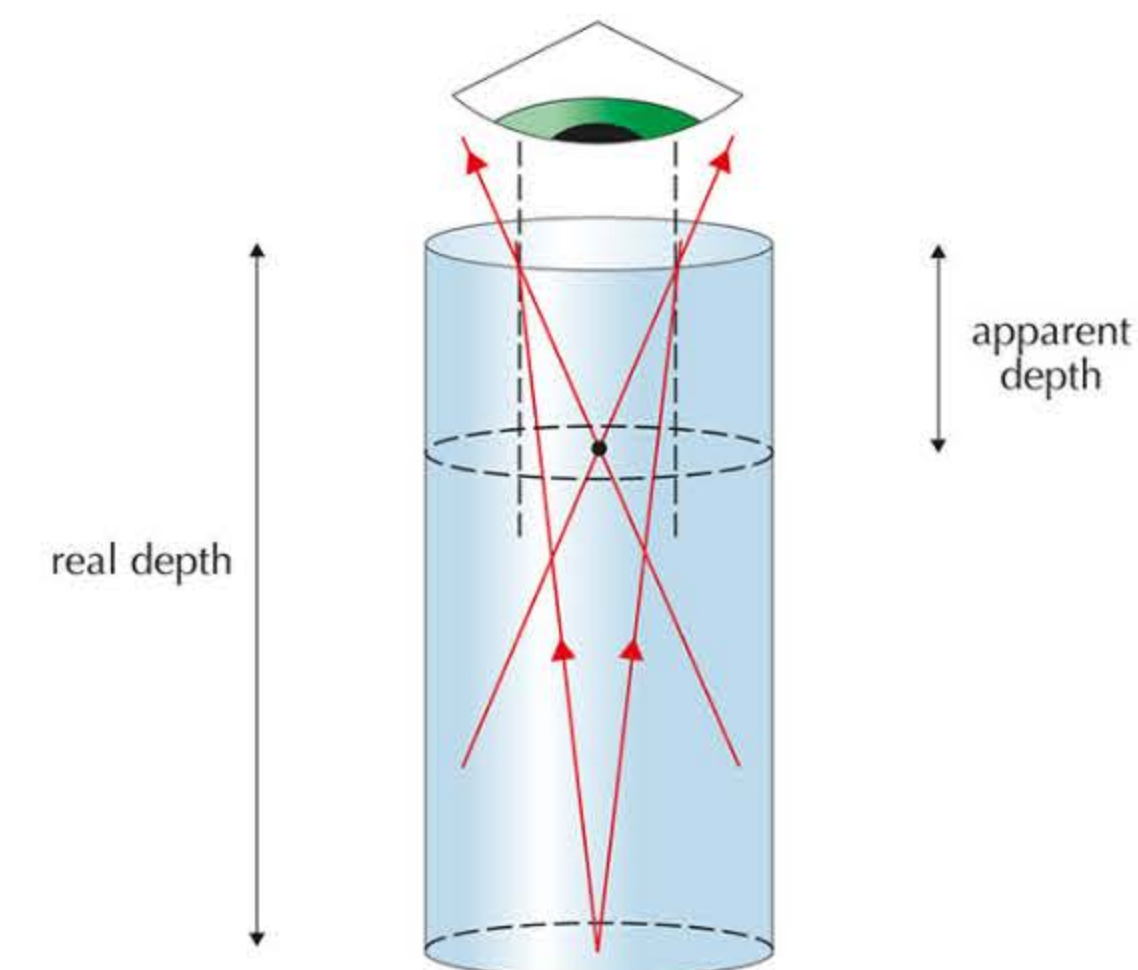
- When light moves from a less dense medium into a more dense medium, it bends towards the normal.
- If light moves into a less dense medium, it bends away from the normal.

As refraction is caused by the change in the speed of light, we can use this to find another formula for the refractive index of a material:

$$n = \frac{\text{speed of light in air/vacuum}}{\text{speed of light in material}}$$

STS

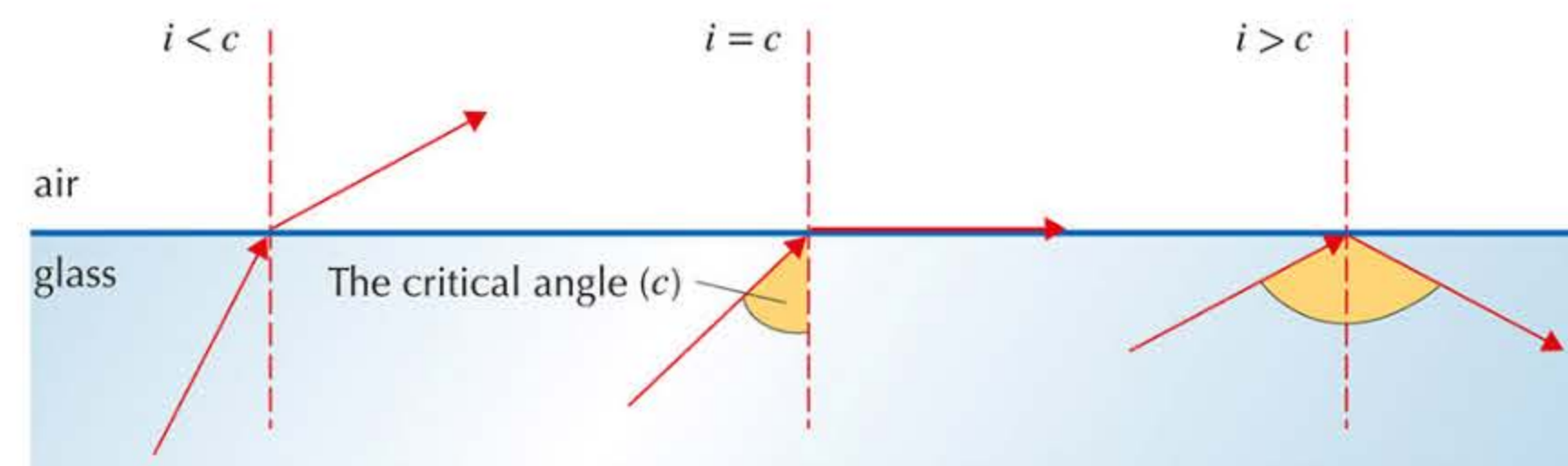
Refraction is responsible for the manner in which a pool of water always seems less deep when viewed from above than it actually is. The light rays are bent outwards on leaving the water and entering the less dense air. To a person above the water, the light appears to be coming from a point closer to the surface than is actually the case.



Another useful formula for refractive index comes from this: $n = \frac{\text{real depth}}{\text{apparent depth}}$

Total internal reflection

If light is moving from a relatively dense material (such as glass) into a less dense material (such as air) it will bend away from the normal. Obviously there is an angle of incidence where the light bends so much it is skimming along the surface. This is known as the critical angle of the material.



If the angle of incidence is any bigger than this, the light cannot leave the glass. Instead it is reflected as if it was hitting a mirror, and the laws of reflection apply. This is **total internal reflection**.

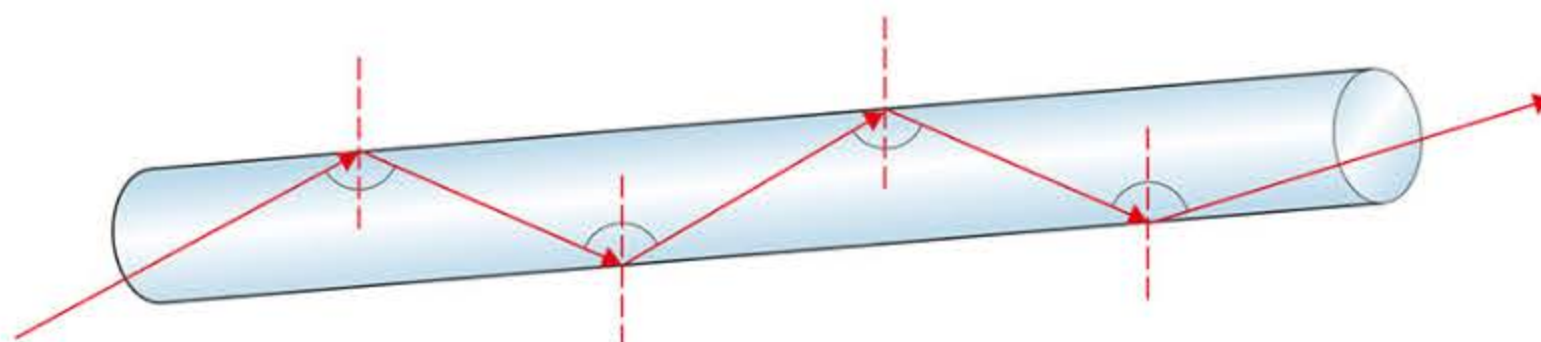
- Total internal reflection occurs when the angle of incidence in a dense material is greater than the critical angle. Light is reflected back into the original material.
- The critical angle is the angle of incidence for which the corresponding angle of refraction is 90° .

We can also use the critical angle, (c), to find the refractive index:

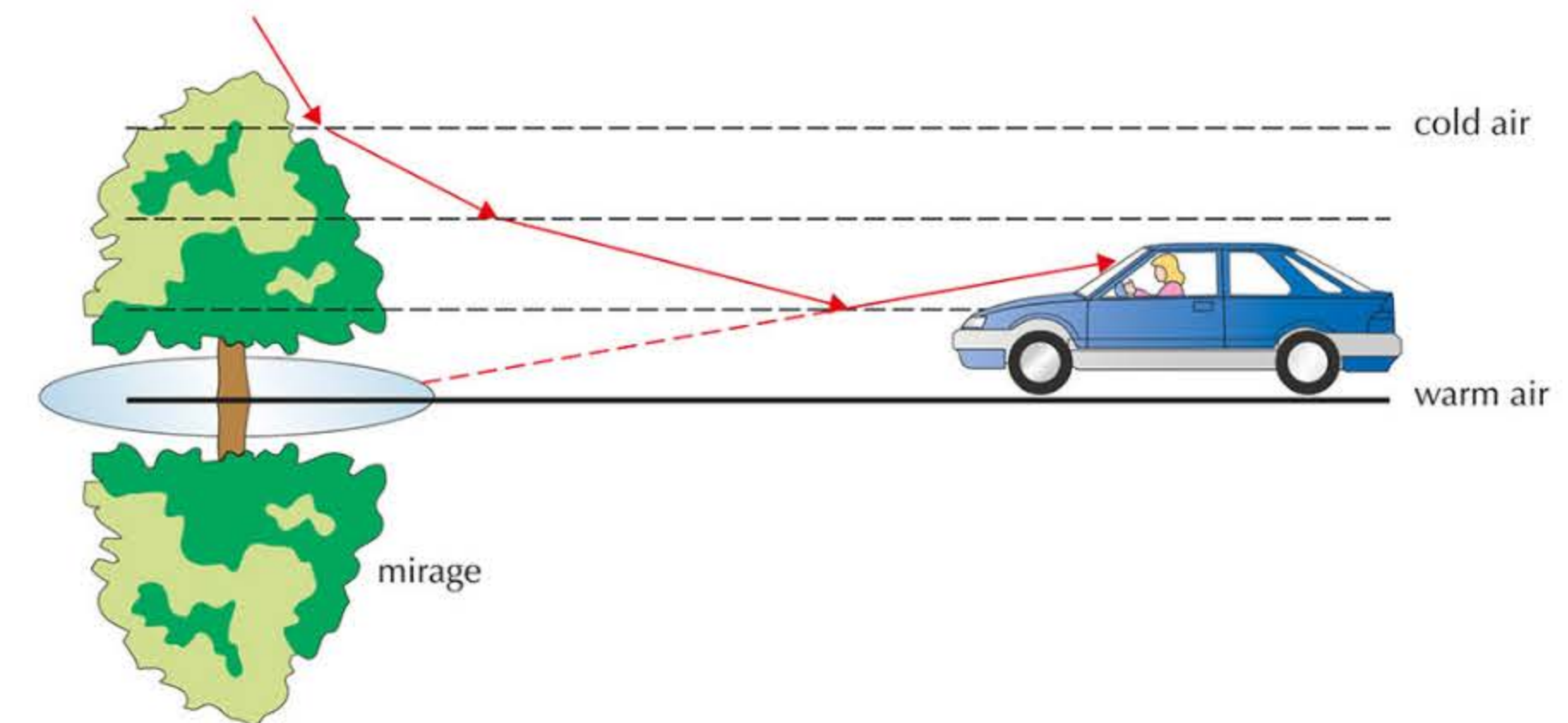
$$n = \frac{1}{\sin c}$$

STS

Total internal reflection has given rise to the use of **optical fibres**, in which light continuously strikes both the top and bottom of the fibre at an angle greater than the critical angle. The light is therefore 'trapped' within the fibre. This technology can be used to transmit information over long distances. Transatlantic telephone messages are carried through optical fibres. They are also used by surgeons to allow them to see into the body quite clearly without having to cut the body open. Cables are coated with a layer of less dense material to ensure that total internal reflection will occur.



Total internal reflection also gives rise to **mirages**. The surface of a road can get very hot on a sunny day. This heats the air directly touching it and leaves layers of cold air higher up. The hot air is less dense and as light enters into it will refract and bend away from the normal. This might happen several times, and eventually the light will hit a layer of hot air at an angle above the critical angle. The light is reflected. A driver can be fooled into thinking this is light coming from the roadway in front of him or her.

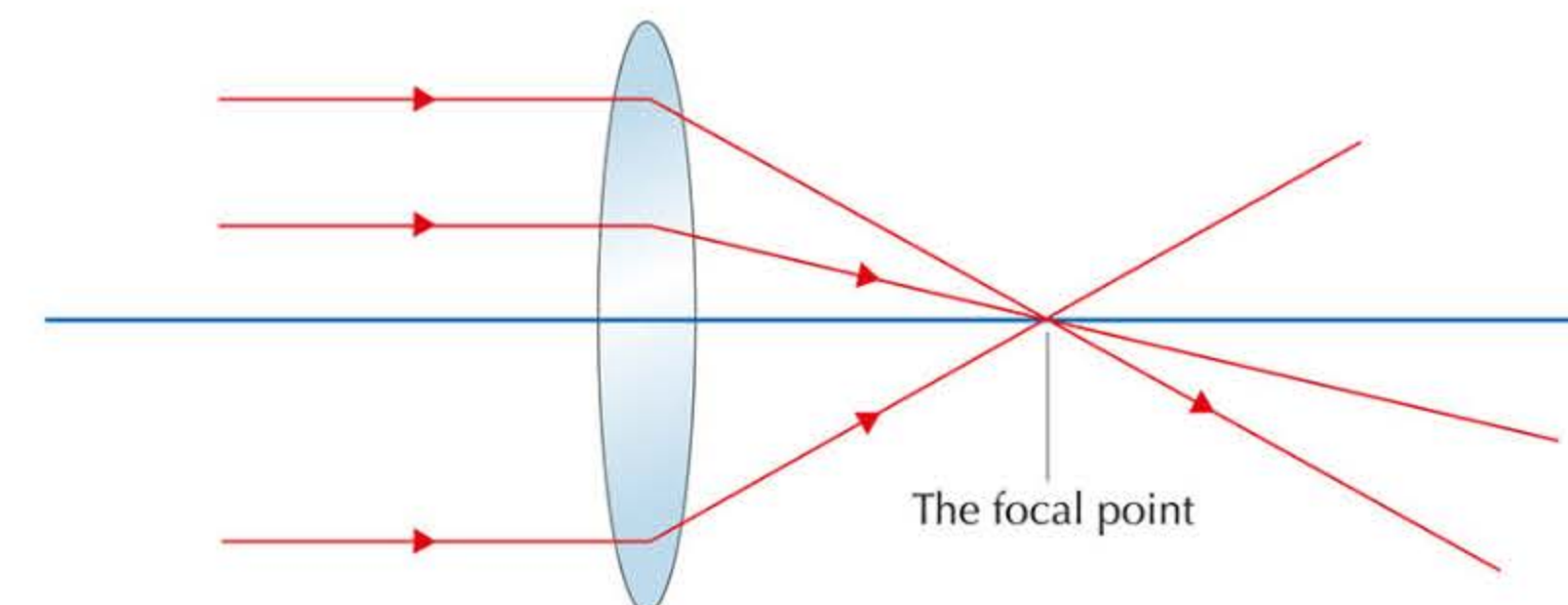


Prism reflectors, used as reflectors on bicycles, also make use of total internal reflection.

Lenses

Converging lenses

Converging lenses are shaped as shown in the diagram below. They are often referred to as **convex lenses**. The light is refracted 'inwards' on both entering and leaving the lens, thus causing the converging effect. All the light that hits a lens 'head-on' passes through a single point, known as the focal point.



Light that passes through a lens will often form what we call a real image on a screen. It can be either magnified or diminished. We see this in the cinema, where the image is magnified.

Converging lens diagrams

Object outside $2f$

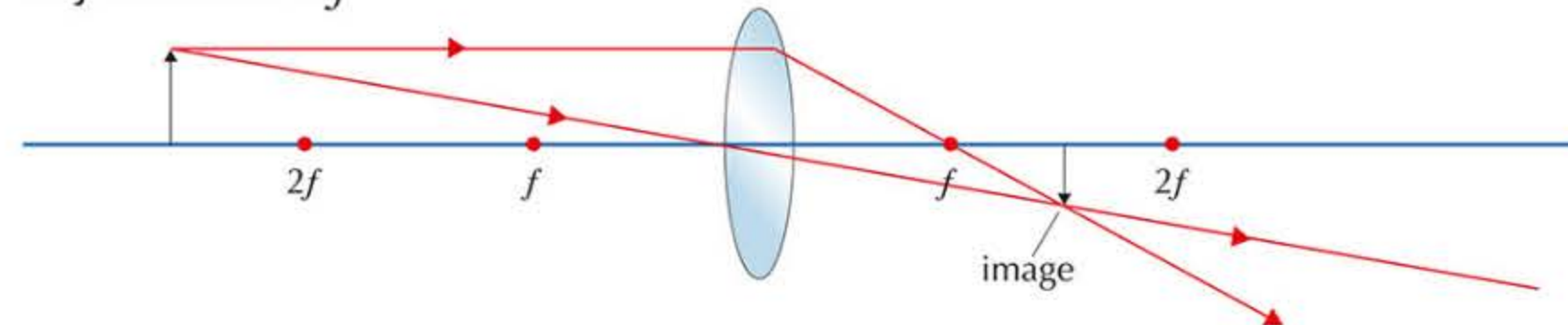


Image is real, inverted and diminished

Object at $2f$

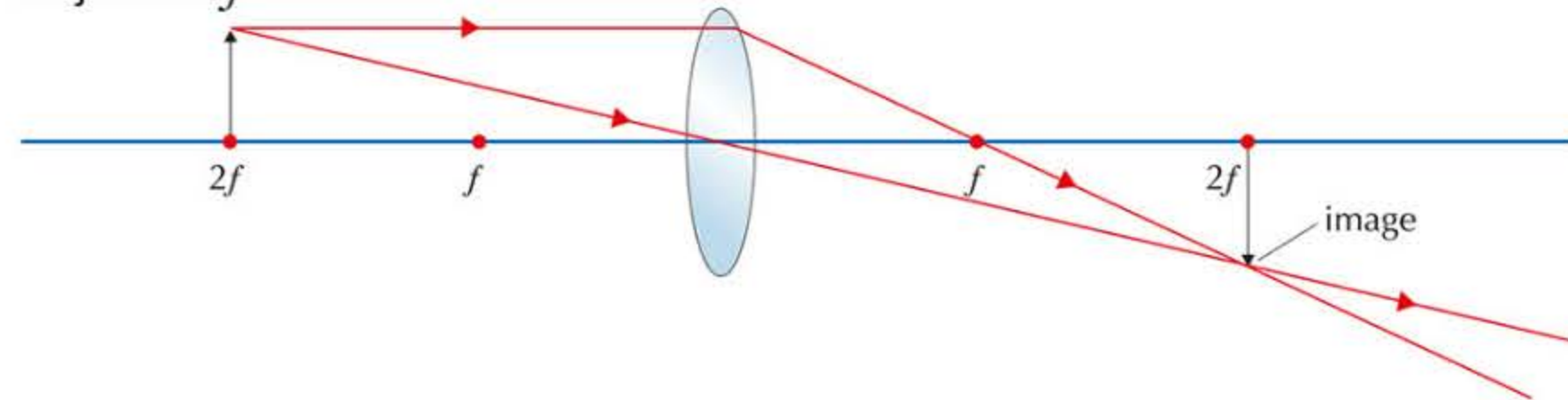


Image is real, inverted and same size

Object between $2f$ and f

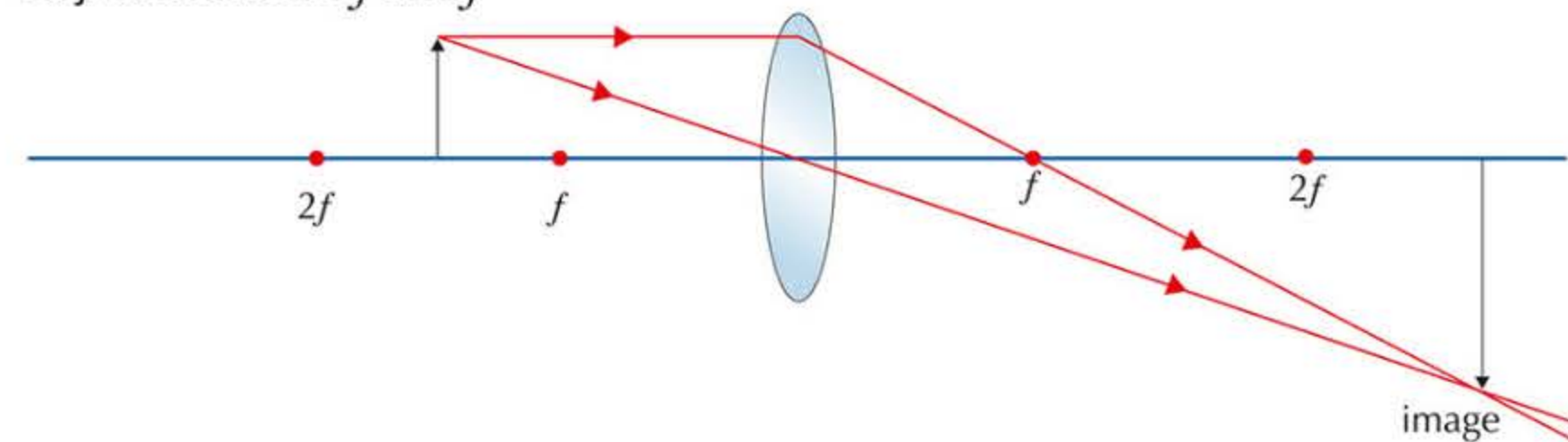


Image is real, inverted and magnified

Object at f

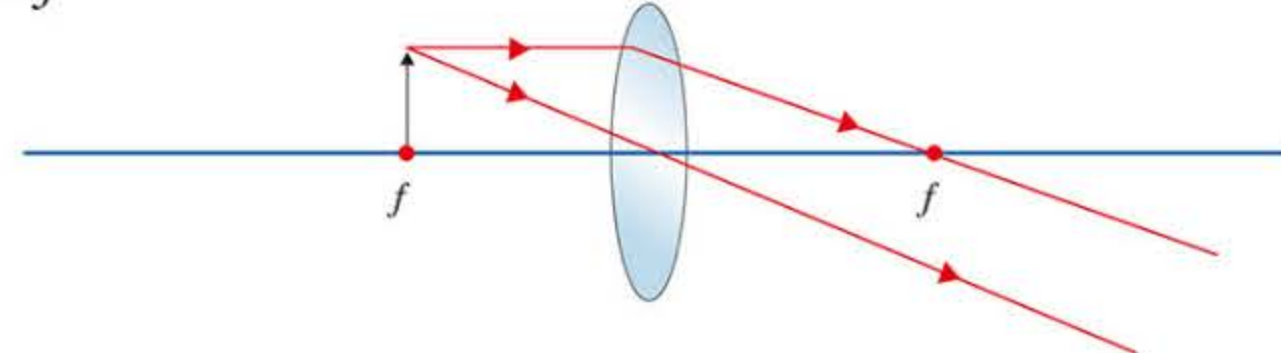


Image is at infinity (blurred)

Object inside f

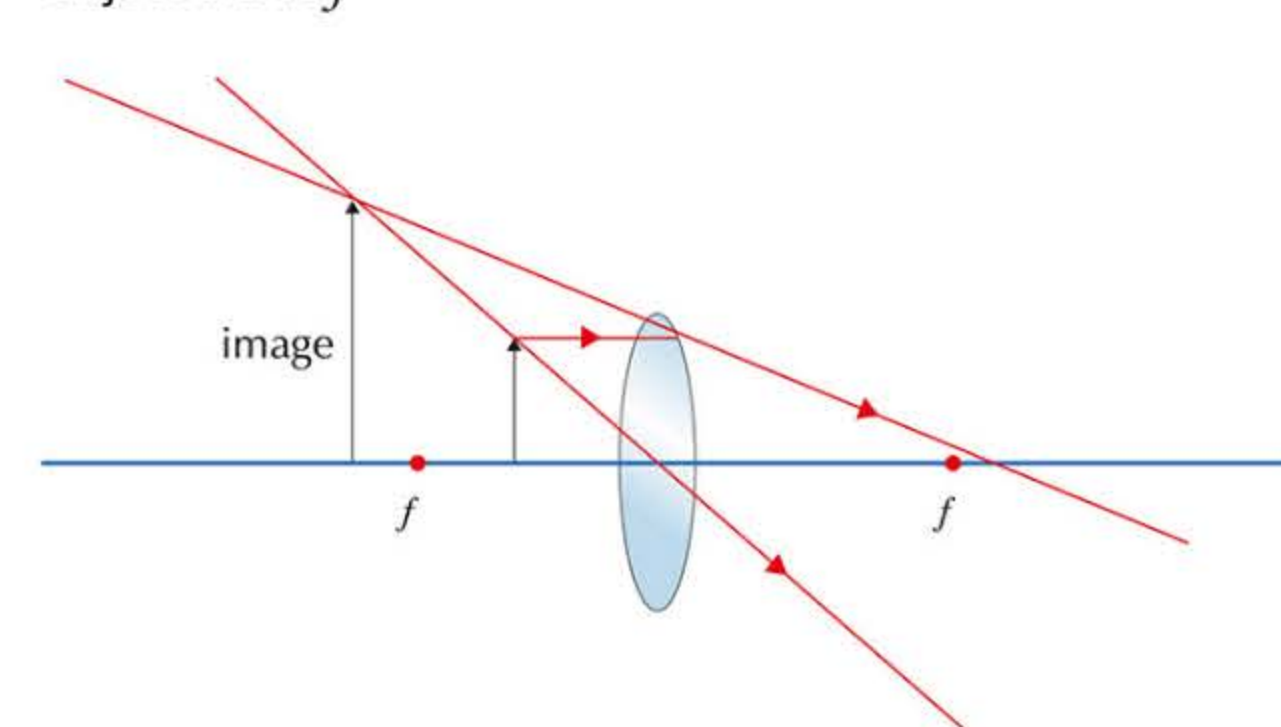
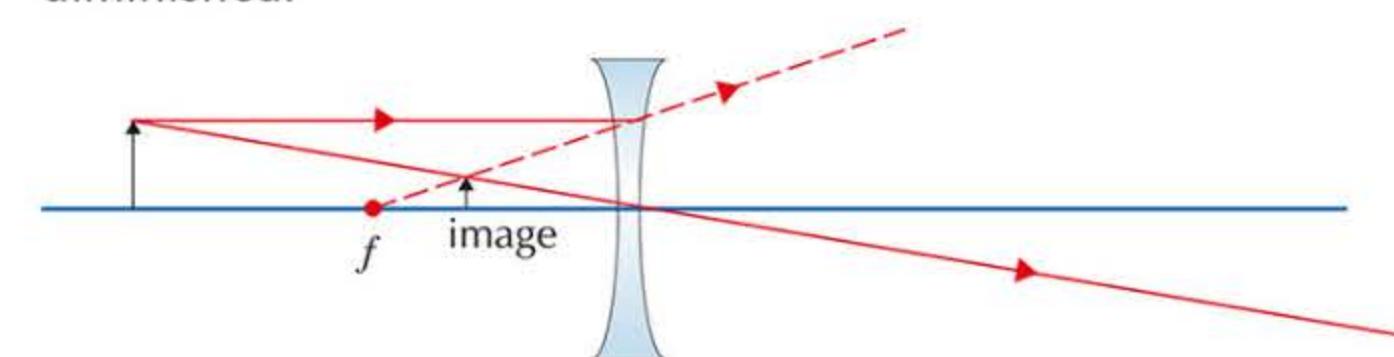


Image is virtual, upright and magnified

Diverging lenses

Diverging lenses are shaped as shown in the diagram below.

A diverging lens will always create an image that is virtual, upright and diminished.



Maths

The lens formula is the same as that we use for curved mirrors:

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$

Again, virtual lengths, including the focal length of a diverging lens, are taken as being negative.

Also the magnification formula is $m = \frac{v}{u}$

or, $m = \frac{\text{height of image}}{\text{height of object}}$

The power, P , of a lens is given by:

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

And for two lenses in contact the total power is the sum of the individual powers:
i.e.

$$P_T = P_1 + P_2$$

The power of a diverging lens is negative.

STS

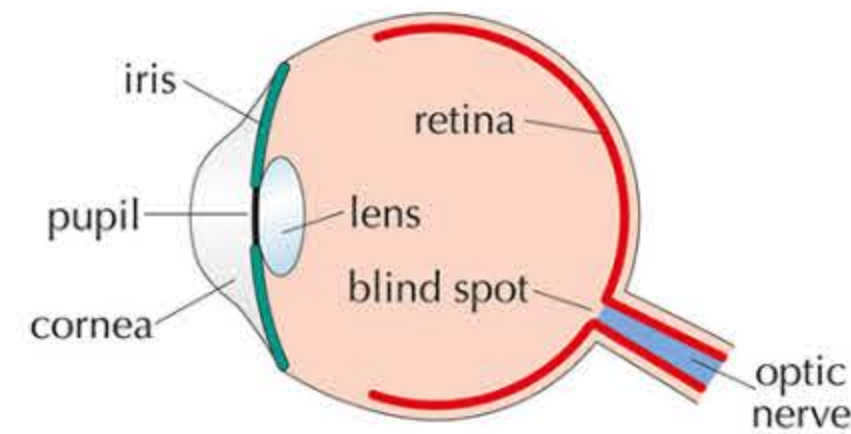
A converging lens can be used as a magnifying glass, as long as the situation is arranged so that an object is inside the focal length of the lens.

Combinations of lenses can be used in microscopes and telescopes.

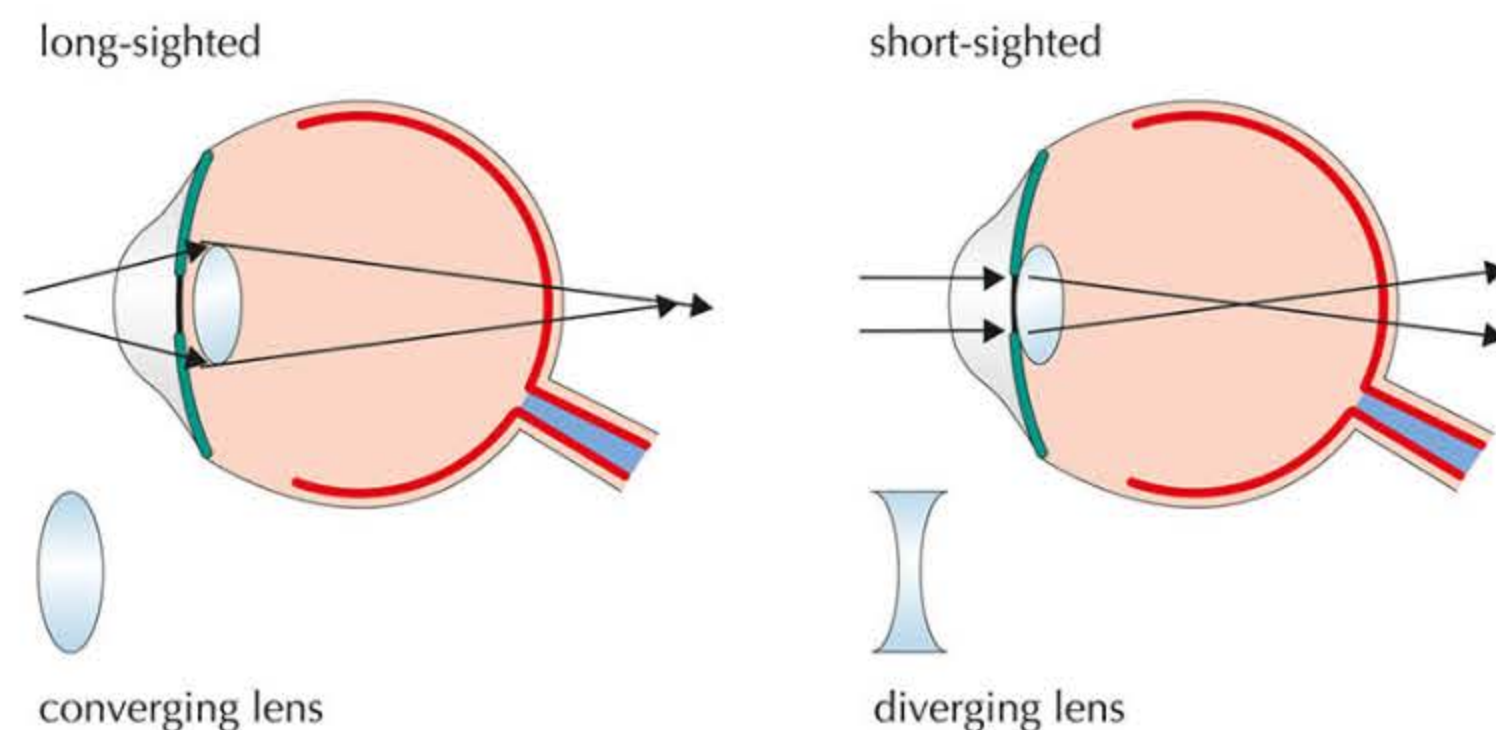
They can also be used as spectacles.

The eye

- We see because light passes through the front of the eye and an image is formed on the retina, where the light energy is converted into electrical energy and a message is sent along the optic nerve to the brain.
- Light entering the eye is incident upon the **retina**, through the **lens**. The shape of the lens, and thus its focal length is controlled by a muscle, and this allows us to focus on objects either near or distant.
- The amount of light entering the eye is controlled by the **iris** (the coloured part of the eye), which has a hole at its centre called the **pupil**. The pupil grows larger when it is dark to allow more light to enter, and smaller when it is bright.
- The image formed on the retina is inverted, but we mentally correct for this fact.
- An image formed on the retina persists for a short time after the object is removed. This is called **image retention** and is what makes the idea of cinema film possible.
- The spot where the optic nerve leaves the eye is not light-sensitive, and so light incident upon this spot is not seen by us. We call this our **blind spot**.



Defects



Long-sighted people are unable to decrease the focal length of their eye sufficiently to see objects close to their face. They need to wear a **converging lens** to correct this problem.

Short-sighted people are unable to increase the focal length of their eye sufficiently to see distant objects. They require a **diverging lens**.

Exam question

2006, HL, Section B, Q7

What is meant by the refraction of light? (6 marks)

A converging lens is used as a magnifying glass. Draw a ray diagram to show how an erect image is formed by a magnifying glass. (12 marks)

A diverging lens cannot be used as a magnifying glass. Explain why. (5 marks)

The converging lens has a focal length of 8 cm. Determine the two positions that an object can be placed to produce an image that is four times the size of the object. (15 marks)

The power of an eye when looking at a distant object should be 60 m^{-1} .

A person with defective vision has a minimum power of 64 m^{-1} .

Calculate the focal length of the lens required to correct this defect. (12 marks)

What type of lens is used? Name the defect. (6 marks)

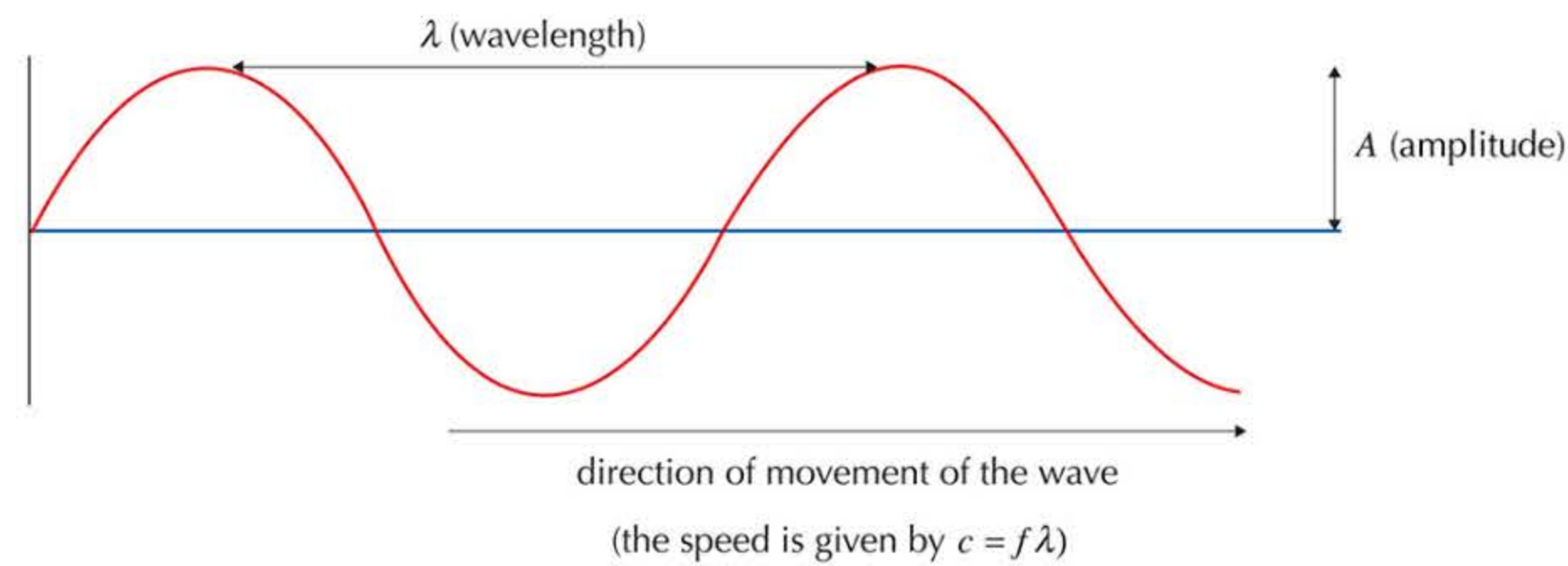
Waves

We are all familiar from a young age with the waves we see on water. There are other examples of waves that are all around us but not so easily seen. Sound travels as a wave. So does light. Radio and TV signals, and the conversations we have on mobile phones all travel by waves. They all have one thing in common. In each case, energy is transferred from one place to another through some medium, but at the same time there is no overall movement of the medium itself.

This idea allows us to give a definition of what a wave is:

A wave is a means of transferring energy through a medium, without any net movement of that medium.

In order to study waves there is some important terminology with which you should be familiar: wavelength, amplitude, frequency and period.



The frequency, f , is the number of cycles completed at any one point per second.

