South Sudan

Secondary

Physics 3

Student's Book

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Secondary Physics Student's Book 3

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South Sudan

SECONDARY
3

Physics

Student's Book 3

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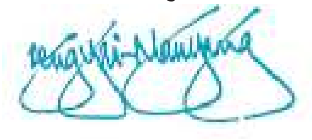
FOREWORD

I am delighted to present to you this textbook, which is developed by the Ministry of General Education and Instruction based on the new South Sudan National Curriculum. The National Curriculum is a learner-centered curriculum that aims to meet the needs and aspirations of the new nation. In particular, it aims to develop (a) Good citizens; (b) successful lifelong learners; (c) creative, active and productive individuals; and (d) Environmentally responsible members of our society. This textbook, like many others, has been designed to contribute to achievement of these noble aims. It has been revised thoroughly by our Subject Panels, is deemed to be fit for the purpose and has been recommended to me for approval. Therefore, I hereby grant my approval. This textbook shall be used to facilitate learning for learners in all schools of the Republic of South Sudan, except international schools, with effect from 4th February, 2019.

I am deeply grateful to the staff of the Ministry of General Education and Instruction, especially Mr Michael Lopuke Lotyam Longolio, the Undersecretary of the Ministry, the staff of the Curriculum Development Centre, under the supervision of Mr Omot Okony Olok, the Director General for Quality Assurance and Standards, the Subject Panelists, the Curriculum Foundation (UK), under the able leadership of Dr Brian Male, for providing professional guidance throughout the process of the development of National Curriculum and school textbooks for the Republic of South Sudan since 2013. I wish to thank UNICEF South Sudan for managing the project funded by the Global Partnership in Education so well and funding the development of the National Curriculum and the new textbooks. I am equally grateful for the support provided by Mr Tony Calderbank, the former Country Director of the British Council, South Sudan; Sir Richard Arden, Senior Education Advisor of DfID, South Sudan. I thank Longhorn and Mountain Top publishers in Kenya for working closely with the Ministry, the Subject Panels, UNICEF and the Curriculum Foundation UK to write the new textbooks. Finally, I thank the former Ministers of Education, Hon. Joseph Ukel Abango and Hon. Dr John Gai Nyuot Yoh, for supporting me, in my previous role as the Undersecretary of the Ministry, to lead the Technical Committee to develop and complete the consultations on the new National Curriculum Framework by 29 November 2013.

The Ministry of General Education and Instruction, Republic of South Sudan, is most grateful to all these key stakeholders for their overwhelming support to the design and development of this historic South Sudan National Curriculum. This historic reform in South Sudan's education system is intended to benefit the people of South Sudan, especially the children and youth and the future generations. It shall enhance the quality of education in the country to promote peace, justice, liberty and prosperity for all. I urge all Teachers to put this textbook to good use.

May God bless South Sudan. May He help our Teachers to inspire, educate and transform the lives of all the children and youth of South Sudan.



Deng Deng Hoc Yai, (Hon.)

Minister of General Education and Instruction, Republic of South Sudan

Contents

UNIT 1 Radiation and quantum phenomena

Topic 1: Radiation and quantum phenomena

Learning outcomes

Knowledge and understanding

Use understanding of particles to explain radiation, electromagnetic radiation and quantum phenomena.

Skills

- Investigate the role of ionisation and excitation in the fluorescent tube.
- Design a simple photoelectric cell and explain the process of photoelectric effect.

Attitude and value

- Appreciate the particulate nature of electromagnetic radiation.
- Appreciate that nucleon number, proton number, and mass-energy are all conserved in nuclear processes.

Key inquiry questions

- Why are electrons produced during photoelectric effect called photoelectrons?
- Why does excitation of the atom cause loss of energy of the atom?
- How does an atom give off light?
- How did Rutherford's experiment help to explain the arrangement of particles in an atom?`

Topic 1 Radiation and quantum phenomena

Topic outlines

1.1 The structure of an atom

Activity 1.1 **To describe atomic structure**

(Work in groups)

Materials

- Reference books
- Internet
- Resource persons

Steps

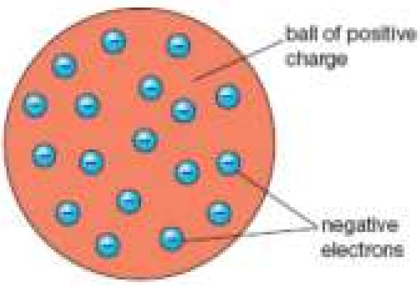
1. Conduct a research from reference books on the structure of an atom.
2. Tell your classmate what an atom is. What is the composition of an atom?
3. Draw and name the parts of an atom. Describe the forces that hold the particles in an atom in place. How does the energy of the particles vary in atoms?
4. Now, conduct research from reference sources on how J.J. Thomson, Ernest Rutherford and Neils Bohr atomic models contributed to the understanding of an atom.
5. Make a brief report on your findings and present it to the whole class during the class discussion.
6. As a class, role play the atomic structure of a given element. Let some represent different particles and their positions in the atom and demonstrate the forces between the particles.

The desire and attempts to investigate what really constitutes matter began long time ago. Overtime, scientists have formulated theories and conducted investigations to answers this question.

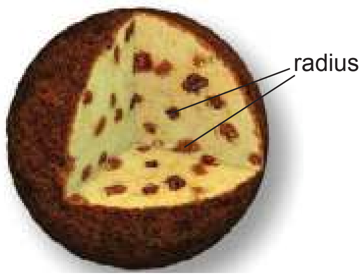
The first person to hypothesis on the constituent of matter was a Greek philosopher called *Democritus* who suggested that everything in the universe is made of tiny indivisible units, which he called *atoms* meaning 'unable to be cut or divided'.

In 1808, an English schoolteacher named *John Dalton* building on the work of the earlier scientists proposed that each chemical element consists of a single type of atoms that could not be destroyed or divided further. By performing experiments, he showed that atoms of different elements could combine in certain ways to form compounds, and formulated what he called the *"law of definite proportions." The law states that a chemical compound always contains the same proportion of a particular element.*

In 1897, a British scientist called *J.J. Thomson* while experimenting with a cathode ray tube demonstrated that cathode rays were negatively charged particles; he discovered the *electron*. He concluded that the electrons were coming from the atoms in the cathode of the tube. His experiment also showed that the atom contained other parts that are positively charged. Therefore, he proposed the *plum pudding model of the atom*, in which *electrons were embedded and evenly spread in the volume a spherical mass of positive charge to yield an electrically neutral atom (Fig. 1.1)*.



(a) A omic model



(b) A plum pudding

Fig. 1.1: J.J. Thomson atomic model

In comparing the atom with the plum pudding, the raisins in the pudding represent the negatively charged electrons while the dough represents the positively charged matter in the atom. However, the Thomson's model of the atom failed to recognize the positive charges in the atom as particles.

In 1898, *Ernest Rutherford*, a student of J. J. Thomson, carried out a landmark experiment to investigate Thomson's model. It resulted in the discovery of the *nucleus* in an atom. In his experiment, he directed a beam of positively charged particles (alpha particles) to a very thin sheet of gold foil. He observed that most of the alpha particles were deflected just slightly from the straight path, some were deflected through small angles and very few of the particles re-bounced at sharp angles (Fig. 1.2).

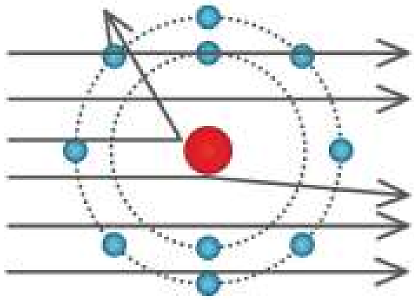


Fig. 1.2: Rutherford experimental results

Rutherford concluded that the particles that sharply re-bounced collided with dense parts of the atoms in the gold foil. The particles bounced back because they had the same charge as the dense parts of the atom. Because very few particles bounced back at sharp angles, he concluded that these dense parts must be very tiny in the atom.

Based on his results, Rutherford concluded that "the atom of an element consist of *a small, positively charged nucleus at the centre*, which carries almost the entire mass of the atom. The electrons revolve around the nucleus at high speed. The number of the positive charge is concentrated at the centre of the atom. This positively charged, dense core of the atom is called the nucleus (plural, nuclei). Fig.1.3 shows the Rutherford's atomic model

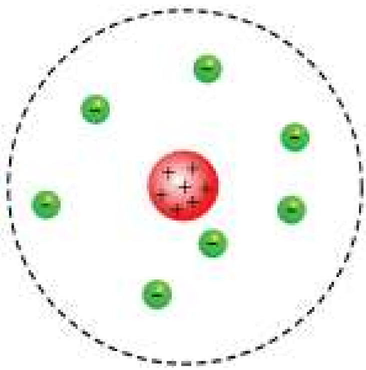
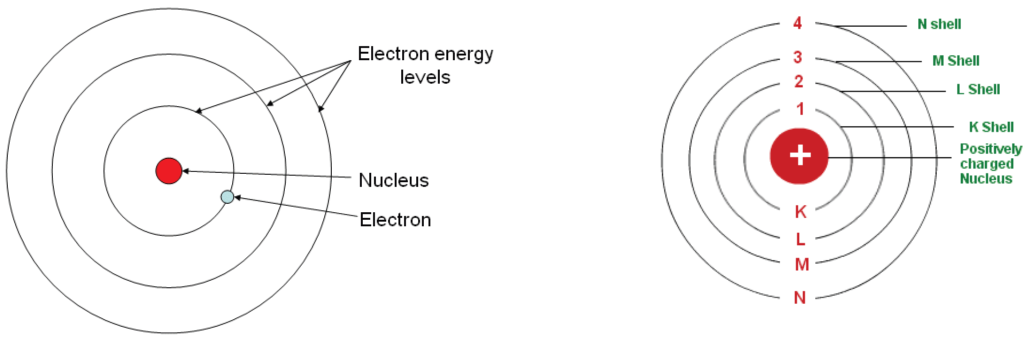


Fig. 1.3: Rutherford's model of an atom

In 1915, *Niels Bohr* made modification to Rutherford's model of atom. The Rutherford's model had explained that the nucleus (positively charged) is surrounded by negatively charged electrons. Bohr modified Rutherford's model and came up with his model that explained that:

- In an atom, electrons (negatively charged) revolve around the positively charged nucleus in a definite (fixed) circular path called *orbits* or *shells* and not anywhere in between. His model was therefore patterned on the solar system and is known as the *planetary model*
- Each orbit or shell has a fixed energy and these circular orbits are known as orbital shells.
- The energy levels are represented by an *integer* also called *quantum number* (n = 1, 2, 3…). The range of quantum number starts from nucleus with n=1 having the lowest energy level. The orbits n = 1, 2, 3, 4… are assigned letters K, L, M, N…. shells. When an electron attains the lowest energy level, it is said to be in the *ground state*.



(a) Bohr' Atomic model

(b) Energy Levels

Fig. 1.4: Bohr's model of an atom

He suggested that the electrons can only orbit the nucleus in specific orbits or shells with a fixed radius. Only shells with a radius given by the equation below would be allowed, that an electron can not exist in between these shells.

$r(n) = n\text{^}2 \times r(1)$, where r *(1)* is the *Bohr radius* with the valuer

(1) = $0.529 \times 10 \times (^{-2})$ m

Bohr's model calculated the energy for an electron in an orbital whose quantum number is *n* as follows:

$$E(n) = -\frac{1}{n^2} \times 13.6\ eV,$$

where the lowest possible energy or *ground state energy* of a hydrogen electron is E(1) = – 13.6 eV.

- When an electron absorbs energy, it jumps from the lower energy level to higher energy level. This process is known as *excitation* (discussed next). When it falls from a higher energy level to lower energy level, it loses energy inform of radiations.

1.2 Excitation and ionisation of an atom

Activity 1.2

To describe excitation and ionisation of an electron

(Work in groups)

Materials

Reference sources

Steps

1. Find out the meaning of excitation and ionisation from the dictionary.
2. Explain to your class partner what happens to the energy of an electron as it moves from a lower to higher energy level and vice versa.
3. Suggest an application of excitation and ionisation of electrons.
4. In groups, role play excitation and ionisation of electrons in an atom i.e gaining or loosing energy.

1.2.1 Excitation

Excitation is the process by which an electron moves from a lower energy level to a higher energy level when it gains a specific amount of energy. The electrons can be excited to a higher level state in several ways including heating the atom strongly, putting it in an electric discharge or colliding it with fast moving particles. The electron will still orbit the nucleus, unless its energy level is greater than the ionization energy level of the atom (energy that removes it from an atom).

Fig. 1.5 demonstrates the excitation of an electron.

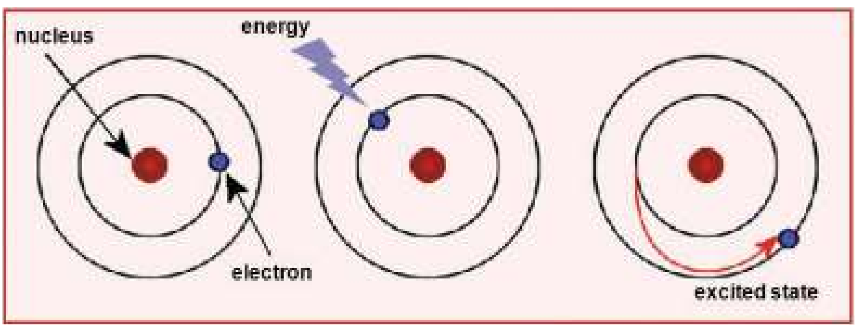


Fig 1.5

When an electron at a higher energy level moves to a lower energy level, it looses (emits) energy inform of electromagnetic radiations, in discrete quantities called *quanta* or *photon*. The amount of the energy that the electron loses is equal to the difference between the two orbital energies, hence equal to that of the photon emitted.

For example, suppose an electron moves from a higher orbital whose energy level is E_i to a lower orbital with energy level E_f, the energy of the emitted radiation (light) is given by the difference in the two energy levels as follows:

$$E = hf = E_f - E_i \text{..........} (i),$$

Where h is called the Planck's constant and f is the frequency of the emitted radiation and its value is $h = 6.63 \times 10^{-34}$ Js.

From equation (i), we can get an expression for the *wavelength of the emitted radiation* as follows:

$$hf = E_f - E_i$$

$$= -\frac{1}{n_f^2} \times 13.6\,eV - \left(-\frac{1}{n_i^2} \times 13.6\,eV\right)$$

$$= -13.6\,eV\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right) \quad \text{(Note that } 13.6\,eV \approx 2.18 \times 10^{-18}\text{ J)}$$

$$\frac{hc}{\lambda} = -13.6\,eV\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right) \quad \text{(Since } f = \frac{c}{\lambda} \text{ where } c \text{ is the speed of light)}$$

$$\frac{1}{\lambda} = -\frac{136\,eV}{hc}\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$$

The constant $\frac{136\,eV}{hc} = R = 1.097 \times 10^{7}\,m^{-1}$ *is called Rydberg constant*.

Hence, $\frac{1}{\lambda} = -R\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$

The hydrogen spectrum

As we have learnt, electron moving from a higher to a lower energy levels emits energy inform radiation (light). The higher the amount of energy lost, the greater the wavelength of the light produced. Lights of different wavelengths have different colours hence when emitted from a hydrogen atom; they form differently coloured *spectral lines*. This causes *a line emission spectra* to be produced as shown in Fig. 1.6.

Fig. 1.6: Line emission spectra

Different types of elements have atoms have at different energy levels, hence the line spectra for different elements will be different. Therefore, line spectra can be used to identify elements.

When photons of light pass through a gas, the photons with the same energy as the energy gaps in the atoms can be absorbed. This causes an absorption spectra as shown in Fig 1.7.

Fig. 1.7: Absorption spectra

The spectral lines are grouped into series according to the energy quantum number of the common lower orbital the electrons fall move to produce them. They are named after the scientists who discovered them, and sequentially starting from the longest wavelength (lowest frequency) of the series.

Fig. 1.8 shows the graphical representation of the hydrogen spectrum.

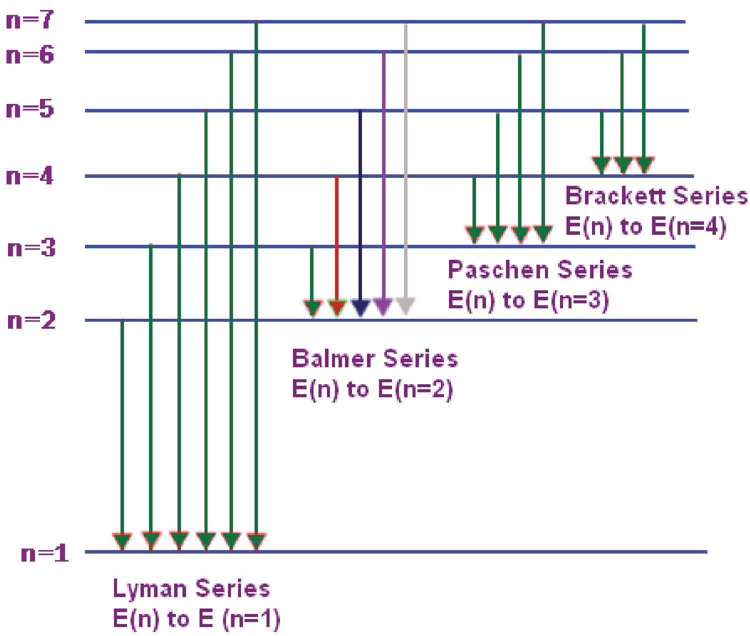


Fig. 1.8: Hydrogen spectrum

Lyman series

- It is obtained for the electron transitions *from n>1* (e.g. n= 2, 3, 4,….) *to n=1*.
- All the wavelengths in the Lyman series are in the ultraviolet (UV) band.

Balmer series

- It is obtained for the electron transitions *from n>2* (e.g. n= 3, 4, 5, ….) *to n=2*.

- Four of the Balmer lines (violet, blue, green and red) are in the *"visible"* part of the spectrum.

Paschen series

- It is obtained for the electron transitions *from n>3* (e.g. n= 4, 5, 6,….) *to n = 3*.
- The Paschen lines all lie in the *infrared (IF)* band.
- This series overlaps with the next series (Bracket series), i.e. the shortest line in the Bracket series has a wavelength that falls within the Paschen series. All the other series beyond the Paschen also overlap.

Brackett series

- It is obtained for the electron transitions *from n>4* (e.g. n= 5, 6, 7….) *to n = 4*.
- The series lines lie in the infrared (IF) band.

Pfund series

- It is obtained for the electron transitions *from n>5* (e.g. n= 6, 7, 8….) *to n = 5*.
- The series lines lie in the far *infrared (IF)* band region.

Humphreys series

- It is obtained for the electron transitions *from n>6* (e.g. n= 6, 7, 8....) *to n = 6*.

Example 1.1

An electron of an atom moved from the n = 3 energy level to the n = 1 energy level. Determine:

(a) In which series the transition is and identify the radiation emitted.

(b) The change in the energy of the electron.

(c) The wavelength of the radiation emitted.

Solution

(a) Transition from n => 1 to n = 1 is in the lyman series emitting ultraviolet (UV) radiation.

(b) $n_i = 3, \qquad n_f = 1$

$$\Delta E = E_f - E_i$$

$$= -13.6\ \text{eV}\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right) = -2.18 \times 10^{-18}\ \text{J}\left(\frac{1}{1^2} - \frac{1}{3^2}\right)$$

$$= -2.18 \times 10^{-18}\ \text{J} \times \frac{8}{9}$$

$$= -1.938 \times 10^{-18}\ \text{J}$$

The negative sign indicates that the electron looses energy.

$$\frac{1}{\lambda} = -R\left(\frac{1}{n_f^2} - \frac{1}{n_I^2}\right)$$

$$= 1.097 \times 10^{-7}\ m^{-1}\left(\frac{1}{1^2} - \frac{1}{3^2}\right) \times \frac{8}{9}$$

$$= 1.097 \times 10^{-7}\ m^{-1} \times \frac{8}{9}$$

$$\frac{1}{\lambda} = -9.751 \times 10^{-6}\ m^{-1}$$

$$\Rightarrow \quad \lambda = \frac{1}{9.752 \times 10^{-6}}\ m = 1.026 \times 10^{-7}\ m$$

Example 1.2

Determine the frequency of the radiation absorbed to make an electron transition from n = 2 to the n = 5 level. Identify the types of radiation absorbed.

Solution

$$n_i = 2, \qquad n_f = 5$$

$$\frac{1}{\lambda} = -R\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$$

$$= -1.097 \times 10^{7}\ m^{-1}\left(\frac{1}{5^2} - \frac{1}{2^2}\right) \times \frac{8}{9}$$

$$= -1.097 \times 10^{7}\ m^{-1} \times \left(\frac{-21}{100}\right) = 2.304 \times 10^{6}$$

$$\Rightarrow \quad \lambda = \frac{1}{2.304 \times 10^{6}}\ m = 4.34 \times 10^{-7}\ m$$

From $c = f\lambda \Rightarrow f = \frac{c}{\lambda} = \frac{3 \times 10^{8}\ m}{4.34 \times 10^{-7}\ m}$

$$= 6.912 \times 10^{14}\ Hz$$

- The transition from n = 2 to n > 2 and vice versa involves the absorbtion or emission of visible light in the Balmer series..

1.2.2 Ionisation

If enough energy is given to the electron to remove it from the atom, then we say *ionisation* has occurred.

Fig. 1.9 illustrates the ionisation of an atom.

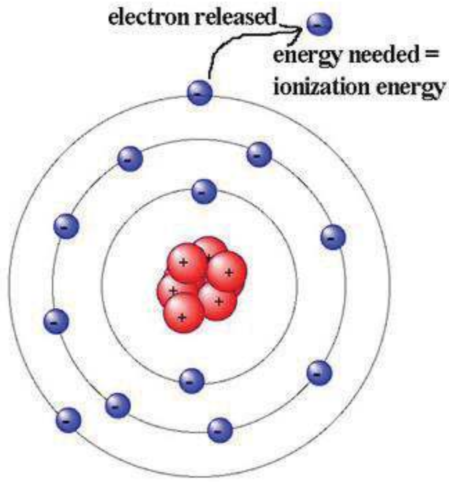


Fig. 1.9: Ionisation of an atom

1.2.3 Applications of excitation and ionisation in fluorescent tubes

A fluorescent tube or fluorescent lamp is a low weight mercury vapour lamp that uses fluorescence to produce visible light. It consists of a long gas-discharging glass tube. Its inner surface is coated with phosphorous and is filled with an inert gas, usually argon with traces of mercury.

The tube is sealed at low pressure with two filament electrodes, each at its ends. The electrodes produce electrons when connected to a high amount of power.

Fig 1.10 shows a fluorescent tube.

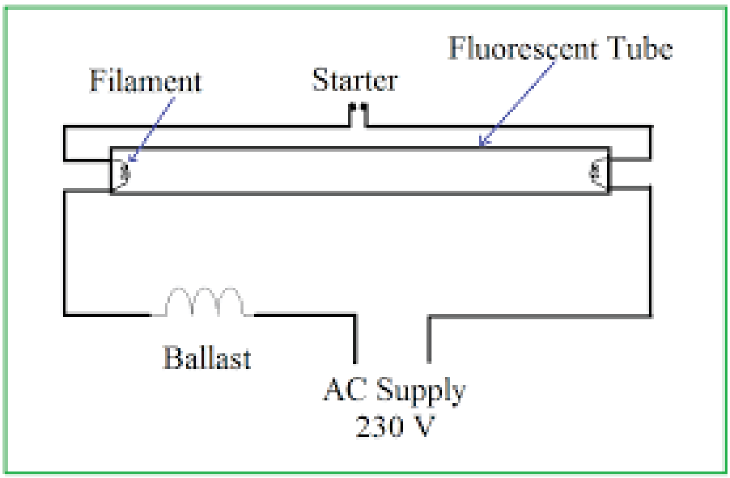


Fig 1.10

The excitation of electrons and photon emission in the tube produce visible light. The tube contains mercury vapour and a high voltage is applied between the ends. This voltage accelerates the fast moving free electrons, which through collisions, ionise some of the mercury atoms and subsequently produce more free electrons. When these free electrons knock the electrons in the mercury atoms, the latter are excited to a higher energy level. When they return to their ground state, they lose the energy by emitting high photons of ultra-violet (UV) radiation. The photons emitted have a range of energies (and wavelengths) that correspond to the different transitions of the electrons in the energy levels.

The phosphorous coating on the inside of the tube absorbs thes UV photons resulting in excitation of its electrons to much higher energy levels. The electrons then move to a lower energy level to maintain a constant energy level, losing energy by emitting many lower energy photons in the range of the visible light that we see.

Exercise 1.1

1. Draw the structure of an atom to show the nucleus, orbit and electrons.
2. What were the limitations of J.J. Thomson's atomic model?
3. Differentiate between excitation and ionisation of electrons.
4. Which of the following statements are true?
   A. Line spectra are produced when electrons move from one energy level within an atom to another energy level.
   B. The energy levels in the atom have indefinite values.
   C. Line spectra are produced when atoms lose electrons.
5. (a) Briefly explain the operation of a fluorescent tube.
   (b) What is the function of the phosphorus coating in a fluorescent tube?
6. Determine the wavelength of the emitted light for the electron transition from energy level n = 4 to energy level n = 1 in hydrogen. In which region of electromagnetic spectrum does this radiation fall?
7. Calculate the wavelength of the first line in the Balmer series of hydrogen spectrum. What is the colour of the line?
8. Assume an electron transition occurs from the n = 2 to the n = 3 energy level, what is the frequency of the absorbed photon?
9. An electron transitioned from the n=1 orbital by absorbing a photon of wavelength 1.7×10^{-7} m. What is the integer number of the orbital it transitioned to?
10. An electron of hydrogen at the orbital n = 6 emitted a photon of infrared light. Determine the: (a) energy lost by the electron (b) wavelength of the emitted photon.

1.3 Photoelectric effect

1.3.1 Demonstration of photoelectric effect

Activity 1.3 **To illustrate photoelectric effect**

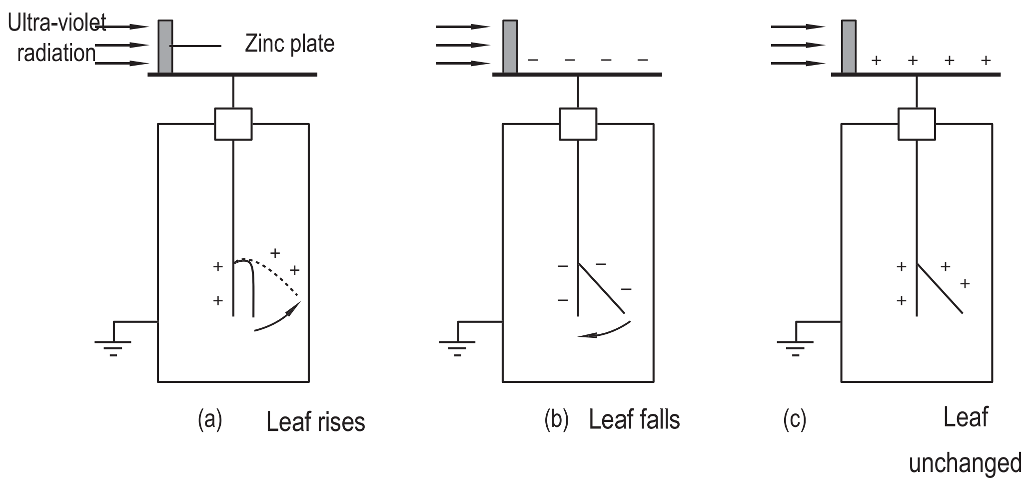
(Work in groups)

Materials

- Zinc plate
- Energy cloth
- Electroscope
- UV light source

1. Clean a zinc plate using an energy cloth.
2. Attach the freshly cleaned zinc plate on the cap of an uncharged electroscope.
3. Shine an ultraviolet radiation on the zinc plate.
   (a) What happens to the leaf of the electroscope? Test the charge on the leaf.
   (b) Explain what happens to the zinc plate and how that leads to the effect you have observed on the leaf of the electroscope.
4. Repeat the activity by first charging the electroscope negatively then shining UV radiation on the zinc plate. Explain why the leaf falls.
5. Repeat Step 4 with a positively charged electroscope and explain your observation.

In Step 3 of Activity 1.3, the leaf rises steadily showing that the electroscope is being charged (Fig. 1.11 (a)).



1.11: To illustrate photoelectric effect

On testing the charge, the electroscope is found to be positively charged. This shows that electrons were removed from the zinc plate by the ultraviolet light making it positively charged. The zinc plate then charged the electroscope positively by contact hence the deflection of the leaf.

When the experiment is repeated with a negatively charged electroscope (Fig. 1.11 (b)), the leaf falls steadily. This shows again that electrons are being ejected from the zinc plate charging it positively hence it attracts electrons from the leaf. When the activity was repeated with a positively charged electroscope (Fig 1.8(c)), the deflection of the leaf showed no change. This is because the ejected electrons were not allowed to leave the zinc plate as they are attracted back by the positive charges on the electroscope. This process of removing electrons from a metal surface by using a radiation is called *photoelectric effect*. The ejected electrons are called *photoelectrons* (Fig. 1.2).

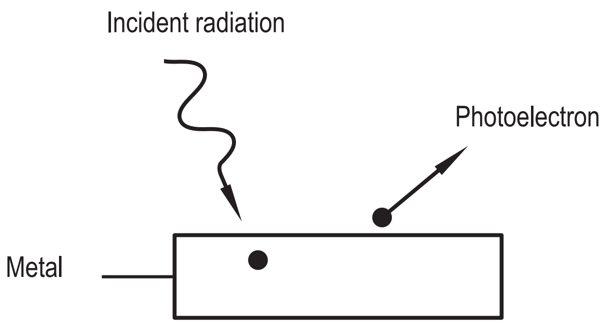


Fig. 1.12: Photoelectric effect

In 1900, Max Planck showed that radiation is not emitted in continuous amounts but in discrete bundles or packets of radiant energy (E). These bundles or packets are called *quanta* or *photons*. He showed that if E represents the smallest permissible energy change, then

$$E = hf$$

The above equation is called *Planck's equation*; where f is the frequency of the radiation and h is called *Planck's constant*. Experiments give the value of Planck's constant to be 6.63×10^{-34} Js.

1.3.2 Threshold frequency and work function

(a) Threshold frequency

Activity 1.4 To show that a given metal surface has a minimum frequency of radiation required to eject electrons

Materials

- Freshly cleaned zinc plate
- Source of visible light
- Negatively charged electroscope
- Source of ultraviolet light

Steps

1. Shine visible light on a freshly cleaned zinc of a negatively charged electroscope (Fig. 1.9). What happens to the leaf when the visible light is shone?
2. Repeat step 1 by shining ultra violet light on the zinc plate and observe what happens to the leaf.
3. Identify one characteristic of the radiations that is different in UV and visible light and explain how the difference led to the different observations.