This means that, if you could stand in one spot and watch the wave pass by, the number of waves that pass every second is the frequency of the wave.

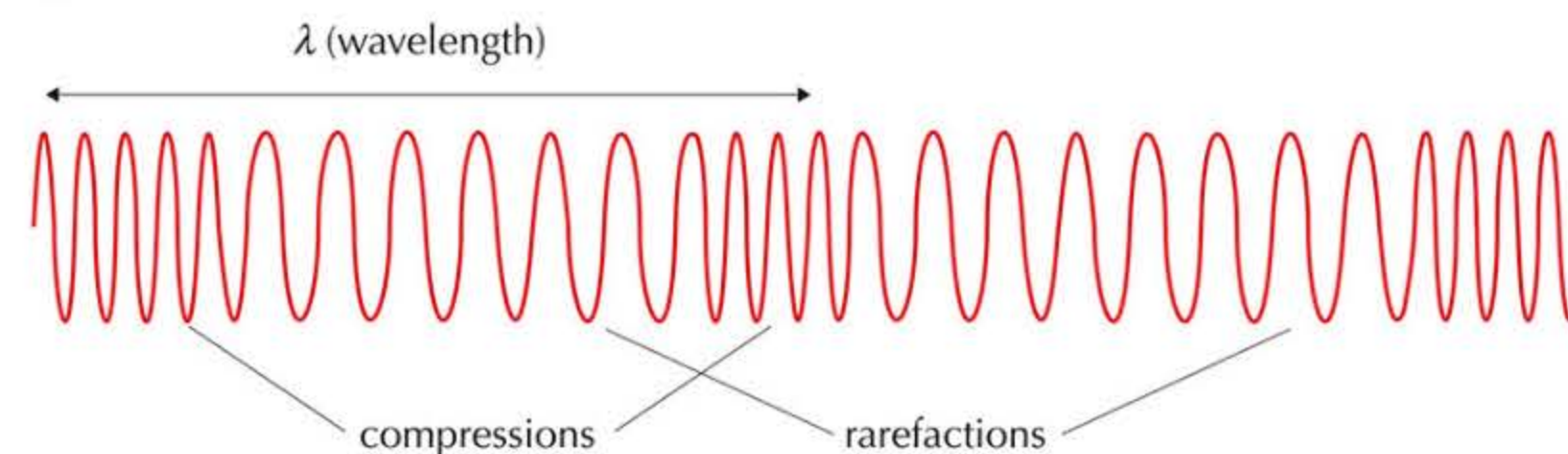
The period of a wave, T , is the time taken to undergo one complete cycle.

In other words, this is the time it would take one complete wave to pass a particular point.

The frequency and the period are connected by the formula: $f = \frac{1}{T}$

The **speed of a wave** c is the speed of propagation through a medium. For example, if you were to drop a stone into water, the speed of the wave would be the rate at which it spreads out from the point where the stone entered the water.

Waves can be **transverse waves**, as seen on the surface of a liquid such as water and similar to the one drawn above, or alternatively they can be seen as **longitudinal waves**, as is often demonstrated using a 'slinky'. Sound waves are longitudinal waves.



In a transverse wave, the movement of the particles is perpendicular to the movement of the wave.

In a longitudinal wave, the movement of the particles is parallel to the movement of the wave.

There are various phenomena that we associate with all waves. These are:

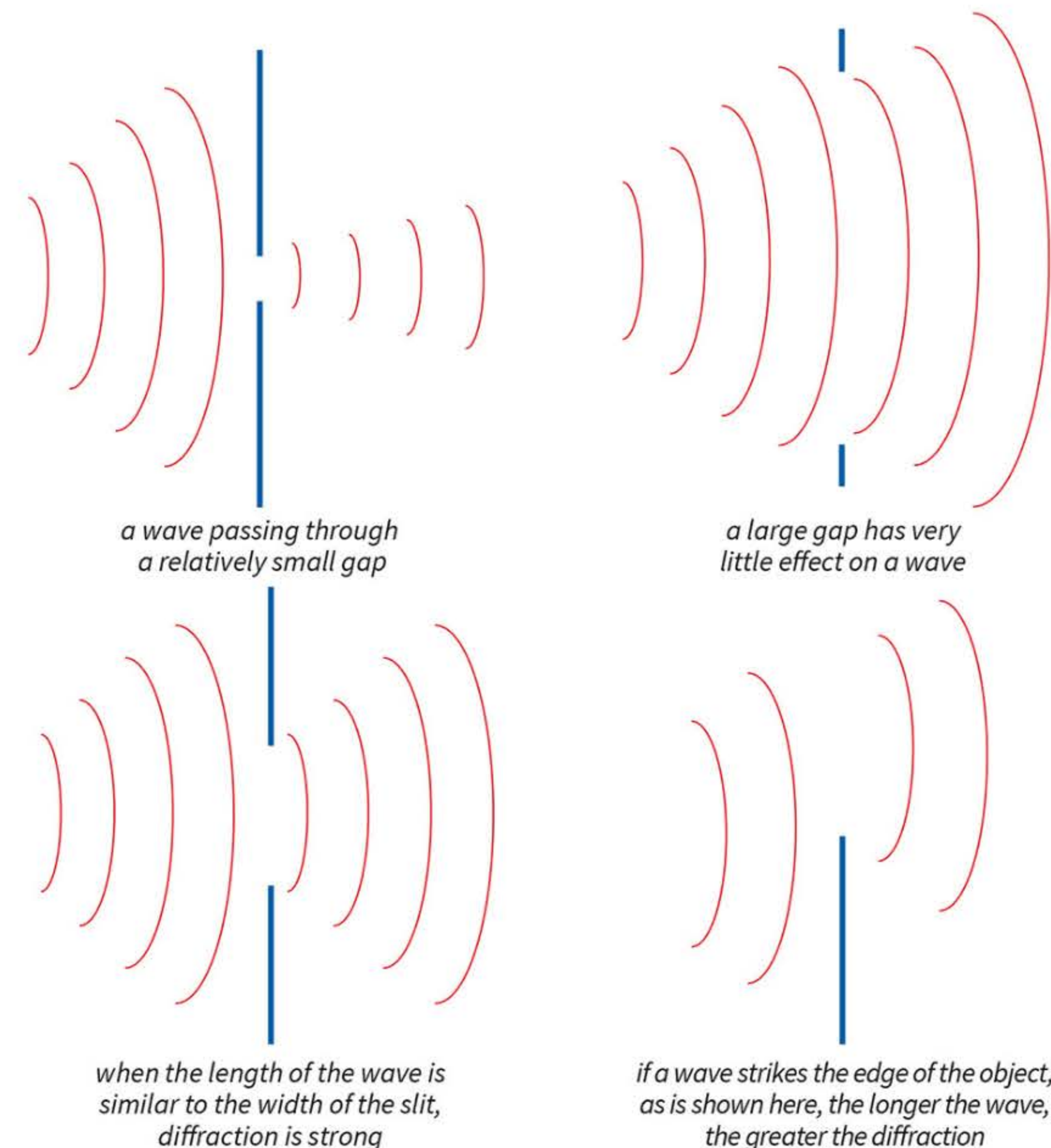
- Reflection
- Refraction
- Diffraction
- Interference

Reflection and refraction are studied in the section on optics, and are best described by the laws of reflection and refraction.

Diffraction

Diffraction is the ability of a wave to recover after meeting an obstacle.

All waves demonstrate diffraction, but in some cases it can be very slight. In general, if a wave passes through a gap in an obstacle where the size of the gap is close to the length of the wave, the diffraction will be strong. If the wave passes through a gap that is either much smaller or bigger than the length of the wave, the effect will be slight:

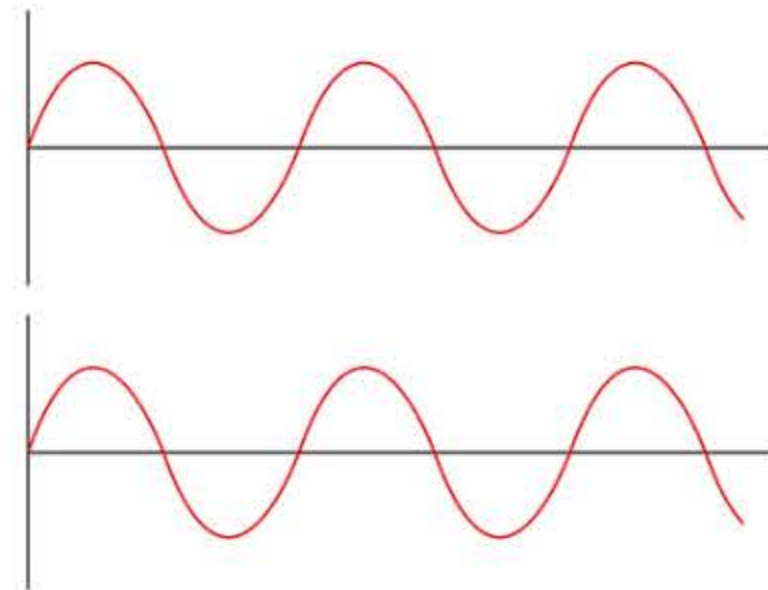


Interference

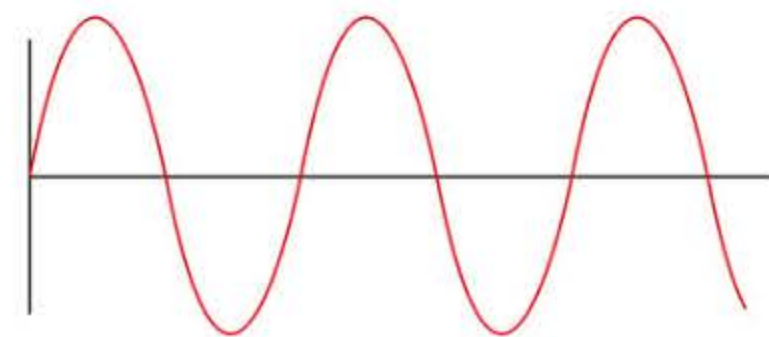
When waves meet, they will combine with each other to create what we call an interference pattern. This pattern can take on many different forms. On water, the choppy surface of the sea is a very complex interference pattern, created by the many hundreds of different waves that are travelling across the surface of the sea. Sometimes we get poor reception on a radio or TV, or on a mobile phone. This is also caused by **interference**.

When two or more waves meet, the total displacement will be equal to the algebraic sum of the individual displacements.

If we think about interference created by just two waves meeting, there are obviously two extreme situations that could occur. In the diagram below we see two **coherent** waves (that is, two waves that have the same frequency and wavelength). If the peak of one wave meets the peak of another, we get **constructive interference**.

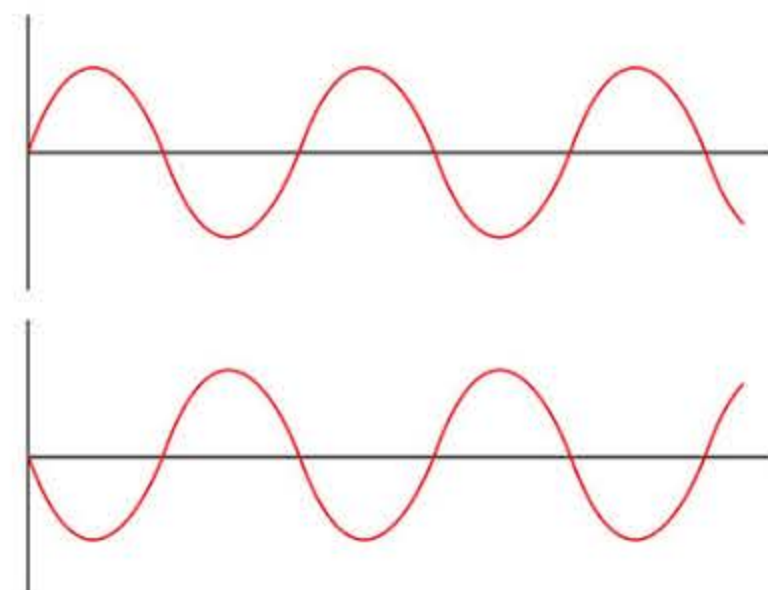


these waves meet, yielding...



...this wave, of the same frequency and wavelength but with greater amplitude

If the peak of one wave meets the trough of another, this is **destructive interference**.



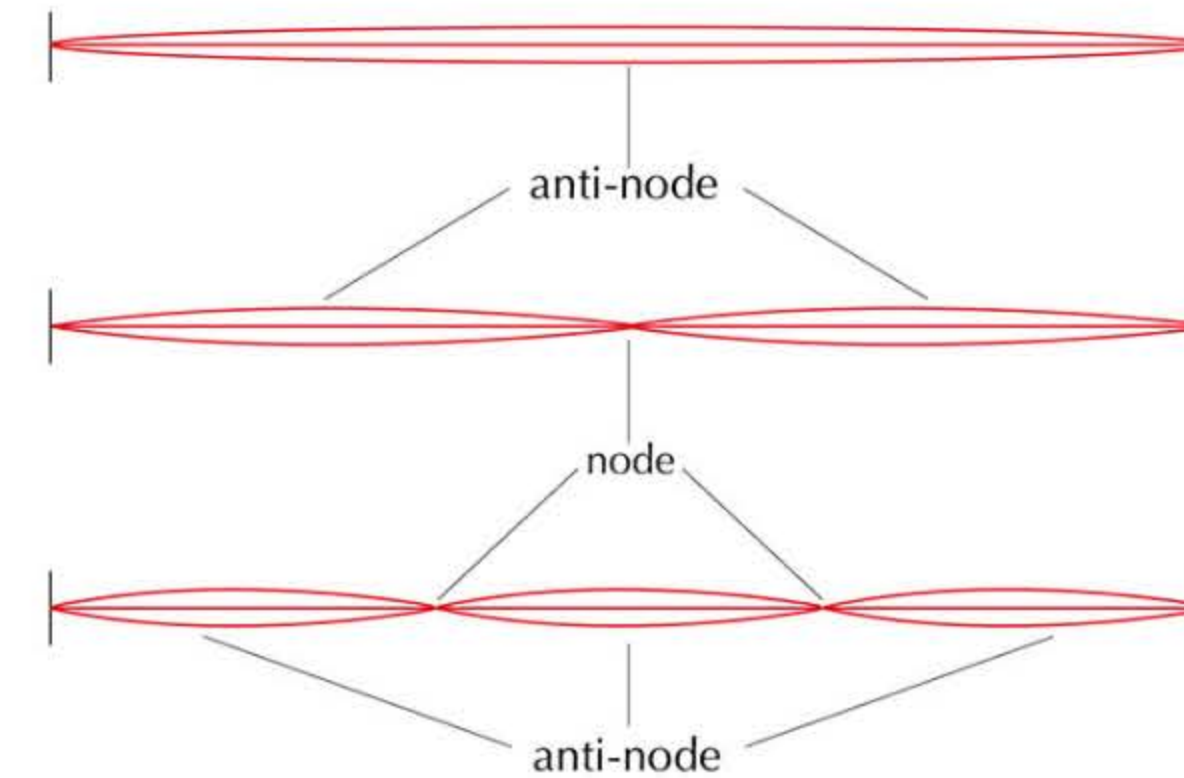
these waves meet, yielding...



...this wave, where all the movement has been cancelled out

Standing (stationary) waves

A standing wave is produced when two waves of the same frequency and wavelength meet, moving in opposite directions.



One example of a standing wave is that seen on a guitar string. When struck, vibrations pass along the string from one end to the other. The wave reflects off the end of the string and then travels back in the opposite direction. That means there are effectively two waves travelling along the string in opposite directions. These two waves meet and create what we call a standing wave. In the simplest example of a standing wave, the end points of the string do not move at all (we call them the nodes), and the part of the string that moves the most is called the anti-node. A string will also sometimes vibrate so that there is a node in the middle as well as at either end or it can vibrate so that there are nodes one-third of the way along the string and two-thirds of the way along it. In all cases, you will note that the distance between the nodes is equal to half the wavelength.

The wave nature of light

Young's slits

Throughout the 1700s it was believed that light was made up of a beam of particles. This theory had been proposed by Newton and because of his reputation and power it had been widely accepted. A Dutchman by the name of Christiaan Huygens had argued against this idea. He had proposed that in fact light was a wave passing through space, but few people paid any attention to him.

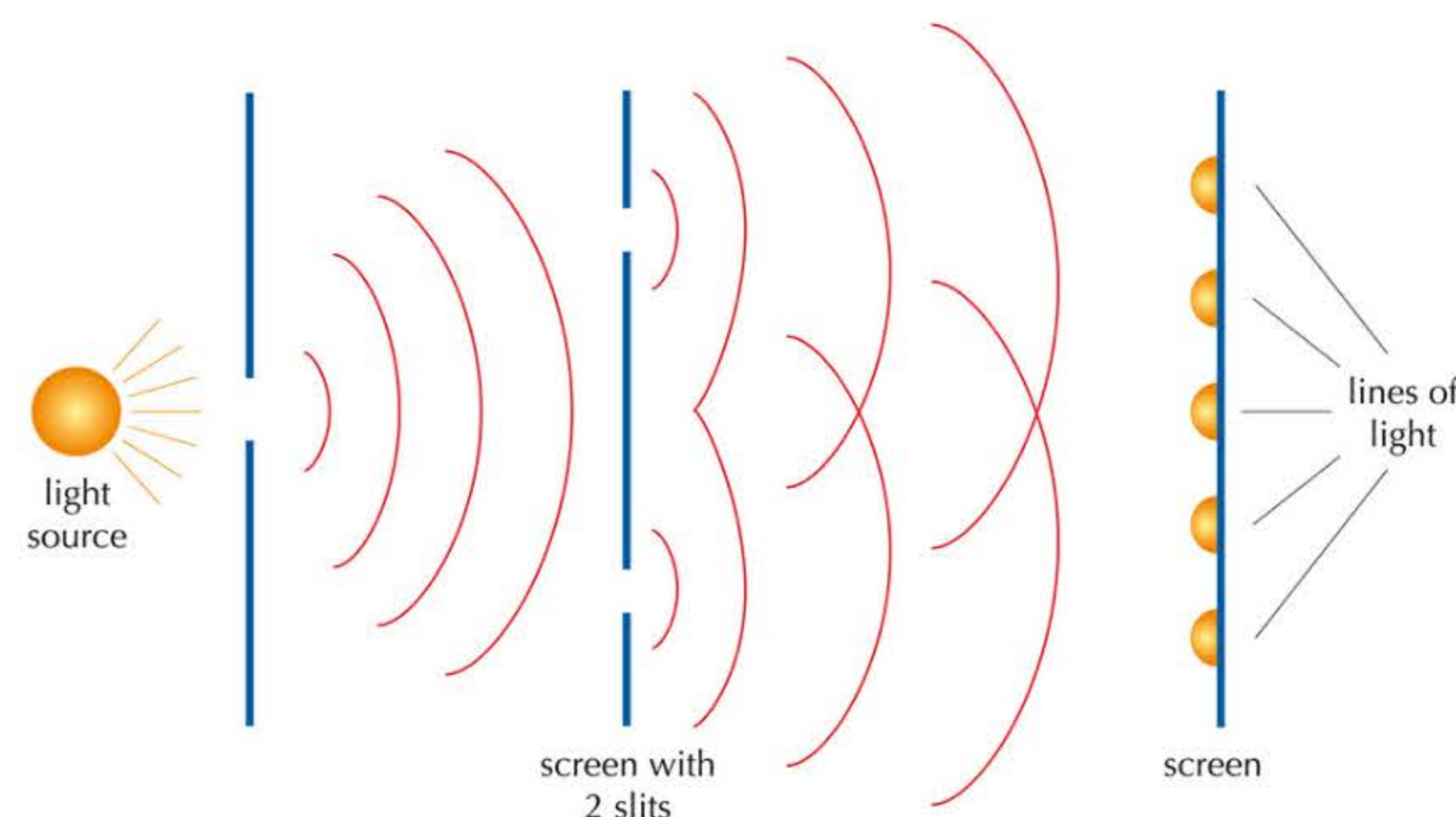
In 1803, however, a British scientist by the name of Thomas Young carried out an experiment that showed Huygens had been correct. In order to show that light is a wave it was necessary to show that it had the key properties common to all waves: reflection, refraction, diffraction and interference. It was obvious that the first two applied, but a beam of particles bouncing off a surface is very similar

to reflection, and passing through a material they would also behave as if they were being refracted: the reflection and refraction of light proved nothing.

Therefore, his experiment had to show that (1) light could be diffracted, and that (2) light creates interference patterns.

Remember that diffraction is the ability of a wave to recover after it has encountered an obstacle, and that when waves meet they create interference patterns (see pages 107–108).

Young set up an apparatus as shown in the diagram below:



A single light source is placed behind a screen. The light passes through this screen and encounters another, with two slits. A third and final screen is found beyond this one.

A pattern is found on it as shown: there is a bright line in the centre, directly opposite the original light, even though there is a screen between this point and the light source. And more lines are noted in a symmetrical pattern to either side. This result can only be explained if light is a wave.

The wave must spread out, or **diffract**, after passing through the first screen.

At the two slits in the second screen two new waves are effectively created, but because they both come from the original light source these are **coherent** waves, that is, they are **in phase** with each other.

These two waves in turn **diffract**, and as they meet and overlap an **interference pattern** is formed.

In the **straight-through position**, both wave fronts will have travelled exactly the same distance, and thus peak will meet peak, and **constructive interference** will occur. There is a bright line.

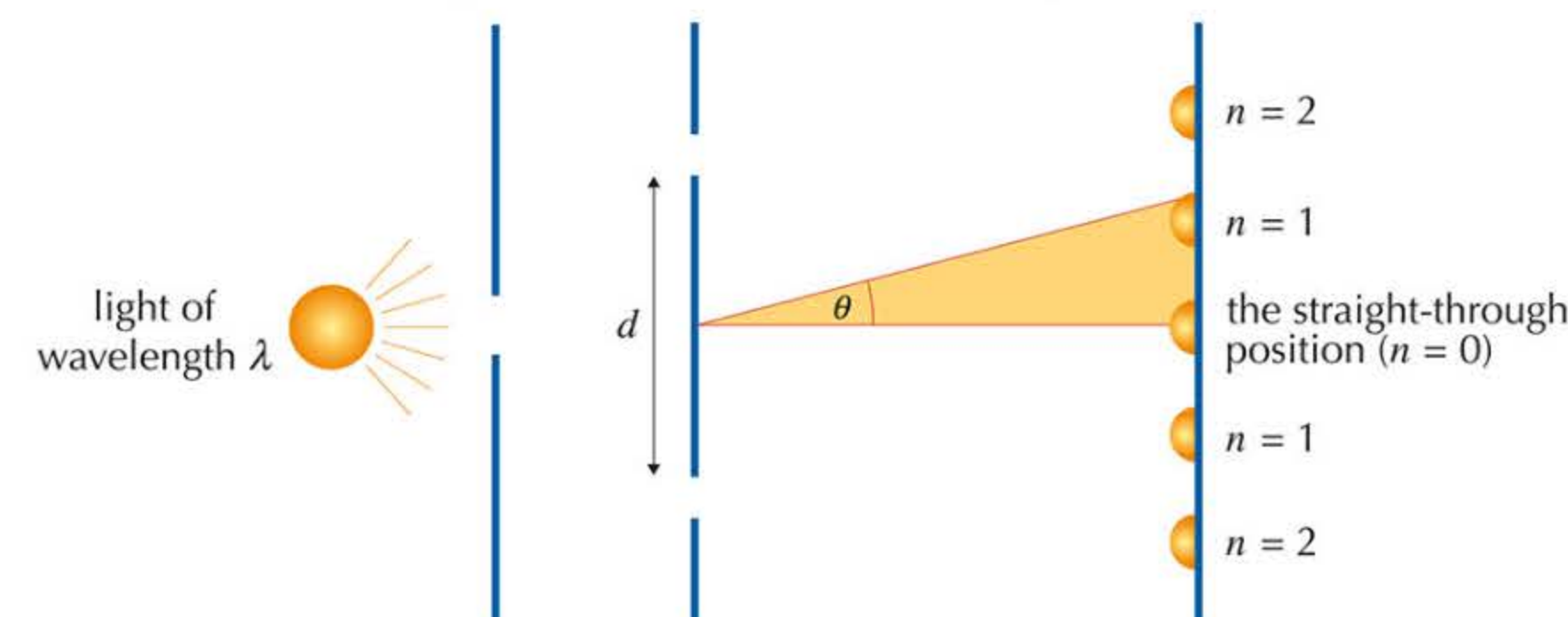
To either side of this, one wave will have travelled slightly further than the other and thus they will be **out of phase** as they meet. The peak of one wave will meet the trough of the other and **destructive interference** will occur. There is darkness on the screen.

Further to each side, it will happen that the **path difference**, the difference in lengths that the waves have travelled, will be exactly equal to one wavelength and thus the waves will be **in phase** once again, and **constructive interference** will occur. There will be another bright fringe.

This pattern will repeat itself according to the formula:

$$n\lambda = d \sin \theta$$

where λ = the wavelength of the light, and the other symbols are as shown.



A diffraction grating is often used in modern times. Because a grating has thousands of lines etched into a very small area of glass, there are not two but thousands of waves creating the interference pattern. This makes it much clearer. If white light is used, a spectrum of blue, green and red light is formed for each value of n . The method can be adapted to find the wavelength of monochromatic light using a spectrometer.

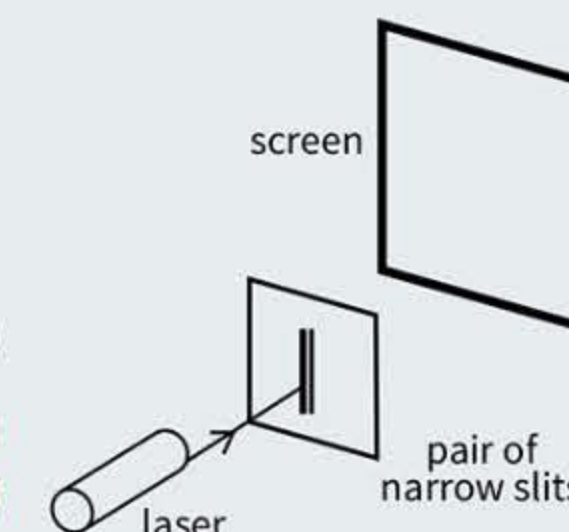
Sample answer

Leaving Certificate, 2005, Higher Level, Section B, Q7

A student used a laser, as shown, to demonstrate that light is a wave motion.

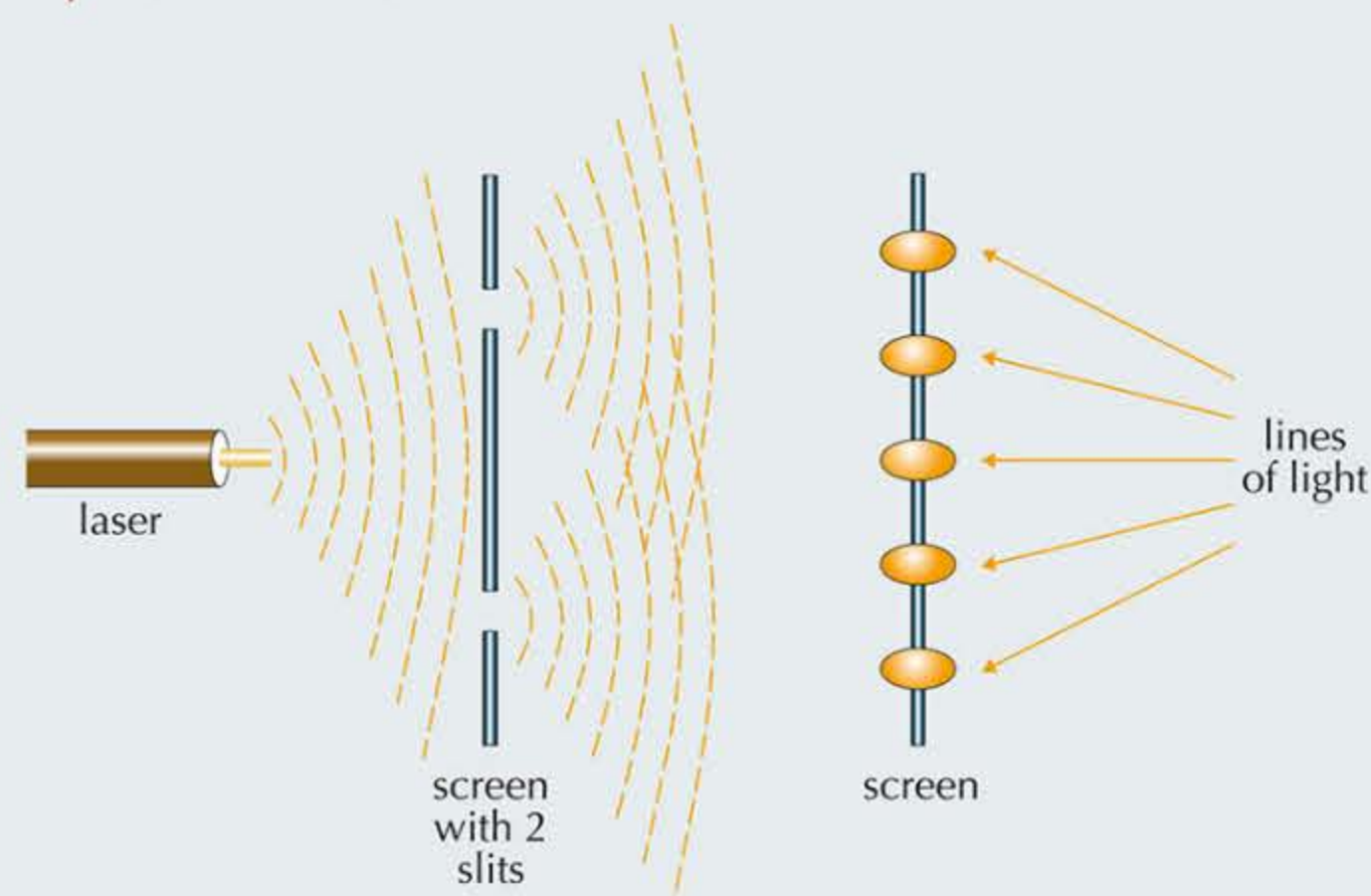
- (i) Name the two phenomena that occur when the light passes through the pair of narrow slits. (6 marks)

The two phenomena that occur are **diffraction** (3) and **interference**. (3)



- (ii) A pattern is formed on the screen. Explain how the pattern is formed. (12 marks)

A pattern is formed as shown below:



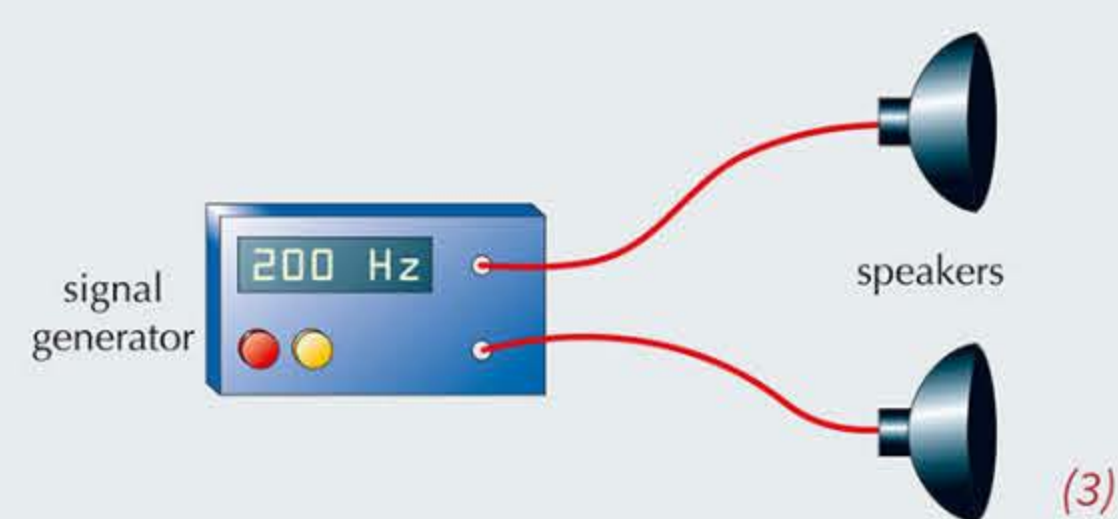
The two slits act as coherent sources, from which two waves emerge, as shown. The two waves then meet and overlap. An interference pattern is created. Where there is constructive interference, we get a line of light on the screen. Where there is destructive interference, we get darkness on the screen. (3, 3)

- (iii) What is the effect on the pattern when
- the wavelength of the light is increased. (3)
 - the distance between the slits is increased. (3)
- (8 marks)
- According to the formula $n\lambda = d \sin\theta$, if λ increases, so will θ . The lines will spread out on the screen. (4)
 - Similarly, if d is increased, with no change in λ , θ will decrease. The lines will move closer together on the screen. (4)

Describe an experiment to demonstrate that sound is also a wave motion. (12 marks)

To show that sound is a wave

Method A single signal generator is connected to two speakers, thus creating coherent waves.



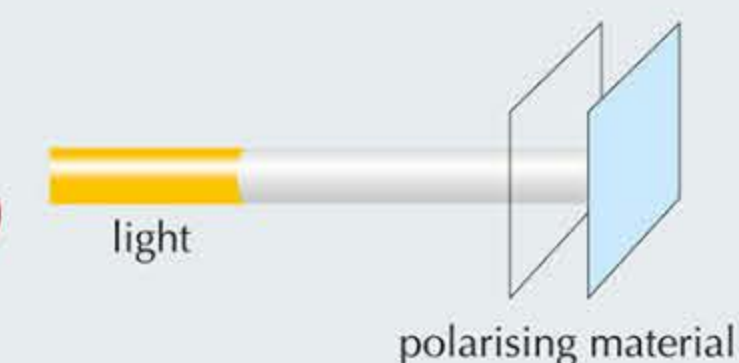
Observation/Conclusion Walking along the dotted line shown in the diagram, we would hear the sound repetitively grow and fall in volume. This can only be explained if the sound is creating an interference pattern, thus demonstrating that it is a wave. (3, 3)

Sound travels as longitudinal waves while light travels as transverse waves. Explain the difference between longitudinal and transverse waves. (9 marks)

In a transverse wave the vibration of the particles through which the wave passes is perpendicular to the direction of the wave. In a longitudinal wave the vibration of the particles through which the wave passes is parallel to the direction of the wave. (3, 3)

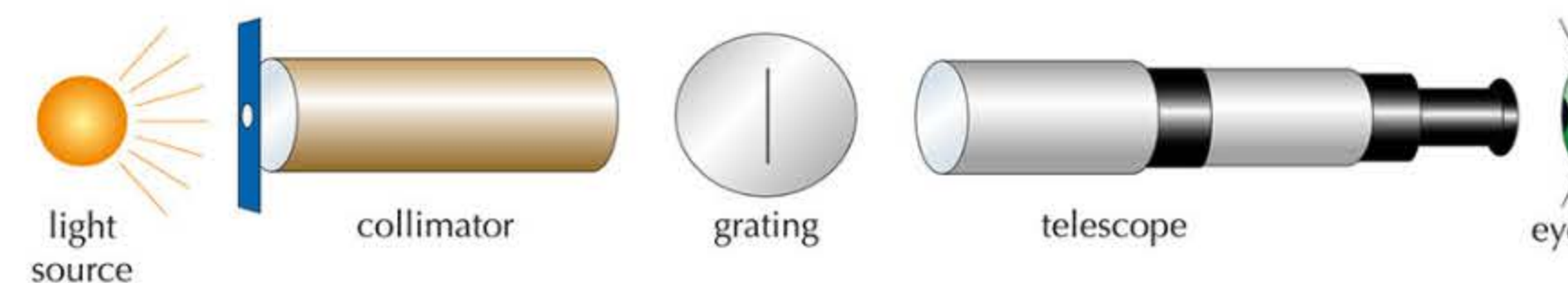
Describe an experiment to demonstrate that light waves are transverse waves. (9 marks)

Method Set up apparatus as shown. Shine the light so that it passes through both pieces of polarising material. Rotate one of the pieces through 90° . Note that the light is now blocked. (3, 3)



Conclusion This demonstrates that the light has been polarised. As polarisation occurs only in transverse waves, light must be a transverse wave. (3)

A spectrometer



STS

When there is a thin layer of oil on top of some water we will normally see a multi-coloured pattern in swirls on the oil. This is because some light reflects from the top of the layer of oil, and some light reflects from the water underneath it. The two waves then meet and overlap and create an interference pattern. This is the pattern we see. Something similar is often visible when we blow soap-bubbles.

Colour

Different colours of light have different wavelengths, or frequencies:

Blue/violet light consists of relatively short waves, or high frequency.

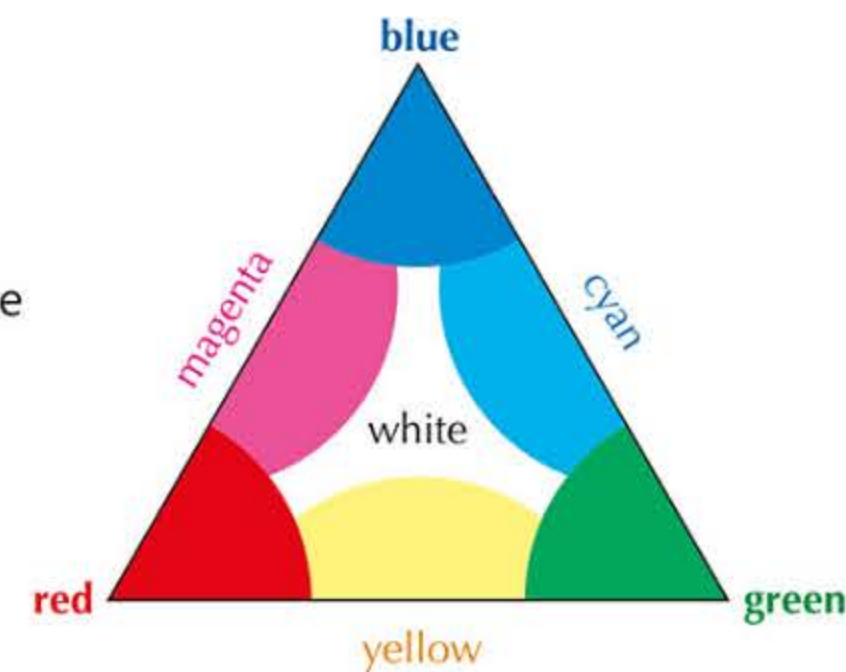
Red light consists of relatively long waves, or low frequency.

Dispersion is the breaking up of white light into its constituent colours.

White light can be formed from the **primary** colours – red, green and blue.

The **secondary** colours – magenta, cyan and yellow – are formed by mixing two of these, as shown in the diagram below.

Complementary colours are combinations of primary and secondary colours that together give white light.