For any given surface there is a minimum frequency of radiation below which no emission of photoelectrons occur (Fig. 1.13 (a)). This minimum frequency is called threshold frequency (f_0). At threshold frequency, all photoelectrons ejected from the metal are just attracted back by the metal (Fig. 1.13 (b)). Beyond threshold frequency, photoelectrons have enough kinetic energy to leave the metal surface (Fig. 1.10(c)).

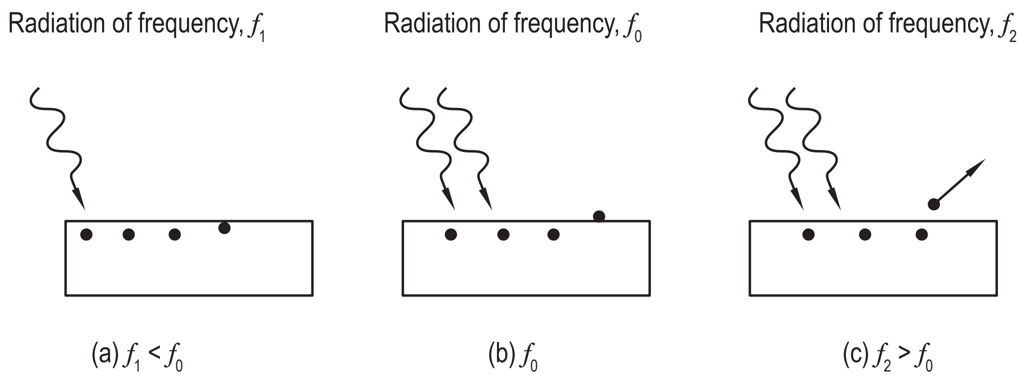


Fig. 1.13: Threshold frequency

In Fig 1.10(a) the frequency of radiation f_1 is below minimum. This is the reason why there were no ejected electrons in Step 1 in Activity 1.4. This is because visible light does not have enough energy to eject surface electrons from the metal. In 1.10(c) the frequency of radiation f_2, is more than the threshhold frequency.

Electron volt

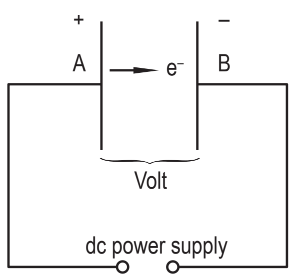


Fig. 1.11: One electron volt

When considering energy associated with sub-atomic particles e.g. electrons, protons, neutrons etc., it is convenient to use a unit of energy called *electron volt (eV)*. One electron volt (1 eV) is the energy gained by an electron when it moves through a potential difference of 1 volt (Fig. 1.11). Since one electron has a charge of 1.6×10^{-19} C;

$$1\ \text{eV} = 1.6 \times 10^{-19}\ \text{C} \times 1\ \text{V}$$
$$= 1.6 \times 10^{-19}\ \text{J}$$

$$1\ \text{eV} = 1.6 \times 10^{-19}\ \text{J}$$

Example 1.3

The earth's surface receives energy from the sun at a rate of 1 500 Wm^{-2}. If the average wavelength of sunlight is 5.5×10^{-7} m, at what rate does the earth's surface receive the photons? Take the speed of light, c, as $3.0 \times 10^{8}\ \text{ms}^{-1}$.

Solution

Energy, $E = hf$; speed of light, $c = f\lambda$

$$\therefore \quad E = \frac{hc}{\lambda}$$

$$= \frac{6.63 \times 10^{-34} \times 3 \times 10^{8}}{5.5 \times 10^{-7}}$$

$$= 3.6 \times 10^{-19}\ \text{J}$$

The number of photons $= \dfrac{1\ 500\ \text{Wm}^{-2}}{3.6 \times 10^{-19}\ \text{J}} = 4.2 \times 10^{21}$.

$\therefore$ the number of photons per square metre per second $= 4.2 \times 10^{21}$.

Example 1.4

An electron is ejected from the surface of a metal with a kinetic energy of 2.24×10^{-19} J. What is the energy of the electron in electron volts?

Solution

K.E of electron $= 2.24 \times 10^{-19}$ J

$$1.6 \times 10^{-19}\ \text{J} = 1\text{eV}$$

$$2.24 \times 10^{-19}\ \text{J} = \frac{2.24 \times 10^{-19}}{1.6 \times 10^{-19}}$$

$$= 1.4\ \text{eV}$$

Example 1.5

A beam of light is shone on a surface of a metal. The photoelectrons liberated are found to have maximum kinetic energy of 3.14 eV. Calculate the maximum velocity of the electron. Take the mass of an electron to be 9.1×10^{-31} kg.

Solution

For maximum kinetic energy, velocity must be maximum.

Maximum kinetic energy $= \frac{1}{2} mv^2_{max}$

Kinetic energy $= (3.14 \times 1.6 \times 10^{-19})$J

But $3.14 \times 1.6 \times 10^{-19} = \frac{1}{2} \times 9.1 \times 10^{-31} \times v^2_{max}$

$$\therefore \quad v^2_{max} = \frac{2 \times 3.14 \times 1.6 \times 10^{-19}}{9.1 \times 10^{-31}}$$

$$v_{max} = 1.05 \times 10^6 \text{ m/s}$$

(b) Work function

Different metals require different threshold frequencies for photoelectric emission to take place, for example, zinc metal requires a higher threshold frequency than sodium metal. This means that surface electrons of different metals are held with different forces within the metal. Zinc metal holds its surface electron more firmly than sodium metal. The energy needed to remove an electron from the zinc surface is therefore more than that of sodium.

The minimum energy required to completely remove an electron from the metal surface without giving any additional kinetic energy is called the *work function* (W) of the metal.

Since the energy, E, of a photon = hf, the minimum energy required to liberate an electron from the metal surface can be given by;

$E_{min} = hf_o$, where E_{min} is the work function W and f_o is the threshold frequency.

Therefore; $W = hf_o$.

Table 1.1 shows some work functions for different metals. Note that alkali earth metals e.g. caesium, lithium, sodium, etc. have low work functions compared to other metals.

Table 1.1

Metal	*Work function (eV)*
Platinum	6.30
Carbon	4.81
Iron	4.63
Tungsten	4.49
Zinc	4.27
Magnesium	3.70
Lithium	2.46
Sodium	2.28
Potassium	2.25
Rubidium	2.13
Caesium	1.93

Example 1.6

Zinc has a work function of 4.27 eV. Find the maximum wavelength of light that is needed to cause photoelectric emission.

Solution

$$W = hf_o \; ; c = f_o \lambda_o$$

$$\therefore \quad W = \frac{hc}{\lambda_0}$$, where λ_0 is the maximum wavelength

$$\lambda_0 = \frac{hc}{W}$$

$$= \frac{6.63 \times 10^{-34} \times 3 \times 10^{8}}{4.27 \times 1.6 \times 10^{-19}} \text{ m}$$

$$= 2.91 \times 10^{-7} \text{ m}$$

Example 1.7

A light beam of frequency 5.7×10^{14} Hz is irradiated on a surface of metal whose work function is 2.6 eV. Explain whether photoelectric effect will take place or not.

Solution

$$hf_0 = W$$

$$f_0 = \frac{W}{h} = \frac{2.6 \times 1.6 \times 10^{-19}}{6.63 \times 10^{-34}} = 6.3 \times 10^{14} \text{ Hz}$$

Photoelectric effect will not take place since the frequency used is less than the threshold frequency.

1.4 Einstein's equation of photoelectric effect

Activity 1.5 **To derive the equation of photoelectric effect**

(Work in groups)

Materials

- Reference sources

Steps

1. Suppose a radiation with immense energy strikes a metal whose function is much less than kinetic energy of the radiation. Discuss with your class partner how the energy of the radiation is transformed/utilised on striking the metal.
2. Basing on the energy transformation you have identified in Step 1, derive the equation of photoelectric effect. What does each term in the equation represent.
3. Now, conduct research from reference sources on the equation of photoelectric effect. Write down the equation. Compare the equation with the one you derived.
4. Present your findings to the whole class on the chalkboard/white board.

Albert Einstein suggested that the energy of a photon in photoelectric effect is used in two ways:

1. To remove the electrons from the metal surface (equal to work function of metal).

2. To provide the ejected electrons with kinetic energy.

Einstein summarised his idea in what is called the *Einstein's equation of photoelectric effect*. It states as follows:

$$hf = W + \frac{1}{2}mv^2_{max} \quad (h \text{ is the Planck's constant})$$

Suppose the ejected electrons have zero kinetic energy i.e,

$hf = W$, then $f = f_0$ (threshold frequency)

thus $W = hf_0$, i.e,

$$hf = hf_0 + \frac{1}{2}mv^2_{max} \quad \text{(Einstein's photoelectric equation)}$$

Example 1.8

Fig. 1.14 shows the graph of a kinetic energy, E, of the emitted electrons against $\frac{1}{\lambda}$, of a radiation falling on a metal surface. Speed of light, $c = 3.0 \times 10^8$ ms^{-1}.

Use the graph to determine:

(a) Planck's constant, h.

(b) Work function of the metal, W in electron volts.

(c) Threshold frequency, f_0.

Solution

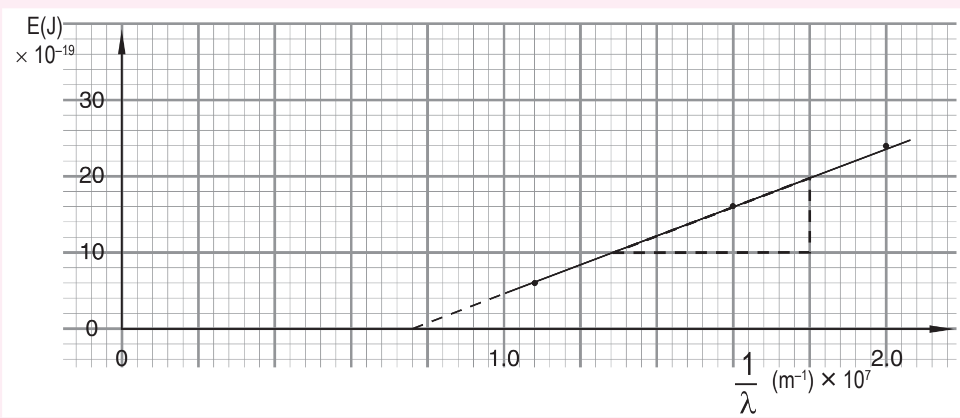


Fig. 1.14

(a) From Einstein's equation of photoelectric effect

$$\frac{1}{2} mv^2_{max} = hf - W$$

In terms of wavelength, λ

$$\frac{1}{2} mv^2_{max} = \frac{hc}{\lambda} - W$$

$$E = \frac{hc}{\lambda} - W :$$

Comparing with $y = mx + c$, the slope = hc.

From the graph, slope $= \frac{10 \times 10^{-19}}{0.52 \times 10^{7}} = 1.92 \times 10^{-26}$ Jm

$$\therefore \quad h = \frac{\text{slope}}{c}$$

$$= \frac{19.2 \times 10^{-26}\,\text{Jm}}{3 \times 10^{8}\,\text{ms}^{-1}}$$

$$= 6.4 \times 10^{-34}\ \text{Js}$$

(b) $W = hf_o = \frac{hc}{\lambda} = \frac{\text{slope}}{\lambda_0}$

From the graph; $\frac{hc}{\lambda_0} = 0.76 \times 10^7$ per metre (x – intercept)

$$\therefore \quad W = 19.2 \times 10^{-26} \times 0.76 \times 10^7\ \text{J}$$

$$= 14.6 \times 10^{-19}\ \text{J}$$

In electron volts $W = \frac{14.6 \times 10^{-19}}{1.6 \times 10^{-19}} = 9.13$ eV

(c) $c = f\lambda$. In this case, $\lambda = \lambda_0$ and $f = f_0$

$$f_0 = \frac{c}{\lambda_0} \Leftrightarrow \frac{1}{\lambda_0} = 0.76 \times 10^7 \text{ per second}$$

$$\therefore \quad f_0 = 3 \times 10^8 \times 0.76 \times 10^7$$

$$= 2.3 \times 10^{15}\ \text{Hz}$$

Example 1.9

The maximum wavelength of light needed to cause photoelectric emission on a metal surface is 6.0×10^{-7} m. The metal surface is irradiated by light of frequency 6.5×10^{14} Hz. Determine:

(a) Threshold frequency.

(b) Work function of the metal in electron volts.

(c) Maximum kinetic energy in electron volts of the electrons emitted.

(d) Maximum speed of the photoelectrons. Take the mass of an electron $m_e = 9.1 \times 10^{-31}$ kg.

Solution

(a) $c = \lambda_0 f_0 \Leftrightarrow f_0 = \frac{c}{\lambda_0} = \frac{3 \times 10^8}{6 \times 10^{-7}} = 5.0 \times 10^{14}$ Hz

(b) $W = hf_0 = 6.63 \times 10^{-34} \times 5.0 \times 10^{14} = 3.32 \times 10^{-19}$ J

1 electron volt = 1.6×10^{-19} J

$\therefore \quad 3.32 \times 10^{-19} \text{ J} = \frac{3.32 \times 10^{-19}}{1.6 \times 10^{-19}} = 2.1$ eV

(c) Maximum kinetic energy = $hf - hf_o = h(f - f_0)$

$= h \times (6.5 - 5.0) \times 10^{14}$

$= 6.63 \times 10^{-34} \times 1.5 \times 10^{14}$

$= 9.95 \times 10^{-20}$ J

Kinetic energy in electron volts $= \frac{9.95 \times 10^{-20}}{1.6 \times 10^{-19}} = 0.622$ eV

(d) $\frac{1}{2} mv^2_{max} = 9.95 \times 10^{-20}$ J

$v_{max} = \sqrt{\frac{2 \times 9.95 \times 10^{-20}}{9.1 \times 10^{-31}}} = 4.68 \times 10^5$ m/s

Exercise 1.2

(Take $h = 6.6 \times 10^{-34}$ Js, $c = 3 \times 10^{8}$ m/s, $e = 1.6 \times 10^{-19}$ C, $m_e = 9.1 \times 10^{-31}$ kg where necessary).

1. Fig. 1.15 shows a charged electroscope with a clean zinc plate placed on the cap. Ultraviolet light is shone on the zinc plate.

   (a) Why should the zinc plate be cleaned?

   (b) Explain what happens to the leaf of the electroscope when ultraviolet light is shone on it.

   (c) What would happen if ultraviolet light is replaced with white light?

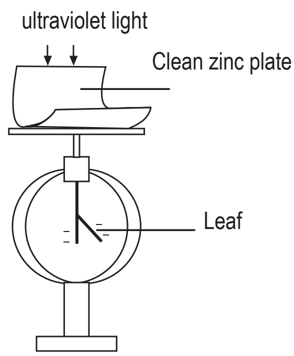


Fig. 1.15

2. Describe with the aid of a labelled diagram an experimental set up to demonstrate photoelectric effect.
3. The energy contained in one photon of radiation is given by the expression $E = hf$. Explain each term in the expression.
4. Define the following terms.

   (a) Threshold frequency (b) Photon

   (c) Electron volt (d) Work function
5. State Einstein's equation of photoelectric effect. Explain all the terms in the equation.
6. Light of wavelength 2.0×10^{-7} m is incident on a metal surface of work function 4.0 eV. Find the maximum velocity of the photoelectrons emitted.
7. A point source gives out a radiation of wavelength 7.5×10^{-7} m at a rate of 0.14 W. Calculate the number of photons that leave the source per second.
8. Fig. 1.14 shows ultraviolet radiation illuminating a zinc plate placed on a positively charged leaf electroscope.

   (a) Show the charge distribution on the electroscope.

   (b) Explain the following observations:

   (i) The leaf does not fall.

   (ii) When the same experiment is performed with a negatively charged electroscope, the leaf falls.

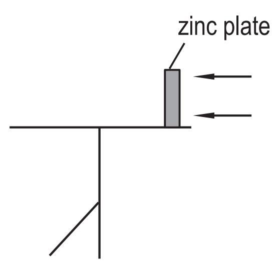


Fig. 1.16

1.5 Factors affecting photoelectric emissions

Activity 1.6 **To find out the factors that affect the emission of photo electrons**

(Work in groups)

Materials

- Reference sources
- Internet

Steps

1. Find out from reference books or the internet three factors that affect photoelectric emission.
2. Explain how each factor affects the photoelectric emission when it is increased or decreased.
3. Present to the rest of the class during class discussion.

A *photocell* is used to study how the factors affect photoelectric emission. A photocell consists of a photosensitive cathode and an anode enclosed in an evacuated container. The symbol of a photocell is shown in Fig. 1.17.

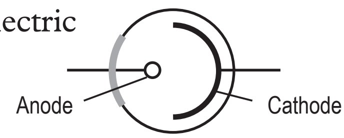


Fig. 1.17: A symbol of a photocell

There are three main factors that affect photoelectric emission.

1. Intensity of the radiation used.
2. Anode-cathode potential difference.
3. Frequency of the radiation used.

Let us examine each of them.

1.5.1 Intensity

Intensity of a radiation is defined as the energy carried by a radiation passing normally through a unit area per unit time.

$$\text{Intensity} = \frac{\text{Energy}}{\text{Area} \times \text{time}}$$

$$= \frac{\text{Power}}{\text{Area}}$$

The unit of intensity is watt per square metre. (W/m^2).

Since radiation spreads out in all directions, the energy carried by such a radiation is also spread out in all directions (Fig. 1.18).

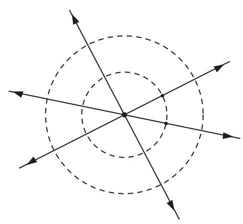


Fig. 1.18: Radiation spreads out in all directions

Fig. 1.19 shows a source of light that spreads out in all directions. Surfaces A, B and C are parts of the surfaces of radii r_A, r_B and r_c. The surface area A is smaller than that of B while B is smaller than the surface area C.

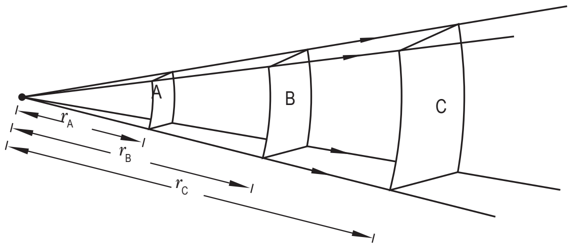


Fig. 1.19: Intensity of radiation

The intensity at A $= \dfrac{\text{Power}}{\text{Area}} = \dfrac{P}{4\pi r^2}$.

It can be seen that the energy at A is spread over a larger area when it arrives at B and even a larger area when it arrives at C. Hence *the intensity decreases* as the light moves away from the source of the radiation.

This shows that intensity is inversely proportional to the square of distance from the source.

.

Activity 1.7 **To investigate the relationship between light intensity and the photoelectric current**

(Work in groups)

Materials

- Photocell
- Source of d.c supply

Steps

1. Write the other materials that you would require in order to carry out this investigation.
2. Write all the steps that you would undertake in the procedure.
3. Set the apparatus as shown in Fig. 1.20. Label the diagrams.

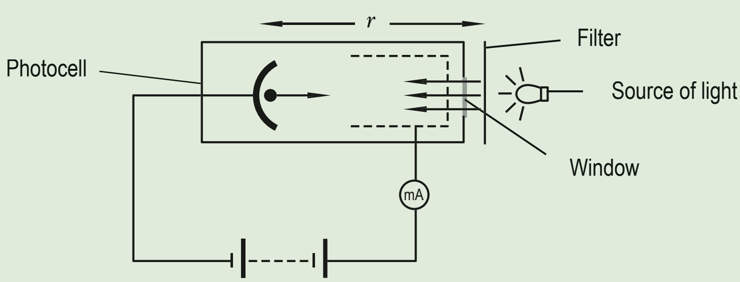


Fig. 1.20: Set up for investigating the effect of intensity on the photocurrent.

4. Measure the photoelectric current *I* and distance, *r*.
5. Let one member of the group record the value of the current, *I*, and the distance, *r*, as shown in Table 1.2.

6. Calculate the value $1/r^2$ in each case and record the values as shown.

Table 1.2

Current I (mA)	Distance r (cm)	$\frac{1}{r^2}$ (cm^{-2})

7. Draw the graph of current against the reciprocal of the square of the distance, ($1/r^2$).
8. From the shape of the graph, describe how the intensity of the radiation affects the photoelectric current. How is the quantity of the current affected when the intensity is doubled?

You may have observed in the activity that as the distance, r decreases, $1/r^2$ increases and the current also increases.

In Fig. 1.21 shows the graph of current I against $1/r^2$.

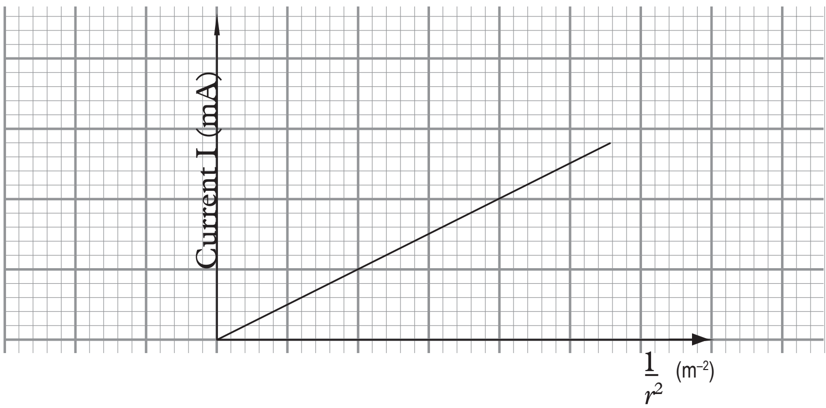


Fig. 1.21:: A graph of current, I, against $\frac{1}{(\text{distance})^2}$

Since current is the rate of flow of electrons, the *number of ejected photoelectrons* also increase. This means that the number of the ejected photoelectrons is *directly proportional to the intensity of the radiation used*.

1.5.2 Anode-cathode potential difference

Activity 1.8 **To investigate the effect of anode-cathode potential difference on photoelectric effect**

(Work in groups)

Materials

- Photocell
- Switch
- Red filter
- Source of visible light
- Variable resistor
- Ammeter
- Voltmeter
- Source of supply

Steps

1. Set the apparatus as shown in Fig. 1.22.

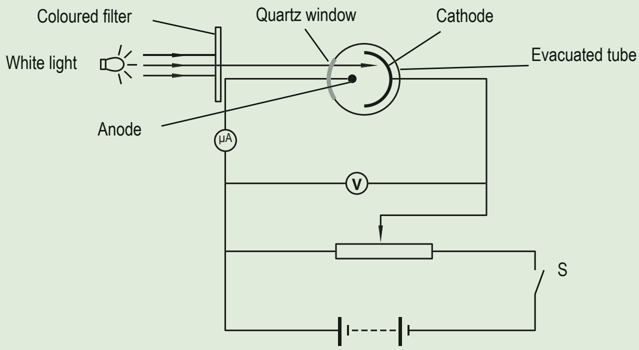


Fig. 9.22: Set to investigating relationship potential difference and photoelectric emission

2. With switch S open, place a red filter between the quartz window and the source of visible light. Which light passes through the filter?
3. Now close the switch and steadily increase the value of potential difference between the anode and the cathode. Give a reason for the change in microammeter reading.
4. Let the group secretary record the potential difference and the corresponding values of the current (Table 1.3). The frequency and the intensity are kept constant.

Table 1.3

	Polarity of the cathode								
	Cathode connected to the positive terminal				Cathode connected to the negative terminal				
P.d (V)									
I (μA)									

5. Reverse the terminals of the battery and repeat the experiment. Suggest a reason for the effect of this on ammeter reading.
6. Plot a graph of the photocurrent, I, against the potential difference, V.
7. Based on the shape of the graph, describe the variation of the photoelectric current with the anode-cathode potential.
8. Appoint one of the group members to make a representation to the rest of the class.

In the activity, red filter allows only the red light to pass through and absorbs all the other colours. This means that light of only one colour (monochromatic) is incident on the cathode. What happens to the microammeter reading? — the microammeter registers a small current although the potential difference between the anode and the cathode is zero. This shows that the photoelectrons are ejected with kinetic energy which enables them to reach the anode. Note that the tube is evacuated to reduce electrons energy loss due to collision with the air molecules inside the tube.

Figure 1.23 shows a typical graph of I against P.d from a similar activity.

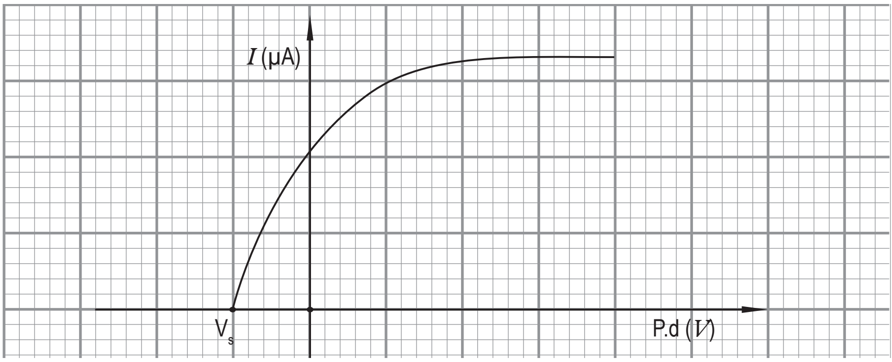


Fig. 1.21: Graph of current, l, against anode-cathode potential difference, V

When the potential difference is zero only the most energetic electrons are able to reach the anode. As the potential difference is increased, more and more electrons are attracted towards the anode hence the current in the circuit increases. However, after a certain potential difference, the current becomes constant. This constant current is called *saturation current*. At this point all the electrons are swept towards the anode as soon as they are ejected.

When the terminals of the battery are reversed the current in the circuit reduces steadily as anode is made more negative until it reaches zero. When the current is zero, it means that the most energetic electrons have been stopped by the retarding voltage applied. This voltage, when no electrons are able to reach the anode, is called *stopping voltage* (V_s). Stopping voltage is a measure of the maximum kinetic energy of the photoelectrons. Therefore:

$$\frac{1}{2}mv^2_{max} = eV_s$$

1.5.3 Frequency of radiation

Activity 1.9 — **To show the effect of frequency on photoelectric effect**

1. Repeat Activity 1.8 with a violet filter (violet light has higher frequency).
2. On the same axis as in Fig. 1.21, plot a graph of current, *I*, against potential difference, *V*.
3. Compare the graphs for red and violet lights and explain the difference in the values of stopping potentials for these two types of lights.
4. Make a representation to the rest of the class.

Fig. 1.24 shows the graphs obtained from a similar activity.

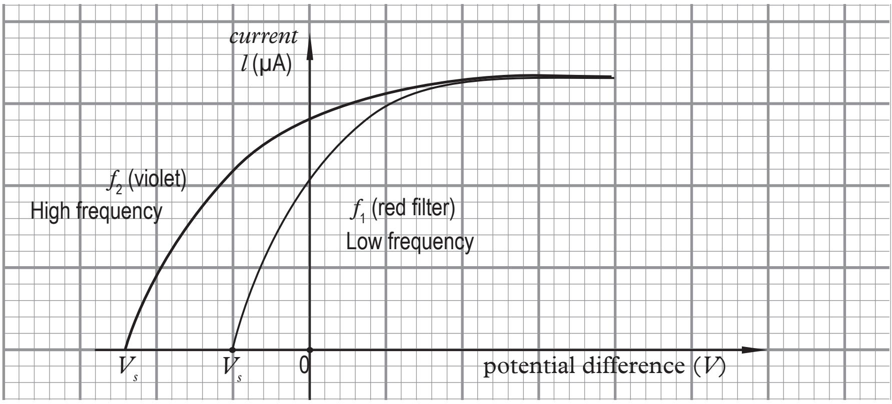


Fig. 1.24: Graph of current, I, against potential difference, V

From the graph, it can be seen that for violet light the stopping voltage, V_s is more negative than V_s for red light. This shows that the electrons of higher maximum kinetic energy are liberated when a radiation of higher frequency is used. Observe that the same saturation current is reached. This means that the number of photoelectrons ejected does not depend on the type of the frequency of radiation. The results of Activities 1.8 and 1.9 can be summarised as follows:

1. When the incident light is monochromatic, the number of photoelectrons emitted per second is proportional to the light intensity. Such an emission occur instantaneously.
2. As the potential difference between the cathode and the anode increases, the photocurrent increases and reaches a constant maximum value called *saturation current*.
3. The kinetic energy of the emitted electrons varies from 0 to a maximum value. This definite maximum value depends only on the frequency of the light and not on its intensity.
4. Electrons are not emitted when the light has a frequency lower than a certain threshold value f_0. The value of f_0 varies from metal to metal.

The above summary may be referred to as *laws of photoelectric effect*. These laws may be deduced from the graph in Fig. 1.25.

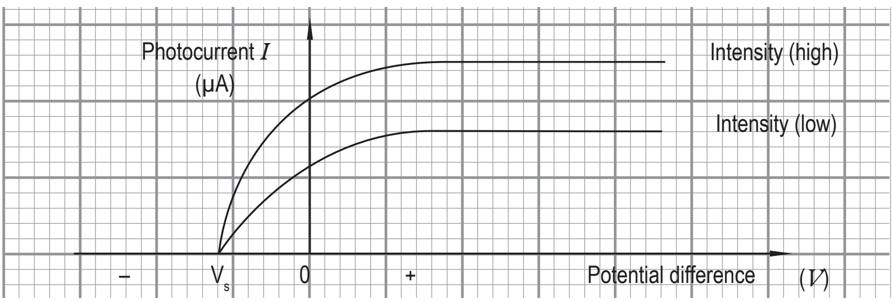


Fig. 1.25: Summary of the laws of photoelectric effect

Activity 1.10 To determine the Planck's constant ***h***, work function ***W*** and the threshold frequency f_0 graphically

(Work in groups)

Materials

- Photocell
- Source of light
- Coloured filters
- Variable resistor
- Voltmeter
- Ammeter
- Source of d.c supply

Steps

1. Set the apparatus as shown in Fig. 1.26.
2. Place the coloured filters in turns, one after the other and record the stopping voltage and the corresponding frequency in each case (Table 1.4).
3. Calculate the kinetic energy, in joules, of the emitted photoelectrons.