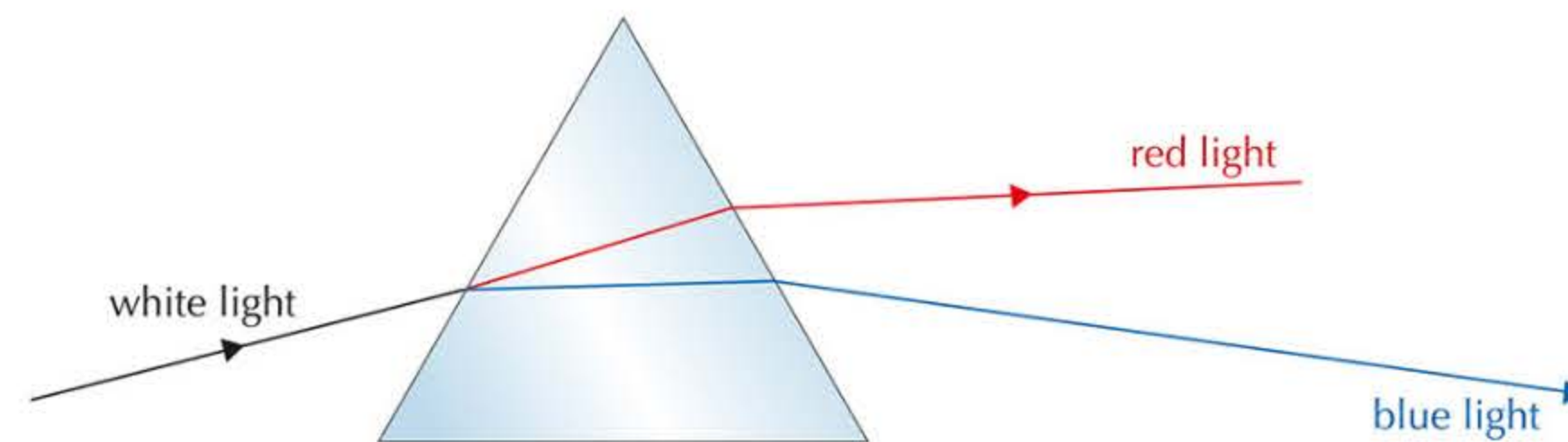


STS

TVs only produce the three primary colours directly. All the other colours are made by mixing the primary colours in the appropriate way.

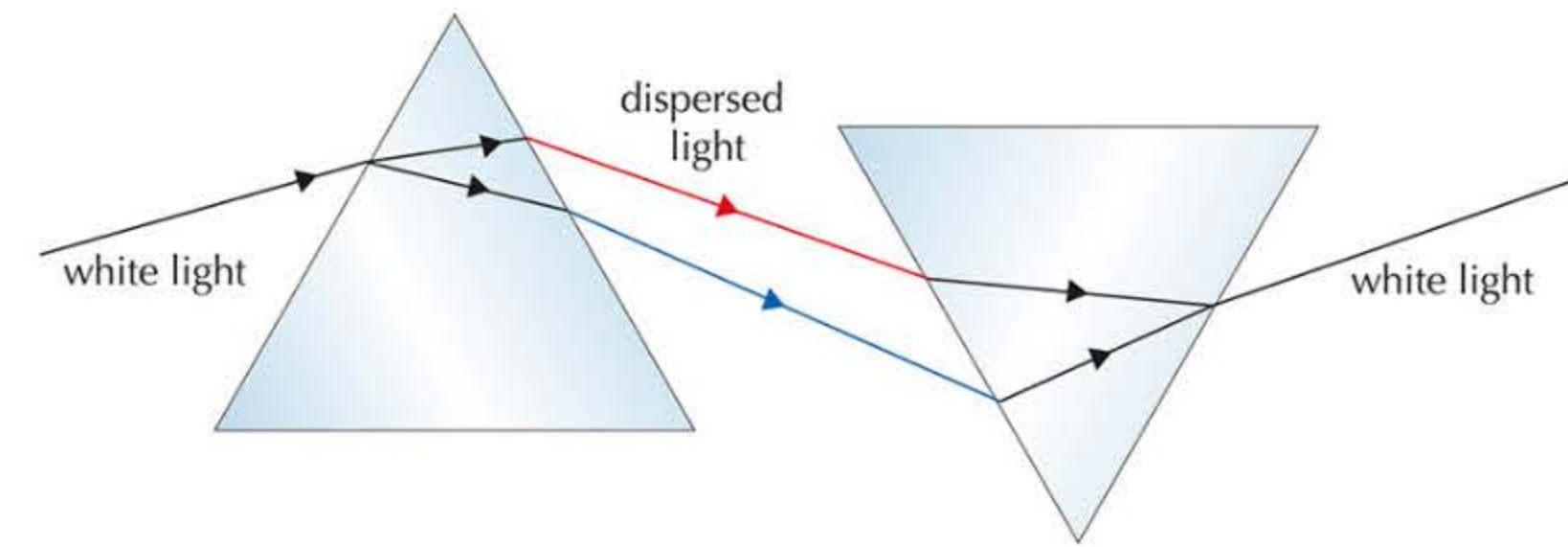
Dispersion

Dispersion by refraction



On entering a dense medium such as glass, all light is refracted.

Refraction is caused by the light wave slowing down on entering the new medium, but not all colours slow down to the same extent and because of this they are not all refracted to the same extent. Blue light slows down the most, and therefore is the most deflected. Red light slows down to a lesser extent, and therefore is deflected to a lesser extent. In this way, white light is broken up into its different colours, and a spectrum is formed. Another prism held in the right location can be used to recombine all the colours and reproduce white light.



Dispersion by diffraction

When white light passes through a diffraction grating an interference pattern is formed. In this case the red light has the longest wavelength and is therefore deflected through a greater angle, and blue light (with the shortest wavelength) is deflected by the least amount. The colours we sometimes see when light reflects off a compact disc are present because the grooves on the disc are acting as a sort of diffraction grating.

Sample answer

Leaving Certificate, 2009, Higher Level, Section B, Q7

An interference pattern is formed on a screen when green light from a laser passes normally through a diffraction grating. The grating has 80 lines per mm and the distance from the grating to the screen is 90 cm. The distance between the third order images is 23.8 cm.

Calculate (21 marks)

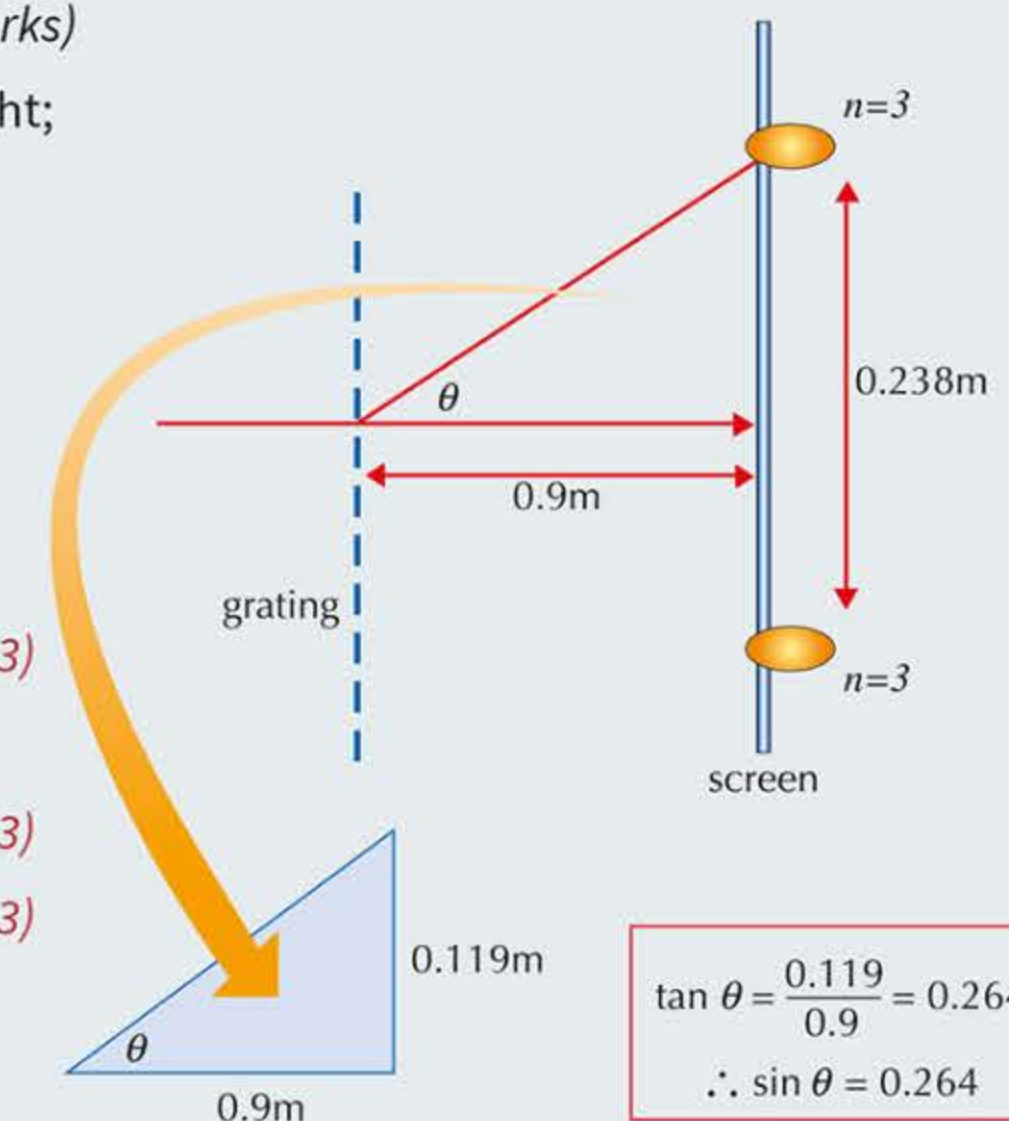
- (i) the wavelength of the green light;

$$d = \frac{1}{80000} = 1.25 \times 10^{-5} \text{ m} \quad (3)$$

$$n\lambda = d \sin \theta$$

$$3\lambda = 1.25 \times 10^{-5} (0.264) \quad (3)$$

$$\lambda = 5.51 \times 10^{-7} \text{ m} \quad (3)$$



$$\tan \theta = \frac{0.119}{0.9} = 0.264$$

$$\therefore \sin \theta = 0.264 \quad (3)$$

- (ii) the maximum number of images that are formed on the screen.

For maximum number: $\theta = 90^\circ$

Therefore $n\lambda = d \sin 90^\circ = d(1)$ (3)

and $n = \frac{d}{\lambda} = \frac{1.25 \times 10^{-5}}{5.51 \times 10^{-7}} = 22.7$

n must have a whole number value, so $n_{\max} = 22$ (3)

the number of images, therefore is $45 (22 + 22 + 1 = 45)$ (3)

The laser is replaced with a source of white light and a series of spectra are formed on the screen.

Explain (11 marks)

- (iii) how the diffraction grating produces a spectrum;

Different colours have different wavelengths. (3)

Differing values of λ lead to different values of θ and, therefore, we get constructive interference for each colour in a different place.

A spectrum is formed. (3, 3)

- (iv) why a spectrum is not formed at the central (zero order) image.

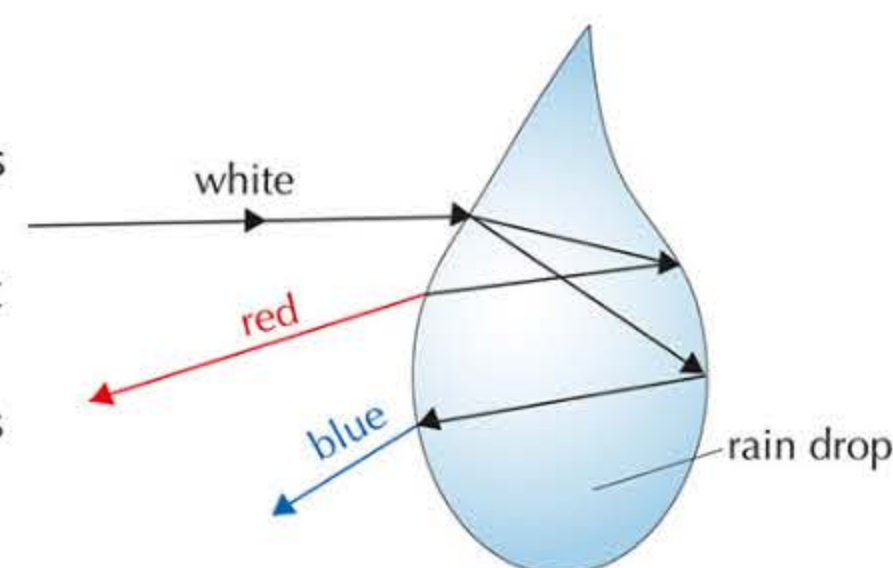
At the central image, constructive interference occurs for all colours at the same value of θ . This means that all the colours overlap and white light is seen. (2)

STS

The rainbow is formed because of the dispersion of white light. The light enters a rain drop and is refracted as shown.

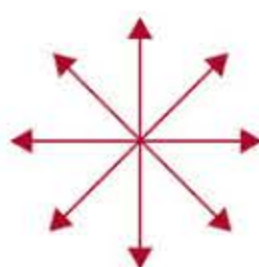
The light hits the back of the rain drop at an angle greater than the critical angle and is therefore reflected. When it leaves the water, the colours are still separated and this creates the rainbow.

The colour of gemstones are created in much in the same way.



Polarisation

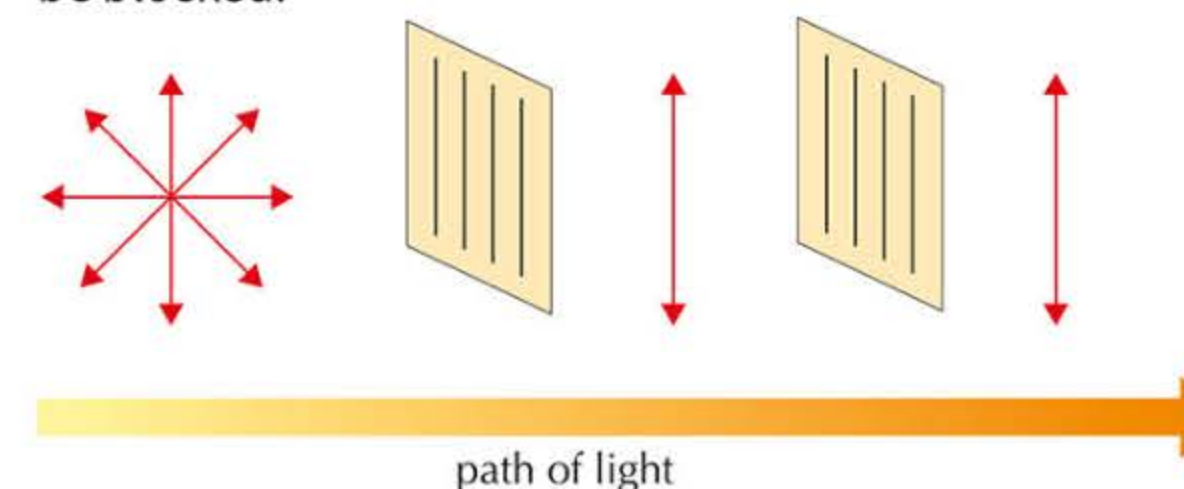
If you could look down along a light wave, you would see that it is vibrating in many directions at once. It would look a little like this:



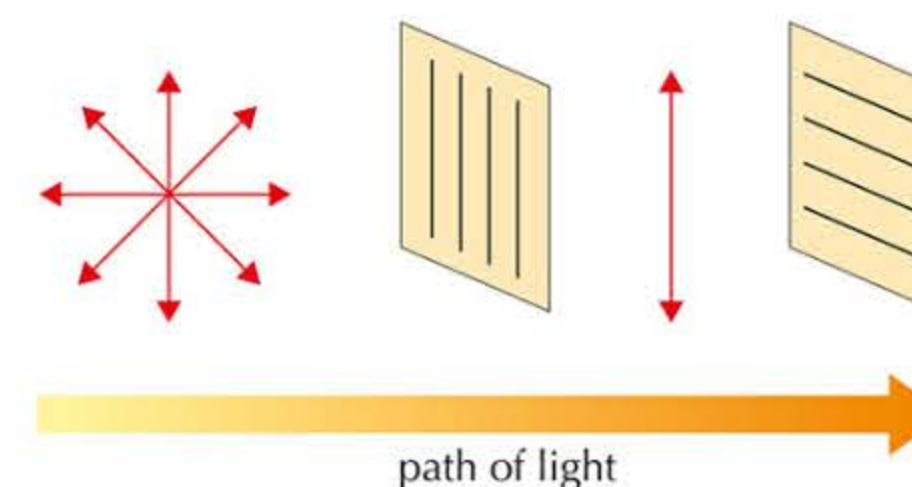
A polarising material restricts the vibration to just one plane. If the light passes through a sheet of this material it would emerge looking more like this:



As is shown below, if two sheets of polarising material are held together, they may allow light to pass through, but if one is rotated through 90° , all light will be blocked.



1. Two sheets of polarising material, parallel to each other, will let light through.



2. When one sheet is rotated through 90° , the light is blocked.

Longitudinal waves (such as sound) vibrate backwards and forwards and cannot be polarised. As light can be polarised, we can take this as evidence that **light is a transverse wave**. Polaroid sunglasses make use of the fact that light can be polarised. In general they only take advantage of the fact that polarised light is less bright than non-polarised light, as the amount of energy in the wave has been reduced. But sometimes wearing polaroid sunglasses you will see strange patterns on the front or back windows of cars. What you are seeing is an interference pattern, but it is a pattern that can only be seen in polarised light. Without the glasses, it is lost in all the surrounding bright light.

Electromagnetic spectrum

Since Young did his experiment we have learned that light is just one part of the spectrum of electromagnetic radiation, as shown here.

γ -rays | X-rays | ultra-violet (UV) | visible light | infra-red | micro-waves | radio waves

High energy
High frequency
Short wavelength

Low energy
Low frequency
Long wavelength

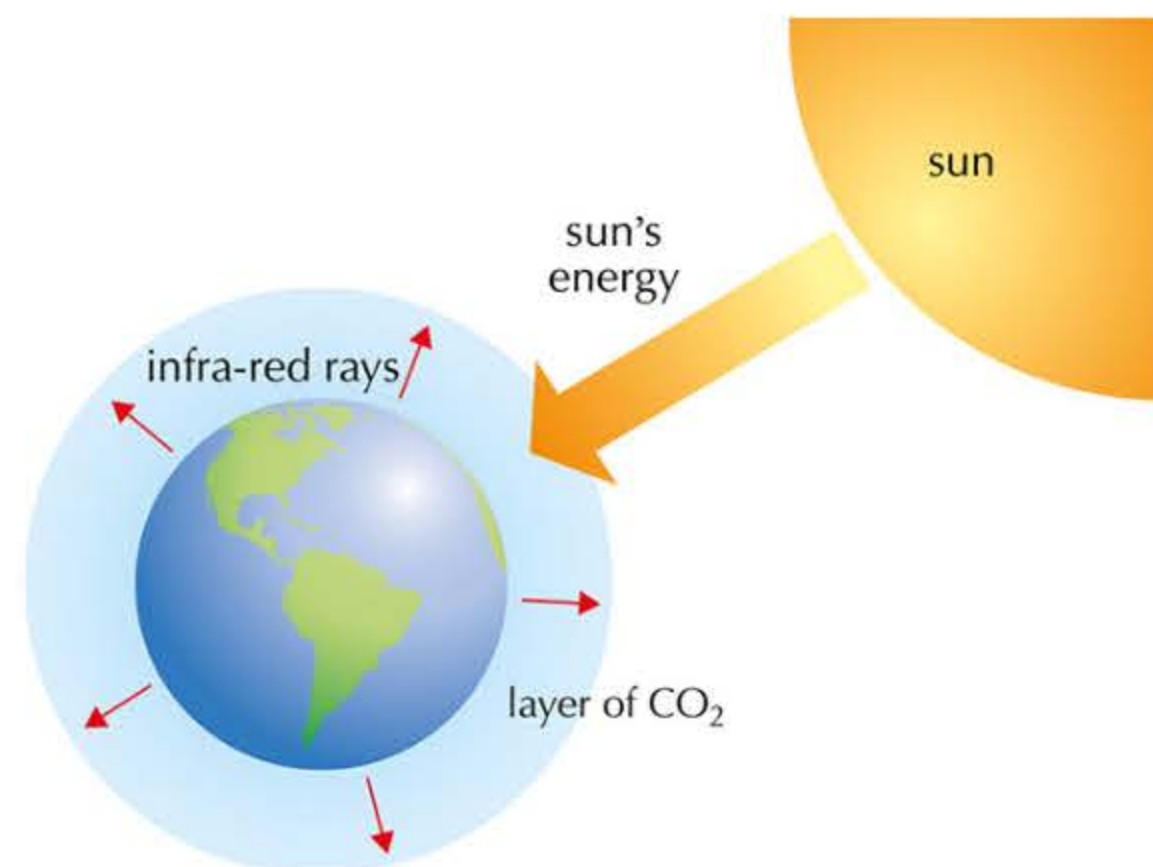
All these waves are very similar in properties. The only substantial difference comes from their varying wavelengths. There is nothing remarkable about visible light apart from the fact that we have evolved in such a way that the retina in our eyes is sensitive to those particular wavelengths.

STS

Ultra-violet (UV) light causes sun burn, and can lead to cancer. It also causes white objects to fluoresce, or to shine brightly in the dark. Much of it is absorbed by the **ozone layer** at the top of the atmosphere. But ozone is destroyed by CFCs, which is a commonly used gas. One of the main reasons why this is so alarming is that we will be exposed to greater amounts of UV light. This situation has improved in recent years.

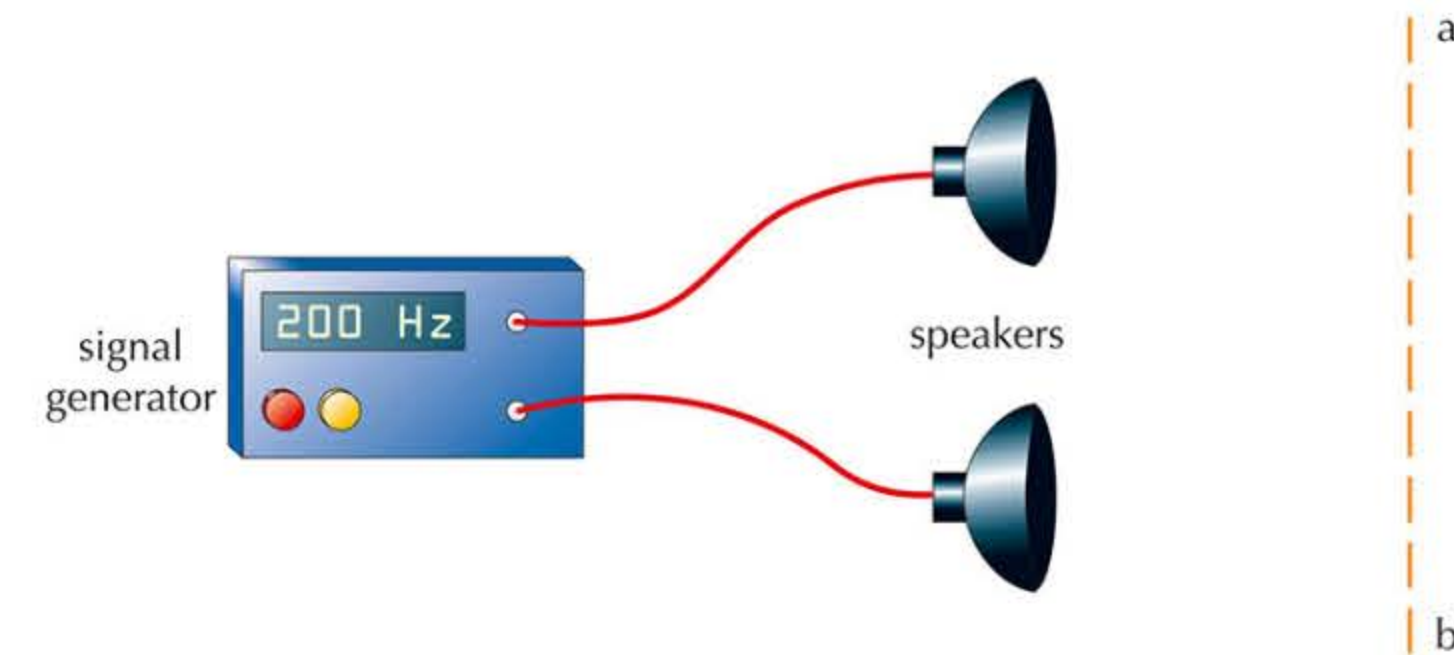
Infra-red light is important because it is emitted by all warm bodies (such as ours). We cannot see infra-red light ourselves, but some cameras can detect it and we can see the images. They are used for tracking objects in the dark. They also have medical uses. Areas of the body that are diseased may give off too little or too much heat and this can be detected using infra-red cameras.

The **greenhouse effect** is caused by the fact that the earth is heated by energy coming from the sun. As a warm object, the earth then emits infra-red radiation. In the past most of this radiation would escape into space. But this is no longer possible because it is been blocked by the growing amount of carbon dioxide and methane in the atmosphere. This is a main cause of global warming.



Sound

Sound is a form of energy. It exists as a wave motion, as we can see because it gives rise to both **interference** and **diffraction**. To demonstrate this we can set up an experiment comparable to Young's slits. A single signal generator is connected to two speakers, thus creating **coherent** waves. Walking along the line *ab* as shown in the diagram at the top of the opposite page we would hear the sound repetitively grow and fall in volume, indicating the presence of an interference pattern.



Sound waves are **reflected**, as we find when we hear an echo. They are also **refracted**. Sound travels more slowly in cold air. On a cold night there is cold air near the cooling surface of the earth. A rising sound wave is refracted downward as it hits the warmer air above, allowing us to hear better by night than during the day. A sound wave is a **longitudinal wave**, as is usually demonstrated using a 'slinky'. It is usually created by a vibrating object. Sound needs a medium through which it can travel, and will travel through different media at different speeds. In air it travels at about 330 ms^{-1} . It is considerably higher in water, and higher again in solids.

Exam question

2010, HL, Section B, Q12 (c)

Explain the term resonance and describe a laboratory experiment to demonstrate it.

(15 marks)

Give two characteristics of a musical note and name the physical property on which each characteristic depends.

(9 marks)

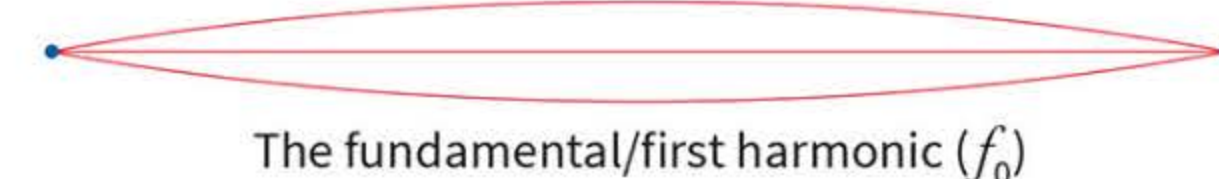
Explain why a musical tune does not sound the same when played on different instruments.

(4 marks)

Harmonics

Harmonics are multiples of the natural frequency of vibration of a body.

All bodies have certain natural frequencies at which they vibrate. As we saw in the section on standing waves, if we consider a string fixed at both ends the simplest way in which it can vibrate is where there is a node at either end and an anti-node in the middle. This is the **first harmonic** of the string, or fundamental.

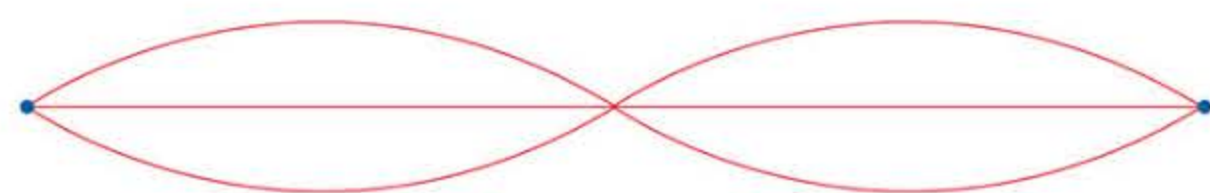


The factors that control the frequency at which a string will vibrate are length (l), tension (T), and mass per unit length (μ). Together these give the formula:

$$f = \frac{1}{2l} \sqrt{\frac{T}{\mu}}$$

The string could also vibrate so that it has a node at either end, and also at the middle. This is the **second harmonic**, or first overtone.

The frequency of the second harmonic is twice that of the first. That of the third would be three times, and so on.



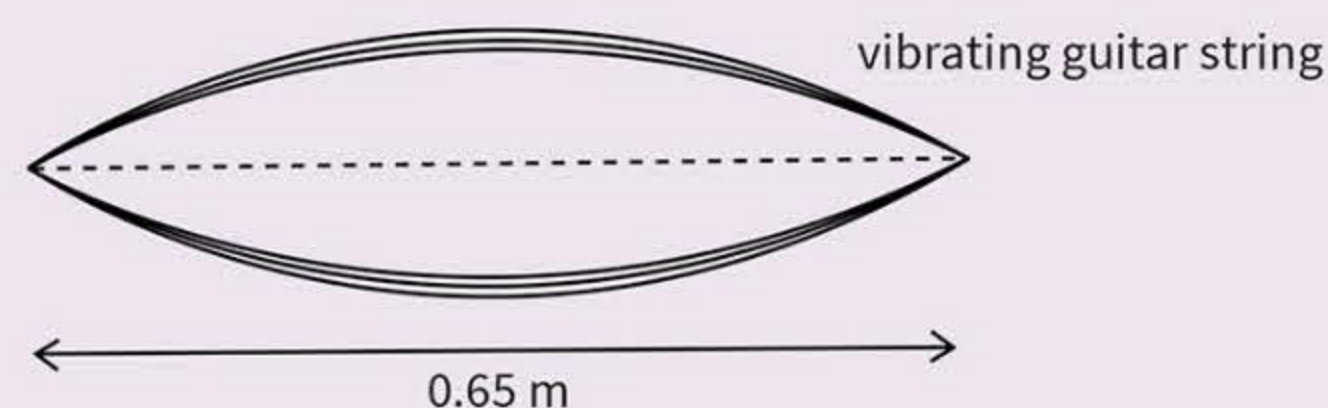
The second harmonic ($2f_0$)



The third harmonic ($3f_0$)

Exam question

2005, HL, Section B, Q12 (c)



The frequency of a stretched string depends on its length. Give two other factors that affect the frequency of a stretched string. (6 marks)

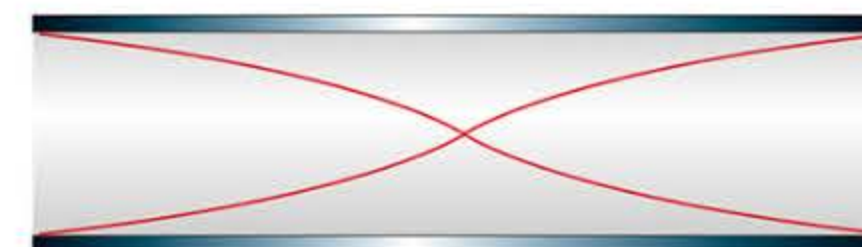
The diagram shows a guitar string stretched between supports 0.65 m apart. The string is vibrating at its first harmonic. The speed of sound in the string is 500 ms^{-1} . What is the frequency of vibration of the string? (9 marks)

Draw a diagram of the string when it vibrates at its second harmonic. (7 marks)

What is the frequency of the second harmonic? (6 marks)

Harmonics in pipes

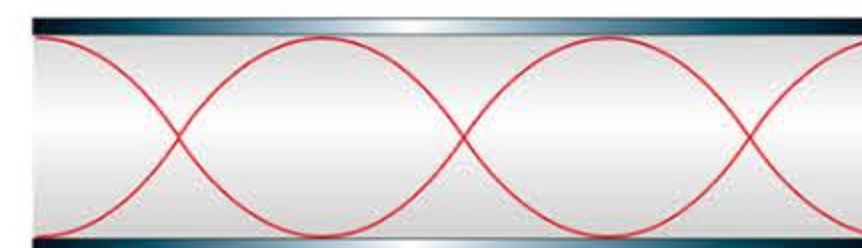
Just as a solid body has a natural frequency at which it will vibrate, a body of air in a pipe will do the same. Many musical instruments operate on this basis. Unlike the string, the wave will have a node at the centre, and anti-nodes at the two ends, as shown. Also like a string, it can vibrate at many frequencies, or harmonics.



Fundamental or first harmonic

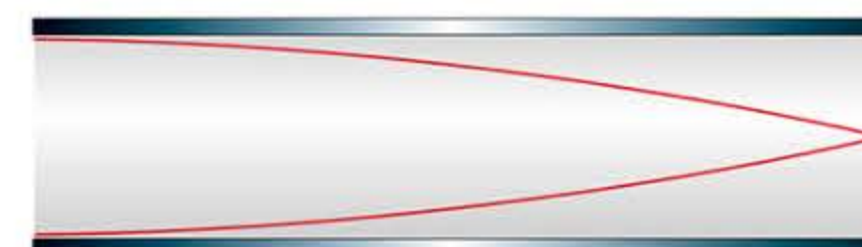


Second harmonic



Third harmonic

We get something similar with pipes that are closed at one end. This happens when we blow across the top of a bottle to make a sound. The main difference is that only odd-numbered harmonics are possible.



First harmonic



Third harmonic



Fifth harmonic

Musical notes

Musical notes are produced by vibrating objects. In a string, the frequency of vibration of the string is the frequency of the note produced. It is varied by the musician's fingers to produce different frequencies or notes. The **effective** length of the column of air in a pipe is controlled by the opening and closing of holes along the pipe, as in a saxophone.

Characteristics of a musical note

The main characteristics of a musical note and their corresponding wave characteristics are:

Pitch, which corresponds to **frequency**.

Loudness, which corresponds to **amplitude**.

Quality, which corresponds to **presence of harmonics**.

Resonance

Resonance is the transfer of energy between two bodies of the same natural frequency.

When a body of a particular natural frequency is brought in contact with a body of the same natural frequency a transfer of energy takes place. We see this in the experiments with a stretched string. The tuning fork is of the same frequency as the string (once the string has been adjusted accordingly), and so once they have been brought into contact, the string begins to vibrate.

Speed of sound

As noted, the speed of sound in air is about 330 m s^{-1} , and is faster in liquids, and more so again in solids. As with all waves the speed is related to the frequency and the wavelength by the expression:

$$c = f\lambda$$

This expression can be used to compare the wavelength, frequency or speed of sound between one medium and another. The different speed of sound in different media, and the fact that it will be reflected from surfaces, as will any other wave, help us to use sound in equipment such as sonar or ultrasounds (used when X-rays would be dangerous).

Sound intensity

HL

The intensity of sound at a point is defined as the rate at which energy is crossing a unit area perpendicular to the direction in which the sound is travelling.

Sound intensity is measured in W m^{-2} .

Sound Intensity level

Sound intensity level is measured in decibels. It is calculated using a log scale and is done in this way so that the number of dB broadly corresponds to our understanding of the volume of a sound. Doubling of the sound intensity increases the sound intensity level by 3 dB.

The threshold of hearing is the lowest sound intensity to which an average human ear can respond at 1 kHz. Its value is taken as $10^{-12} \text{ W m}^{-2}$.

The frequency limits of audibility are the highest and lowest frequency sound waves that the average human can hear. Generally the lower limit is taken as 20 Hz, and the upper limit as 20 kHz. As people grow older they lose the ability to hear these higher frequencies.

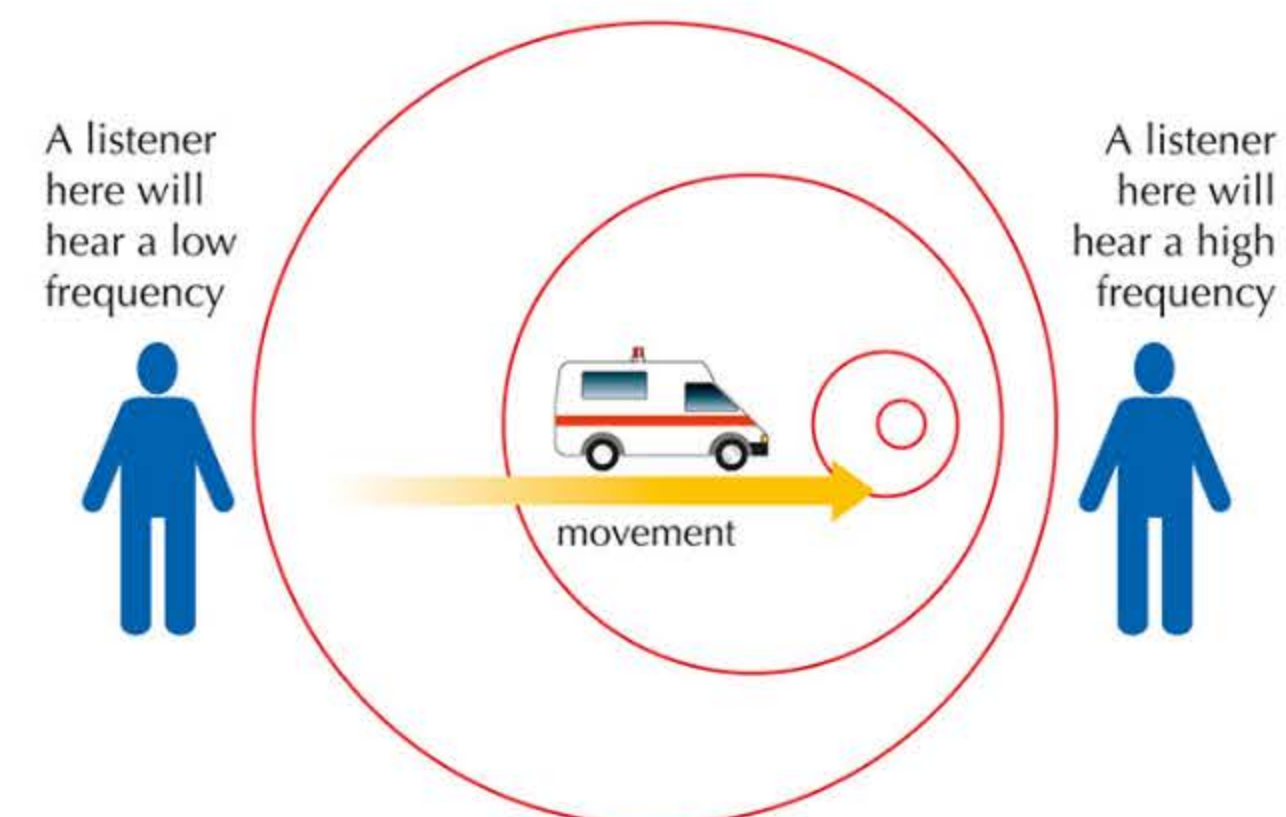
Doppler effect

The apparent change in the frequency of a wave due to the relative motion of the source of the wave or an observer is known as the Doppler effect.

We are all familiar with the way we hear a change in the sound from a car or an ambulance just at the moment it drives past. When the sound is approaching us the pitch (or the frequency) is higher. When it moves away from us, it is lower. This effect is known as the Doppler effect. It applies to all waves, not just to sound waves.

The diagram below shows us how a wave spreads out around a stationary object. It forms circles about the central point. You should try to picture the circles constantly moving out from that point. If this was a sound wave and somebody was listening to it they would hear the same note, or the same frequency, wherever they were standing.

In the diagram below, you should picture the source of the sound wave – whether it is a car or an ambulance or anything else – moving from left to right. Each sound wave will still spread out in a circle, and the centre of that circle will be the point the source was when it emitted the wave. But as the source is moving, each circle has a different centre. And you can see how the waves become bunched up together in front of the source, and become spread out behind it. Where the waves are bunched up, they will pass by more quickly – that is, they will have a higher frequency (or a higher pitch). Behind the source, they will pass more slowly, so the sound will be of lower frequency.