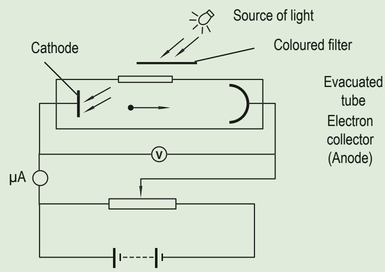


Fig. 1.26: Determination of work function, W and threshold frequency

4. Let the group secretary write your results in Table 1.4.

Table 1.4

Filter	Frequency, $f \times 10^{14}$ (Hz)	Stopping potential, V_S (V)	Energy, eV_S
Red	4.3		
Orange	4.8		
Yellow	5.3		
Green	5.8		
Blue	6.6		
Violet	7.5		

5. Plot a graph of energy, eV_S against frequency, f.
6. Determine the slope of a graph, and use it to determine Planck's constant of the metal.
7. From the intercepts of the graph on the axes, determine the work function and threshold frequency of the metal.

A sample graph of eVs against frequency, f is as shown in Fig. 1.27.

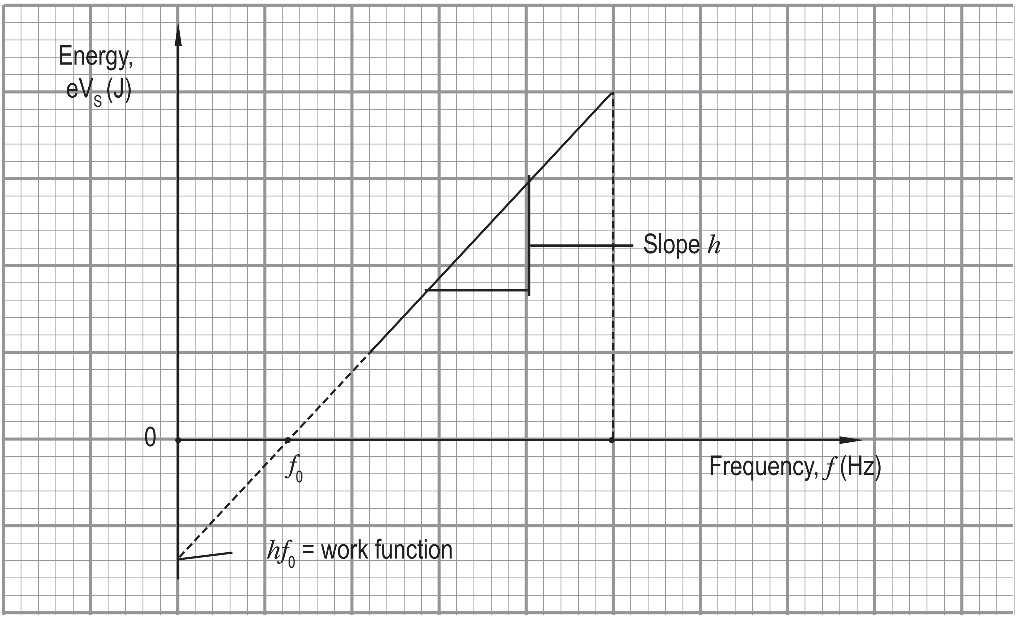


Fig. 1.27: A graph of energy (eV_S) against frequency (f)

The slope = $\frac{eV_S - 0}{f - f_0}$ .... equation (1)

Rearranging equation (1)

eV_S = slope $\times (f - f_0)$ .... equation (2)

Comparing equation (2) with Einstein's equation of photoelectric effect i.e

$eV_S = hf - hf_0$ and comparing with that $y = mx + c$,
we see that the slope = h and the y-intercept = hf_0.
But hf_0 = work function W.

Therefore, the Planck's constant, h, can be calculated from the slope of the graph. The work function, W, can be read from the y-intercept. The x-intercept gives the threshold frequency, f_0.

When the metal used in Activity 1.10 as a cathode is replaced with different metals, straight line graphs similar to that of Fig. 1.26 are obtained for each metal.

Since the different metals have different threshold frequencies their graph start at different points on the x-axis. However, they have exactly the same slope as shown by the parallel lines in Fig.1.28. This is because the Planck's constant, *h*, is the same for all.

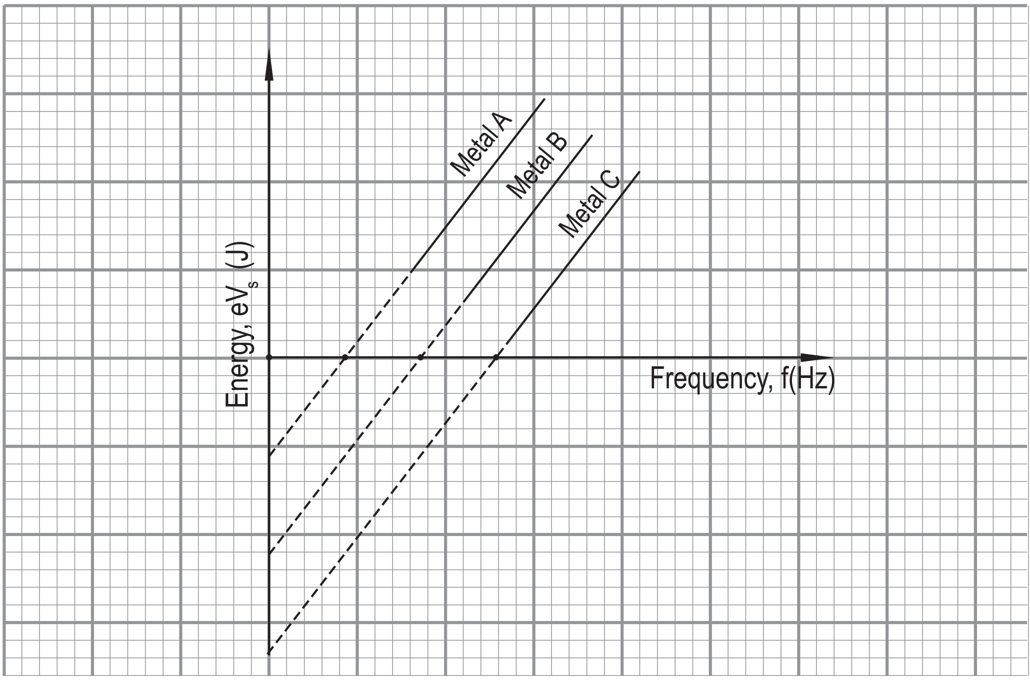


Fig. 1.28: Different metals have different threshold frequencies but show the same value of h.

Example 1.10

Fig. 1.26 shows the graph of stopping voltage against frequency for a radiation falling on a photosensitive surface. Given that $e = 1.6 \times 10^{-19}$C determine the:

(a) Threshold frequency.

(b) Planck's constant, *h*.

(c) Work function of the metal.

Solution

Extrapolate the line by a dotted line to cut the x-axis and the y-axis as shown.

(a) f_0 = x-intercept

= 4.5×10^{14} Hz

(b) $eV_S = hf - hf_0$

$V_S = \frac{h}{e}f - \frac{h}{e}f_0$

Slope $= \frac{h}{e}$

$h = e \times$ slope

$= 1.6 \times 10^{-19} \times \frac{2.0}{5 \times 10^{14}}$

$= 6.4 \times 10^{-34}$ Js

(c) $\frac{h}{e}f_0$ = y-intercept $= \frac{W}{e}$

$W = e \times$ y-intercept

$= 1.6 \times 10^{-19} \times 1.8$

$= 2.88 \times 10^{-19}$ J

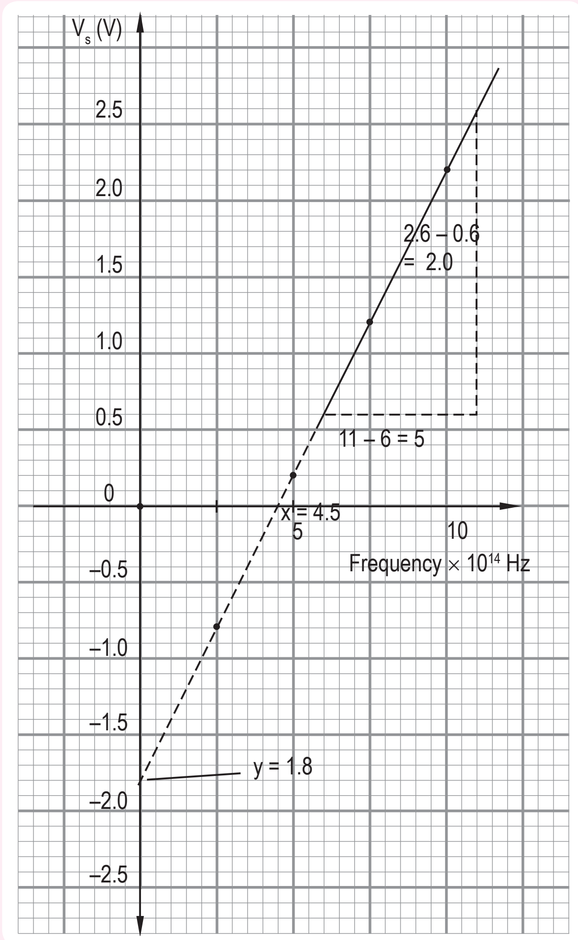


Fig. 1.29

Exercise 1.3

1. Describe the term 'intensity of light'.
2. Describe an experiment to show that the intensity of a radiation follows the inverse square law.
3. Ultraviolet light is incident on a metal surface. Sketch a graph of:
   (a) Current against time of exposure of the metal when potential difference and intensity are held constant.
   (b) Current against light intensity when potential difference is held constant.
   (c) Current against the potential difference.
4. Fig. 1.30 shows a set up to investigate photoelectric effect. Sketch on the same axes the graph of current against the applied potential difference in photoelectric effect for red, blue and violet filters.
   (a) Explain what would happen if the intensity of light is increased.
   (b) Indicate the stopping voltage for each filter.

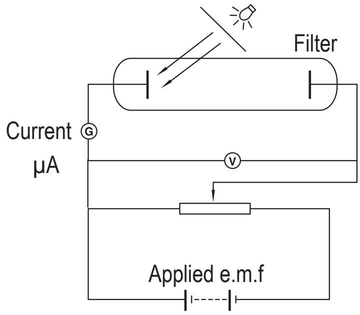


Fig. 30

5. Table 1.5 shows the values of stopping voltage and radiation frequency on a clean metal surface.

Table 1.5

Stopping voltage (V)	0.6	1.0	1.4	1.8	2.2
Frequency × 10^{14} (Hz)	6.05	7.00	8.00	8.9	9.8

   (a) Draw a graph of stopping voltage against frequency.
   (b) Determine: (i) threshold frequency (ii) the Planck's constant, *h*.
6. The diagram in Fig. 1.31 shows the set up used to investigate the photoelectric effect.
   (a) Label parts A, B, C, and D.
   (b) What is the functions of the part labelled E?
   (c) Explain the adjustment that is needed on the setup so as to measure the maximum speed of the photoelectrons emitted.

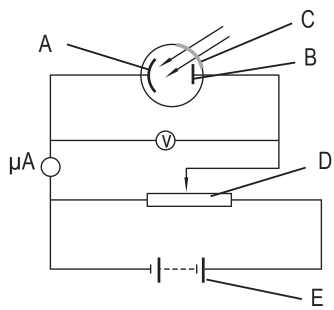


Fig. 1.31

(d) Why is the tube fitted with a quartz window and not a glass window?

(e) Explain why the tube is evacuated.

(f) Using appropriate diagrams describe experiments that would give results as depicted in each of the graphs in Fig. 1.32.

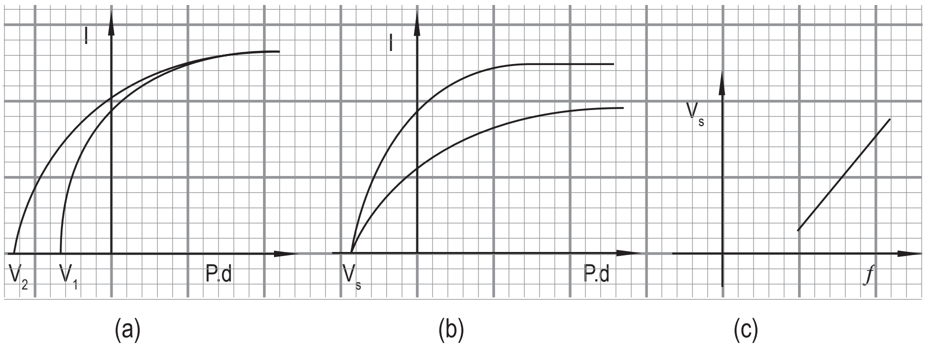


Fig. 1.32

7. (a) State two factors which determine the speed of photoelectrons emitted by a metal surface.

(b) A photosensitive cathode of work function 2.1 eV is illuminated with a radiation of wavelength 4.5×10^{-7} m. Find the voltage that would be needed to reduce the current to zero.

8. State the laws of photoelectric effect. Outline an experiment you would perform to determine:

(a) work function W,

(b) threshold wavelength λ_o,

(c) Planck's constant h,

(d) electronic charge e.

9. The graph in Fig. 1.33 shows the relationship between the anode–cathode potential difference and the frequency of incident radiation in a photocell.

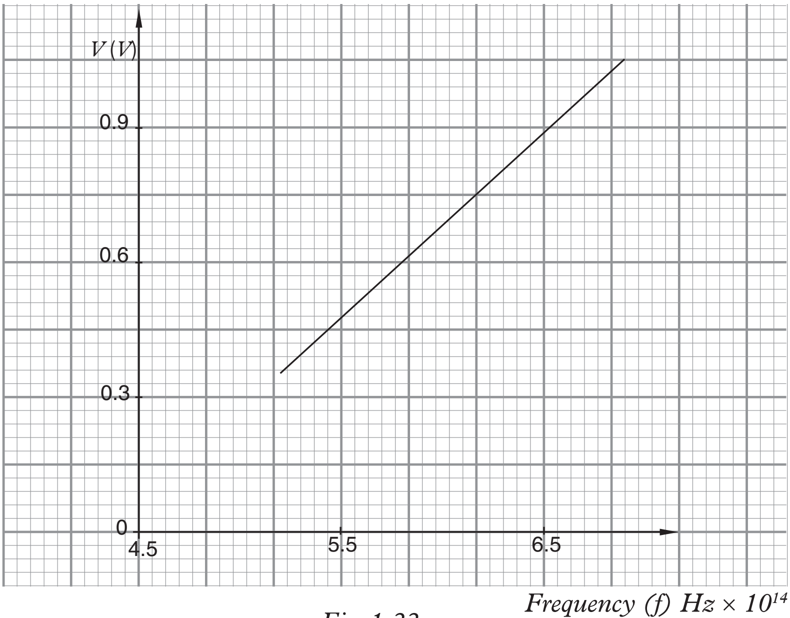


Fig. 1.33

(a) Draw a circuit diagram that may be used to obtain this relationship.
(b) Explain how the results were obtained.
(c) From the graph, determine the:
   (i) value of Planck's constant,
   (ii) threshold wavelength,
   (iii) minimum energy needed to cause photoelectric emission.

1.6 Applications of photoelectric effect

Activity 1.11 **To find out the applications of photoelectric effect**

(Work in groups)

Materials

- Reference books
- Resource persons
- Internet

Steps

1. Based on the ideas acquired on photoelectric effect, suggest two applications of photoelectric effect you can think of.
2. Now, conduct research from reference books, internet or resource persons on the applications of photoelectric effect including the working of solar panels and burglar alarms.
3. Appoint one of the group members to present your findings to the whole class during the class discussion.