HL The formula that allows us to determine what the various frequencies might be and how they are related is:

$$f' = \frac{f c}{c \pm u}$$

Where: f = the frequency of the waves as they are emitted
 f' = the frequency of the waves according to the observer
 c = the speed of the wave
 u = the speed of the source

We use the '+' if the source is moving away, and the '-' if it is moving closer.

Exam question

2002, HL, Section B, Q7

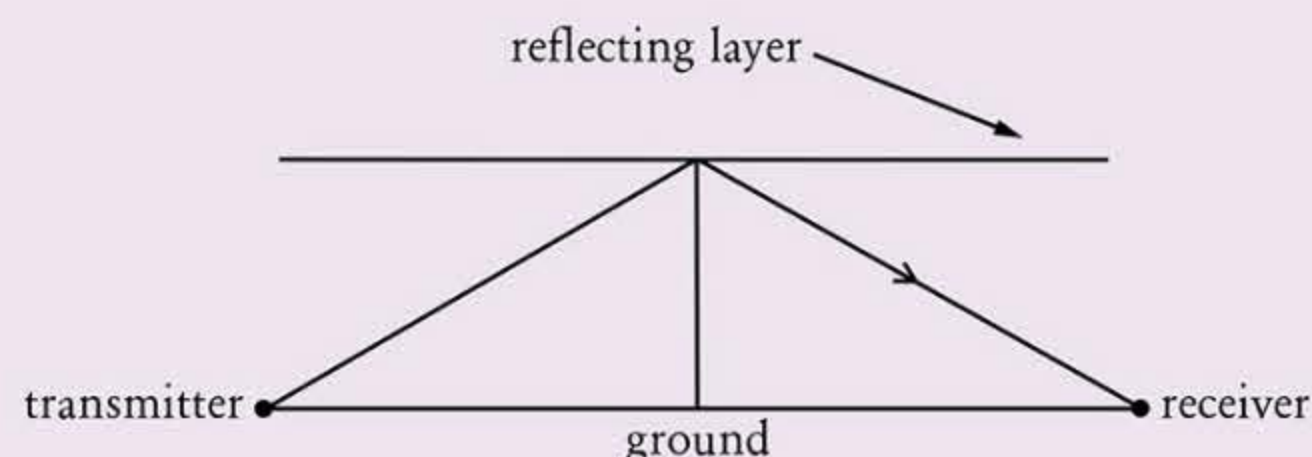
"Constructive interference and destructive interference take place when waves from two coherent sources meet."

Explain the underlined terms in the above statement. (12 marks)

What is the condition necessary for destructive interference to take place when waves from two coherent sources meet? (6 marks)

Describe an experiment that demonstrates the wave nature of light. (12 marks)

Radio waves of frequency 30 kHz are received at a location 1500 km from a transmitter. The radio reception temporarily 'fades' due to destructive interference between the waves travelling parallel to the ground and the waves reflected from a layer (ionosphere) of the earth's atmosphere, as indicated in the diagram.



- Calculate the wavelength of the radio waves. (6 marks)
- What is the minimum distance that the reflected waves should travel for destructive interference to occur at the receiver? (9 marks)
- The layer at which the waves are reflected is at a height h above the ground. Calculate the minimum height of this layer for destructive interference to occur at the receiver. (Speed of light, $c = 3.0 \times 10^8 \text{ m s}^{-1}$) (11 marks)

STS

The Doppler effect is used by the Gardaí in speed traps. A wave is emitted by a device and then reflects off an approaching car and is detected again by the device as it returns. The extent to which the frequency of the wave is increased allows the Gardaí to determine the speed at which the car is travelling.

It is also used by astronomers. They look at the light emitted by distant stars and measure the frequency of the different waves (and therefore different colours) that make up the light. By comparing these results to similar colours on earth, they have found that the frequencies of light waves coming from the stars are nearly always slightly decreased. This is known as the 'red shift', because red light has a low frequency. Astronomers have deduced that this is because the stars are moving away from us. And because the stars are (nearly) all moving away from us, it would suggest that the universe is constantly expanding and spreading out as if it came originally from a single point. This is the basis for the Big Bang Theory.

Sample answer

Leaving Certificate 2003, Higher Level, Section B, Q7

Describe an experiment to show that sound is a wave motion. (12 marks)

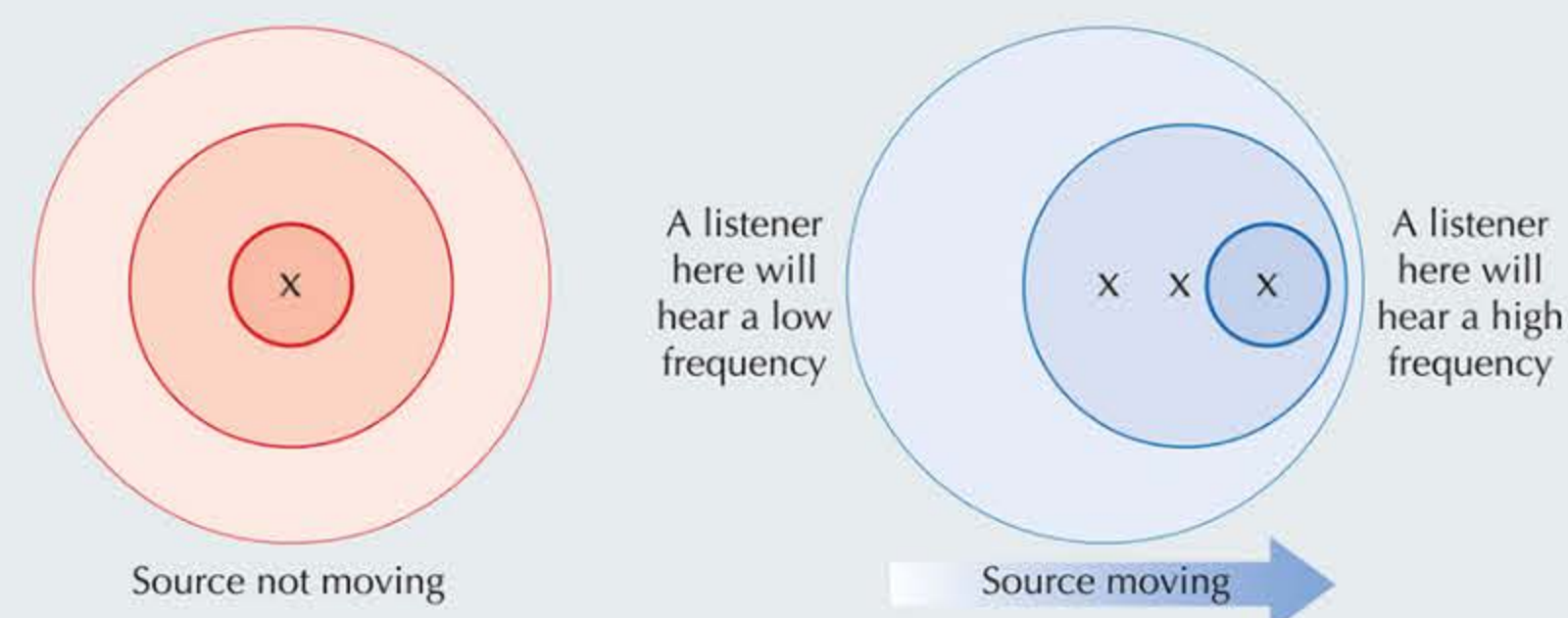
To show that sound is a wave motion:



- | | |
|---------------------|---|
| Method | Strike a tuning fork and hold it to your ear. (3) |
| | Rotate the tuning fork, as shown. (3) |
| Observations | You will hear the sound repetitively grow and fall in volume. (3) |
| Conclusion | This is an interference pattern, showing that the sound is undergoing diffraction and interference and is therefore a wave. (3) |

What is the Doppler effect? Explain, with the aid of labelled diagrams, how this phenomenon occurs. (14 marks)

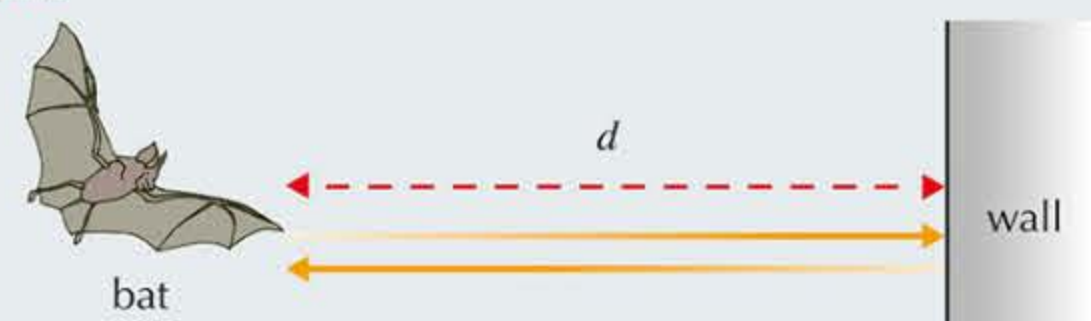
The Doppler effect is the apparent change in the frequency of a wave due to the motion of the source or observer. (6)



In the first of these diagrams, the source of the wave is motionless and the wave spreads out in concentric circles around that source. In the second diagram, the source is moving. Each wave front spreads out in a circle around the position the source is in when the wave is emitted. The waves bunch up as shown. An observer in front of the wave will hear an increased frequency. Behind the source, as it moves away, an observer will hear a decreased frequency. (3) (3) (2)

Bats use high frequency waves to detect obstacles. A bat emits a wave of frequency 68 kHz and wavelength 5.0 mm towards the wall of a cave. It detects the reflected wave 20 ms later. Calculate the speed of the wave and the distance of the bat from the wall. (12 marks)

$$\begin{aligned} c &= f\lambda \\ &= (68 \times 10^3) (5 \times 10^{-3}) \\ &= 340 \text{ ms}^{-1} \end{aligned} \quad (3) \quad (3)$$



$$\begin{aligned} s &= ut + \frac{1}{2}at^2 \\ &= 340(20 \times 10^{-3}) \\ &= 6.8 \text{ m} \\ \text{but } d &= \frac{1}{2}s \\ \Rightarrow d &= 3.4 \text{ m} \end{aligned} \quad (3) \quad (3)$$

Give two other applications of the Doppler effect. (6 marks)

- 1 The Doppler effect is used by police in speed checks. A wave is emitted and reflected from a car, and the change in frequency is used to calculate the speed at which the car was travelling. (3)
- 2 The Doppler effect is used in analysing the light coming from distant galaxies. Variations in frequency can be used to detect whether the star is moving towards the earth or away from it. (3)

Exam questions

1 2007, HL, Section B, Q12 (b)

Define sound intensity. (6 marks)

A loudspeaker has a power rating of 25 mW. What is the sound intensity at a distance of 3 m from the loudspeaker? (9 marks)

The loudspeaker is replaced by a speaker with a power rating of 50 mW. What is the change:

- (i) in the sound intensity? (ii) in the sound intensity level? (9 marks)

The human ear is more sensitive to certain frequencies of sound. How is this taken into account when measuring sound intensity levels? (4 marks)

2 2004, HL, Section B, Q2

In an experiment to measure the wavelength of monochromatic light, the angle θ between a central bright image ($n = 0$) and the first and second order images to the left and the right was measured. A diffraction grating with 500 lines per mm was used.

The table shows the recorded data.

n	2	1	0	1	2
$\theta/\text{degrees}$	36.2	17.1	0	17.2	36.3

Describe, with the aid of a diagram, how the student obtained the data. (12 marks)

Use all of the data to calculate a value for the wavelength of the light. (15 marks)

Explain how using a diffraction grating with 100 lines per mm leads to a less accurate result. (7 marks)

The values for the angles on the left of the central image are smaller than the corresponding ones on the right. Suggest a possible reason for this. (6 marks)



7 Heat and Temperature

Learning objectives

In this chapter you will learn about the following:

- 1 Thermometers and temperature scales
- 2 Heat capacity
- 3 Latent heat
- 4 Heat transfer

Key definitions relevant to this chapter

Heat capacity (C)

Specific heat capacity (c)

Latent heat (L)

Specific latent heat (l)

Conduction

Convection

Radiation

U -value

Solar constant

Thermometric property

Key formulae

Celsius temperature $T(K) = T(^{\circ}C) + 273.15$

Energy needed to change temperature $Q = mc\Delta\theta$ $Q = C\Delta\theta$

Energy needed to change state $Q = ml$ $Q = L$

Heat and temperature

The temperature of a body is a measure of how hot it is. The SI unit of temperature is the kelvin (K). In practice the Celsius or centigrade scale is used.

Conveniently, the size of a degree kelvin is equal to the size of a degree Celsius, and the two are connected by the following formula:

$$T(K) = T(^{\circ}C) + 273.15$$

A **thermometric property** is any measurable property of a body that changes with temperature. Examples include:

- The length of a column of liquid in a tube
- The resistance of a wire or a thermistor
- The emf of a thermocouple
- The colour of some substances
- The pressure and volume of a fixed mass of gas.

Thermometers and temperature scales

To establish a temperature scale we need two fixed temperature points (such as the boiling point and melting point of water) and a device with which we can measure a thermometric property. The length of a column of mercury in a glass tube is often used. Once graduated (marked), the temperature can be measured by checking the length of the column of mercury.

Because of variations within thermometric properties, however, different thermometers do not necessarily give the same reading at the same temperature. This is not just a case of inaccuracy, it can happen even with highly accurate thermometers. Because of this we must designate one thermometer to be a **standard**, i.e. a thermometer against which others are measured. Whatever temperature our standard thermometer reads, is taken to be the correct temperature. For reasons of simplicity, in schools the standard thermometer is usually taken to be a mercury thermometer.

Remember

Heat is a form of energy that causes a rise in temperature when added to a body or a fall in temperature when withdrawn.

Heat capacity

Different substances respond differently to heat. Some heat up more easily than others. Storage heaters, for example, contain bricks that heat up slowly but once hot take a long time to cool down. Such a body is said to have a high heat capacity.

The heat capacity of a body is the amount of energy needed to raise the temperature of the body by 1 K.

The specific heat capacity, c , of a substance is the amount of energy required to raise the temperature of 1 kg of the substance by 1 K.

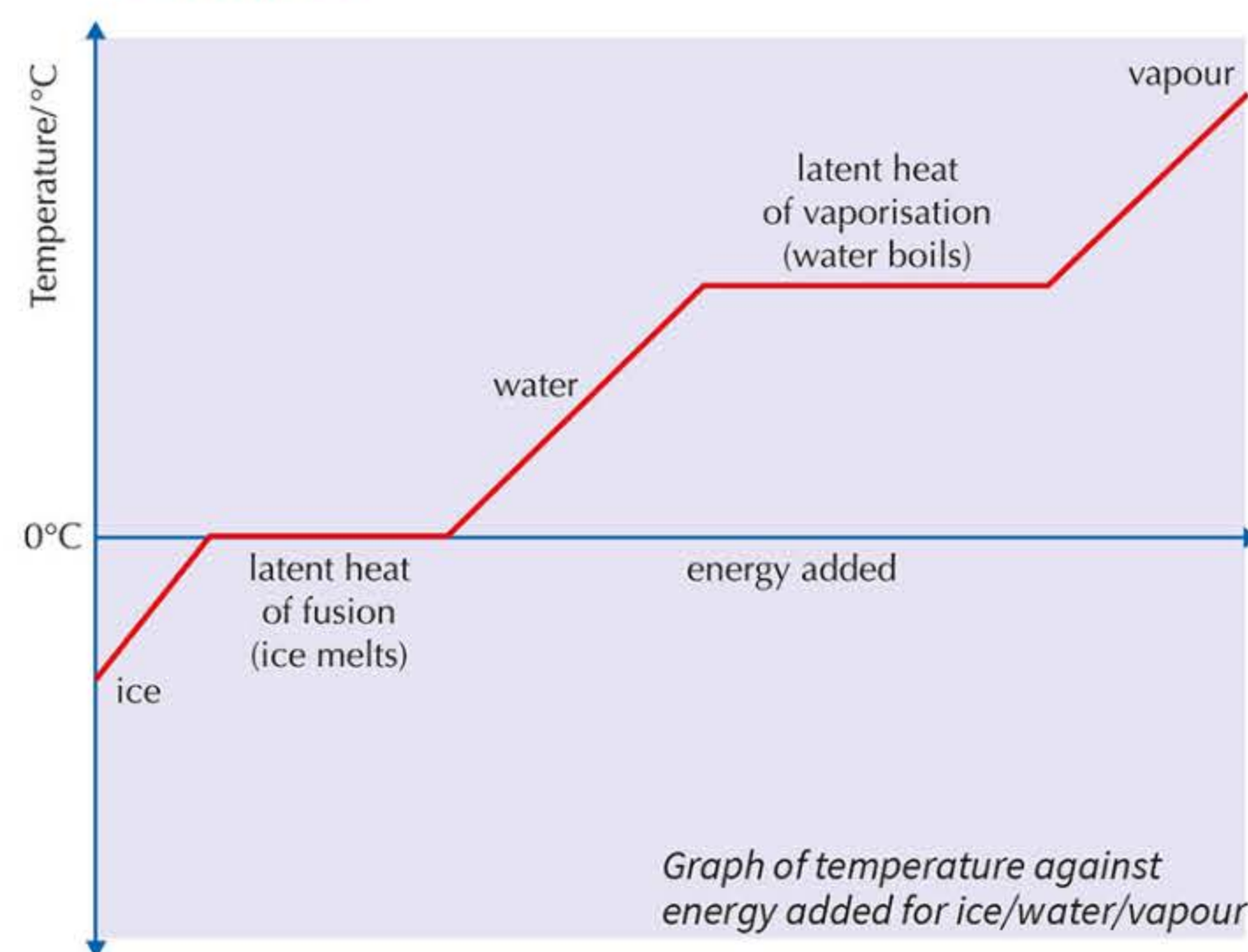
This definition can be rearranged to tell us the amount of energy required to raise the temperature of a body by any amount.

$$Q = mc\Delta\theta$$

Q = energy
 c = specific heat capacity
 $\Delta\theta$ = change in temperature

Latent heat

When a solid melts and becomes a liquid, it absorbs a certain amount of energy, which does not lead to a rise in temperature. The same thing happens when it changes to a gas. The heat absorbed, or released, in changing between states is known as the **latent heat**.



The latent heat of a body is the energy required to change the state of the body without changing its temperature. The specific latent heat, l , of a substance is the amount of energy required to change the state of 1 kg of that substance.

There will be different values for the specific latent heats of vaporisation and fusion.

$$Q = ml$$

Q = energy
 l = specific latent heat

Exam question

2004, HL, Section B, Q7

Define (i) specific heat capacity, (ii) specific latent heat. (12 marks)

500 g of water at a temperature of 15°C is placed in a freezer. The freezer has a power rating of 100 W and is 80% efficient.

- Calculate the energy required to convert the water into ice at a temperature of -20°C.
 - How much energy is removed every second from the air in the freezer?
 - How long will it take the water to reach a temperature of -20°C?
- (27 marks)

Allowing a liquid to evaporate in a closed pipe inside the freezer cools the air in the freezer. The vapour is then pumped through the pipe to the outside of the freezer, where it condenses again. Explain how this process cools the air in the freezer. (12 marks)

The freezer causes the room temperature to rise. Explain why. (5 marks)

(Specific heat capacity of ice = 2100 J kg⁻¹ K⁻¹; specific heat capacity of water = 4200 J kg⁻¹ K⁻¹; specific latent heat of fusion of ice = 3.3 × 10⁵ J kg⁻¹)

Heat transfer

Heat can be transferred from one location to another by three methods:

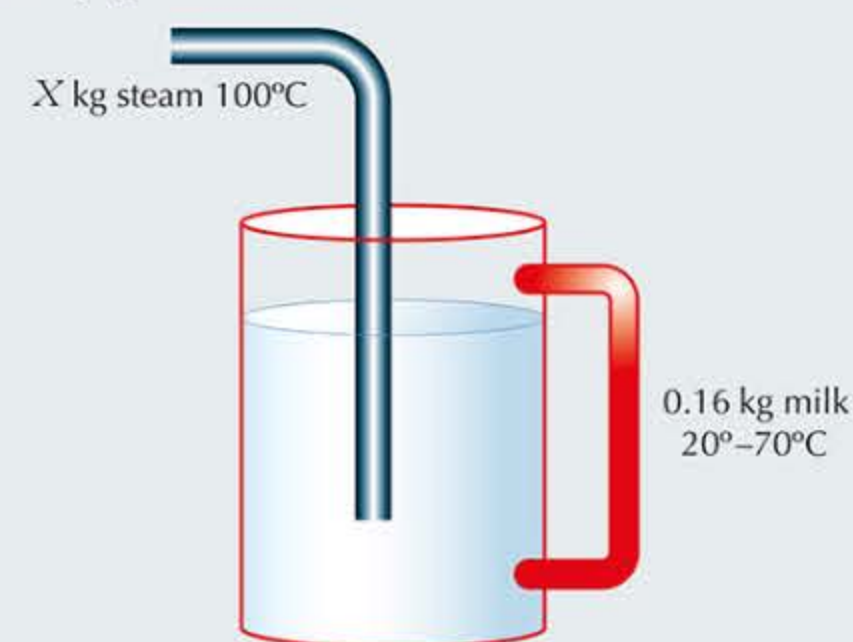
- Conduction.** This is the transfer of heat within a body without any net movement of the particles of that body. Most good conductors are solids, such as metals. A poor conductor, such as rubber, is often referred to as an insulator. Liquids, in general, are not good conductors of heat. The **U-value** of a body is the measure of how heat passes through the body (i.e. a low U-value implies a body is well insulated).
- Convection.** This is the transfer of heat within a body accompanied by the movement of the particles of that body. Fluids (i.e. liquids and gases) tend to be good convectors.
- Radiation.** This is the transfer of energy across empty space. This is how the heat and light from the sun reach earth.

Sample answer

Leaving Certificate, 2011, Higher Level, Section B, Q7

- (a) When making a hot drink, steam at 100°C is added to 160 g of milk at 20°C . If the final temperature of the drink is to be 70°C , what mass of steam should be added? You may ignore energy losses to the surroundings.

(12 marks)



Energy lost = Energy gained

$$(ml)_{\text{st}} + (mc\Delta\theta)_{\text{st/water}} = (mc\Delta\theta)_{\text{milk}} \quad (2, 2, 2)$$

$$(2.34 \times 10^6 X)_{\text{st}} + (4.18 \times 10^3 X(100 - 70))_{\text{st/water}} = ((0.16)(3.9 \times 10^3)(70 - 20))_{\text{milk}} \quad (3)$$

$$2\,465\,400 X = 31\,200$$

$$X = 0.0127\text{ kg} \quad (3)$$

This means that it takes 12.7 g of steam to heat the milk.

A metal spoon, with an initial temperature of 20°C , is then placed in the hot drink, causing the temperature of the hot drink to drop to 68°C . What is the heat capacity of the spoon? You may ignore other possible heat transfers.

(12 marks)

Energy lost = Energy gained (3)

$$(mc\Delta\theta)_{\text{hot drink}} = (C\Delta\theta)_{\text{spoon}} \quad (3)$$

$$((0.16 + 0.0127)(4.05 \times 10^3)(2)) = (C(68 - 20)) \quad (3)$$

$$48C = 1398.87$$

$$C = 29.143\text{ J K}^{-1} \quad (3)$$

- (b) Name two processes by which a hot drink cools. How is the energy lost by each of these processes reduced for a hot drink supplied in a disposable cup?

(14 marks)

A hot drink cools through convection, conduction and radiation. (4)

Convection

The air above the drink is heated and then rises to be replaced by cooler air, which in turn will heat and then rise. Heat is therefore constantly transferred away from the drink.

This process will be affected very little by using a disposable cup, unless of course a lid is used, which is often the case. The lid would trap a layer of heated air above the drink and not allow it to escape, thus limiting the creation of convection currents. (3)

Conduction

The container in which the drink is held will absorb some heat from the drink and transfer this drink from particle to particle within the cup. For this reason, most drink containers are poor conductors. (4)

A polystyrene disposable cup is an excellent insulator and therefore reduces this effect in comparison with most other containers. A standard ceramic cup, however, is probably a better insulator than a paper disposable cup. (3)

Radiation

All warm bodies emit radiation into their surroundings. A disposable cup would have little effect on this.

- (c) A thermocouple is used to measure the temperature of the steam. How would you demonstrate the principle of operation of a thermocouple? (9 marks)

A thermocouple is made from a pair of metals connected. (3)

When there a difference in temperature between the two junctions, a voltage is created and a current will flow. (3)

This is a thermometric property, which means that it can be used to measure the temperature. (3)

Exam questions

1 2010, HL, Section B, Q5 (d)

Explain why snow is slow to melt as the air temperature rises above 0°C . (7 marks)

2 2006, OL, Section B, Q7

Heat can be transferred in a room by convection. What is convection?

Name two other ways of transferring heat. (12 marks)

Describe an experiment to demonstrate convection in a liquid. (12 marks)

Name a material that could be used as insulation. (12 marks)

Explain how a storage heater heats the air in a room. (8 marks)

3 2005, OL, Section B, Q5 (d)

Name two methods by which heat can be transferred. (7 marks)

4 2004, HL, Section B, Q5 (c)

Explain the term thermometric property. (7 marks)

5 2004, OL, Section B, Q7

Heat can be transferred by conduction. What is meant by conduction?

Name two other ways of transferring heat. (12 marks)

Describe an experiment to show how different solids conduct heat at different rates. (12 marks)

The U -value of a house is a measure of the rate of heat loss to the surroundings.

Give two ways in which the U -value of a house can be reduced. (8 marks)

8 Electricity

Learning objectives

In this chapter you will learn about the following:

1 Charges

- Static electricity
- Charging by contact
- Charging through induction
- Distribution of charge
- The Van de Graaff generator

2 Electric fields

- Electric field strength
- Potential difference

3 Capacitance

4 Electric current

- Voltage-current graphs

5 Resistance

- Resistance and temperature
- Resistivity
- Resistors in series
- Resistors in parallel
- Potential divider
- Wheatstone bridge

6 Effects of an electric current

7 Domestic wiring

8 Semiconductors

- Intrinsic conduction
- Extrinsic conduction

9 Electricity and magnetism

- A current-carrying conductor in a magnetic field experiences a force
- The ampere
- Electromagnetic induction
- Rms value
- Mutual induction
- Self-induction

Key definitions relevant to this chapter

Coulomb's law

Electric field strength

Electromagnetic induction (Faraday and Lenz)

Capacitance

Joule's law

The ampere

Potential difference

The volt

Resistance

Resistivity

Ohm's law

The ohm

Magnetic flux density

Key formulae

$$\text{Induced emf } E = n \frac{\text{change in flux}}{\text{time}}$$

$$\text{Rms voltage } V_{\text{rms}} = \frac{V_0}{\sqrt{2}}$$

$$\text{Rms current } I_{\text{rms}} = \frac{I_0}{\sqrt{2}}$$

$$\text{Capacitance } C = \frac{Q}{V}$$

$$\text{Capacitor } C = \frac{A\epsilon_0}{d}$$

$$\text{Energy in a capacitor } W = \frac{1}{2} CV^2$$

$$\text{Resistivity } \rho = \frac{RA}{l}$$

$$\text{Power } P = VI$$

$$\text{Magnetic flux } \phi = BA$$

$$\text{Transformer } \frac{V_{\text{in}}}{V_{\text{out}}} = \frac{N_{\text{p}}}{N_{\text{s}}}$$

$$\text{Coulomb's law } F = \frac{1}{4\pi\epsilon} \frac{Q_1 Q_2}{d^2}$$

$$\text{Electric field strength } E = \frac{F}{Q}$$

$$\text{Potential difference } V = \frac{W}{Q}$$

$$\text{Ohm's law } V = IR$$

$$\text{Resistors in series } R = R_1 + R_2$$

$$\text{Resistors in parallel } \frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$

$$\text{Wheatstone bridge } \frac{R_1}{R_2} = \frac{R_3}{R_4}$$

$$\text{Joule's law } P \propto I^2 \text{ (} P = RI^2 \text{)}$$

$$\text{Force on a conductor } F = IlB$$

$$\text{Force on a moving charge } F = qvB$$

Charges

Static electricity

Nearly all electric charge comes from the charges on **protons** (positive) and **electrons** (negative).

- If an object is electrically neutral, it has the same number of protons and electrons.
- If it is negatively charged, it has more electrons than protons.
- If it is positive there is a majority of protons.

Generally speaking, because it is much easier to either add or remove electrons from atoms, we can say that:

- When an object is negative, electrons have been added.
- When it is positive, electrons have been taken away.

We know that opposite charges attract, and that like charges repel each other.

Charging by contact

Small 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 done when a plastic pen is rubbed against a jumper and shown to have a charge by lifting a small piece of paper, or when a balloon is rubbed and can be made to stick to a wall without any obvious reason.

STS

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 tends to cause dust to settle on the mirror or the screen. It can also create a hazard in flour mills, where a built-up charge can cause an explosion.

Charge is measured in coulombs

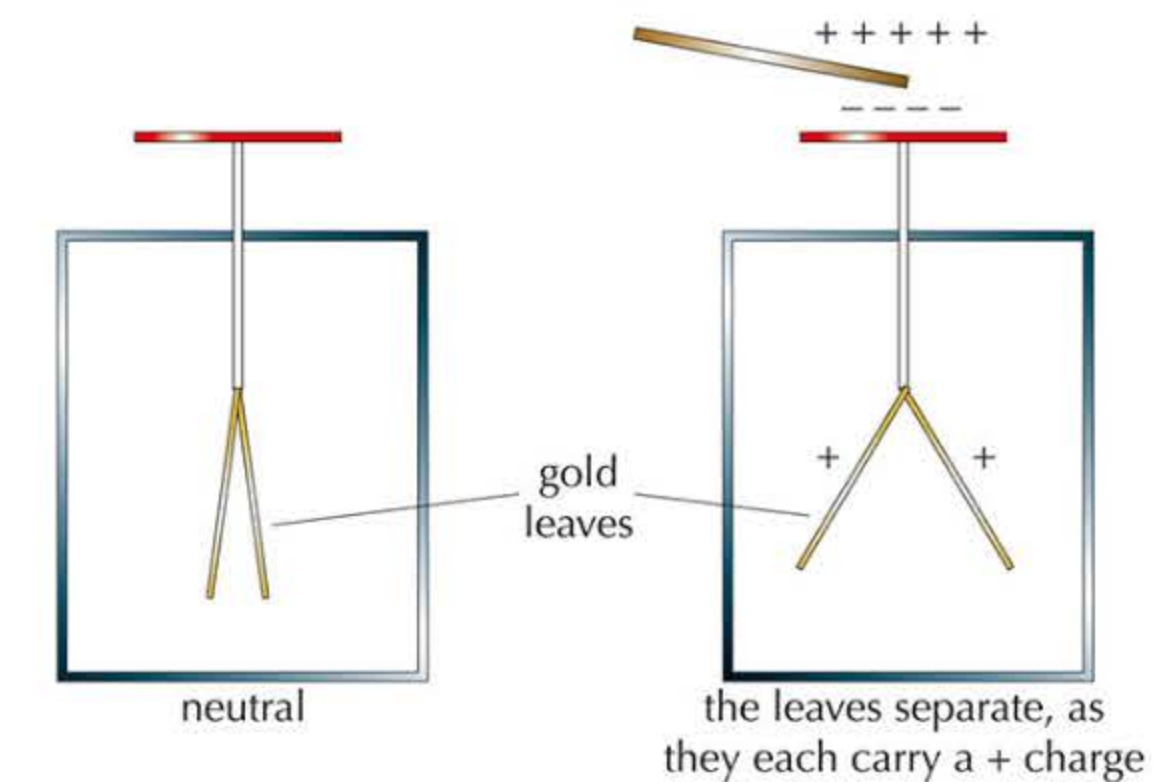
Because the coulomb is a large charge, very often we deal with millicoulombs (mC), or even microcoulombs (μC).

A conductor is a material that will tend to allow a flow of electrons.

An insulator is a material that tends to restrict the flow of electrons.

Charging through induction

An object that becomes charged without any contact with another body has been charged by induction. The gold-leaf **electroscope** demonstrates that an object can be charged through induction.

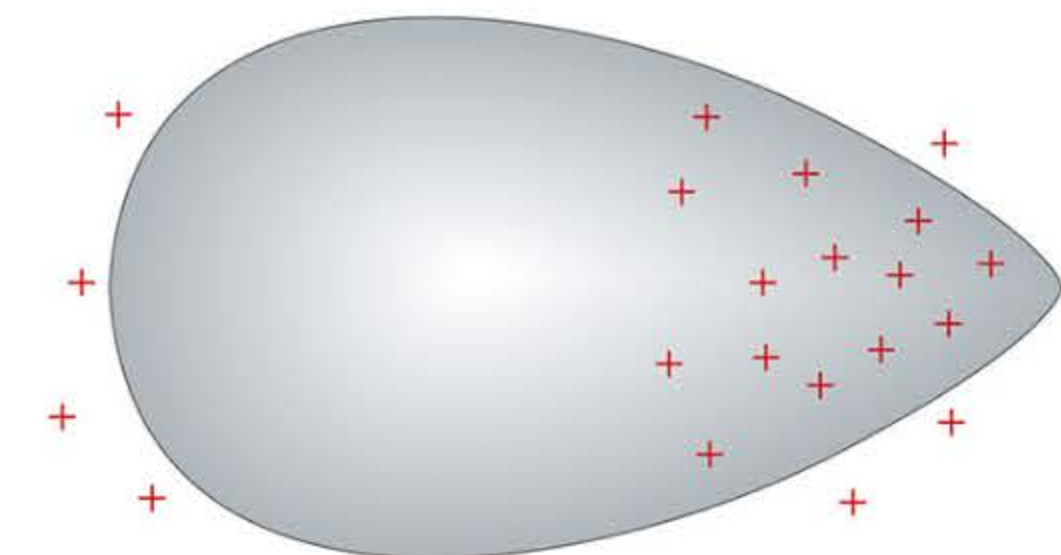


Distribution of charge

An electric charge will always tend to spread itself out as much as possible. 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. On a metal object, where charges are free to move, all electric charge will move to the outside of the object. If the object is spherical, or smoothly curved as it is on a Van de Graaff generator, the charge will be evenly spread over the outside surface.

Point effect

Wherever an object is less curved, and in particular at sharp points, there will be a build-up of charge. This is the point effect.



Point discharge

The point effect can actually lead to the object becoming discharged, as the air surrounding the point becomes ionised (charged), and negative charges attach to the point and cancel the positive charge (or vice versa). This is how lightning conductors work. Lightning conductors have two purposes:

- 1 To provide a path to earth for the lightning should it strike a tall building
- 2 To discharge air, in an opposite process to that described above, reducing the chance of a lightning strike occurring.

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.

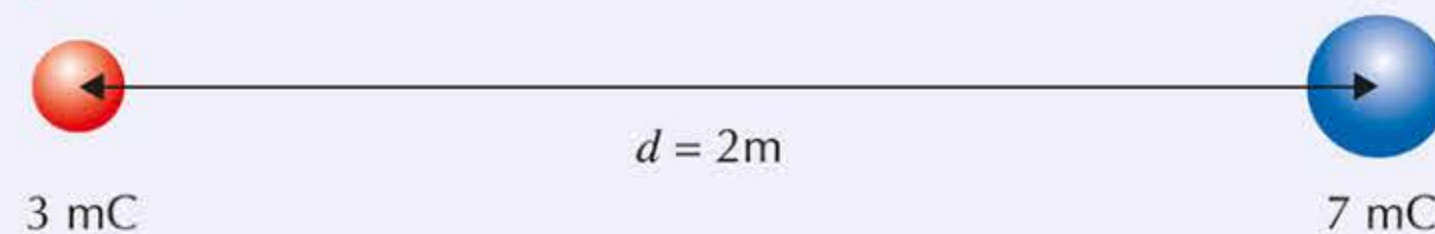
$$F \propto \frac{Q_1 Q_2}{d^2}$$

or,

$$F = \frac{1}{4\pi\epsilon} \frac{Q_1 Q_2}{d^2}$$

This is an example of an inverse square law. Newton's law of gravitation is another example of an inverse square law.

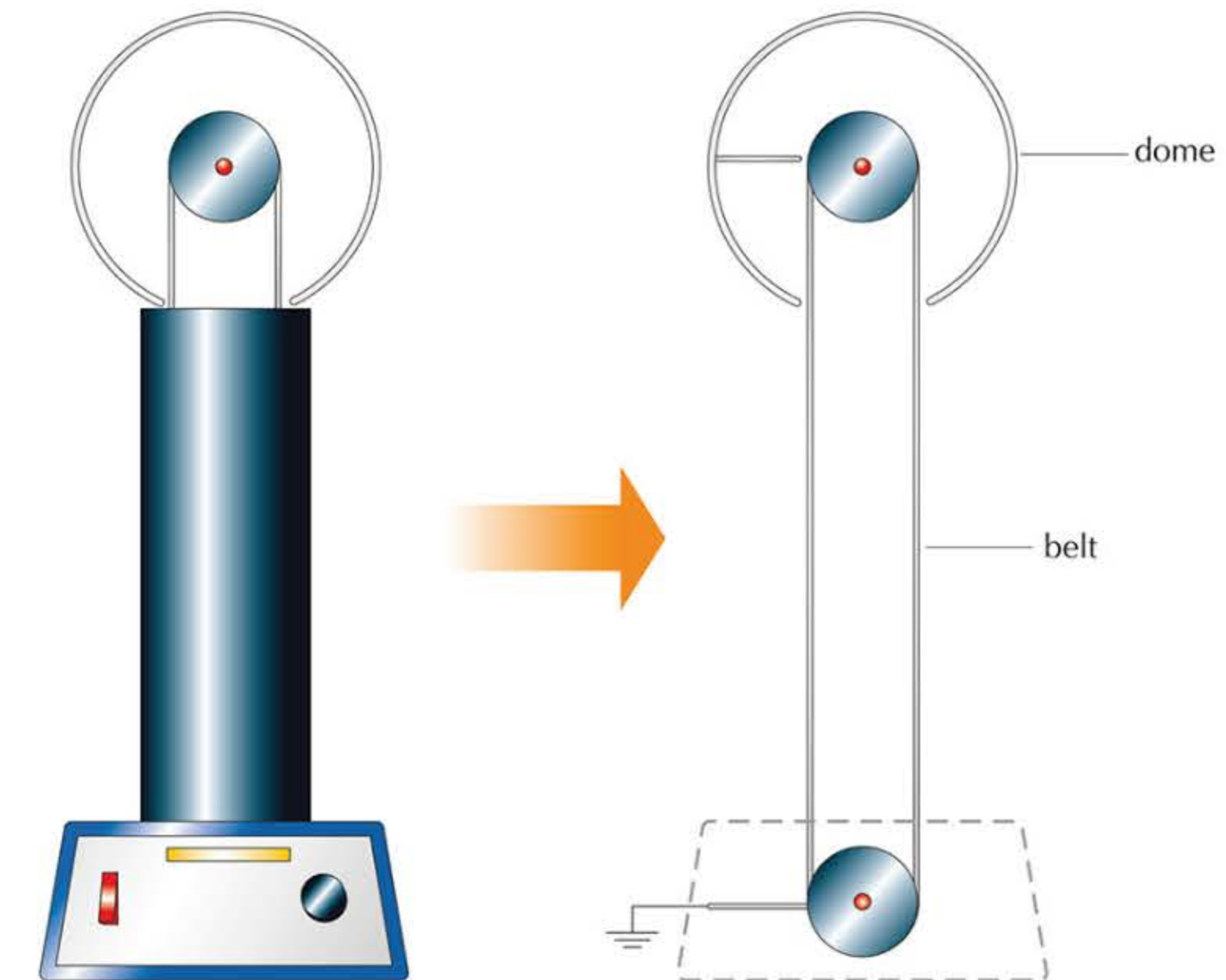
Example of Coulomb's law



$$\begin{aligned} F &= \frac{1}{4\pi\epsilon_0} \frac{Q_1 Q_2}{d^2} \\ &= \frac{1}{4\pi \times 8.9 \times 10^{-9}} \frac{(3 \times 10^{-3})(7 \times 10^{-3})}{2^2} \\ &= 8.9 \times 10^9 \frac{21 \times 10^{-6}}{4} \\ &= 46.96 \text{ N} \end{aligned}$$

The Van de Graaff generator

This device is used to build up large static charges. A charge is transferred to the rotating belt, either through friction or through the point effect, and then to the metal dome, by point effect. The belt can only hold a small charge, but the dome (as a curved piece of metal) can hold a very large charge.

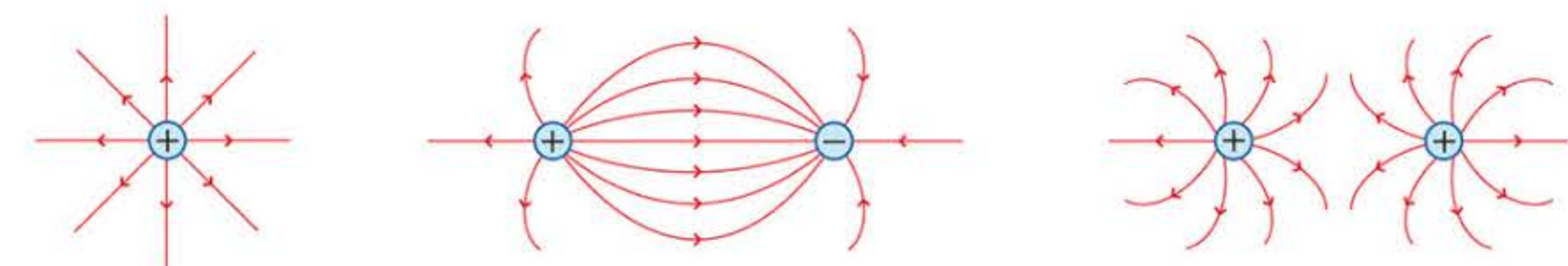


Electric fields

An electric field is the area around a charge where its effect can be felt. In drawing electric fields, we always draw the arrows to show the path a point positive charge would take.

Remember

You should be able to draw diagrams to represent at least each of the situations indicated in the diagrams below.

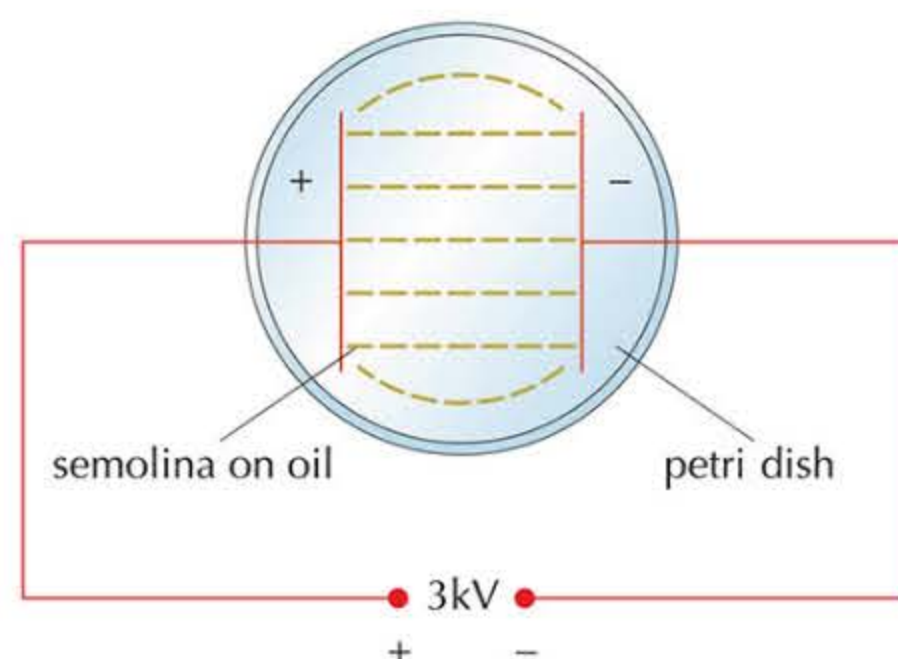




Experiment

To demonstrate an electric field

- Method** Add some semolina to a shallow dish of oil, as shown in the diagram below.
- Observation/Conclusion** The semolina (rice) particles become slightly charged at each end, and line up along the lines of force, showing the shape of the field.



HL Electric field strength

From Coulomb's law we can derive the formula for **electric field strength** (or electric field intensity) E .

Electric field strength is the force per unit positive charge at a point in an electric field, i.e.

$$E = \frac{F}{Q} \quad \text{or} \quad E = \frac{1}{4\pi\epsilon} \frac{Q_1}{d^2}$$

(where the electric field is *created* by the charge Q_1 , and *experienced* by the charge Q)

STS

Photocopying makes use of electric fields. A rotating drum inside the machine is charged. An image of the document to be copied is projected onto the drum. A light discharges those parts of the document that are white. Charged toner (ink) is then attracted to the remainder, and the copy is printed.

Modern electronic equipment works on very low voltages. People working with this equipment must be careful to have earthed themselves prior to touching circuitry to prevent damage.

Sample answer

Leaving Certificate 2005, Higher Level, Section B, Q10

Define electric field strength. State Coulomb's law of force between electric charges. (12 marks)

Electric field strength is the force per unit charge at a point in the electric field. (3)

E = electric field strength

F = force

Q = charge

$$E = \frac{F}{Q}$$

(3)

Coulomb's law states that the force between any two point charges is directly proportional to the product of the charges and inversely proportional to the square of the distance between them. (3)

F = force

Q = charges

d = distance

$$F \propto \frac{Q_1 Q_2}{d^2}$$

(3)

Why is Coulomb's law an example of an inverse square law? (6 marks)

This is an example of an inverse square law because the force is inversely proportional to d^2 . (6)

Give two differences between the gravitational force and the electrostatic force between two electrons. (6 marks)

The gravitational force is much smaller than the electrostatic force. (3)

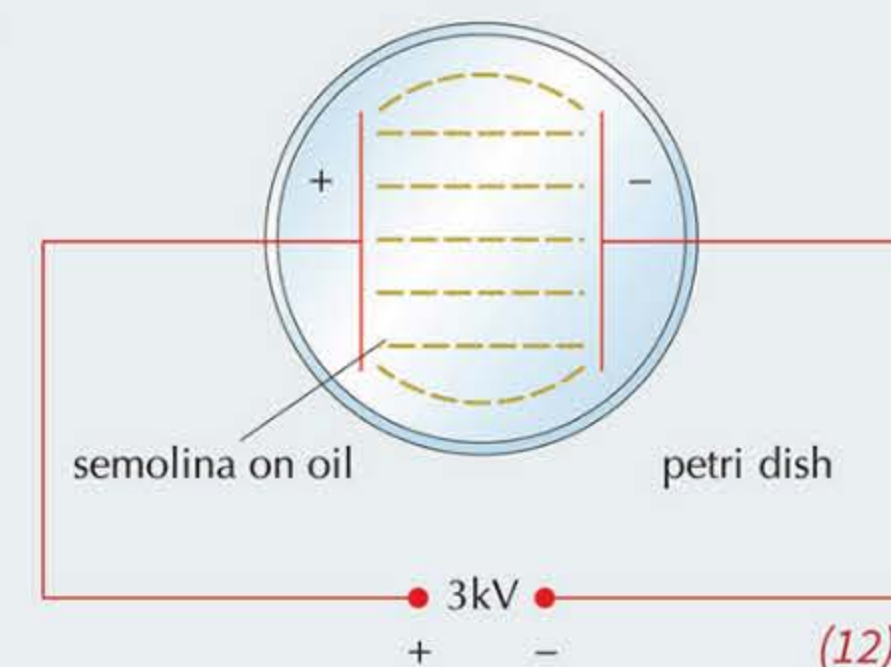
The gravitational force attracts the electrons to each other. They are repelled from each other by the electrostatic force. (3)

Describe an experiment to show an electric field pattern. (12 marks)

To demonstrate an electric field:

Method Add some semolina to a shallow dish of oil. Attach electrodes as shown in the diagram.

Observation/Conclusion The semolina (rice) particles become slightly charged at each end and line up along the lines of force. This demonstrates the shape of the electric field. (12)



Calculate the electric field strength at the point B, which is 10 mm from an electron.

(9 marks)



$$E = \frac{1}{4\pi\epsilon_0} \frac{Q}{d^2} \quad (3)$$

$$E = \frac{1}{4\pi(8.9 \times 10^{-12})} \frac{1.6 \times 10^{-19}}{(0.01)^2} \quad (3)$$

$$E = 1.4 \times 10^{-5} \text{ NC}^{-1} \quad (3)$$

What is the direction of the electric field strength at B?

(3 marks)

The direction of the field is towards the electron.

(3)

A charge of $5 \mu\text{C}$ is placed at B. Calculate the electrostatic force exerted on this charge.

(8 marks)

$$E = \frac{F}{Q} \quad (3)$$

$$F = EQ \quad (3)$$

$$F = (1.4 \times 10^{-5})(5 \times 10^{-6}) \quad (3)$$

$$F = 7.2 \times 10^{-11} \text{ N} \quad (2)$$

towards the electron

Exam question

2003, OL, Section B, Q12 (c)

State Coulomb's law of force between electric charges.

(6 marks)

Define electric field strength and give its unit.

(9 marks)

How would you demonstrate an electric field pattern?

(9 marks)

The diagram shows a negative charge $-Q$ at a point X. Copy the diagram and show on it the direction of the electric field strength at Y.

(4 marks)



Potential difference

A difference in potential is what drives an electric charge to move from one place to another. It can be created because of a combination of factors, such as the presence of other charges and the shape and material of an object. We can measure potential difference (p.d.) by measuring the work done in moving a charge from one point to another:

The potential difference between two points is the work done in moving a unit positive charge from one point to the other.

The unit of p.d. is the volt.

The potential difference between two points is 1 volt if the work done in moving a charge of 1 coulomb from one point to the other is 1 joule. From this we get the formula:

$$W = QV$$

Though we are normally only interested in measuring a p.d. 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** (0V) for this purpose.

Capacitance

The **capacitance** of a body is defined as the ratio of the charge on the body to its potential $C = \frac{Q}{V}$

In effect, the capacitance of a body is a measure of the ability of the body to hold charge. The unit of capacitance is the farad:

A body has a capacitance of 1 farad if the addition to the body of 1 coulomb raises the potential of the body by 1 volt.

A common arrangement used to increase capacitance and therefore to store electric charge is the parallel-plate capacitor. This device stores electrical energy as demonstrated by the experiment overleaf.

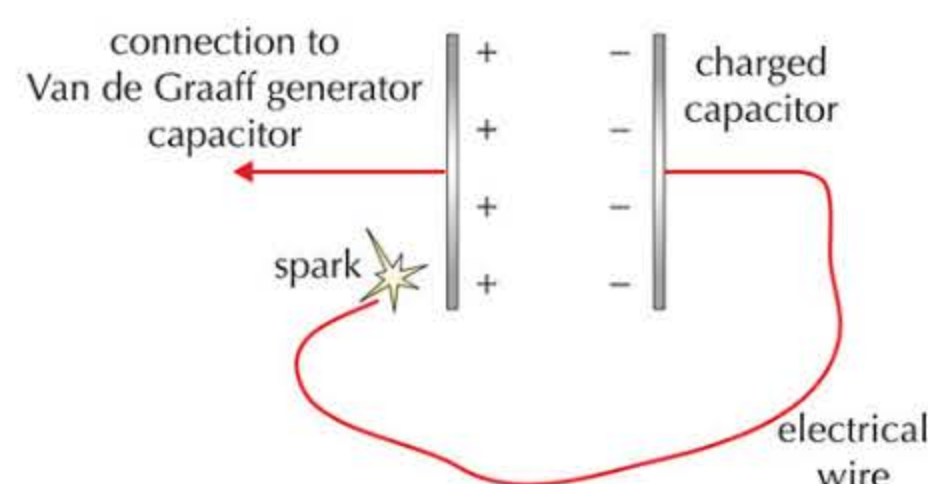


Experiment

To demonstrate that a capacitor stores energy

Method Set up the apparatus as shown in the diagram below. Allow the capacitor to build up a charge. Bring a conducting wire from one plate towards the other.

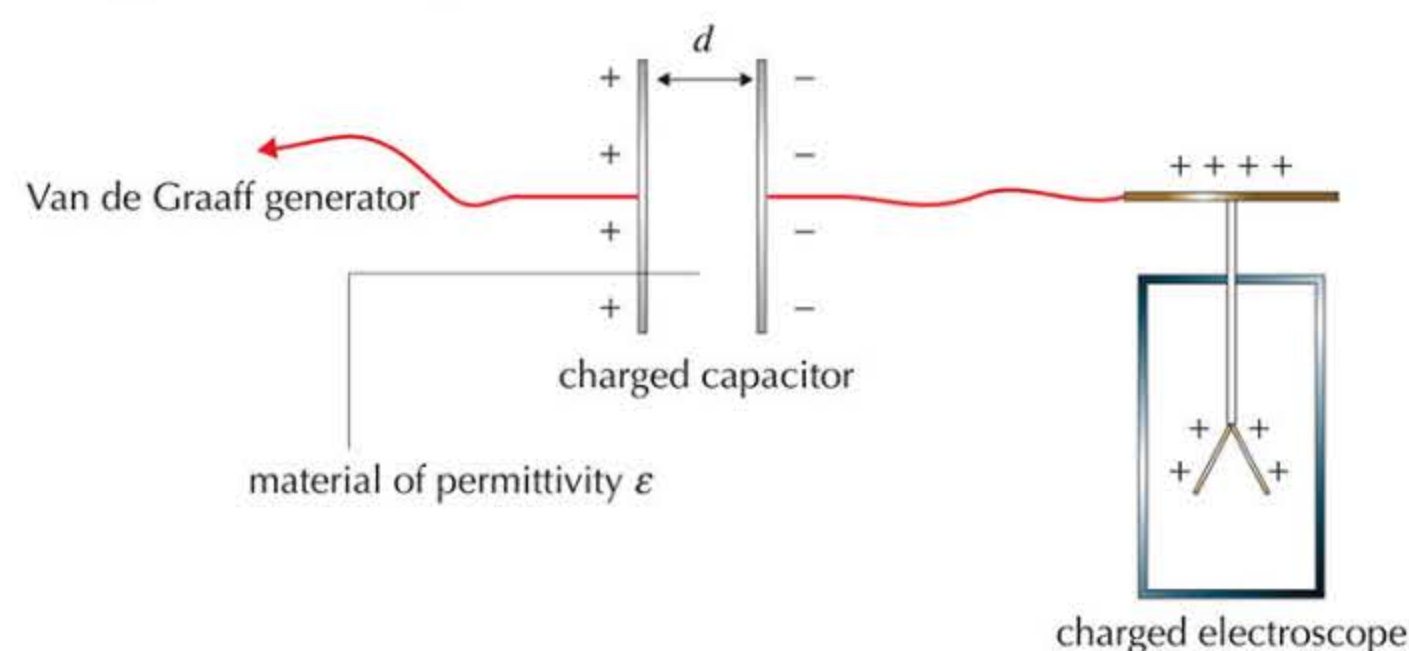
Observation/Conclusion As it approaches we will see and hear a spark. The presence of light and sound energy indicates that energy had been stored on the capacitor.



HL The energy (W) stored is given by the formula: $W = \frac{1}{2}CV^2$

Factors determining capacitance of a capacitor

The capacitance of a capacitor is controlled by three factors: the common area (or A , the area of overlap), the distance between the plates (d) and the permittivity (ϵ) of the material between the plates. This can be demonstrated using an electroscopes.



When the plates are drawn apart, the leaves collapse, indicating that the stored charge, and therefore the capacitance, is inversely proportional to d . Similarly we can show that reducing A and varying the material between the plates affects the capacitance according to the formula: $C = \frac{\epsilon A}{d}$

Capacitors conduct ac, but block the flow of dc.

STS

Capacitors are used in flash photography: a charged capacitor discharges through the bulb at the instant the photo is taken. They are also used in the tuning of radios.

Exam question

2006, HL, Section B, Q12 (b)

List the factors that affect the capacitance of a parallel plate capacitor.

(6 marks)

The plates of an air filled parallel plate capacitor have a common area of 40 cm^2 and are 1 cm apart. The capacitor is connected to a 12 V d.c. supply. Calculate (i) the capacitance of the capacitor; (ii) the magnitude of the charge on each plate.

(15 marks)

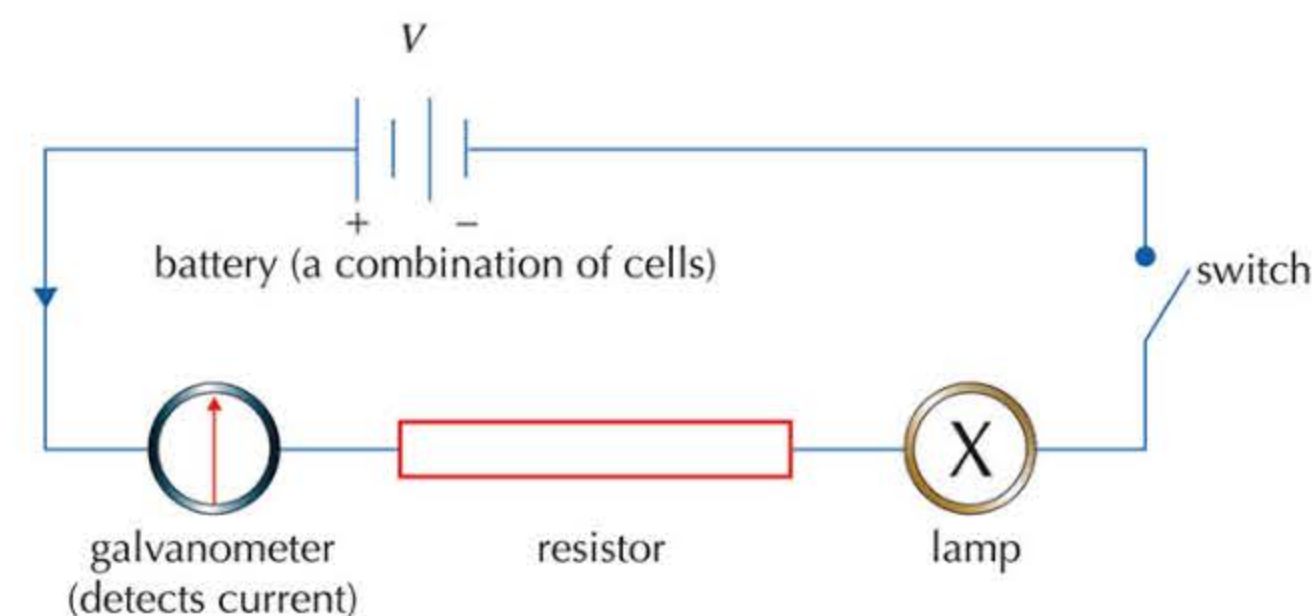
What is the net charge on the capacitor? Give a use for a capacitor.

(Permittivity of free space = $8.85 \times 10^{-12} \text{ Fm}^{-1}$)

(7 marks)

Electric current

The diagram below shows some of the symbols most commonly used in electric circuits.

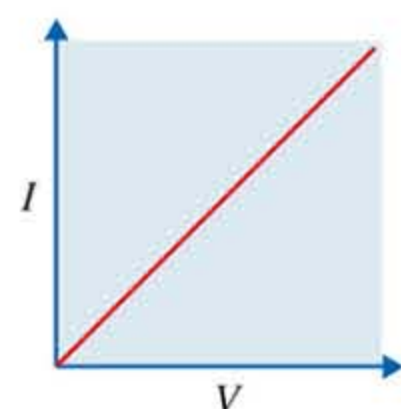


An electric current is a flow of charge. A current of 1 amp (or ampere) is a movement of 1 coulomb per second, i.e. $I = \frac{Q}{t}$

In an electric circuit, the current (I) is usually shown travelling from the positive pole of a battery to the negative. This is done for historical reasons, but it is quite misleading. The current actually consists of the movement of electrons from the negative pole to the positive. A **voltage** (V), when applied to a circuit, is known as the **emf** (electromotive force). 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.

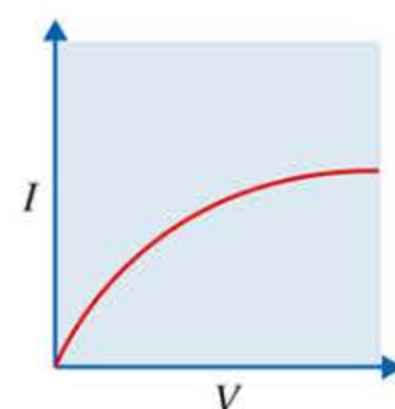
Voltage-current graphs

In a standard electric circuit, where electrons are passing through a metal, Ohm's law is obeyed, i.e. the voltage is proportional to the current. On a graph of current against voltage you get a straight line through the origin. There are other situations though, in which a current will flow but Ohm's law is not obeyed. Some examples are outlined below.



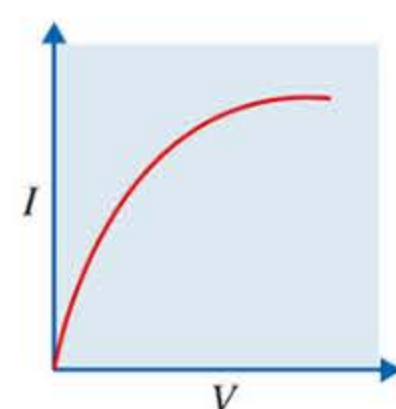
Metal

- Current is carried by electrons



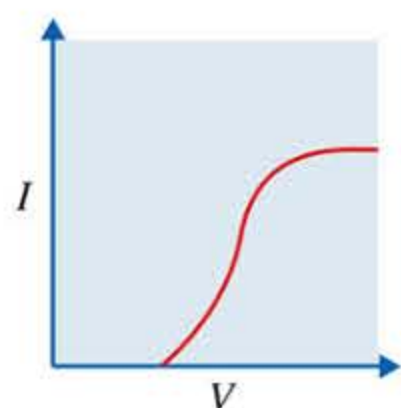
Filament bulb

- Current is carried by electrons
- At higher voltages, the increased heat increases resistance, and limits the current



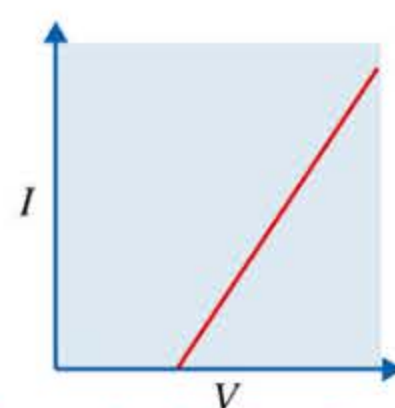
Gases

- Current is carried by ions
- At higher voltages, no more ions can be created, limiting the current



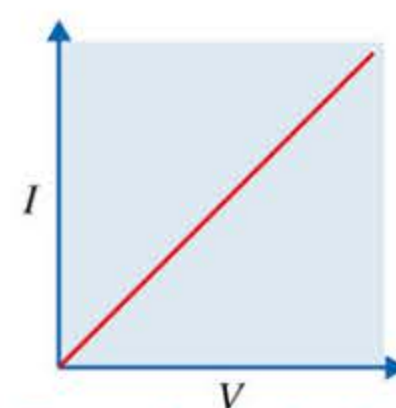
Vacuum

- The cathode must be warmed
- At higher voltages, electrons move across the vacuum



Electrolysis (inactive electrodes)

- The current carried by ions



Electrolysis (active electrodes)

- The current carried by ions

Exam question

2003, HL, Section B, Q8

Define the unit of current, i.e. the ampere. (9 marks)

Describe an experiment to demonstrate the principle on which the definition of the ampere is based. (15 marks)

Various materials conduct electricity. Draw a graph to show the relationship between current and voltage for each of the following conductors: (i) a metal at constant temperature (ii) an ionic solution with inactive electrodes (iii) a gas. (18 marks)

How would the graph for the metal differ if its temperature were increasing? (7 marks)

How would the graph for the ionic solution differ if its concentration were reduced? (7 marks)

Resistance

Ohm's law states that for a metallic conductor at constant temperature, the current will be proportional to the voltage, i.e.

$$V \propto I$$

$$\Rightarrow V = RI$$

$$\Rightarrow R = V/I$$

This gives us a definition of resistance, and the unit of resistance, the ohm.

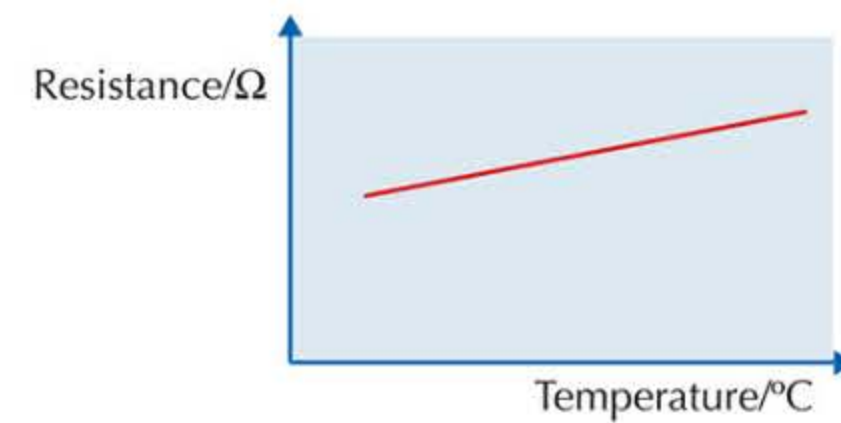
The **resistance** of an object within an electrical circuit is defined as the ratio of the voltage across it to the current flowing through it, i.e. $R = \frac{V}{I}$

A conductor has a resistance of 1 ohm (1Ω), if a current of 1 amp (1 A) flows when a voltage of 1 volt (1 V) is applied.

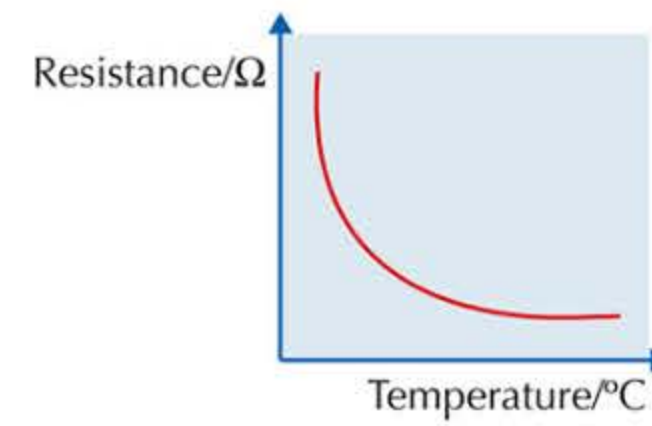
Resistance and temperature

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.

Metals (resistance increases with temperature)



Semiconductors (resistance decreases with temperature)



Resistivity

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 (the wider an 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, i.e.

$$R = \frac{\rho l}{A}$$

The resistivity of a material is the resistance of a unit cube of that material, or,

$$\rho = \frac{RA}{l}$$

Resistors in series

This diagram shows an example of three resistors connected in series:



For this setup, the total voltage drop from a to b is given by $V_{ab} = V_1 + V_2 + V_3$

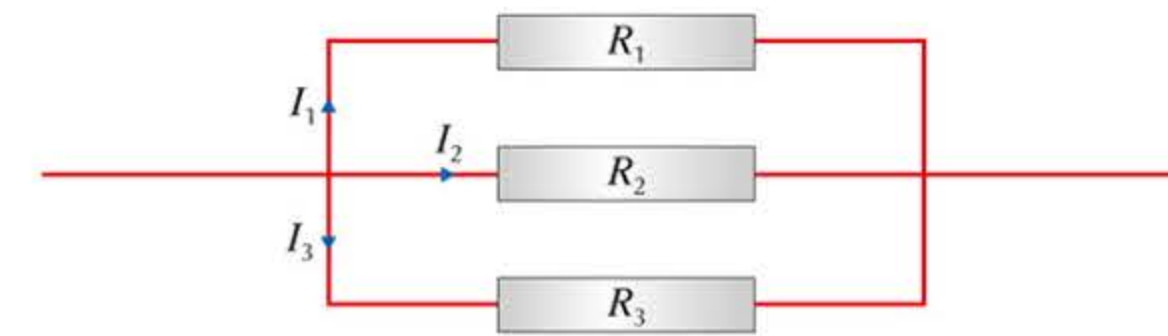
Where V_1 is the voltage drop across R_1 , and so on.

Following Ohm's law we can say: $IR_T = IR_1 + IR_2 + IR_3$

dividing by I ,

$$R_T = R_1 + R_2 + R_3$$

Resistors in parallel



The total current is given by $I = I_1 + I_2 + I_3$

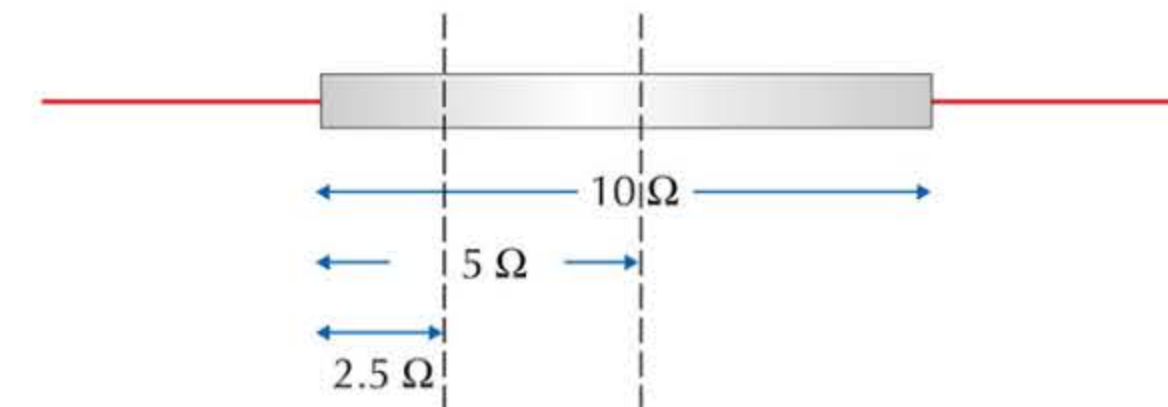
The total voltage drop across the group of resistors is the same, regardless of the path followed, so $\frac{V}{R_T} = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3}$

And dividing across by V gives:

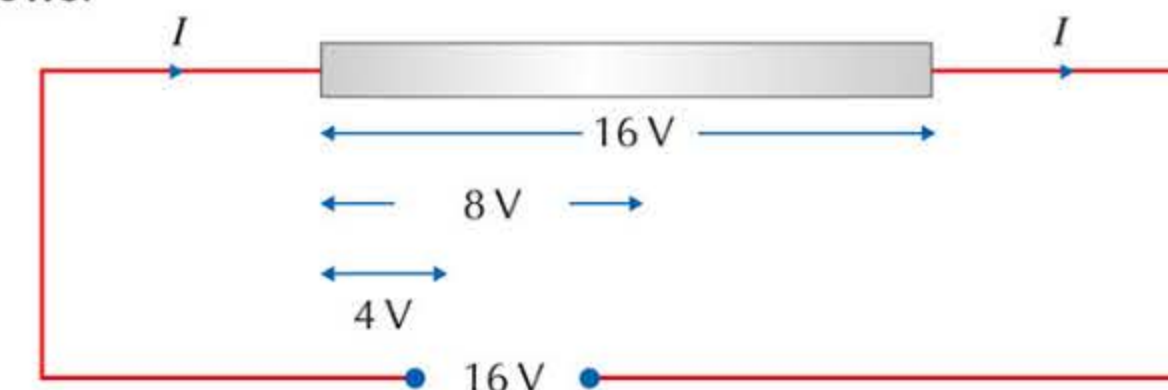
$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

Potential divider

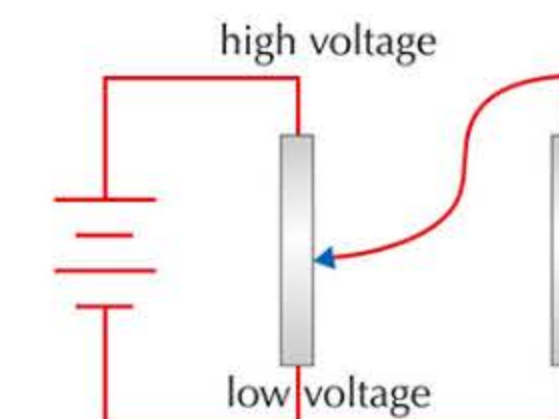
The longer a resistor is, the larger its resistance becomes. If a current flows only across a section of a resistor, the resistance is proportionately reduced, as shown in the diagram below.



Following on from the formula $V = IR$, we can see that the potential drop across a resistor is also in proportion to the fraction of a resistor across which a current flows.

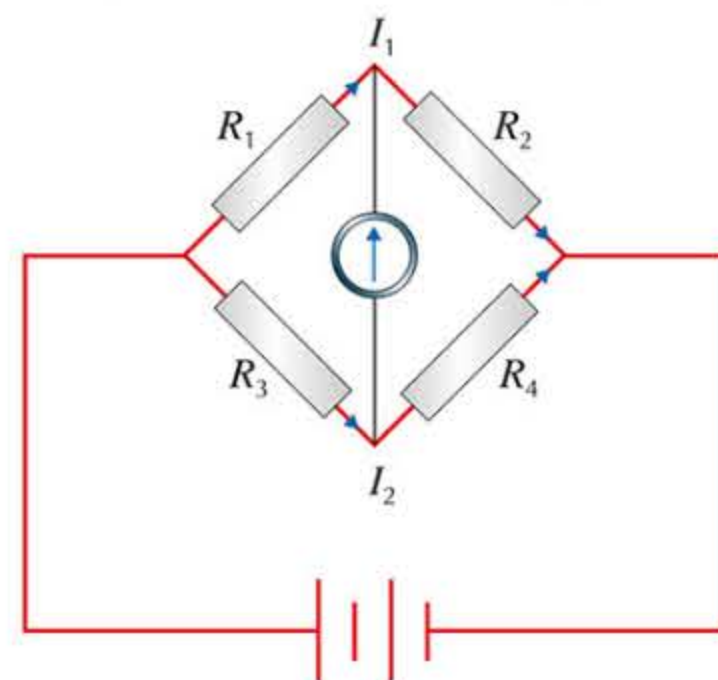


A potential divider works in this way, making two connections to a resistor across which a current is flowing. In this way, smaller voltages can be supplied.



Wheatstone bridge

A Wheatstone bridge is set up as shown in the diagram below.



When **balanced**, the resistors are such that no current flows through the galvanometer. For this to happen, this formula must apply:

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}$$

STS

The Wheatstone bridge was originally used to measure an unknown resistance. They are still used in thermostats and related circuits today. For example, if an oven needs to be set to maintain a temperature of 200°C, a Wheatstone bridge is used. R_2 could be inside the oven. Its resistance will change as the oven heats up or cools down. We choose resistances so that the bridge is balanced only when the oven is at 200°C. Above or below this temperature, a current flows through the galvanometer and the oven can be switched either on or off as needed.

Effects of an electric current

There are three effects of an electric current:

- The chemical effect: e.g. an electric current can cause a chemical reaction, as happens in electrolysis. The current is carried by ions, created from the chemicals involved. In particular this is used in electroplating materials.
- The magnetic effect: all magnetism is associated with the movement of an electric charge.
- The heating effect: e.g. as seen in a kettle, or a light bulb.

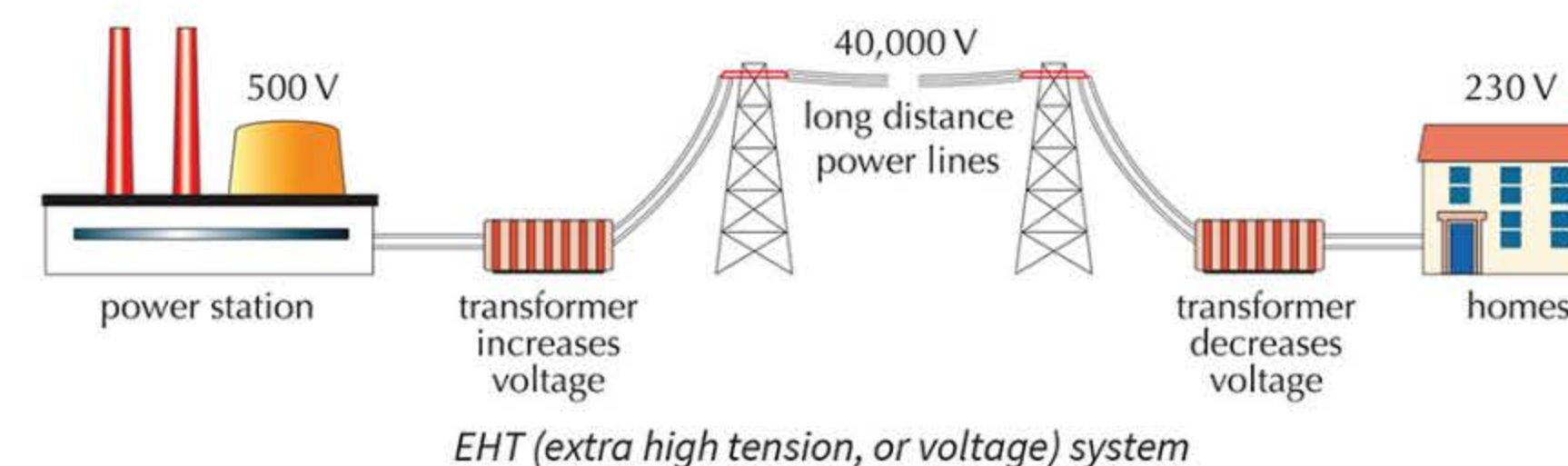
Joule's law states that the rate at which heat is produced by an electric current is proportional to the square of the current, i.e. $P \propto I^2$. The constant involved is the resistance, giving:

$$P = RI^2 \text{ or } P = VI$$

Remembering that $P = \frac{W}{t}$ (work/energy divided by time), we can conclude that heat energy produced in an electric circuit, W , is given by $W = RI^2t$.

STS

Moving electrical energy across large distances (e.g. from power stations to towns) involves the 'loss' of much energy in the form of heat. As Joule's law explains, the heat produced every second is larger if the current is larger. Increasing the voltage will cause the current to be reduced. As a high power corresponds to a high loss of energy from a system, we are obviously better off transmitting energy at high voltage rather than at high current.