Photoelectric effect is applied mainly in photocells. A photocell converts electromagnetic radiation directly into electrical energy. Let us consider three types of photocells:

1. Photoemissive photocells.
2. Photoconductive photocells.
3. Photovoltaic photocells.

1.6.1 Photoemissive cell

A photoemissive cell consists of a cathode and an anode plate. These two plates are enclosed in a glass bulb that may be evacuated or contain an inert gas at low pressure (Fig. 1.34).

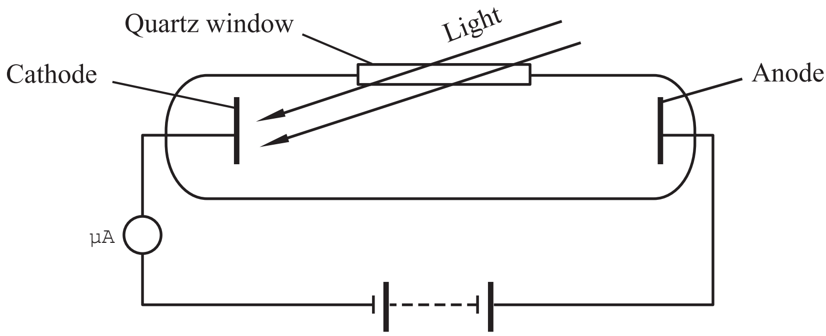


Fig. 1.34: A photoemissive cell

The cathode, often called *photocathode*, is coated with a photosensitive material. The material to be used for cathode surface depends mostly on the frequency range within which the cell is to operate. Most photocathode surfaces are composite materials of alkali earth metals. For example, caesium or oxidised silver is used with infrared radiation. In this type of a photocell, electrons are emitted from the cathode once light of enough energy falls on the cathode. The electrons ejected from the cathode are attracted by the anode. The current that flows in the circuit is in the order of microamperes. The photocurrent increases with the intensity of the incident radiation. The cell with inert gas at low pressure produces greater current. However, the cell is slow in responding to very rapid changes of radiation. This makes it unsuitable for some purposes. The cell is best used in situations where the radiation falling on the cell is interrupted. Some of the situations where the cell is applied are:

1. Automatic counting of items and in automatic opening of doors. Every time a person or an object intercepts the radiation, the current in the cell switches off. In case of counting, the counter moves up by one unit.

2. Sorting out items on a factory belt.
3. Reproduction of sound from a film.

Fig. 1.33 shows how a photocell is used in the production of sound in films. Light is focused on the sound track at the side of the moving film and then falls on a photocell (Fig. 1.35 (a)). The intensity of light passing through depends on the width of the transparent part of the sound track (Fig. 1.32 (b)). This causes the photocell to produce a varying current that is a true copy of that in the sound track. A varying potential difference that develops across the resistor R is amplified and converted to sound by the loudspeaker.

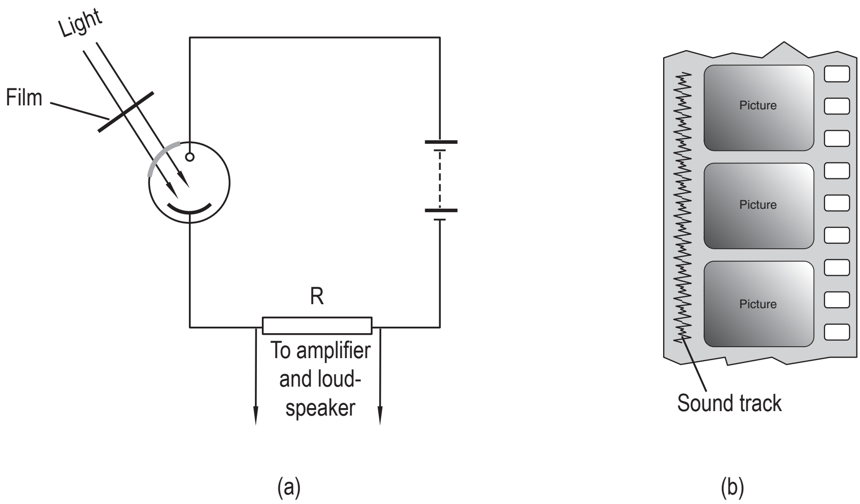


Fig. 1.35: Sound reproduction from a film

4. Burglar alarm.

   When light falling on the photocell is interrupted, no current flows in the circuit. This triggers off the relay system and the siren or bell is switched on (Fig. 1.36).

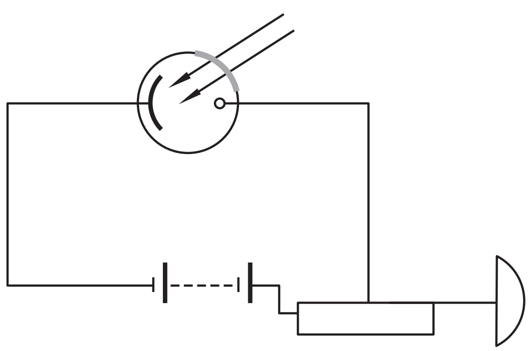


Fig. 1.34: A sketch of a burglar alarm relay system

1.6.2 Photoconductive cell

A photoconductive cell is also known as *light dependent resistor* (LDR). Its resistance decreases as the intensity of the radiation falling on it increases i.e. incident light set the electrons free and hence reduce its resistance.

A common form of a photoconductive cell consists of a pair of interlocking comb-like electrodes made of gold placed on glass (Fig. 1.37 (a)). A thin layer of a semiconductor e.g. cadmium sulphide or selenium is deposited on the interlocking electrodes (Fig. 1.37 (b)). A glass window is placed over them. This cell is used in an alarm circuits and also in exposure meters in cameras. Fig. 1.37 (c) shows the circuit symbol for LDR.

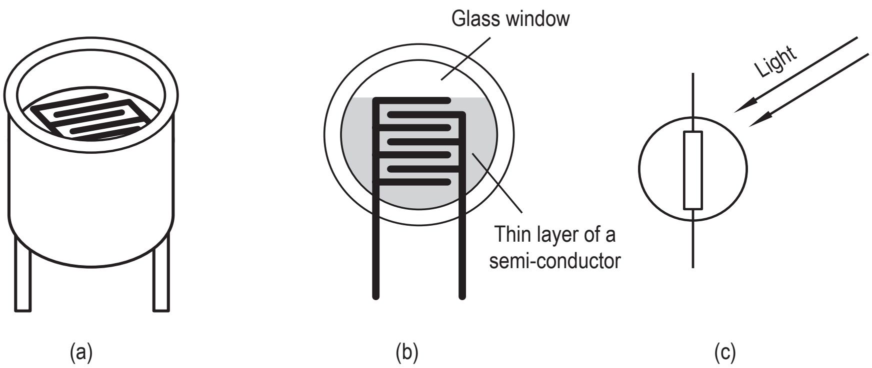


Fig. 1.37 A photoconductive cell

1.6.3 Photovoltaic cell

As the name suggests, the cell generates an electromotive force between two terminals when light shines on it and can therefore provide a current without a battery. It consists of a very thin film of metal e.g. gold, which is deposited on a layer of semiconductor material e.g. copper oxide. (Fig. 1.38)

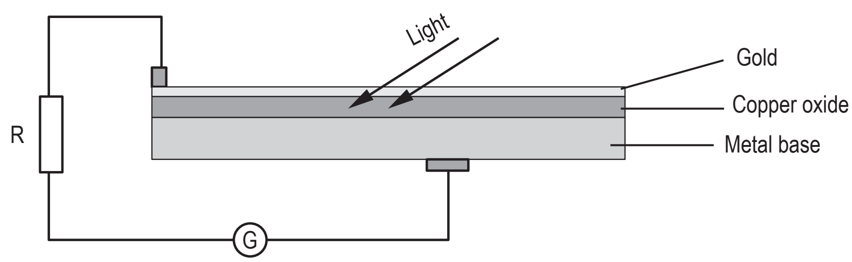


Fig. 1.38: A photovoltaic cell

Since the film of metal is very thin, it allows light to pass. Photoelectrons are ejected from copper oxide and a current flows through the resistor R. These types of cells are sensitive to visible light hence suitable in exposure meters of cameras used in photography. These meters measure the amount of light entering a camera. Photovoltaic cells have been used to power satellites and space station sky lab.

1.7 De Broglie wavelength equation

Activity 1.12 **To analyse De Broglie wavelength equation**

(Work in pairs)

Materials

- Reference sources

Steps

1. Light exhibits both wave and particle behaviour. Support this argument.
2. Research from reference books or internet on De Broglie wave equation. What is the significance of this equation.
3. Make a presentation to the rest of the class.

In some situations, light behaves like a wave while in others, it behaves like particles. As we have already learnt, the particles are called *photons*. This photons can be thought of as both wave and particles.

Louis de Broglie (1892 - 1987) developed a formula to relate this dual wave and particle behaviour. The formula relates the wavelength to the momentum of a Broglie particle.

The formula states that, at non-relativistic speed, the momentum of a particle is equal to its rest mass, m, multiplied by its velocity, v, that is;

$$\text{De Broglie wavelength} = \frac{\text{Planck's constant}}{\text{Momentum}} = \frac{\text{Planck' s constant}}{\text{Mass} \times \text{Velocity}}$$

$$\lambda = \frac{h}{p} = \frac{h}{mv}$$

where; the De Broglie wavelength (in metres)

h = planck's constant (6.63 x 10^{-34} Js)

p = momentum of the particle ($kgms^{-1}$)

m = mass of a particle (kg)

v = velocity of a particle (ms^{-1})

The unit of the De Broglie wavelength is metre (m), though it is often very small, and so expressed in nanometres (1nm = 10^{-9}m), or Agstroms ($\mathring{A} = 10^{-10}$m).

De Broglie wavelength equation can also be applied to other particles like electrons and protons that have mass. We will learn about this at higher levels.

Example 1.11

A certain photon has momentum p = 1.50 x 10^{-27} kgmls. What is the photon's De Broglie wavelength?

Solution

$h = 1.63 \times 10^{-34}$ Js, P = 1.50 x 10^{-27}kgm^{-1} λ =?

$$\lambda = \frac{h}{p}$$

$$= \frac{(6.63 \times 10^{-34}\ \text{Js})}{(1.50 \times 10)\ \text{kgm/sj})}$$

$$= \frac{(6.63 \times 10^{-34}\ \text{kgm}^2/\text{s})}{(1.50 \times 10\text{-}^{27})\ \text{kgm/sI}}$$

$$= \frac{(6.63 \times 10^{-34})}{(1.50 \times 10\text{-}^{27})}\ \text{m}$$

$$= 4.42 \times 10^{-7}\text{m}$$

$$= 442 \times 10^{-9}\ \text{m} \quad \text{or } 442\ \text{nm}$$

Exercise 1.4

1. With a well-labelled diagram, briefly explain how photoemissive cell is used as burglar alarm.
2. The De Broglie Wavelength of a certain electron is 2.60 Angstroms.

   ($\mathring{A} = 10^{-10}$m). The mass of an electron is me = 9.109×10^{-31}kg. What is the magnitude of the velocity of the electron?

Project work 1.1: Construction of a burglar alarm

Materials needed

Photocell, (lithium cathode), soft iron, alarm system e.g. a bulb or a bell, dry cell, spring, a 6 V d.c. power supply, connecting wires, permanent bar magnets

Assembly

Connect the circuit as shown in Fig. 1.39.

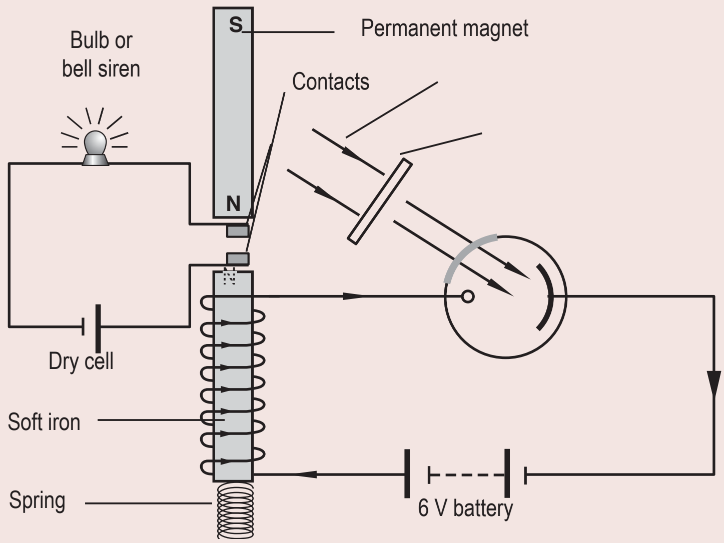


Fig. 1.39: Burglar alarm

How it works

When light falls on the cathode a current flows in the circuit. This makes the soft iron core to be magnetised. Repulsion takes place and the spring is then compressed maintaining an open circuit of the alarm system circuit. When an intruder blocks light from reaching the cathode, the soft iron core losses its magnetism. The permanent magnet attracts the soft iron. Also the spring presses the contact together, completing the alarm system circuit; switching on the alarm.

Topic summary

- An atom consists of nucleus and electrons orbiting around a nucleus.
- Electrons in an atom are at different energy levels.
- An electron at the lowest energy level is said to be at ground state while that at the higher level is said to be at excited state.
- Excitation is the process by which electrons gain energy to move from a lower to a higher energy level.

- Ionisation is the process where when an electron gets enough energy to move from the atom.
- Electromagnetic radiation is emitted or absorbed in form of 'packets' or quanta of energy called photons.
- Metals can lose electrons (photoelectrons) when irradiated by some electromagnetic radiations. This process is called photoelectric effect.
- Work function is the minimum energy required to eject an electron from the metal surface
- Einstein's photoelectric equation in photoelectric emission is given by:

$$hf = hf_0 + \frac{1}{2}mv^2_{max}$$

- Threshold frequency f_0, is the minimum frequency photons should have to effect the emission of electrons. The energy of a photon with threshold frequency f_0 is equal to the work function W, of the metal i.e. $W = hf_0$.
- Einstein's equation may also be written as:

$$hf = W + eV_S$$ where V_S is the stopping voltage.

Therefore, $eV_S = hf - W$

$$\frac{1}{2}mv^2_{max} = eV_S$$

- The number of photoelectrons emitted depends on the intensity AND NOT frequency of the radiation.
- The maximum kinetic energy of a photoelectron depends on the frequency used AND NOT the intensity.
- Photocells use the photoelectric effect. They convert light energy directly into electrical energy.
- De Broglie wavelength equation is written as

$$\text{De Broglie wavelength} = \frac{\text{Planck's constnt}}{\text{Momentum}} = \frac{h}{mv}$$

Topic Test 1

(Take $c = 3 \times 10^8$ m/s and $h = 6.6 \times 10^{-34}$ Js, where necessary).

1. Write down Einstein's equation of photoelectric emission. Give the meaning of each term used.
2. State three factors that affect photoelectric effect.
3. Give the conditions necessary for:
   (a) electrons to be emitted from the cathode of a photocell.
   (b) electrons to reach the anode of a photocell.
4. A beam of light has a wavelength of 4.7×10^{-7} m. Calculate its energy in:
   (a) joules, (b) electron volt.