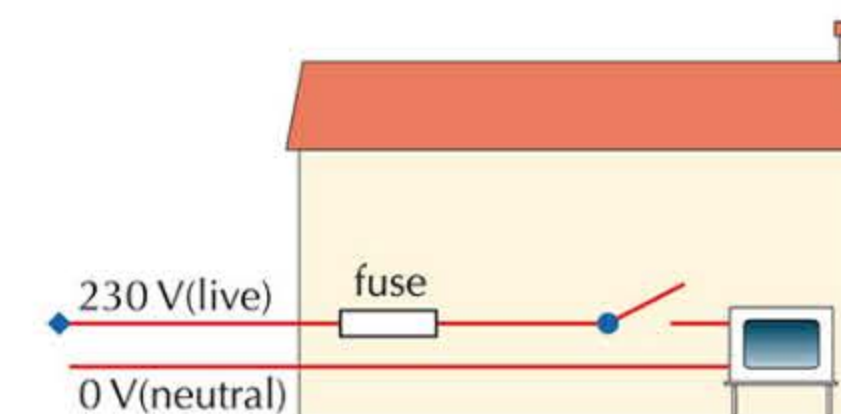


Domestic wiring

In a very simplified form, all homes are connected to the electricity network by two wires: one of which is at 230 V (the live wire), and the other at 0 V (the neutral wire). Obviously 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.

Remember

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.



- 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.
- An alternative safety feature is a **miniature circuit breaker** (MCB). It

contains both an electromagnet and a bimetallic strip. These again will break the circuit if a current above a certain safety limit should flow through it.

- A **residual circuit breaker** (RCD) functions by detecting a difference between the current flowing in the live and neutral wires. These should be the same. If they vary by a significant amount, the circuit is broken.
- A number of devices connected along one circuit is called a **ring circuit**. A single device, usually requiring a large current, connected by itself to the mains is called a **radial circuit**.
- 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.
- All metal surfaces used near water (pipes, taps, etc) should be **bonded**, i.e. they should be connected to earth. This is to protect from injury, should any part of them become connected to a power supply.

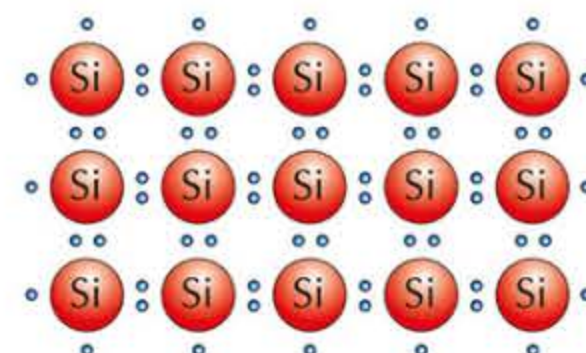
Semiconductors

A semiconductor is a material whose resistivity lies between that of a conductor and an insulator.

Take the example of silicon, which has a valency of four. This means that it has four electrons in its outermost shell but, like other atoms, it would 'prefer' to have eight electrons.

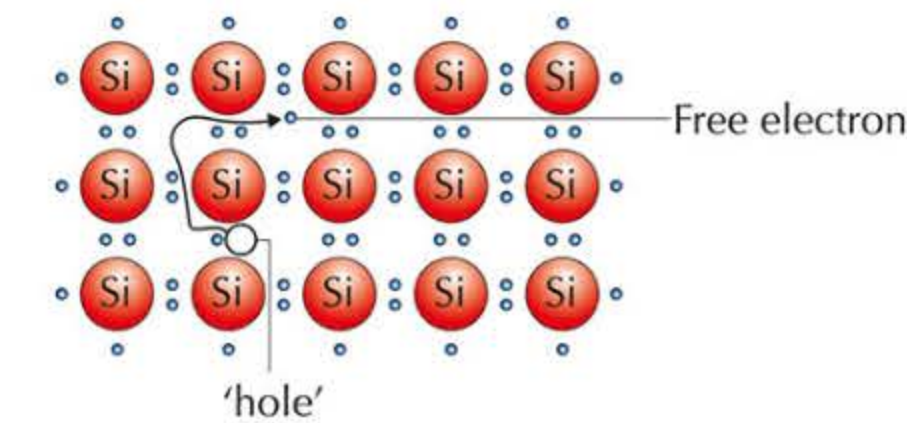


In a silicon crystal, in order to achieve a situation where each atom is surrounded by eight electrons, the atoms arrange themselves in such a way that each atom shares an electron with each of four neighbours:



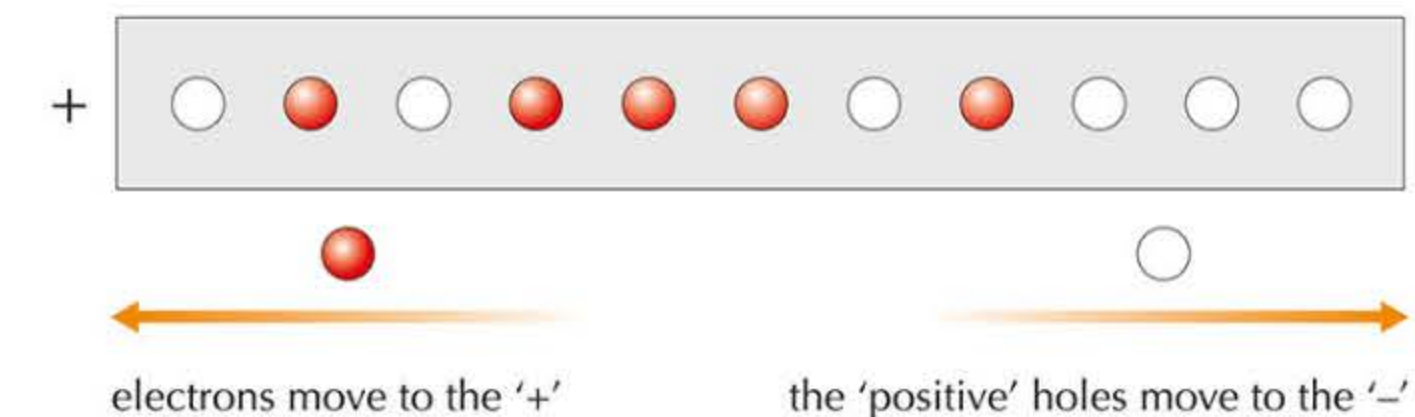
At a temperature 0 K, this is a perfect insulator. No electrons are free to move and they are therefore not free to carry a current.

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

These free electrons are now 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 move 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 referred to as **positive holes**. We can simplify a crystal as shown in the following diagram.



Extrinsic conduction

Conduction can be improved by adding either extra free electrons (**n-type**) or extra holes (**p-type**).

n-type doping

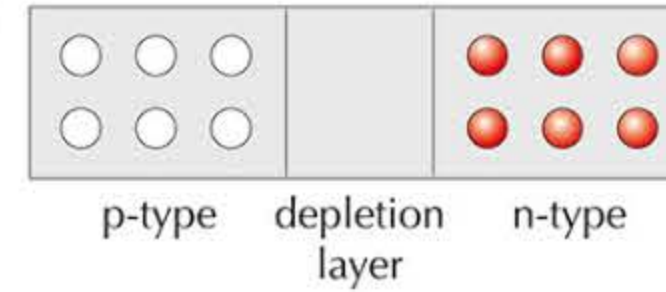
When constructing a silicon crystal, a small number of phosphorous atoms can be introduced. These will try to fit into the overall crystal structure, sharing one electron with each of four neighbours. But they have five electrons in their outer shell and will therefore have one 'extra electron'. This is likely to break free from the atom and to become available for conduction. As there are extra free electrons, conductivity is improved.

p-type doping

If a small quantity of boron is added to a growing crystal of silicon, it will try to fit into the structure of the crystal. It only has three electrons in its outer shell, however, so an extra 'hole' will be created. The extra holes act as stepping stones for the moving electrons, and this will also improve the conductivity.

p-n junction

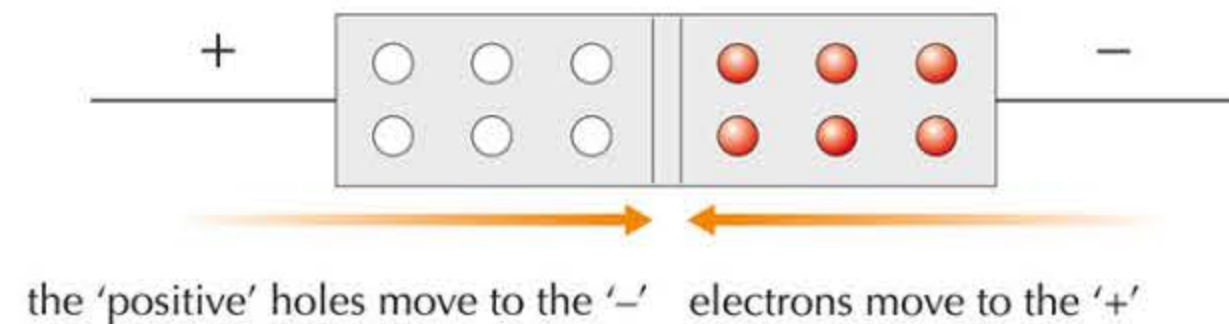
n-typing and p-typing are really only of any use to us when the two are placed together at a p-n junction. The simplest example of this is in a **diode**. At the junction of the two materials, the extra free electrons tend to occupy the extra free holes. This is known as the depletion layer. It acts as a block of insulating material in the middle of the diode.



This is the symbol for a diode:

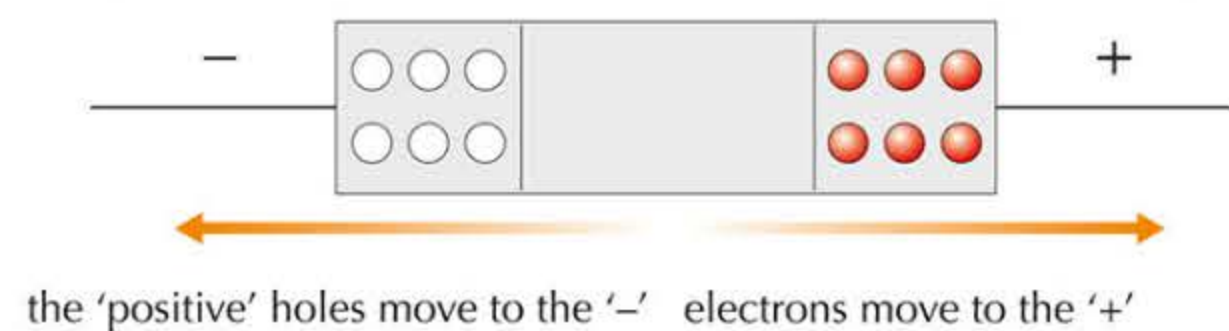
Forward bias

In **forward bias** 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.

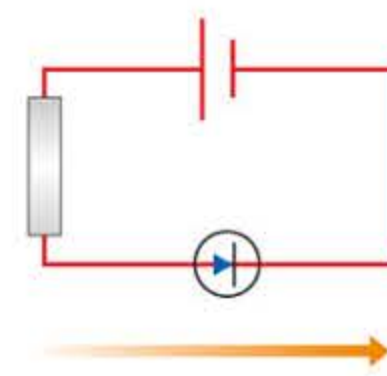


Reverse bias

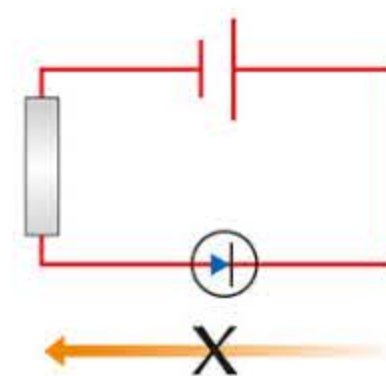
For **reverse bias**, the p-type material is attached to the negative terminal, and the n-type to the positive. The electrons are drawn backwards from the centre and the depletion layer grows. A current will not be able to move through the device.



Using electrical symbolism, these circuits could be shown like this:



a current flows
Forward bias



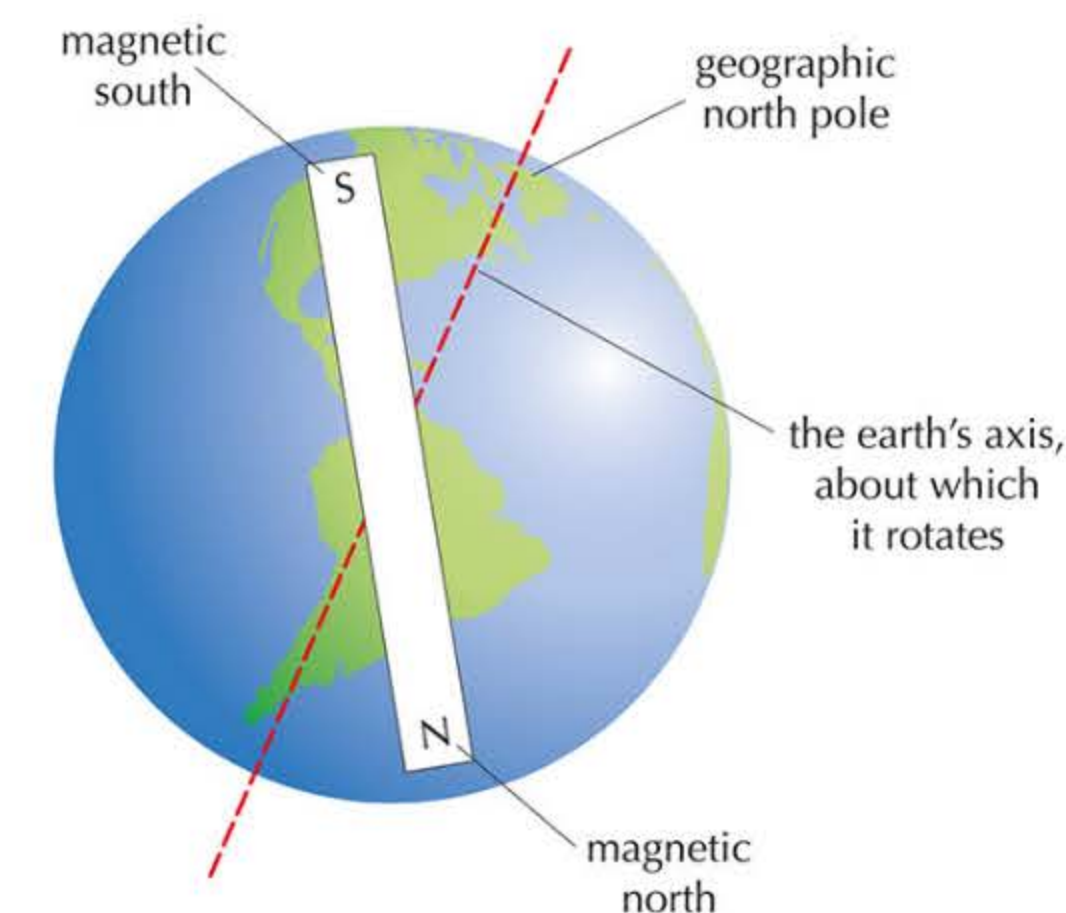
no current flows
Reverse bias

STS

One use of a diode is what we call **rectification**. That is the conversion of ac to dc. The diode blocks the current flow in one direction allowing it through only when it is in forward bias. The current is not constant, but it is only flowing in one direction and is therefore dc. A **light dependent resistor (LDR)** is a semiconductor in which the resistance is large in the dark and low in light. They are used in automatic street lights. **Thermistors** are semiconductors in which the resistance is controlled tightly by the temperature. Any increase in temperature creates a large decrease in resistance.

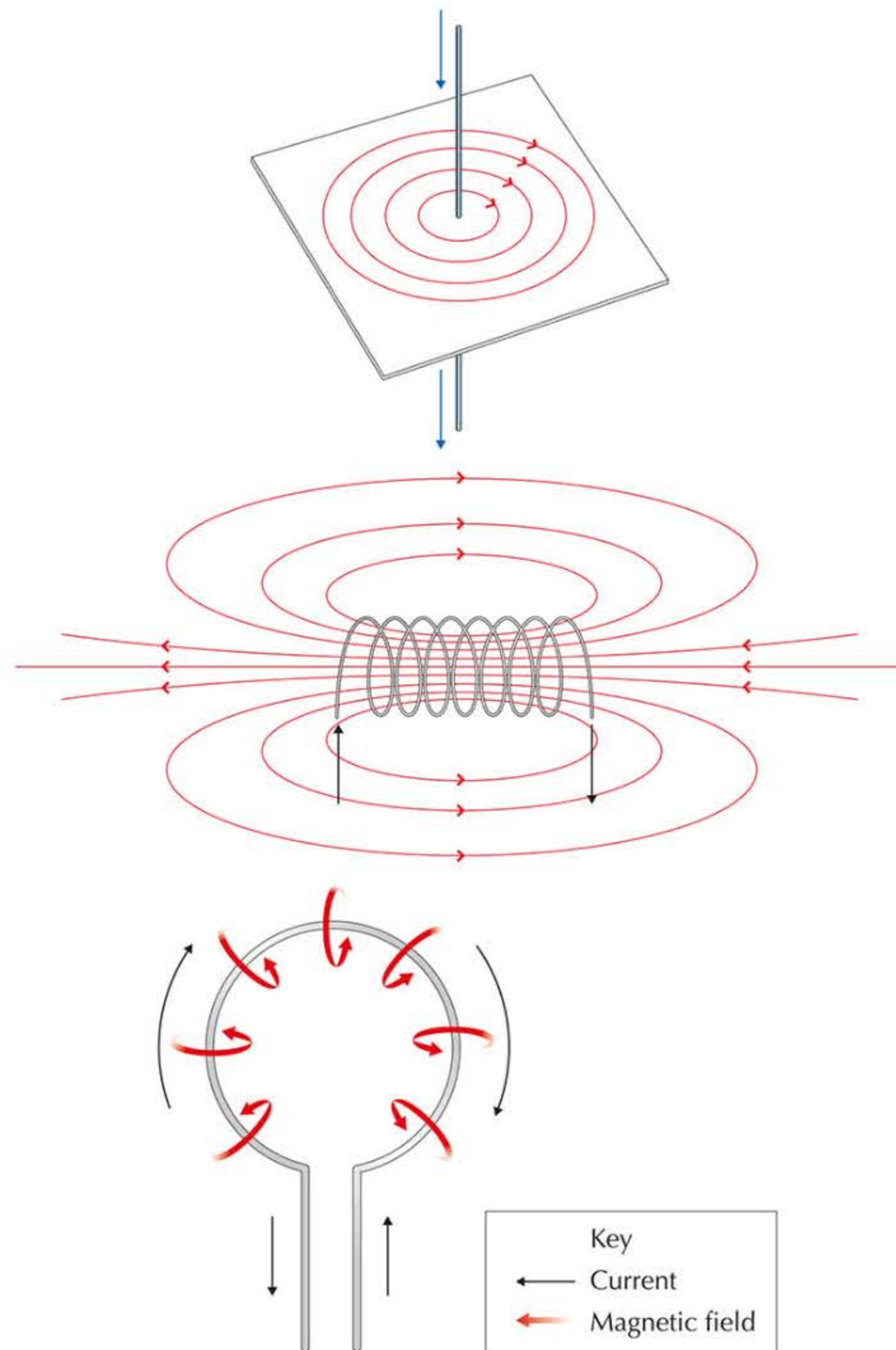
Electricity and magnetism

- All magnetism is created by the movement of electric charges.
- All permanent magnets are made from **nickel, cobalt, iron** or alloys that contain these elements. They can be magnetised because of the arrangements of electrons inside their atoms.
- Other materials can be magnetised by electric currents; we call these **electromagnets**.
- There are **north** and **south magnetic poles**. Like poles repel each other, opposite poles attract.
- 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 north, and the other, the south pole (S), pointing to the south. This is due to the earth's magnetic field. The earth acts as if there was a large bar magnet at its centre.



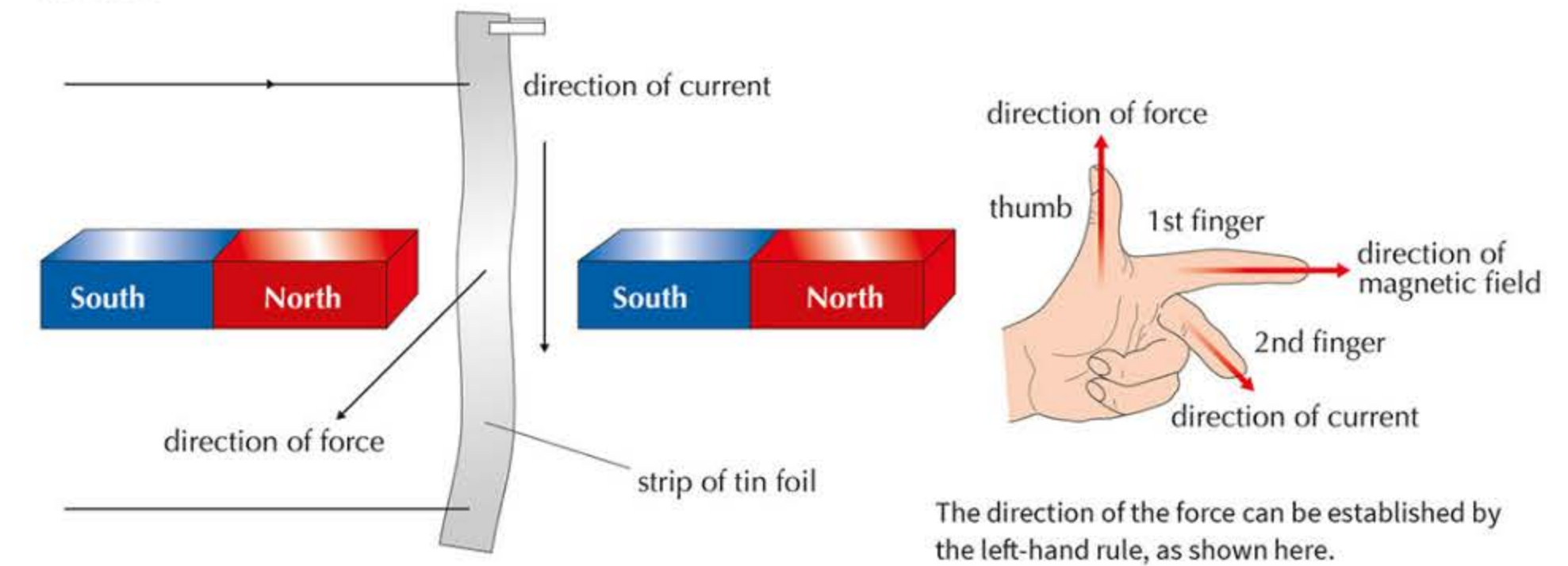
- As a compass needle will always point towards the north, it follows that the earth's magnetic field acts as if the south pole of a magnet was at the north pole, and vice versa.
- A **magnetic field** is the area around a magnet where its effect can be measured. As it has both strength and direction, it is obviously a **vector** quantity.
- Magnetic field lines are drawn pointing from north to south.
- Magnetic fields can be demonstrated with iron filings, or with plotting compasses.

All electrical currents create a magnetic field. The shapes of some important arrangements are shown here.



A current-carrying conductor in a magnetic field experiences a force

A strip of tin foil that carries a current in a magnetic field can be used to demonstrate that a current-carrying conductor in a magnetic field experiences a force.



The strength of the force F depends on the current I the length of the wire l and the strength of the magnetic field B , i.e. $F = BIl$

The magnetic flux density (B) can be defined using this formula.

Magnetic flux density is the force experienced by a conductor of length 1 m carrying a current of 1 A at right angles to the field. Its direction is the direction of the magnetic field lines.

$$B = \frac{F}{Il}$$

The ampere

The phenomenon described above also leads us to a definition of the ampere.

The ampere is that current which, if maintained in two infinitely long parallel wires of negligible cross-section placed one metre apart in a vacuum, would produce between the wires a force of 2×10^{-7} newtons per metre length of the wire.

A similar force exists on a positive charge, q , moving through a magnetic field at velocity v . We can say that the current in this case is the quantity of charge passing any point per second, $\left(I = \frac{q}{t}\right)$, and the effective length of the charge in the magnetic field is given by $l = vt$.

HL Substituting into $F = BIl$
 Gives $F = B \frac{q}{t} vt$
 $\Rightarrow F = qvB$

A positive charge obeys the left-hand rule. A negative charge will not, but will move in the opposite direction. Any single charge experiencing such a force will move in a spiral.

Electromagnetic induction

Electromagnetic induction is best described by Faraday's and Lenz's laws.

Faraday's laws

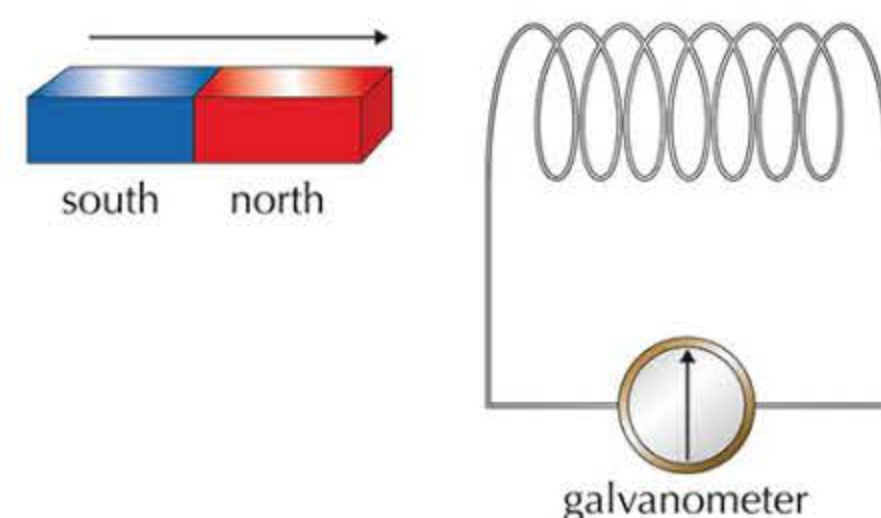
When there is a change in the magnetic flux linking a coil, an emf is induced in that coil. The strength of the emf is proportional to the rate of change of the flux linking the coil.

Lenz's law

The direction of an induced current is such as to oppose the change causing it.

Experiment

To demonstrate Faraday's laws



Method Set up the apparatus as shown. As the magnet is moved towards the coil, a current flows (which can be seen with the galvanometer). The faster the magnet moves, the greater the current.

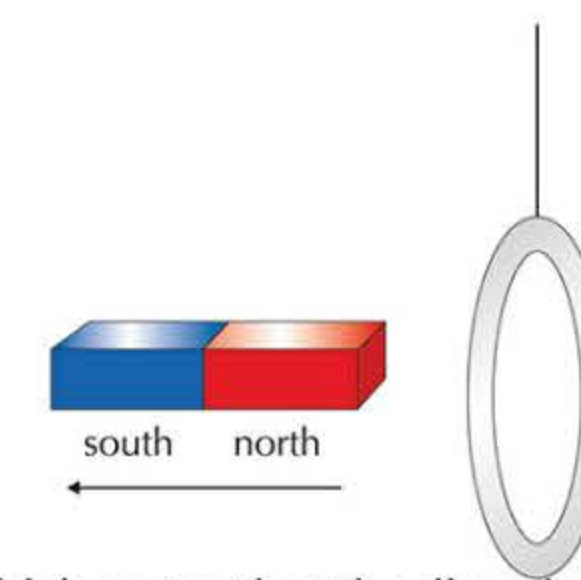
Conclusion This confirms Faraday's law. If the magnet is moved away from the coil, the current changes direction, demonstrating Lenz's law.

Experiment

To demonstrate Lenz's law

Method

A light aluminium ring is suspended from a long thread as shown in the diagram. When a strong magnet is moved away from it, the ring follows the magnet. When the magnet moves towards it, the ring moves away from the magnet.



Conclusion

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.

Mathematically, induction can be described using the formula:

$$E = n \frac{\text{change in flux}}{\text{time}}$$

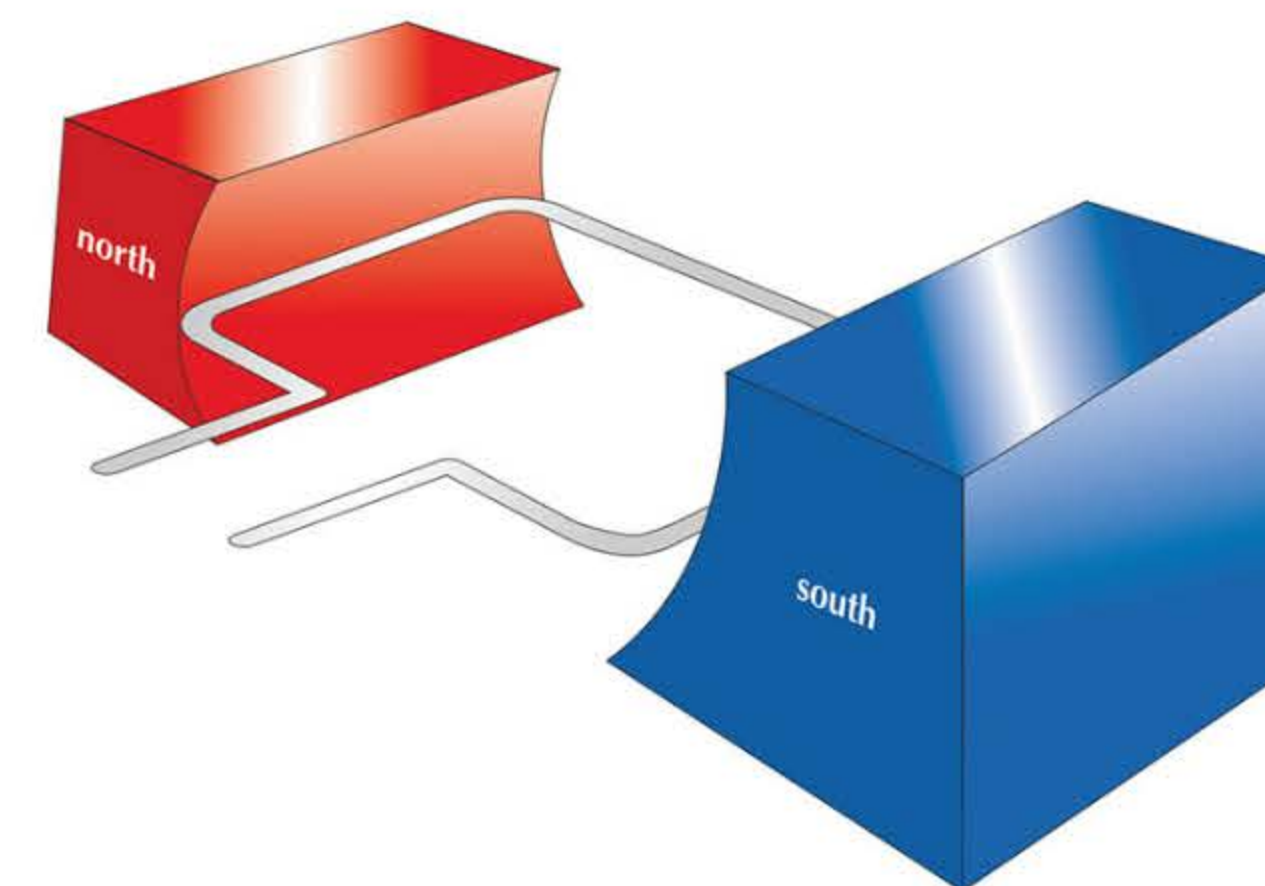
where E = induced voltage

n = number of turns in a coil

The flux, ϕ , can be found using the formula $\phi = BA$

STS

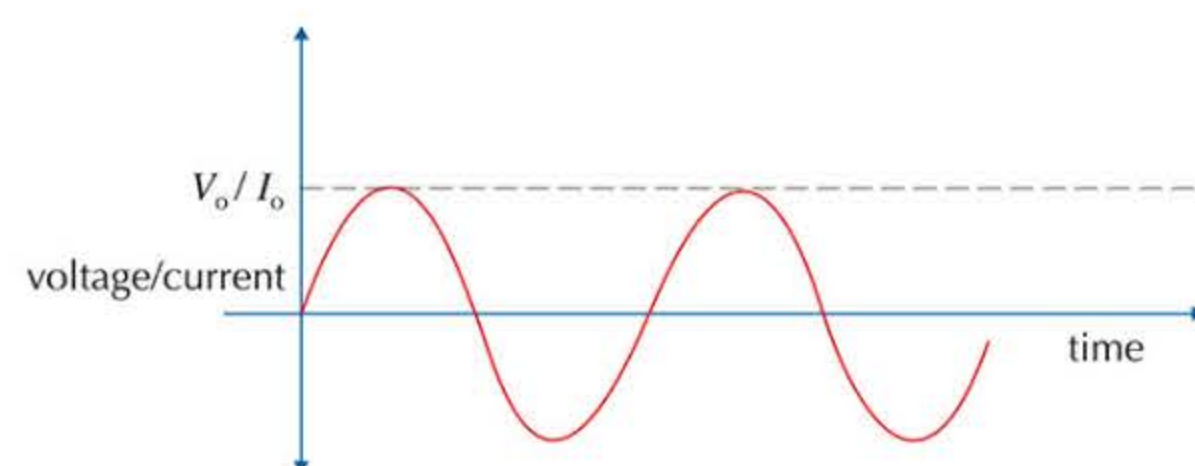
In an **ac generator**, a magnet is constantly turned near to a coil of wire (or vice versa) and an emf is set up. This emf will constantly change direction, thus creating a current that constantly changes direction. This is an alternating current, or ac.



Rms value

The effective value of an alternating current (that is the direct current that would have a similar effect) is known as the **Rms** value. The same can be done for a voltage.

$$I_{\text{rms}} = \frac{I_0}{\sqrt{2}} \quad V_{\text{rms}} = \frac{V_0}{\sqrt{2}}$$

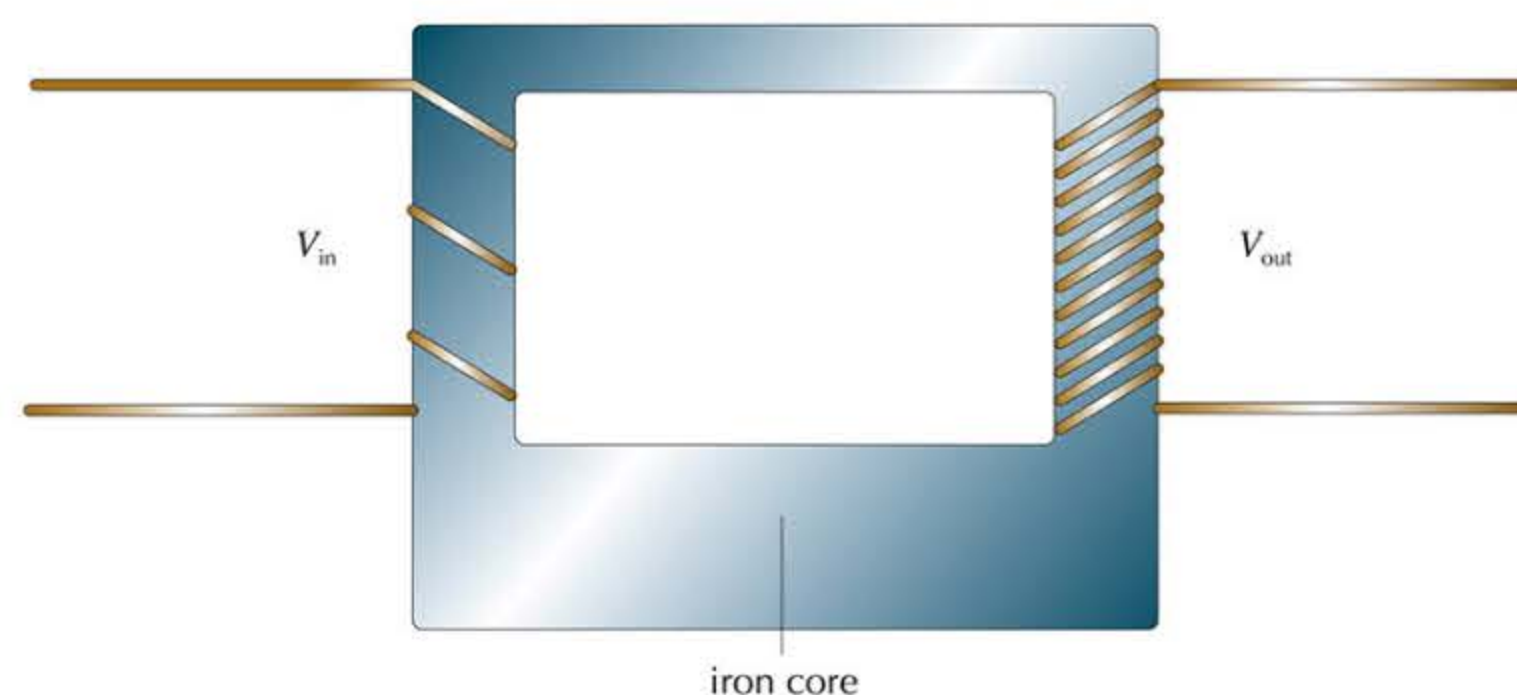


Mutual induction

As all electrical currents create magnetic fields, an alternating current can create a changing magnetic field, an effect similar to that of spinning a magnet. Because of this, when two coils are side by side, a changing current in one will induce a similar changing current (and emf) in the other. This is known as **mutual induction**.

STS

We make use of this fact in a **transformer**. The ac in the first, or primary, coil creates a changing magnetic field and therefore an emf in the secondary coil. The voltage can either be increased (a step-up transformer) or reduced (stepped down). This is controlled by the relative number of turns in the primary (N_p) and the secondary (N_s).



$$\frac{N_p}{N_s} = \frac{V_{\text{in}}}{V_{\text{out}}}$$

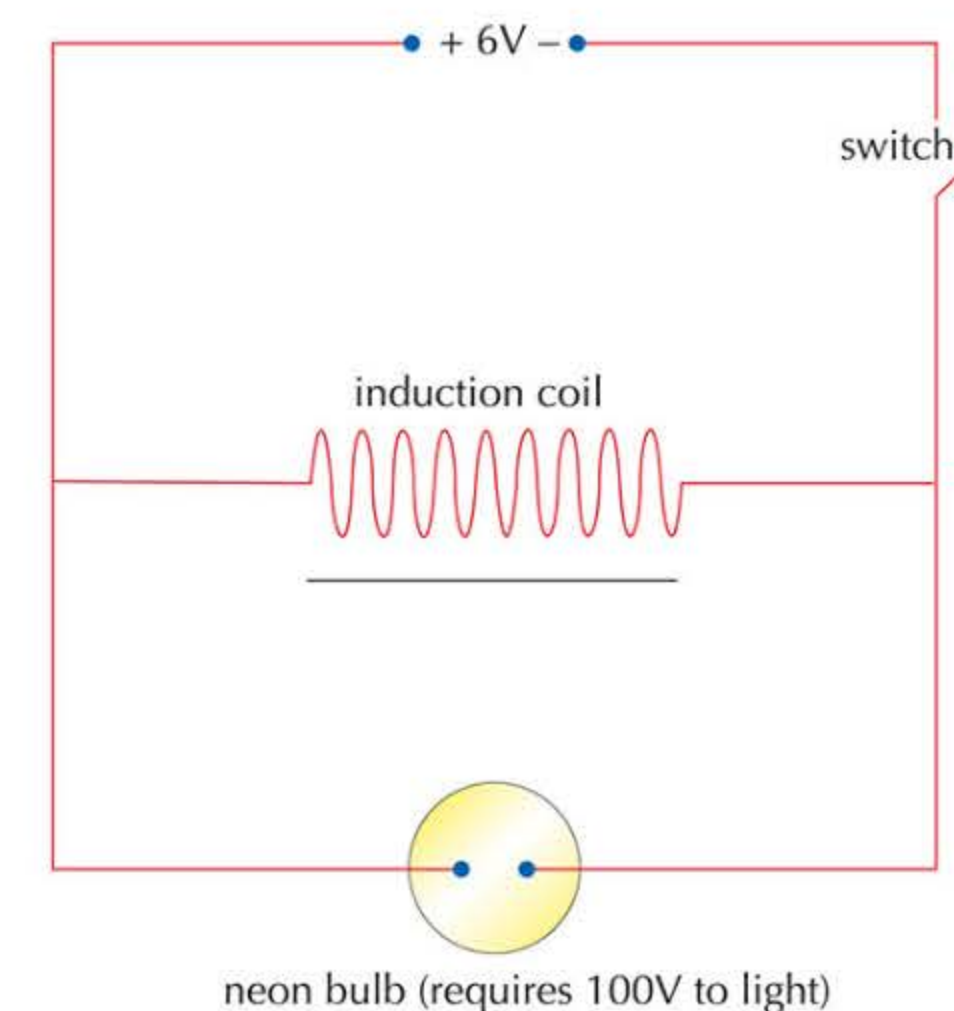
If there are no energy losses between the primary and secondary, the following formula also applies:

$$(VI)_{\text{primary}} = (VI)_{\text{secondary}}$$

Self-induction

If an alternating current is flowing through a coil, the coil will be surrounded by a constantly changing magnetic field. This will create an emf in the coil according to Faraday's laws. According to Lenz's law the induced emf will oppose the change. This is **self-induction**. Its significance is that, with an alternating current, a coil acts as a resistor, reducing the current that flows through it.

It can be demonstrated with a circuit like the one in the diagram below.



When the switch is closed we see nothing: the voltage is insufficient to light the bulb. But when the switch is opened and the circuit is broken, the bulb lights up for a moment.

This is because:

- The current through the coil creates a magnetic field
- When the current falls to zero, the magnetic field disappears as well; the coil therefore is in the centre of a changing magnetic field
- The changing magnetic field induces a voltage sufficiently large to light the bulb.

Sample answer

Leaving Certificate, 2008, Higher Level, Section B, Q8

What is electromagnetic induction? (6 marks)

When the magnetic flux passing through a coil changes, an emf is induced in the loop. (3, 3)

State the laws of electromagnetic induction. (12 marks)

Faraday's law states that the magnitude of the induced emf is proportional to the rate of change of flux. (3, 3)

Lenz's law states that emf is created in such a direction as to oppose the change that causes it. (3, 3)

A bar magnet is attached to a string and allowed to swing as shown in the diagram. A copper sheet is then placed underneath the magnet. Explain why the amplitude of the swings decreases rapidly. (12 marks)

Electromagnetic induction occurs and an emf is induced in the copper. (3)

The emf causes a current to flow, which generates a magnetic field. (3, 3)

According to Lenz's law, this field will oppose the motion of the magnet, causing the amplitude of its swings to decrease. (3)

What is the main energy conversion that takes place as the magnet slows down? (6 marks)

The kinetic energy of the motion is converted into both heat and electrical energy in the copper sheet. (3, 3)

A metal loop of wire in the shape of a square of side 5 cm enters a magnetic field of flux density 8 T. The loop is perpendicular to the field and is travelling at a speed of 5 m s⁻¹.

(i) How long does it take the loop to completely enter the field? (6 marks)

$$\begin{array}{lcl}
 s = 0.05\text{m} & s = ut + \frac{1}{2}at^2 & \begin{array}{c} \times \times \times \times \times \\ \times \times \times \times \times \\ \times \times \times \times \times \\ \times \times \times \times \times \\ \times \times \times \times \times \\ \text{Flux density 8T} \end{array} \\
 a = 0 & 0.05 = 5t + \frac{1}{2}(0)t^2 & \begin{array}{c} \leftarrow 5\text{ m/s} \\ \square \\ \rightarrow 5\text{ cm} \end{array} \\
 u = 5 & t = \frac{0.05}{5} = 0.01\text{s} & \end{array}$$

(ii) What is the magnetic flux cutting the loop when it is completely in the magnetic field? (14 marks)

$$\begin{aligned}
 \Phi &= BA & (4) \\
 &= (8)(0.05)^2 = 0.02\text{ Wb} & (3)
 \end{aligned}$$

(iii) What is the average emf induced in the loop as it enters the magnetic field?

$$\begin{aligned}
 \text{emf} &= \frac{\Delta\Phi}{t} \quad (\Delta\Phi = \text{change in flux}) & (4) \\
 &= \frac{0.02 - 0.0}{0.01} & \\
 &= 2\text{ V} & (3)
 \end{aligned}$$

Exam questions

1 2007, HL, Section B, Q12 (c)

State Faraday's law of electromagnetic induction. (6 marks)

Describe an experiment to demonstrate Faraday's law. (12 marks)

A resistor is connected in series with an ammeter and an ac power supply.

A current flows in the circuit. The resistor is then replaced with a coil. The resistance of the circuit does not change. What is the effect on the current flowing in the circuit? Justify your answer. (10 marks)

2 2008, HL, Section B, Q7

Define resistivity and give its unit of measurement. (9 marks)

An electric toaster heats bread by convection and radiation.

What is the difference between convection and radiation as a means of heat transfer? (8 marks)

A toaster has a power rating of 1050 W when it is connected to the mains supply. Its heating coil is made of nichrome and it has a resistance of 12 Ω. The coil is 40 m long and it has a circular cross-section of diameter 2.2 mm.

Calculate:

- the resistivity of nichrome;
- the heat generated by the toaster in 2 minutes if it has an efficiency of 96%. (18 marks)

The toaster has exposed metal parts. How is the risk of electrocution minimised? (9 marks)

When the toaster is on, the coil emits red light. Explain, in terms of movement of electrons, why light is emitted when a metal is heated. (12 marks)

3 2008, HL, Section B, Q12 (d)

Define capacitance. (6 marks)

Describe how an electroscope can be charged by induction. (10 marks)

How would you demonstrate that the capacitance of a parallel plate capacitor depends on the distance between its plates? (12 marks)

9 Modern Physics

Learning objectives

In this chapter you will learn about:

- 1 Cathode ray tube (CRT)
 - Properties of a cathode ray
- 2 X-rays
 - Properties of X-rays
- 3 The photoelectric effect
- 4 Nuclear physics
 - The atom
 - Spectra
 - How to detect radioactivity
 - The law of radioactive decay
- 5 Nuclear fission
- 6 Nuclear fusion

Key definitions relevant to this chapter

Thermionic emission

Photoelectric effect

Radioactivity

Law of radioactive decay

The becquerel

Nuclear fission

Nuclear fusion

Key formulae

Energy of a photon $E = hf$

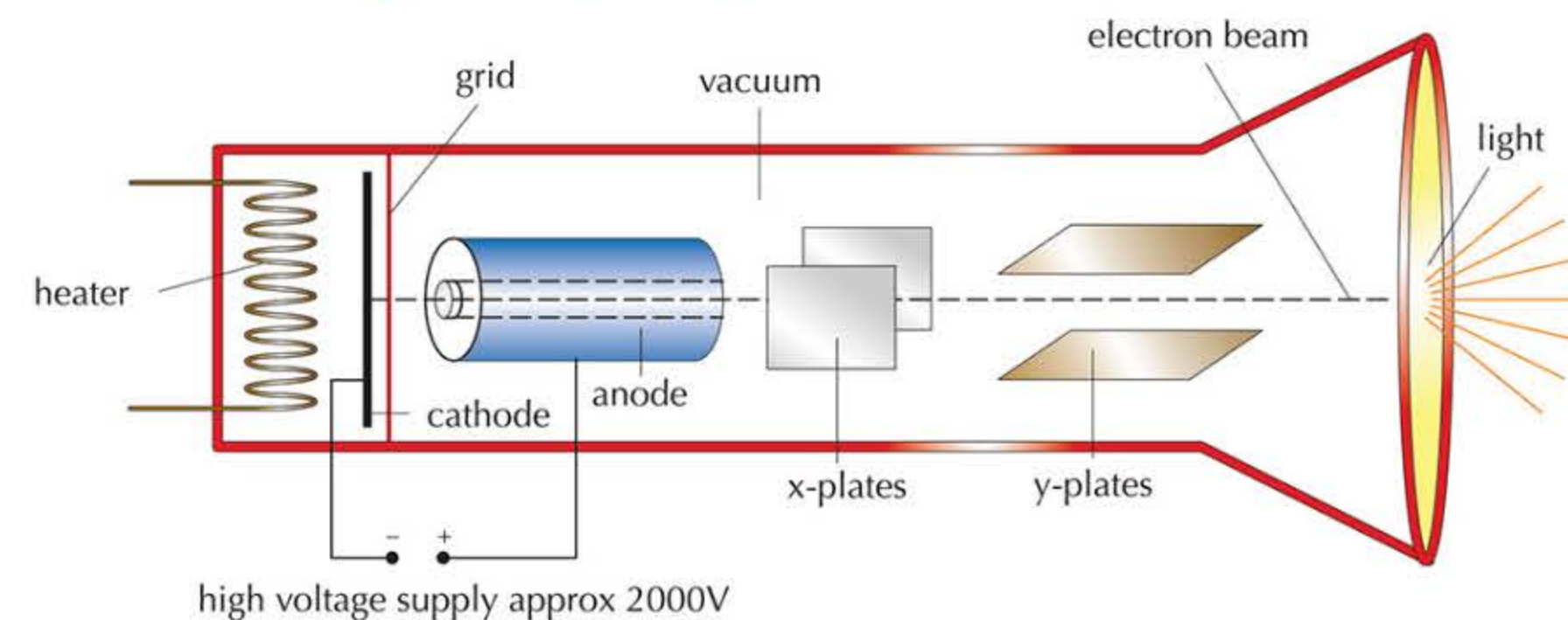
Einstein's photoelectric law $hf = \Phi + \frac{1}{2}mv^2$

Law of radioactive decay rate of decay = λN

Half-life $T_{\frac{1}{2}} = \frac{\ln 2}{\lambda}$

Mass-energy equivalence $E = mc^2$

Cathode ray tube (CRT)



- Thermionic emission occurs at the cathode.
- The electrons are accelerated towards the anode, but most overshoot and continue in a straight line, as shown.
- They strike the screen, producing a spot of light at its centre.
- The **potential**, and **shape**, of the **anodes** controls the **focusing of the spot**.
- The **beam** can be **deflected** by the **x-** or **y-plates**.
- The **brightness** is **controlled** by the **grid**. It is negative with respect to the cathode. The more negative it is, the more electrons are repelled back towards the cathode, and the fewer electrons there are to strike the screen.

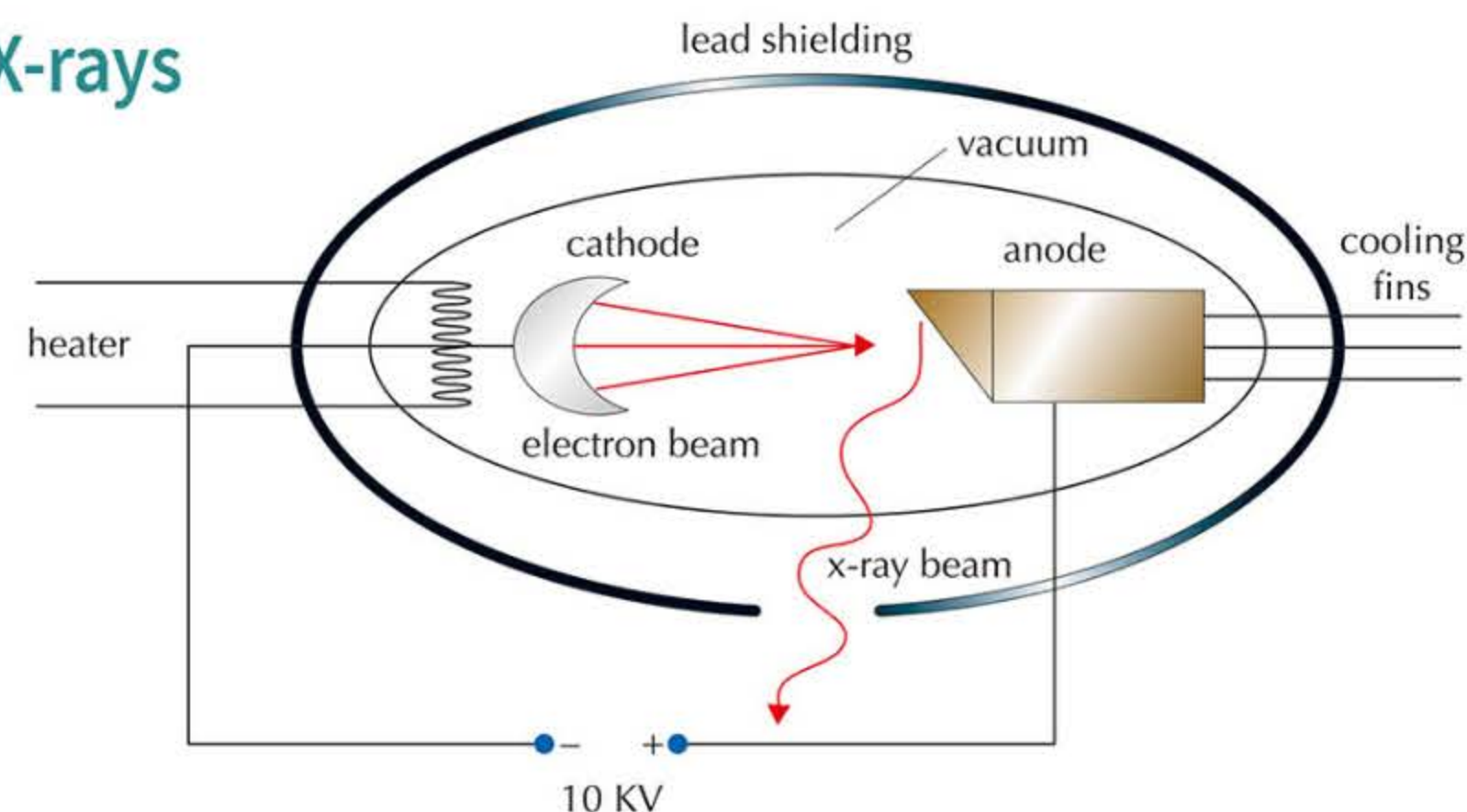
Remember

Thermionic emission is the emission of electrons from the surface of a hot metal.

Properties of a cathode ray

- They consist of electrons travelling at high speed.
- They travel in straight lines from the cathode to the anode.
- They cause certain substances to **fluoresce** (give out light) when struck.
- They have kinetic energy.
- They can be deflected by electric and magnetic fields.

X-rays



- A very high voltage accelerates the electrons to a high speed.
- When they strike the tungsten target, their kinetic energy is absorbed by the anode.
- Most of this energy (99%) becomes heat energy, which is dispersed using some cooling system.
- A small amount of the electrons' energy (1%) is absorbed by individual atoms, which then re-emit this energy in the form of X-rays.

Properties of X-rays

- They are electromagnetic radiation, of very high energy.
- They pass through many materials, such as skin and muscle tissue.
- They will not pass through more dense material such as bone.
- They affect photographic film.

STS

X-rays, which were discovered by Röntgen, can be used to 'photograph' inside the human body, and can also be used in a similar way to search for structural flaws in the construction industry. As X-rays are ionising radiation they can cause severe burns to human tissue, and increase the risk of cancer developing. We can protect ourselves from them by using lead plates. However, this ionising ability can be utilised in a positive manner to kill cancerous cells.

In both X-ray machines and the CRT, the kinetic energy gained by the electron as it crosses the tube is given by:

$$E_k = QV \quad (\text{from the formula } W = QV)$$

where Q = charge on the electron
 V = voltage between cathode and anode

Sample answer

Leaving Certificate, 2010, Higher Level, Section B, Q9

What is thermionic emission?

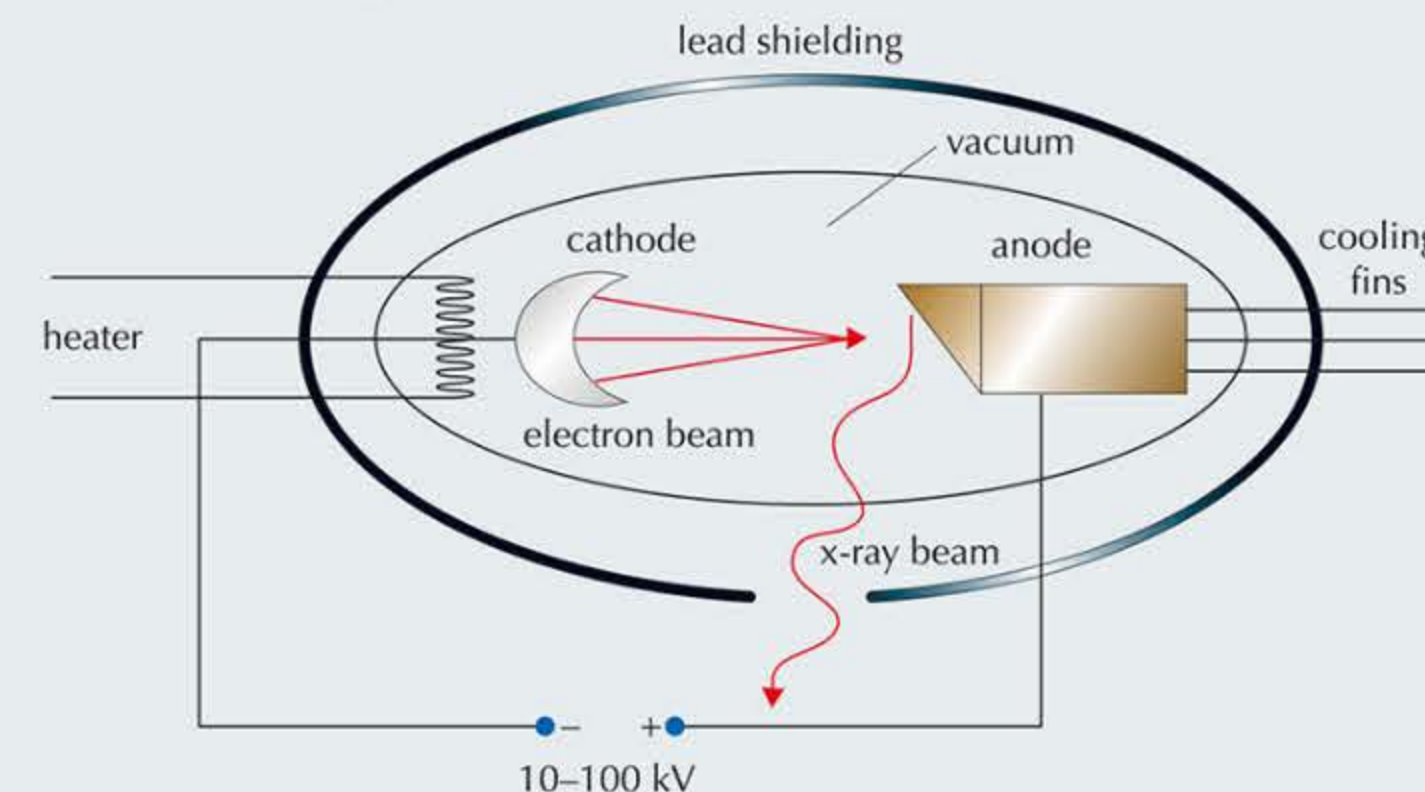
(6 marks)

Thermionic emission is the emission of electrons from the surface of a hot metal. (3, 3)

X-rays are produced when high-energy electrons collide with a target.

Draw a labelled diagram of an X-ray tube.

(12 marks)



What are X-rays and how do they differ from light rays?

(12 marks)

X-rays are electromagnetic radiation of high frequency.

(6)

They differ from light rays in that

- They have higher frequency (3)
- They can penetrate many low-density materials (e.g. flesh). (3)

Give two uses of X-rays.

(6 marks)

X-rays are used for diagnosis in medicine. They penetrate low-density material (flesh, muscle) but not high-density material (bone). They also affect photographic plates, allowing them to be used to essentially 'photograph' our bones. (3)

X-rays are also ionising radiation, and as such they have a tendency to cause cancer in those who are exposed to them.

Conversely, they can be focused onto already cancerous growths to either kill, or limit the development of, that growth. (3)

When electrons hit the target in an X-ray tube, only a small percentage of their energy is converted into X-rays. What happens to the rest of their energy and how does this influence the type of target used? (9 marks)

The rest of the energy is converted into heat energy in the target. Obviously this causes it to become very hot, and consequently this means that material of high melting point (such as tungsten) must be chosen for the target. (9)

A potential difference (voltage) of 40 kV is applied across an X-ray tube

Calculate:

- (i) the maximum energy of an electron as it hits the target (5 marks)

energy W : $W = QV$ (3)

$$= (1.6 \times 10^{-19})(40 \times 10^3)$$

$$= 6.4 \times 10^{-15} \text{ J} \quad (2)$$

- (ii) the frequency of the most energetic X-ray produced. (6 marks)

$$E = hf \quad (3)$$

$$\Rightarrow f = \frac{E}{h} = \frac{6.4 \times 10^{-15}}{6.6 \times 10^{-34}} = 9.7 \times 10^{18} \text{ Hz} \quad (3)$$

Exam question

2006, HL, Section B, Q12 (d)

The first Nobel Prize in Physics was awarded in 1901 for the discovery of X-rays. What are X-rays? Who discovered them? (9 marks)

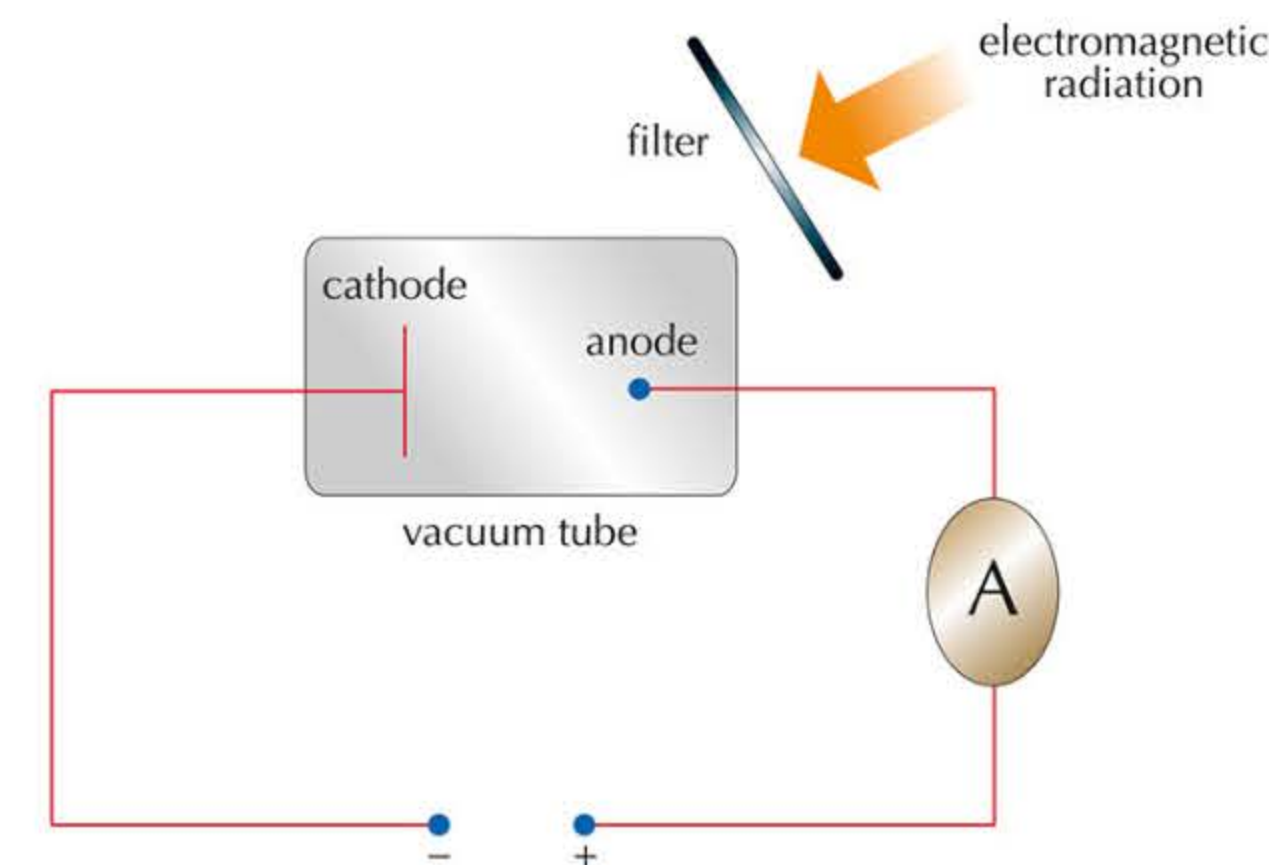
In an X-ray tube electrons are emitted from a metal cathode and accelerated across the tube to hit a metal anode. How are the electrons (i) emitted from the cathode; (ii) accelerated? (6 marks)

Calculate the kinetic energy gained by an electron when it is accelerated through a potential difference of 50 kV in an X-ray tube. Calculate the minimum wavelength of an X-ray emitted from the anode. (Planck constant = $6.6 \times 10^{-34} \text{ J s}$; speed of light = $3.0 \times 10^8 \text{ m s}^{-1}$; charge on electron = $1.6 \times 10^{-19} \text{ C}$) (13 marks)

The photoelectric effect

The **photoelectric effect** is the emission of electrons from a metal, caused by the incidence of electromagnetic radiation of suitable frequency. The photoelectric effect was first noticed in 1888. It was noticed that UV light shining on a negatively charged electroscope caused it to lose its charge.

The same effect was not found with a positively charged electroscope. The effect can be studied more closely with the arrangement shown in the diagram at the top of the opposite page. Both frequency and intensity of incident radiation can be varied.



The following are the key points to note:

- Below a threshold frequency, f_0 , there is no current
- Above f_0 , increasing the frequency does not increase the current
- Above f_0 , the current does vary with the intensity (brightness) of the light.

In summary:

	Under f_0	Over f_0
	Current does not flow	Current does flow
Increasing frequency	No effect	No effect
Increasing intensity	No effect	Increases current

Einstein's explanation of the effect was that light consists of tiny particles, little bundles of energy called **photons**. The energy in each photon is given by:

$$E = hf$$

where f = frequency of light, h = Planck's constant.

- Each photon hits one electron, and gives its energy to that electron. If the photon contains sufficient energy, i.e. if it is above the threshold frequency (f_0), the electron can then escape from the metal and travel to the anode.
- As each photon can strike only one electron, increasing the energy (or frequency) of the photon does not increase the number of electrons released, and therefore does not affect the current. Any extra energy the photon has is given to the electron as **kinetic energy**.
- Only by increasing the number of photons, or the brightness/intensity of the light, can the number of electrons, and hence the current, be increased.

The formula Einstein used to describe this effect is:

$$E_{in} = \phi + E_k$$

where E_{in} = the energy of the incident photon

ϕ = the work function of the metal, the energy required for an electron to escape from the cathode

E_k = the kinetic energy of the electron once it has escaped.

Each of these terms can be expressed in other ways:

$$E_{in} = hf$$

$$\phi = hf_0$$

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

Einstein's theory does not contradict Young's experiment, which showed that light was a wave. Light is both a wave *and* a beam of particles. How it can be both is not something that anybody can really understand on an intuitive level, but it is well established. We refer to this as the **wave-particle duality** of light.

STS

Photoemission, in a circuit similar to that shown on the previous page is used in the light detectors operated by professional photographers, and in industry to count the number of items on a conveyor belt.

Exam question

2005, HL, Section B, Q12 (d)

One hundred years ago, Albert Einstein explained the photoelectric effect. What is the photoelectric effect?

(6 marks)

Write down an expression for Einstein's photoelectric law.

(9 marks)

Summarise Einstein's explanation of the photoelectric effect.

(9 marks)

Give one application of the photoelectric effect.

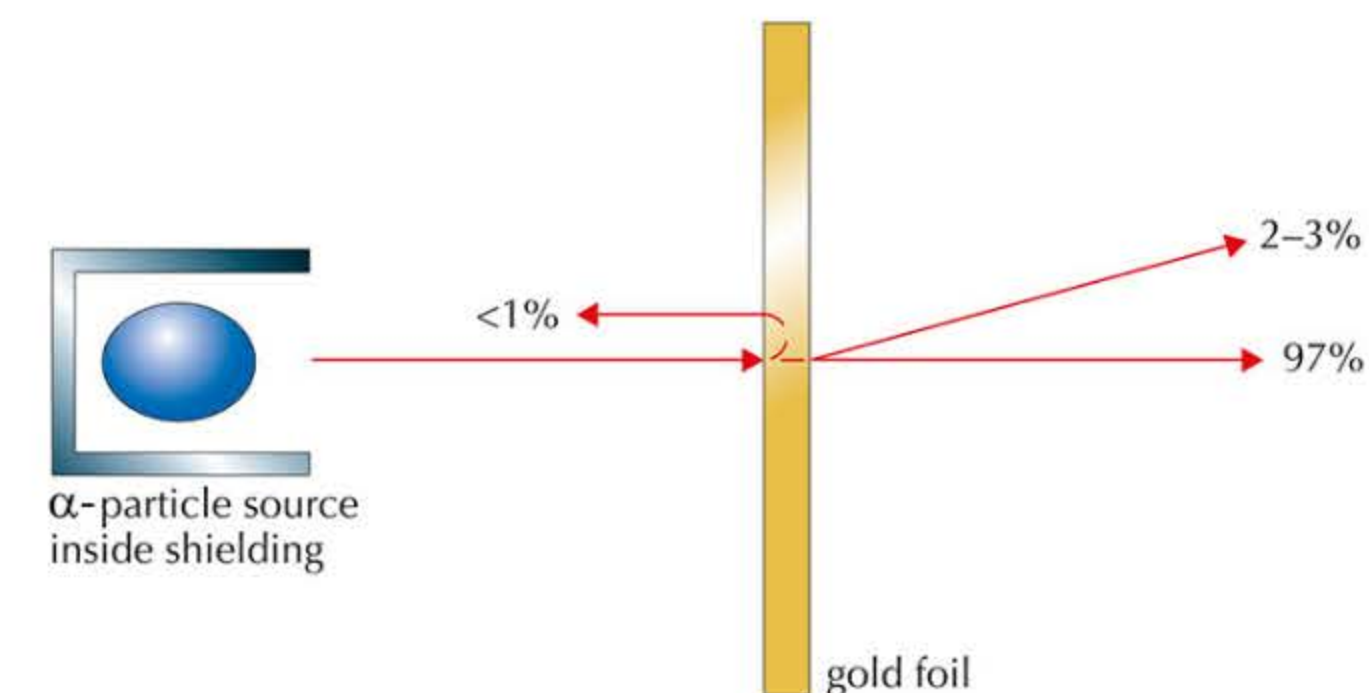
(4 marks)

Nuclear physics

The atom

At the end of the 1800s the common idea was that the atom consisted of a solid, positively charged sphere, into which electrons were imbedded, much as fruit is embedded in a plum pudding, which gave this picture of the atom its name, the plum pudding model. This idea was challenged by **Rutherford's gold foil**

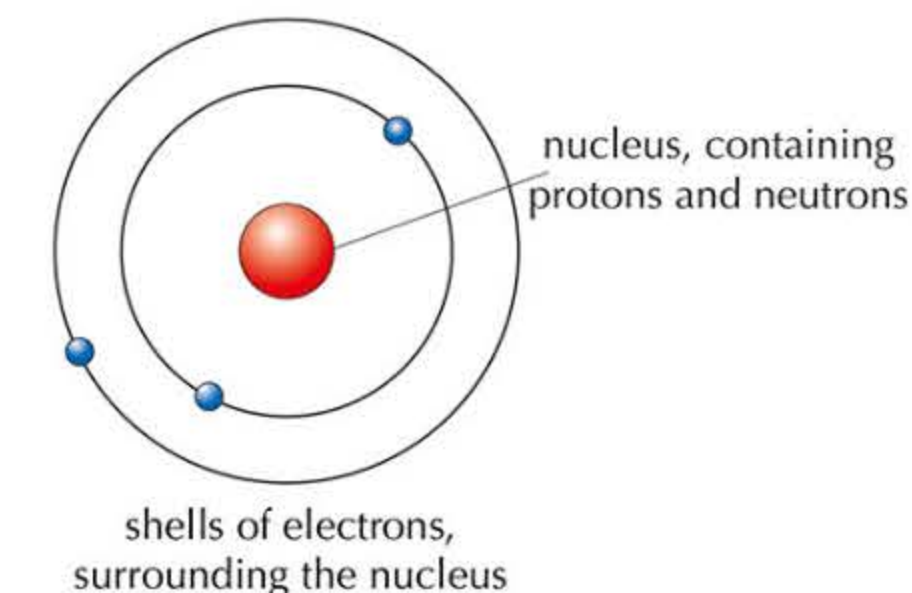
experiment. He fired a beam of alpha particles towards a thin sheet of gold. Alpha particles are small, positively charged particles. He chose gold because it can be pressed very thinly, so thin that it is only a few atoms from front to back.



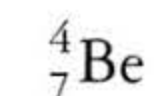
What Rutherford found was that most particles went through the foil, without damaging it. A small percentage was diverted as shown, while an even smaller percentage was repelled back towards the source.

This experiment gave rise to the idea of the **Rutherford-Bohr model of the atom**, with which we are already familiar. In this model:

- Most of the atom is empty space
- There is a positively charged nucleus, which contains the protons and neutrons
- The nucleus is surrounded by several 'shells' of negatively charged electrons.

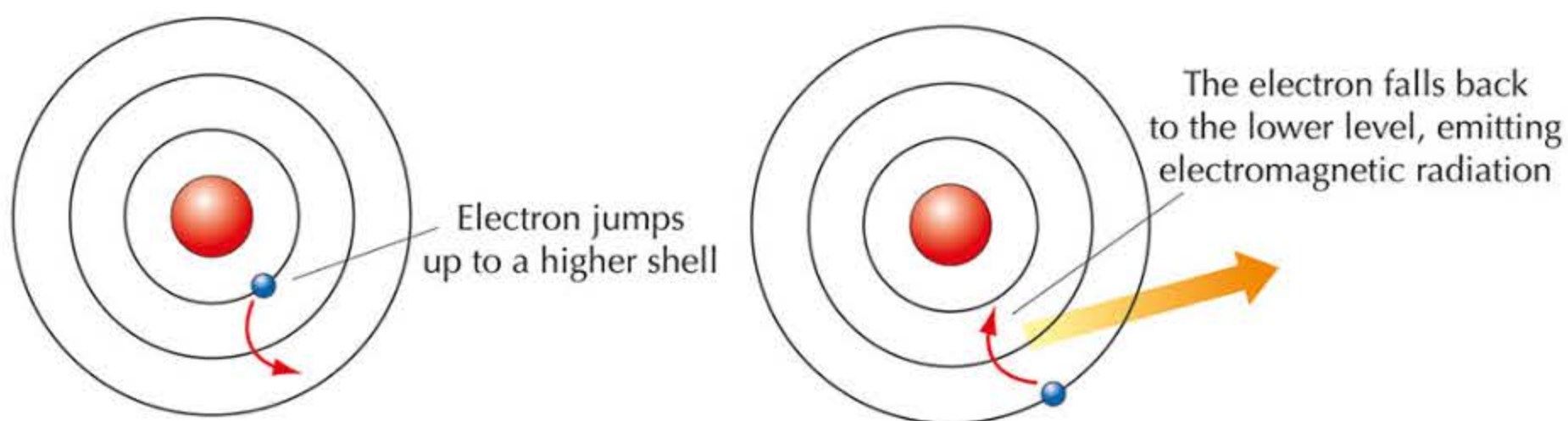


Each element is defined by its **atomic number**, which is the number of protons in the nucleus. The **mass number** tells us the total number of protons and neutrons in the nucleus; e.g. for beryllium, the atomic number is 4, indicating there are 4 protons, and the mass number is 7, indicating there are 3 neutrons alongside the 4 protons in the nucleus:



Spectra

In general in a neutral atom, the number of electrons is the same as the number of protons. The electrons are generally found in the lowest shell available, but if the element is given extra energy, for example as heat, an individual electron in an atom may gain this energy and use it to move to an outer shell. Later it is likely to fall back to the original shell, releasing the energy in the form of electromagnetic radiation.



The energy of the radiation released will vary according to which shells were involved. Energy corresponds to frequency and therefore to colour. For this reason, each element, when heated, will give out a very particular mix of colours, known as its spectrum.

Isotopes are atoms of the same element that have different numbers of neutrons and therefore different mass numbers.

Radioactivity is the emission of either particles or electromagnetic radiation from the nucleus of an atom. The main forms of radiation are: α -particles, β -particles, and γ -rays.

α -particles

These are the nucleus of a helium atom (2 protons and 2 neutrons). They are relatively big, and have a positive charge. They have very good ionising ability, but poor penetrating ability (a few cm in air). The emission of an α -particle reduces the atomic number by 2, and the mass number by 4.

β -particles

These are electrons. They are formed when a neutron divides in the nucleus to become a proton and an electron. They have good ionising ability and reasonably good penetrating power (30–40 cm in air, a few mm of aluminium). The emission of a β -particle increases the atomic number by 1.

γ -rays

This is high energy electromagnetic radiation. It is released because the protons and neutrons rearrange themselves inside the nucleus. It is poor at ionising, but has very good penetrating power. It can even pass through a few cm of lead. The emission of an γ -ray has no effect on the mass and atomic numbers.

In summary:

	Nature	Charge	Range	Ionising ability	Penetrating ability
α -particles	Helium nucleus	+	2–3 cm air	Best	Worst
β -particles	Electron	–	30 cm air		
γ -rays	EM radiation	0	Thick lead	Worst	Best

Remember

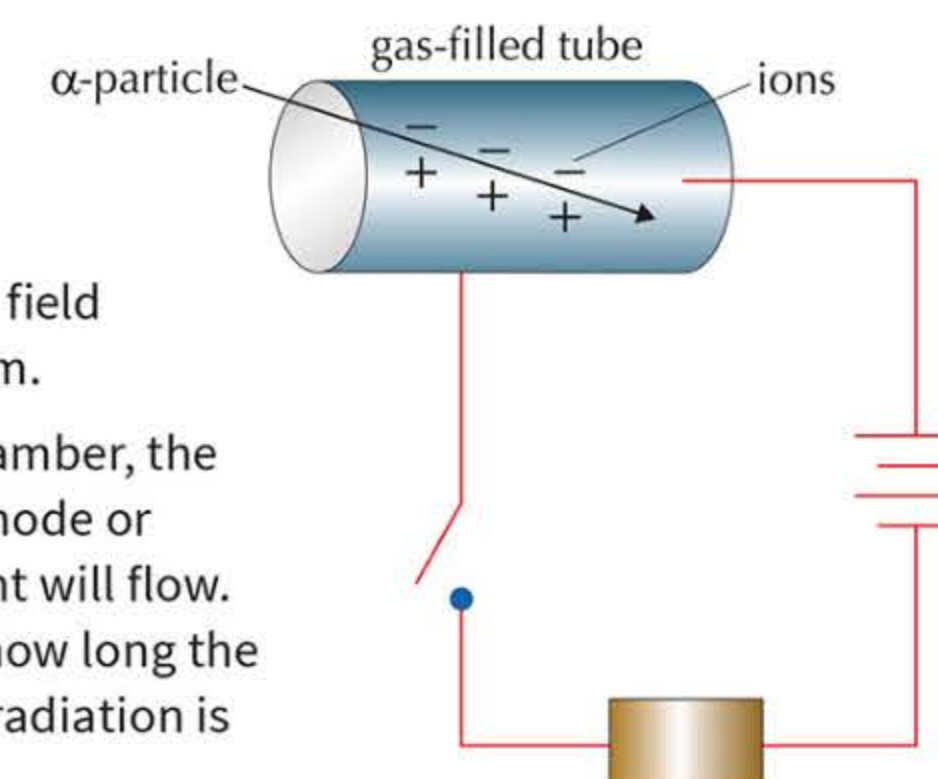
Ions are atoms that have either gained or lost electrons and are therefore either positively or negatively charged.