5. Calculate the wavelength of a light photon of energy 1 electron volt.
6. A certain metal has a threshold wavelength of 4×10^{-7} m. Calculate the work function of the metal.
7. A metal of work function 6.0 eV is illuminated with light. If the electrons emitted have a maximum speed of 1×10^{6} m/s, calculate the wavelength of the light used.
8. A metal surface is irradiated with a radiation of frequency 6.0×10^{14} Hz and then with a radiation of energy 3.2×10^{-19} J. The maximum kinetic energy of the electrons emitted by the radiations are 2.8×10^{-19} J and 2.0×10^{-19} J respectively. Determine the value of the Planck's constant.
9. The stopping voltage of a metal illuminated with a radiation of wavelength 4×10^{-7} m is 0.3 V. Calculate the work function of the metal.
10. Explain how photoelectric effect is used in:
    (a) sound reproduction from films.
    (b) automatic sorting out of items on a factory belt
    (c) photography.
    (d) burglar alarm.
11. A photocell has a cathode made of caesium metal which is enclosed in an evacuated space. When a monochromatic radiation is shone on the cathode, photoelectrons are emitted. The kinetic energy of the most energetic electrons is measured when radiation of various known frequencies is used. The graph of the kinetic energy against the frequency is shown in Fig. 1.38.

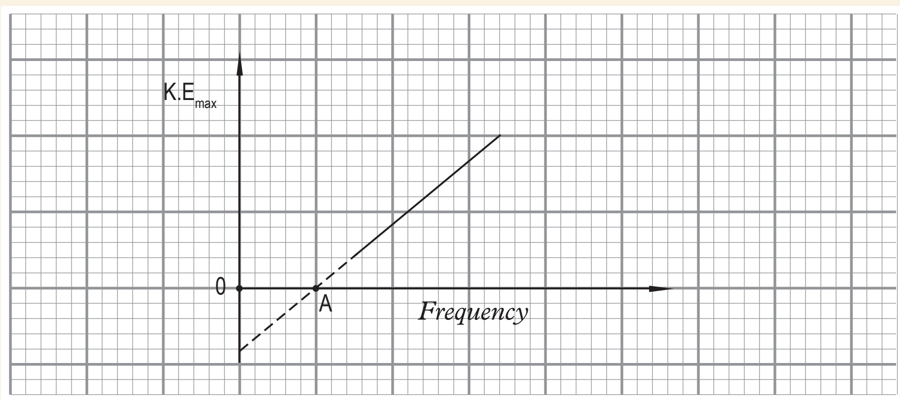


Fig. 1.40

    (a) Describe with aid of a diagram how the experiment was carried out.
    (b) What quantity is obtained from the slope?
    (c) What physical quantity is represented by point A?

(d) What does the term monochromatic mean?

(e) Lithium metal has a higher work function than caesium. On the same set of axes, sketch the graphs of stopping potential against frequency for lithium and caesium.

(f) Explain the statement, "When a photosensitive metal is irradiated with a radiation, the photoelectrons emitted have energies ranging from zero to a certain maximum."

12. (a) State the factors that affect tphotoelectric emission.

(b) A metal surface was illuminated with light of different wavelengths. Values of the maximum kinetic energy of the emitted photoelectrons were determined for each wavelength. The results obtained are tabulated in Table 1.6.

Table 1.6

$\lambda \times 10^{-9}$ (m)	365	404.7	435.8	479.7	546.1
max. k.e (eV)	1.32	0.98	0.77	0.50	0.19

Draw a suitable graph to determine:

(i) Maximum wavelength for which photoemission can be observed for the metal.

(ii) Speed of light.

(iii) Work function for the metal.

13. (a) Describe a simple experiment to illustrate photoelectric emission.

(b) Describe with aid of a diagram an experiment to measure the maximum kinetic energy of photoelectrons.

(c) In an experiment involving photoelectric emission from a clean metal surface the following measurements were obtained as shown in Table 1.7.

Table 1.7

Stopping voltage V_s(V)	0.2	0.6	1.0	1.6	2.2
Frequency $f \times 10^{14}$ (Hz)	8.2	9.10	10.00	11.5	13.00

(i) Why should the metal surface be clean?

(ii) Explain how you would change the frequency without changing the source of radiation.

(iii) Plot a graph of stopping potential V_S against frequency f and determine:

I Planck's constant.

II Work function of the metal.

UNIT 2 The nature of electrostatics

Topic 2: Electrostatics

Learning outcomes

Knowledge and understanding

- Understand the nature of electrostatics.
- Know that an electric field has magnitude and direction.

Skills

- Investigate the constituents of an atom, the position of nucleus, electrons and protons.
- Investigate the process of electrification using different methods .
- Investigate the process of capacitors.
- Use Coulomb's law to calculate the forces between charges.
- Use the formula for electron volts to calculate the energy change when particles move in an electric field.
- Solve problems on series and parallel connection of capacitors.

Attitude and value

- Appreciate the importance of electrostatics.

Key inquiry questions

- How can we test the presence of charges on an object?
- Why are alpha particles directed towards an atom of an element deflected away from the centre of the atom?
- Why is charging by induction temporary?
- How does lightning conductor protect our house from lightning strikes?
- Why is it easy to charge polythene by rubbing, but not copper?
- How can we charge and discharge capacitors.

Topic 2 Electrostatics

Topic outline

2.1 The origin of charge

Activity 2.1 To investigate the constituents of an atom

Instructions

In this activity, you are required to investigate the constituents of an atom using materials of your own choice. You may rely on prior knowledge acquired in Unit 1 of this book and what you learnt in Secondary 2 Chemistry.

1. From the knowledge:

(a) Describe the structure of an atom.

(b) Sketch the structure of a carbon atom on a manilla paper.

(c) Place the materials suggested on the sketch to represent the different particles in a carbon atom.

2. Explain to your partner how an atom charges.

In Topic 1, we learnt that matter is made up of tiny particles called *atoms*.

An atom is made up of two parts: a central core called the *nucleus,* and outer orbits where electrons go round the nucleus. The nucleus contains protons and neutrons that are closely and tightly packed (Fig. 2.1). The electrons are extremely light compared to protons and neutrons. They carry a *negative charge*. Protons carry a *positive charge*. Neutrons carry *no charge*. The number of protons and electrons in an atom are equal and hence an atom is electrically neutral.

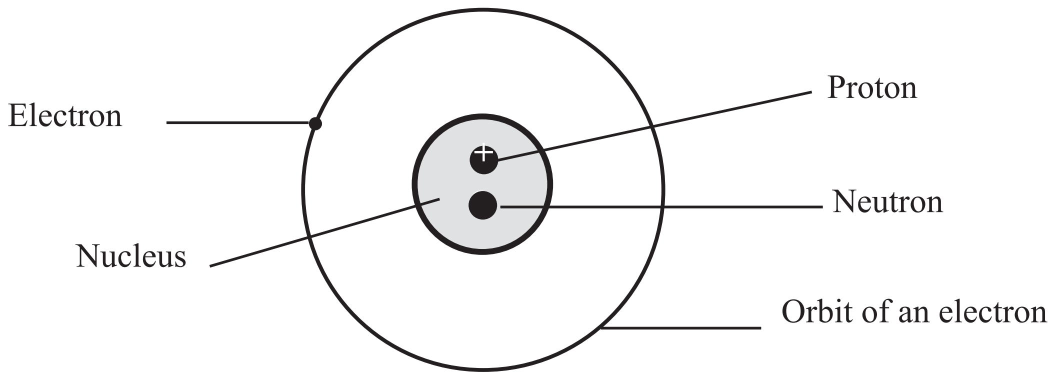


Fig. 2.1: Structure of an atom

When an atom losses electrons, a net positive charge is left (i.e. it becomes positively charged). The atom that gains electrons becomes negatively charged.

In Secondary 1, we learnt that like charges repel while unlike charges attract as summarised in the law of electrostatics. This knowledge will help us to explain how objects are charged using different methods.

2.2 Methods of charging objects

(a) Charging by friction method

Activity 2.2 **To charge a body by friction**

(Work in groups)

Materials

- A pen
- A polythene rod

Steps

1. Take a pen near to small pieces of paper or tissue. What do you observe? Explain. Does it attract the pieces of paper?
2. Now, rub the pen on your hair and take it near the small pieces of paper or tissue. What do you observe in this case? Explain what happened to the hair and the pen during rubbing.
3. Repeat Steps 1, 2 and 3 using the polythene rod. Compare the observations in each case with the corresponding observations for the plastic pen? Between the pen and the polythene rod, which one is easier to charge under the same condition?
4. Let one of your group members make a presentation of your results to the rest of the class.

Secondary 1 Student's Physics Book, Topic 7 gave an introduction to static electricity. This topic shall give an introduction into electrostatics.

In activity 2.2 above, you may have observed that, nothing happens when the pen is brought near the small pieces of paper in the first step. However, in the second step, when it was rubbed against the hair it attracted pieces of paper. This is because it got charged i.e gained charges while the pieces of paper are neutral.

In general, when two *materials* are rubbed against each other, the heat energy developed due to friction, can move some of those loosely held electrons from one material and transfer them to the other i.e. the electrons may be *rubbed off* from one material to the other because in some materials, the electrons are not tightly bound to the nucleus.

Materials like polythene *gain* electrons from flannel cloth (cotton wool) when rubbed and become negatively charged. Flannel cloth *loses* electrons and becomes positively charged (Fig. 2.2).

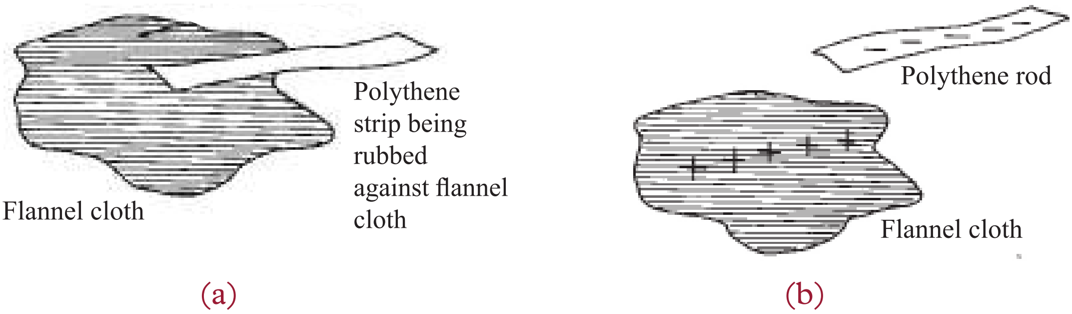


Fig. 2.2: Rubbing polythene against flannel cloth

Materials like glass *lose* electrons when rubbed with silk cloth and become positively charged. The silk material gains electrons and becomes negatively charged (Fig. 2.3).

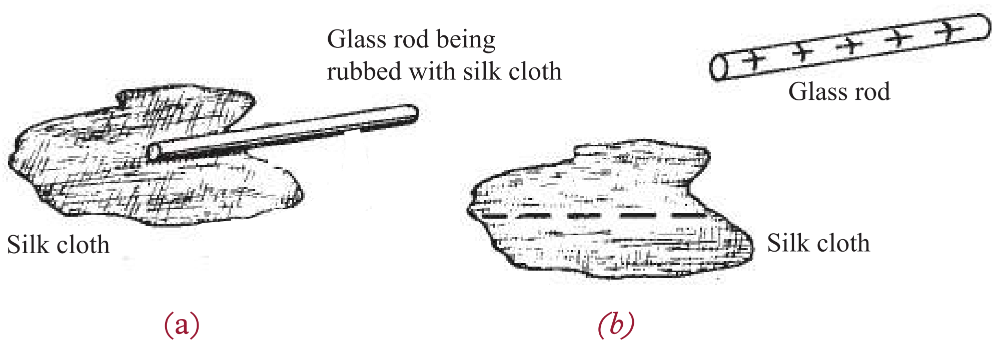


Fig. 2.3: Rubbing glass against silk cloth

A body is said to be negatively charged if it has an excess or surplus of electrons. It is said to be positively charged if it has a deficiency or shortage of electrons.

It is important to note the following when materials are charged by friction method:

- The excess negative charges on one body is equal to the excess positive charges on the other. No new charges have been created.
- During the rubbing process, some materials always acquire the same kind of charge whereas some materials may acquire either negative or positive charges.
- The quantity of charge produced in some cases may be small and in some cases the charges may escape before they are detected. A dry atmosphere and a clean dry state of the body are essential for holding the electrical charges.

Experiments show that the nature of charge on a rubbed body depends upon the nature of the rubbing material. From experience, physicists have classified the substances in a particular order. The list in Table 2.1 shows such a classification where the substance higher in the list acquires a negative charge while the lower one acquires a positive charge. The table only covers some commonly used substances.

Polythene
Ebonite
Metals
Silk
Flannel or wool
Glass
Fur

Table 2.1: Classification of substances

Example 2.1

Polythene is rubbed with wool. What charge does:

(a) polythene acquire?

(b) wool acquire?

Solution

(a) Polythene acquires negative charge because polythene is higher in the list than wool.

(b) Wool acquires a positive charge.

Example 2.2

Glass is rubbed with silk. What charges do the two materials acquire?

Solution

Glass is lower in the list than silk. Therefore, glass acquires positive charge while silk acquires a negative charge.

Exercise 2.1

1. (a) Name three particles that are found in an atom.
   (b) What is meant by 'neutral body' in electrostatics?
2. Name two types of charges and state the SI unit of electric charge.
3. (a) Explain how an object becomes positively charged when rubbed using another material.
   (b) What type of material is most likely to keep its charges?

(b) Charging by induction method

Activity 2.3 To charge a body by induction method

(Work in groups)

Materials

- Insulated metal sphere
- Conducting wire
- Glass rod
- Polythene rod

Steps

1. Rub a glass rod with silk cloth. What type of charges does it acquire?
2. Bring the charged glass rod close to but not touching the insulated uncharged metal sphere (Fig. 2.4 (a)).

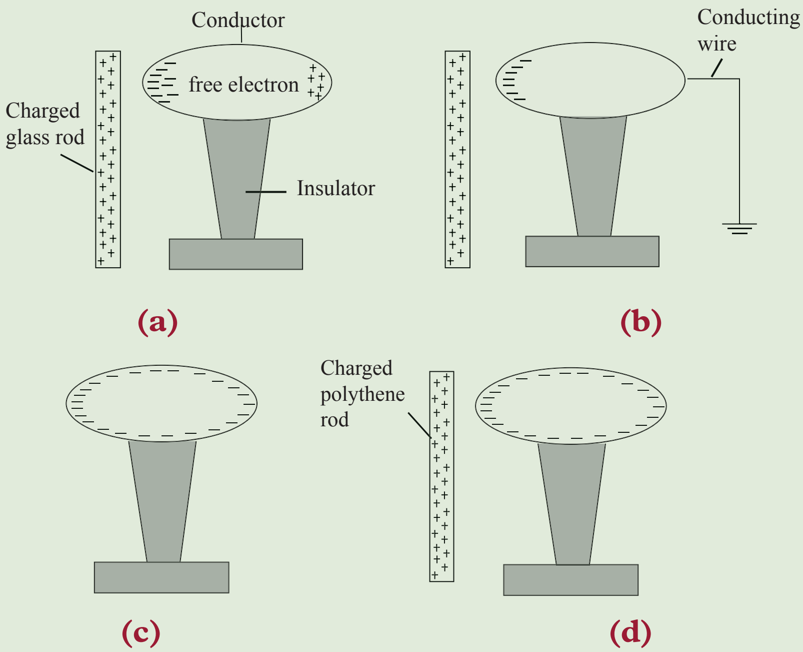


Fig. 2.4: Charging a conductor by induction method

3. Touch the metal sphere with a conducting wire on the opposite side and connect the wire to the ground (Fig. 2.4 (b)). What do we call this process? What happens during this process?
4. While holding the glass rod near the sphere, withdraw the conducting wire first then the glass rod (Fig. 2.4 (c)). Explain what would happen if the glass rod was removed before the conducting wire?