How to detect radioactivity

Geiger-Müller tube

A Geiger-Müller tube is a metal cylinder containing a mixture of argon and bromine at low pressure. An electric field exists in the tube as shown in the diagram.

If ionising radiation should enter the chamber, the ions it creates flow towards either the anode or cathode and for a few moments a current will flow. The counter can be used to register for how long the current flows, and therefore how much radiation is present.



The law of radioactive decay

The law of radioactive decay states that the number of disintegrations per second is proportional to the number of nuclei present (N).

$$\text{activity} = \lambda N$$

λ is known as the decay constant. A high value indicates a very radioactive material.

Radioactivity is often measured in terms of the half-life of an element. The half-life of an element is the time taken for half of the nuclei in any given sample to decay or the half-life of an element is the time taken for the activity of any given sample to decrease to half its original value.

The half-life is related to the decay constant by the formula:

$$T_{\frac{1}{2}} = \frac{\ln 2}{\lambda}$$

The unit of activity is the **becquerel**. One becquerel is defined as the disintegration of one nucleus per second.

STS

Radioactivity has many effects, some of which are dangerous to us and some of which are positive. The ionising effect of radioactivity causes damage to human cells and can lead to cancer. Exposure to radon gas, which is an alpha-emitter, is a major cause of lung cancer in Ireland. On the other hand, radioactivity can be used to treat cancer. In order to avoid causing cancer while trying to cure it, the treatment is usually administered in several small doses.

Exam question

2003, HL, Section B, Q11

Read the following passage and answer the accompanying questions.

Irish Times: Monday, January 11, 1999.

Radioactive decay helps to determine exact dates.

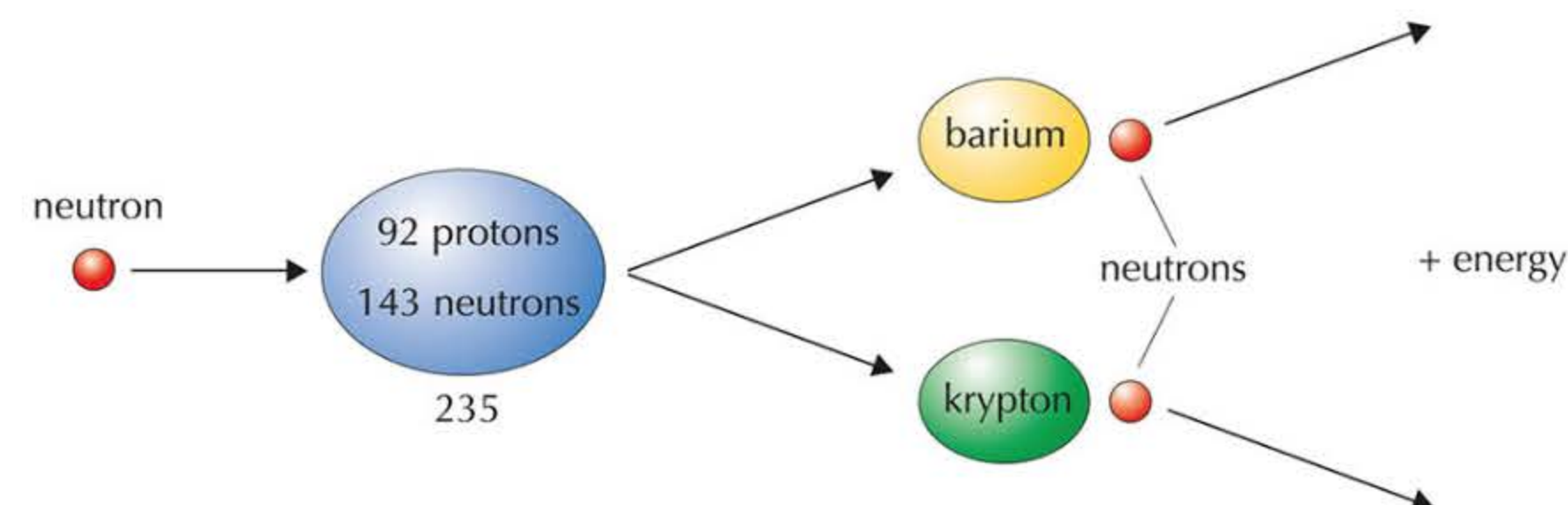
Radioactive decay occurs with such precision that it is often used as a clock. Carbon dating has been invaluable to archaeologists, historians and anthropologists. The method is based on the measurement of ^{14}C , a radioactive isotope of carbon with a half-life of 5730 years. ^{14}C occurs to a small extent in the atmosphere together with the much more common ^{12}C . Living

organisms constantly exchange carbon with the atmosphere and the ratio of ^{14}C to ^{12}C in living tissue is the same as it is in the atmosphere. This ratio is assumed to have remained the same since prehistoric times. When an organism dies, it stops exchanging carbon with the atmosphere, and its ^{14}C nuclei keep disintegrating while the ^{12}C in the dead tissue remains undisturbed.

- (a) What is radioactive decay? (7 marks)
- (b) What is an isotope? (7 marks)
- (c) Apart from 'carbon dating', give two other uses of radioactive isotopes. (7 marks)
- (d) How many neutrons are in a ^{14}C nucleus? (7 marks)
- (e) ^{14}C decays to ^{14}N . Write an equation to represent this nuclear reaction. (7 marks)
- (f) How much of a ^{14}C sample remains after 11 460 years? (7 marks)
- (g) Calculate the decay constant of ^{14}C . (7 marks)
- (h) Why does the ^{12}C in dead tissue remain 'undisturbed'? (7 marks)

Nuclear fission

Nuclear fission is the breaking up of a large nucleus into two smaller nuclei of similar size with the release of energy. Most uranium is U-238. A relatively rare isotope however is U-235. This isotope is the most important atom likely to undergo fission. When bombarded with neutrons, it splits in two to create barium and krypton, along with the release of two or three neutrons.

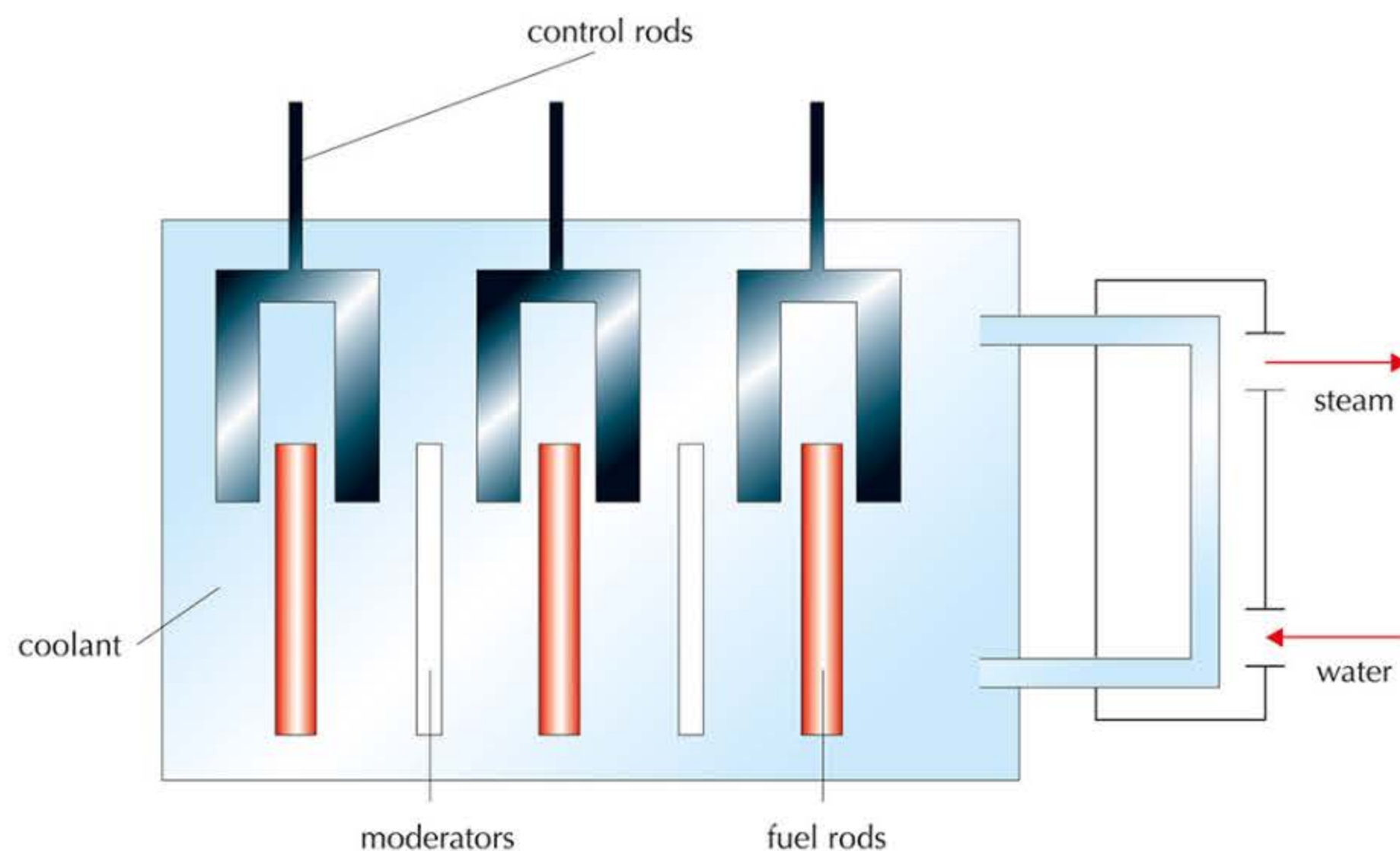


If on average one of these neutrons should go on to create fission in another atom, the reaction is sustained with the gradual release of energy. If, on the other hand, all two or three neutrons create fission in another atom, the reaction quickly escalates in what is known as a **chain reaction**. The amount of energy released is enormous. The difference is the difference between an atomic bomb and a nuclear power station.

When a piece of U-235 exceeds a particular mass, it is most likely that a chain reaction will occur. This mass, known as the **critical mass**, is about 10 kg.

STS

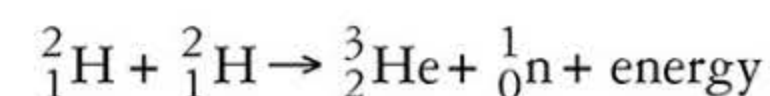
In a fission reactor, the **fuel rods are enriched uranium**, i.e. uranium that has extra U-235. The **control rods** are there to absorb neutrons, and thus control the speed of the reaction. The **moderators** slow down neutrons, as they are most efficient at creating fission when they are travelling slightly less than the speed at which they are emitted from the atom. The energy released turns water to steam, which drives the turbines.



Nuclear fusion

Nuclear fusion occurs when two small atomic nuclei join together to form a larger nucleus, accompanied by the release of large amounts of energy. It is the reaction that sustains the sun and other stars.

One form is the fusion of deuterium (${}^2_1\text{H}$) atoms (an isotope of hydrogen) to form helium.



As a source of energy fusion offers several advantages:

- We have a huge resource of fuel as the oceans are full of hydrogen
- There are no dangerous waste products
- A large amount of energy is released.

Unfortunately the reaction only takes place at extremely high temperatures ($>1,000,000\text{ K}$). Creating and sustaining these temperatures in a safe manner is very difficult.

Sample answer

Leaving Certificate, 2013, Higher Level, Q9

Define the becquerel. (6 marks)

The becquerel is defined as the decay of radioactive nucleus per second. (6)

Name one device used to detect ionising radiations. (3 marks)

The Geiger-Müller tube is used to detect radioactivity. (3)

Compare alpha, beta, and gamma emissions using the following headings:
(a) penetrating ability, (b) deflection in a magnetic field. (9 marks)

α -particles:

Their penetrating ability is the least of the radioactive emissions. They travel only about 2 cm through air. They can be blocked by thin sheets of paper.

They are positively charged, so they are deflected by electric fields in the way predicted by the left-hand rule. (3)

β -particles:

Their penetrating ability is moderate. They travel about 30 cm through air. They can be blocked by thin sheets of aluminium.

They are negatively charged, so they are deflected by electric fields, but in the opposite direction to that predicted by the left-hand rule. (3)

γ -rays:

Their penetrating ability is the greatest of the radioactive emissions. They can be blocked by thick sheets of lead or other dense materials.

They are not electrically charged, so they are not deflected by electric fields. (3)

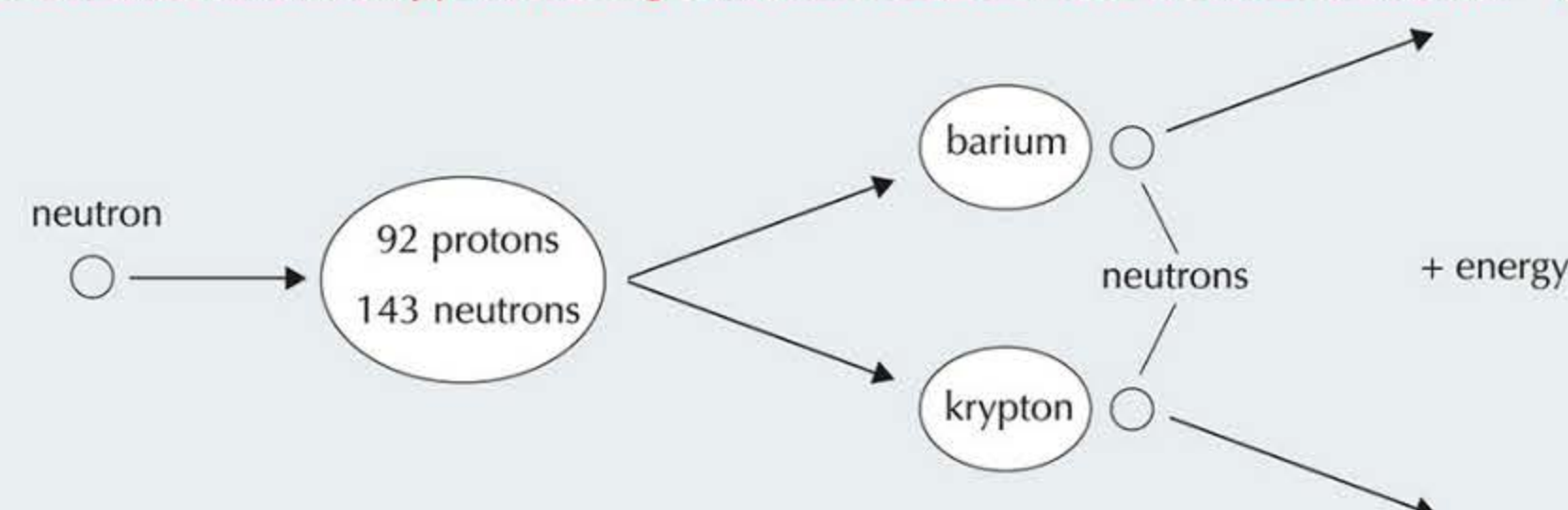
The photograph shows one of the nuclear reactors at Chernobyl, where there was a fire in April 1986 that released large quantities of radioactive contaminants. Among the contaminants were iodine-131 and caesium-137, which are two of the unstable isotopes formed by the fission of uranium-235.

Explain what happens during nuclear fission. (8 marks)

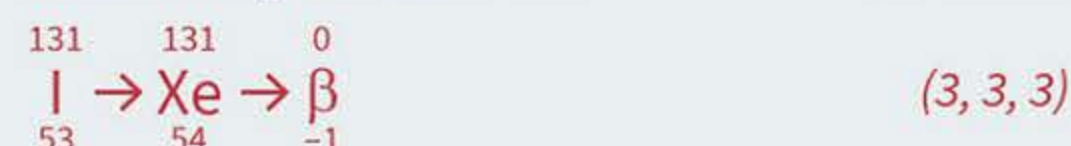


Nuclear fission is the breaking up of a large nucleus into two smaller nuclei of similar size, with the release of energy. (3, 3)

In the case of uranium-235, when bombarded with neutrons, it splits in two to create barium and krypton, along with the release of two or three neutrons. (2)



Iodine-131 decays with the emission of a beta-particle and has a half-life of 8 days. Write an equation for the beta-decay of iodine-131. (9 marks)



Estimate the fraction of the iodine-131 that remained after 40 days. (6 marks)

$$40 \text{ days} = 5 \times 8 \text{ days} = 5 \text{ half-lives} \quad (3)$$

After 5 half-lives the fraction of the original sample remaining will be:

$$\frac{1}{2^5} = \frac{1}{32} \quad (3)$$

Caesium-137 has a half-life of 30 years and it remains a significant contaminant in the region around Chernobyl. It is easily absorbed into the tissues of plants as they grow. Scientists collected a sample of berries growing near the abandoned power station. The activity of the sample was measured at 5000 Bq.

Calculate the decay constant of caesium-137. Hence calculate the number of caesium-137 atoms present in the sample. (You may assume that all of the activity was caused by caesium-137.) (15 marks)

The tables tell us $T_{\frac{1}{2}} = \frac{\ln 2}{\lambda}$

which we can rearrange to give: $\lambda = \frac{\ln 2}{T_{\frac{1}{2}}} \quad (3)$

$$= \frac{\ln 2}{(60 \times 60 \times 24 \times 365 \times 30)} = 7.327 \times 10^{-10} \text{ s}^{-1} \quad (3)$$

From the tables: activity = $(-\lambda)N$

The number of nuclei, N , is given by

$$N = \frac{\text{activity}}{\lambda} = \frac{5000}{7.327 \times 10^{-10}} = 6.824 \times 10^{12} \text{ nuclei} \quad (3, 6)$$

Exam question

2008, HL, Section B, Q11

Read the following passage and answer the accompanying questions.

The Miracle Year: 1905

"There is nothing new to be discovered in physics now," Lord Kelvin reportedly said in 1900. He was wrong.

Isaac Newton had laid the foundations of classical physics in the late seventeenth century. He developed laws that described a mechanical universe: a falling apple and an orbiting moon governed by the same rules of gravity, mass, force and motion. In the mid-1800s, Newtonian mechanics was joined by another great advance. Michael Faraday discovered the properties of electric and magnetic fields. James

Clerk Maxwell subsequently showed how changing electric and magnetic fields united to form electromagnetic radiation.

Physics was upended in the early twentieth century by Albert Einstein. In 1905 he devised a revolutionary quantum theory of light to explain the photoelectric effect, helped prove the existence of atoms, united the concepts of space and time, and produced science's best-known equation.

(Adapted from *"Einstein: His Life and Universe"*; Isaacson; 2007)

- The SI unit is named in honour of Lord Kelvin. What is the temperature of the boiling point of water in kelvin? (7 marks)
- Define the newton, the unit of force. (7 marks)
- A force of 9 kN is applied to a golf ball by a golf club. The ball and club are in contact for 0.6 ms. Using Newton's laws of motion, calculate the change in momentum of the ball. (7 marks)
- Name three different electromagnetic radiations. (7 marks)
- What is the photoelectric effect? (7 marks)
- Why was the quantum theory of light revolutionary? (7 marks)
- High-energy radiation of frequency $3.3 \times 10^{14} \text{ Hz}$ is used in medicine. What is the energy of a photon of this radiation? (7 marks)
- 100 MJ of energy are released in a nuclear reaction. Calculate the loss of mass during the reaction. (7 marks)

(Planck constant = $6.6 \times 10^{-34} \text{ J s}$; speed of light = $3.0 \times 10^8 \text{ m s}^{-1}$)

10 Option 1: Particle Physics

Learning objectives

In this chapter you will learn about:

Nuclear reactions

- The Cockcroft-Walton experiment
- Particle zoo
- Anti-matter
- The neutrino
- Quarks
- Fundamental forces

Nuclear reactions

In all nuclear reactions, the following will be observed:

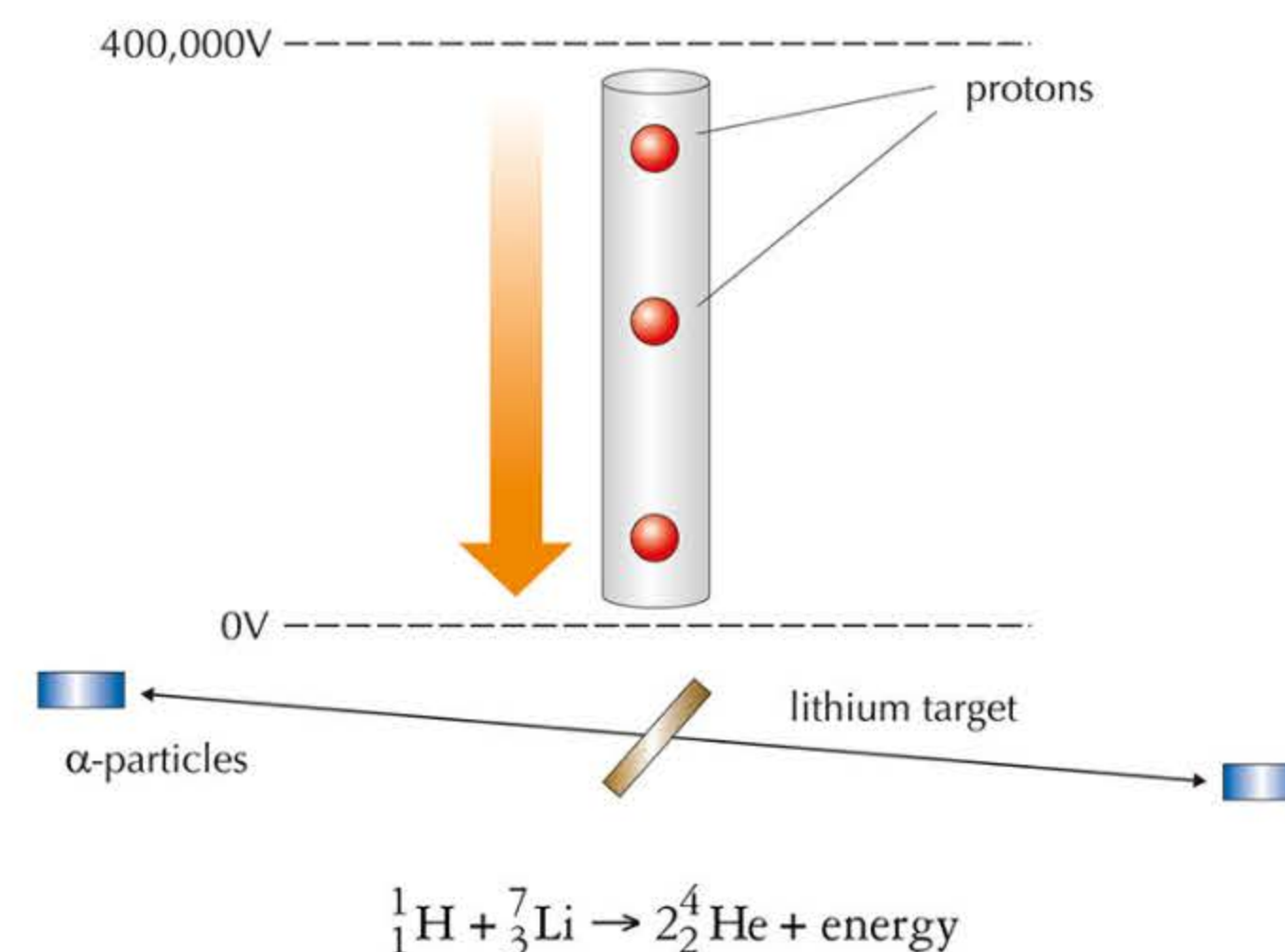
- Conservation of mass-energy
- Conservation of electric charge
- Conservation of momentum.

It is important to remember that mass must be treated as a form of energy: mass can be converted into energy and vice versa, according to Einstein's equation:

$$E = mc^2$$

The Cockcroft-Walton experiment

The Cockcroft-Walton experiment was the first splitting of the nucleus, using artificially accelerated particles. Most importantly, it was the first experiment to verify Einstein's equation. In it Cockcroft and Walton accelerated a proton into a lithium target, and produced two alpha particles:



They noted a considerable gain in energy, and a slight loss in mass. In other words, after the reaction, some mass had 'disappeared', but energy had 'appeared'. It turned out that the loss in energy and gain in mass fitted perfectly with Einstein's equation ($E = mc^2$): the mass had been converted into other forms of energy.

This was a very early **linear particle accelerator**. In researching subatomic particles today, circular accelerators such as those at CERN are more common. Using magnetic fields, these move the particles in a circular path, and accelerate them using potential differences. As the particles reach very high speeds, there is a great deal of energy present, which can lead to the creation of particles (as $m = E/c^2$ the greater the energy, the greater the mass, and the greater the number of particles that may be created).

Particle zoo

Work in these accelerators meant that the old idea that the proton, neutron and electron were the fundamental particles had to be abandoned. Many hundreds of subatomic particles were discovered over a few decades. So great was the variety of particles, and there was so little apparent order into which the particles could be categorised, that they became known as the 'particle zoo', by comparison with the many entirely different species found all jumbled together in a typical zoo.

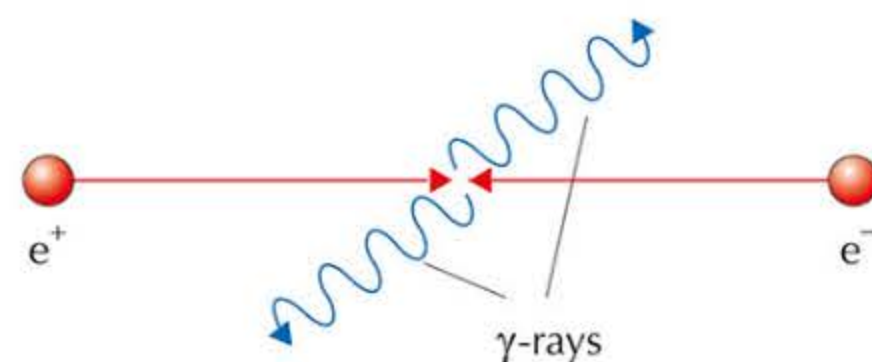
HL

Anti-matter

It also became clear that for every particle, there is an anti-particle: an anti-particle tends to be very similar to a particle but to be opposite in charge (or spin). The anti-particle of the electron, for example, is the anti-electron (or positron), which has a positive charge. The anti-particle for the proton is the anti-proton, which is negative, and so on.

Annihilation

When particle and anti-particle meet, they annihilate each other. That means that their mass disappears. According to the equation $E = mc^2$, that mass is converted into energy and is usually found to be two γ -rays. Two γ -rays must be produced to maintain the principle of conservation of momentum.



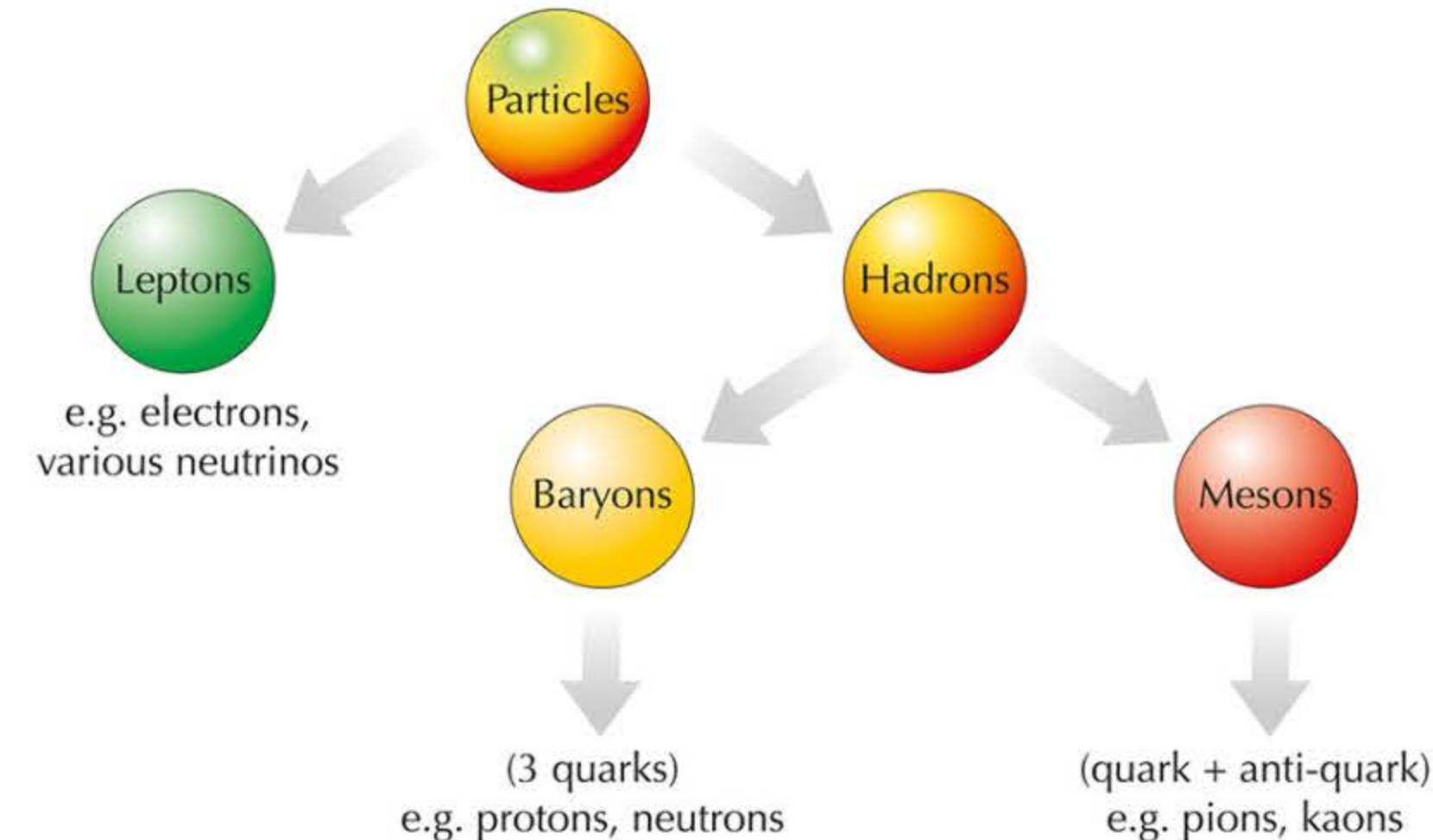
Pair production is the opposite of annihilation. In it, a photon hits the nucleus of an atom, and (for example) an electron and positron are formed. If sufficient energy is present, larger particles will be formed.

The neutrino

It was noticed in the 1920s that in some reactions momentum did not *seem* to be conserved. One example was the emission of a β -particle from the nucleus of an atom. There did not seem to be any particle travelling in the opposite direction to balance the momentum of the β -particle. It was suggested that there was, but that this particle was very small and uncharged, and therefore very difficult to detect. This tiny particle was eventually proven to exist and it is called the **neutrino**.

Quarks

Eventually, some order was found in the mess of particles that made up the particle zoo. It was decided that there are two categories of fundamental particle: leptons and quarks. Leptons (such as electrons) are often found by themselves, whereas quarks come together to make up different particles. Matter is now believed to be categorised as shown in the diagram at the top of the opposite page.



The different quarks and anti-quarks are as follows:

Name	Charge	Name	Charge
up (u)	$+\frac{2}{3}$	anti-up ($\bar{u}$)	$-\frac{2}{3}$
down (d)	$-\frac{1}{3}$	anti-down ($\bar{d}$)	$+\frac{1}{3}$
charmed (c)	$+\frac{2}{3}$	anti-charmed ($\bar{c}$)	$-\frac{2}{3}$
strange (s)	$-\frac{1}{3}$	anti-strange ($\bar{s}$)	$+\frac{1}{3}$
top (t)	$+\frac{2}{3}$	anti-top ($\bar{t}$)	$-\frac{2}{3}$
bottom (b)	$-\frac{1}{3}$	anti-bottom ($\bar{b}$)	$+\frac{1}{3}$

A **proton** is made of 2 up and 1 down quark (uud).
A **neutron** is made from 2 down quarks and 1 up quark (udd).

So, for example, if a particle is made of 2 up-quarks and 1 down-quark, it has a total charge of $+1\left(+\frac{2}{3} + \frac{2}{3} - \frac{1}{3}\right)$ (it would in fact be a proton). If it consisted of a strange-quark and an anti-bottom-quark, it would have a charge of $0\left(-\frac{1}{3} + \frac{1}{3}\right)$, and it would be a meson.

Fundamental forces

The four fundamental forces of nature are shown in the following table.

Force	Relative strength	Acts on	Occurrence	Range
Gravitational	Weakest	All particles	Everywhere	Infinite
Weak nuclear		All particles	β -decay	10^{-18} m
Electromagnetic		Charged particles	Atoms/molecules	Infinite
Strong nuclear	Strongest	Protons/neutrons	Nucleus	10^{-15} m

Sample answer

Leaving Certificate 2003, Higher Level, Section B, Q10 (a)

Leptons, baryons and mesons belong to the 'particle zoo'.

Give (i) an example, and (ii) a property of each of these particles. (18 marks)

An example of a lepton is the electron. It is a negatively charged particle. (3, 3)

An example of a baryon is a proton. It is a positively charged particle. (3, 3)

An example of a meson is a kaon. It consists of a quark and an anti-quark. (3, 3)

The following reaction represents pair-production $\gamma \rightarrow e^+ + e^-$

Calculate the minimum frequency of the γ -ray photon required for this reaction to occur. (15 marks)

$$E = mc^2 + mc^2 \quad (3)$$

$$= 2 \times 9.1 \times 10^{-31} \times (3 \times 10^8)^2 \quad (3)$$

$$= 1.638 \times 10^{-13} \quad (3)$$

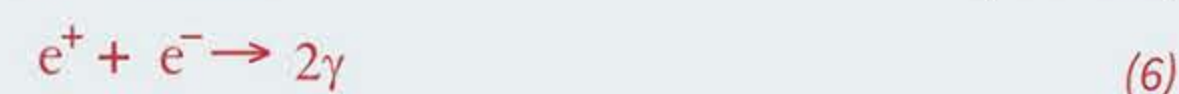
$$E = hf \quad (3)$$

$$\Rightarrow hf = 1.638 \times 10^{-13} \quad (3)$$

$$\Rightarrow f = \frac{1.638 \times 10^{-13}}{6.6 \times 10^{-34}} \quad (3)$$

$$f = 2.5 \times 10^{20} \text{ Hz} \quad (3)$$

The reverse of the above reaction is known as pair annihilation. Write a reaction that represents pair annihilation. (6 marks)



Explain how the principle of conservation of charge and the principle of conservation of momentum apply in pair annihilation. (12 marks)

Charge: The charge before annihilation is zero ($+1 -1 = 0$), as it is after: charge is conserved. Momentum: The total momentum beforehand is zero, as the particles have equal momentum in opposite directions. Afterwards, the two photons also move in opposite directions and also with equal momentum. The total momentum is still zero. (6)

Exam questions

1 2007, HL, Section B, Q10

Read the following passage and answer the accompanying questions.

ERNEST WALTON WAS ONE of the legendary pioneers who made 1932 the *annus mirabilis* of experimental nuclear physics. In that year James Chadwick discovered the neutron; Carl Anderson discovered the positron; Fermi articulated his theory of radioactive decay; and Ernest Walton and John Cockcroft split the nucleus by artificial means. In their pioneering experiment

Cockcroft and Walton bombarded lithium nuclei with high-energy protons linearly accelerated across a high potential difference (c.700 kV). The subsequent disintegration of each lithium nucleus yielded two helium nuclei and energy. Their work gained them the Nobel Prize in 1951.

(Adapted from Ernest Thomas Sinton Walton 1903–1995: *The Irish Scientist* by Vincent J. McBrierty)

(i) Draw a labelled diagram to show how Cockcroft and Walton accelerated the protons. (6 marks)

What is the velocity of a proton when it is accelerated from rest through a potential difference of 700 kV? (12 marks)

Write a nuclear equation to represent the disintegration of a lithium nucleus when bombarded with a proton. (9 marks)

Calculate the energy released in this disintegration. (12 marks)

(ii) Compare the properties of an electron with that of a positron. (5 marks)

What happens when an electron meets a positron? (3 marks)

(iii) In beta decay it appeared that momentum was not conserved.

How did Fermi's theory of radioactive decay resolve this?

(charge on electron = 1.6022×10^{-19} C; mass of proton = 1.6726×10^{-27} kg; mass of lithium nucleus = 1.1646×10^{-26} kg; mass of helium nucleus = 6.6443×10^{-27} kg; speed of light = 2.9979×10^8 m s⁻¹). (9 marks)

2 2006, HL, Section B, Q10(a)

During a nuclear interaction an antiproton collides with a proton. Pair annihilation takes place and two gamma ray photons of the same frequency are produced. What is a photon? Calculate the frequency of a photon produced during the interaction. (12 marks)

Why are two photons produced? Describe the motion of the photons after the interaction. (9 marks)

How is charge conserved during this interaction? (6 marks)

After the annihilation, pairs of negative and positive pions are produced. Explain why. (6 marks)

Pions are mesons that consist of up and down quarks and their antiquarks. Give the quark composition of (i) a positive pion, (ii) a negative pion. (9 marks)

List the fundamental forces of nature that pions experience. (6 marks)

A neutral pion is unstable with a decay constant of $2.5 \times 10^{12} \text{ s}^{-1}$. What is the half-life of a neutral pion? (8 marks)

(mass of proton = $1.673 \times 10^{-27} \text{ kg}$; Planck constant = $6.626 \times 10^{-34} \text{ Js}$; speed of light = $2.998 \times 10^8 \text{ ms}^{-1}$)

3 2005, HL, Section B, Q11

(i) What is the structure of an alpha particle? (7 marks)

(ii) High voltages can be used to accelerate alpha particles and protons but not neutrons. Explain why. (7 marks)

(iii) Cockcroft and Walton, under the guidance of Rutherford, used a linear particle accelerator to artificially split a lithium nucleus by bombarding it with high-speed protons. Copy and complete the following nuclear equation for this reaction. (7 marks)



(iv) Circular particle accelerators were later developed. Give an advantage of circular accelerators over linear accelerators. (7 marks)

(v) In an accelerator, two high-speed protons collide and a series of new particles are produced, in addition to the two original protons. Explain why new particles are produced. (7 marks)

(vi) A huge collection of new particles was produced using circular accelerators. The quark model was proposed to put order on the new particles. List the six flavours of quark. (7 marks)

(vii) Give the quark composition of the proton. (7 marks)

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