5. Bring a charged polythene and the charged glass rods in turns close but not touching the sphere (Fig 2.4 (d). Observe and explain what happens in each case.

From your discussion, you should have established that the glass rod becomes positively charged when rubbed against a silk cloth. When the rod was brought near the insulated conductor, the negative charges on the conductor were attracted (Fig. 2.4(a)The process is called *electrostatic induction*.

When the sphere was earthed (connected to the ground with the wire) the negative charges moved from the earth into the sphere and neutralised the positive charges on one side of the sphere (Fig. 2.4 (b)).

When the rod was removed, the negative charges redistributed themselves uniformly on the surface of the conductor (Fig. 2.4 (c)).

In Step 5, the conductor has been charged. The charge on the conductor is opposite to that of the charged glass rod. This is because it attracts the glass rod (positively charged) and it repels the polythene rod (negatively charged). There is always attraction between charged bodies and neutral bodies.

This method of charging objects is called *induction method*. The charge acquired by the conductor being charged is opposite to that of the charging rod.

(c) Charging by contact (conduction) method

Activity 2.4 **To charge a body by contact method**

(Work in groups)

Materials

- Insulated uncharged metal sphere
- Conducting wire
- Glass rod
- Polythene rod

Instructions

1. Using the set-up in Fig. 2.5 and the materials provided above, write a procedure you would use to charge an uncharged conductor positively.

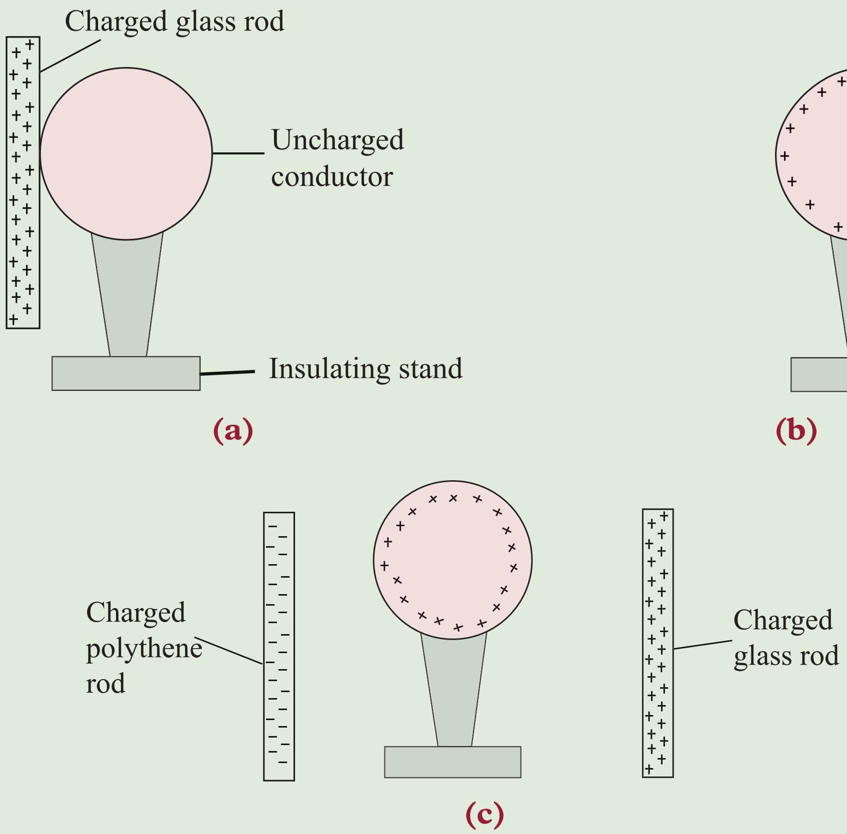


Fig. 2.5: Charging by contact method

2. In each step, explain what happens to the charges on the conductor i.e Fig. 2.5(a) and (b).
3. What is the importance of the charged glass and polythene rods? How are they used in charging the body?
4. Have a discussion on your observation in all the steps. Note down your findings.
5. Have a class presentation on your findings.

In Activity 2.4, you should have observed that when a positively charged glass rod is brought in contact to the conductor, they share the available electrons resulting to deficiency of negative charges in the sphere i.e. positive charges are retained on the conductor. (Fig. 2.5(a)).

When the positively charged glass rod is removed (contact broken), the deficiency of the electrons is distributed on the whole metal making it positively charged.

The positively charged conductor repels the glass rod and attracts the polythene rod when they are brought close to it one at a time.

Therefore, the conductor becomes charged by *contact method*. The charge on the ball is the same as the charge on the charged glass rod (charging rod).

(d) Charging by contact separation method

Activity 2.5 **To charge a body by separation method**

(Work in groups)

Materials

- Two metal spheres (A and B)
- Polythene rod

Steps

1. Place two neutral identical metal spheres on insulating stands in contact with each other (Fig. 2.6 (a)). Explain what happens to the positive and negative charges in two spheres.
2. Bring a charged polythene rod close but not touching sphere A (Fig. 2.6(b)). Explain what happens to the positive and negative charges in the two spheres.
3. Separate spheres A and B while holding the charged polythene rod in position. (Fig. 2.6(c)). What happens to the charges in the two spheres?
4. Remove the polythene rod (Fig. 2.6(d). Identify the charge on each sphere.
5. Test and identify the charges on the two spheres (A and B). Use a negatively charged polythene rod to observe what happens.
6. Hold a discussion on your observations in Step 5.

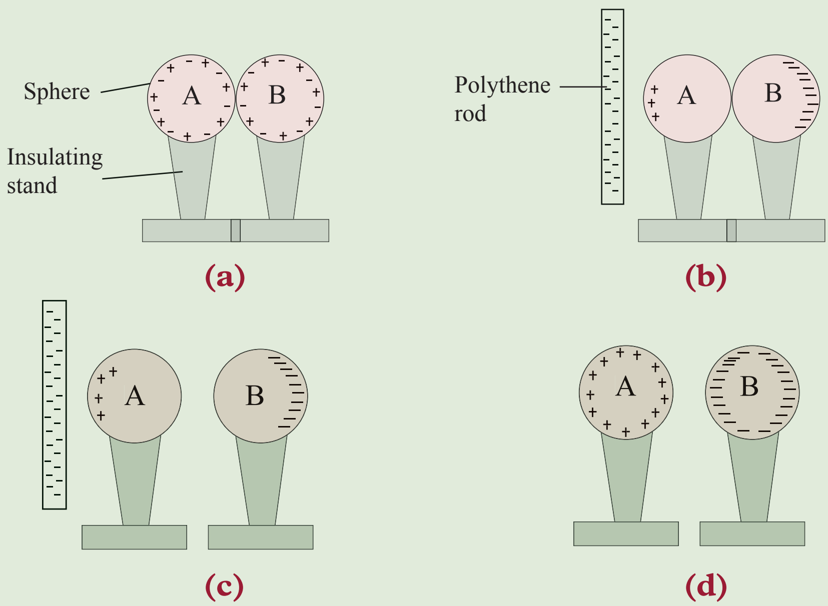


Fig. 2.6: Charging by separation method

In Activity 2.5, before the polythene rod was brought near the spheres (Fig. 2.6(a)), the positive and negative charges were balanced in each sphere hence the spheres were uncharged.

When the polythene rod was brought closer to the two spheres, charge separation occured i.e. negative charges from both spheres were repelled to sphere B and the positive charges were left in sphere A. When the spheres were separated, positive charges remained in sphere A and negative charges in sphere B. When the charged polythene rod was removed, the charges distributed themselves uniformly on the spheres.

A negatively charged rod would be attracted by sphere A and repelled by sphere B.

From Activity 2.5, we conclude that:

- The two spheres have become *charged by separation.*
- It can be seen from Figure 2.5(c) that sphere A has acquired a charge opposite to that of the charging rod while sphere B has acquired a charge similar to that of charging rod.

In Activity 2.5, you must have observed that the charged polythene rod repels the charged ebonite rod. This shows that there is a force of repulsion between the two rods with the same charges.

Activity 2.6 **To confirm that a body is charged**

(Work in groups)

Materials: Glass rod, ebonite rod, silk cloth , thread, pieces of papers, polythene rod

Steps

1. Rub both the glass and ebonite rods with a silk cloth. What charge is acquired in each of them?
2. Bring each rod at a time near to the pieces of paper. What do you observe?
3. Suspend one rod with a string and bring the other one close to it. What do you observe?
4. Suspend the glass and ebonite rods with a stirrup (support) and thread.
5. Charge a polythene rod by rubbing it with silk, pass it over the pieces of paper and bring it near the suspended ebonite rod, then to the glass rod. What are your observations?
6. Record your observations as shown in Table 2.2.

Table 2.2

Charged ebonite rod	Charged glass rod	Wire attraction or repulsion
Charged ebonite rod	Piecess of paper	
Charged ebonite rod	Charged polythene rod	
Charged glass rod	Piecess of paper	
Charged glass rod	Charged polythene rod	

7. Discuss you observations in Steps 2, 3 and 5 with your partner and then report to the whole class.

In Activity 2.6, you should have observed that both the ebonite and glass rods attracted the pieces of paper because they were charged. They attracted each other because they were oppositely charged by friction. i.e negatively and positively respectively.

The negatively charged polythene rod attracted the uncharged pieces of papers and the positively charged glass rod but, repelled the negatively charged ebonite.

From this activity it is clear that:

- Attraction occurs when a charged body is brought either near an uncharged body or near an oppositely charged object.
- Repulsion only occurs between two like charged bodies.
- Uncharged bodies are not repelled by charged bodies.

This is why repulsion, is the best test to confirm that a body is charged.

Exercise 2.2

1. (a) What is meant by 'charging by contact'?

   (b) Why is it not possible to charge a metal rod held in the hand by rubbing it with cloth?

2. State the basic law of electrostatics.

3. Mary rubbed a pen (biro) with a handkerchief and held it near a stream of water running slowly from a tap. She observed that the stream of water curved and followed the movement of the charged pen. When she touched the water with the pen, the curving stopped. Explain these observations.

4. (a) A student intends to charge a narrow metallic spherical ball. State two methods that can be used to attain this objective.

(b) State the precaution that should be taken into account when charging metallic objects.

5. The electrostatic forces between four spheres A, B, C and D were investigated. It was observed that A repels C, C attracts B and D attracts C. what kind of force would be between spheres:

   (a) A and B? (b) A and D (c) B and D?

6. (a) What is meant by 'charging by induction'?

   (b) Explain how a charged body attracts a neutral material.

7. State the main methods of charging objects.

2.3 Coloumb's law

We have already learnt that like charges repel while unlike charges attract. But what determines the magnitude of the force? The following activities will help us investigate and establish the relationship between the force and these factors.

Activity 2.7 **To determine the effect of quantities of charge on the magnitude of force between two charged bodies**

(Work in groups)

Materials:
- Two identical polythene rods A and B
- One perspex rod C
- Two clamps and stands

Steps

1. Charge polythene rod A *strongly* by rubbing it with a piece of dry cloth and suspend it on a stand Fig. 2.7(a).
2. Charge polythene rod B *lightly* by rubbing it with a piece of dry cloth and suspend it on a stand Fig. 2.7(b).
3. Charge perspex rod C strongly by rubbing it with a piece of dry cloth. Bring it in turns near the suspended polythene rods A and B. Compare the magnitudes of the force of attraction in both cases. Suggest the relationship between the quantity of charge and the force of attraction between two charged rods.

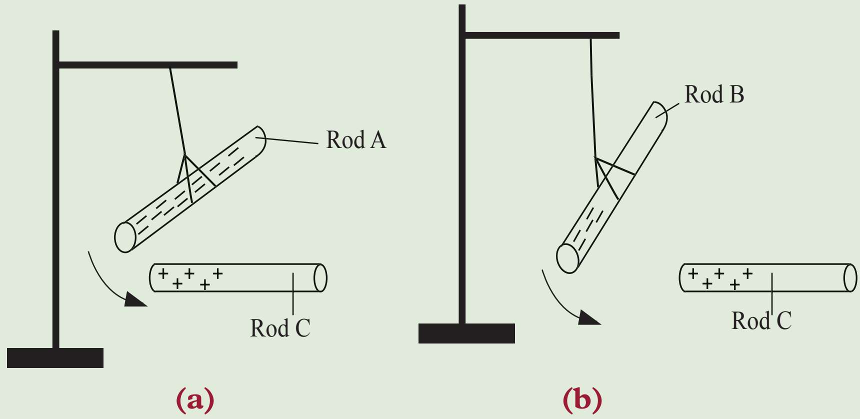


Fig. 2.7: Effect of magnitude of a force

4. Discuss the observations in Step 3 with other members of your class.

In Activity 2.7, you should have observed that there is a strong force of attraction between rods A and C than between rods B and C.

Therefore, the electrostatic force between two charged objects depends on the quantity of the charge on the two objects. The *greater the quantities of charge on the two objects, the greater the force between them*.

Activity 2.8 **To determine the effect of the distance between two charged bodies on the magnitude of the force between them**

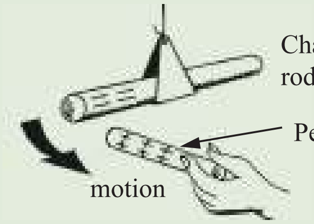
(Work in groups)

Materials

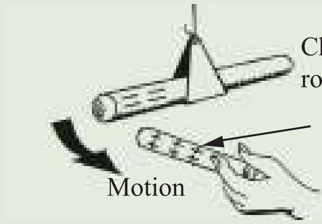
- Two identical polythene rods A and B
- One perspex rod C
- Two clamps and stands

Steps

1. Use the set-up in Fig 2.8 (a) to carry out this activity.
2. Bring the charged perspex rod C very close to the suspended charged polythene rod A. Note the strength of the force of attraction between the two rods (Fig 2.8(a)).
3. Bring the charged Perspex C near the suspended charged polythene rod A, a distance far than in Step 2 (See Fig 2.8(b)). Note the strength of the force of attraction between the two charged rods.



(a) Charges close



(b) Charges far apart

Fig. 2.8: Effect of separation distances on the magnitude of force

4. Compare the strength of the forces of attraction in Steps 2 and 3 into the relationship between separation distance and the magnitude of a force between two charged objects.
5. Through your secretary, give a report to the whole class on your findings.

In Activity 2.8, you should have observed that there is a stronger force of attraction between rods A and C when the separation distance between them is short and vice versa.

Therefore, electrostatic force between two charged objects depends on the separation distance between the two charged objects. *The greater the distance, the smaller the force and vice versa*.

The summary from Activities 2.7 and 2.8 actually leads to Coulomb's law.

The law was first developed by a French Physicist called Charles de Coulomb and it states that:

The force of attraction or repulsion between two charges is directly proportional to the product of their charges and inversely proportional to the square of the distance between the to charges, Q_1 and Q_2.

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

$$F \propto Q_1.Q_2$$

$$F \propto \frac{Q_1.Q_2}{r^2}$$

Removing the proportionality sign, we introduce in a constant k.

Therefore, force becomes

$$F = k\frac{Q_1.Q_2}{r^2}$$

Where, the constant, $k = \frac{1}{4\pi\varepsilon}$ where ε is the *permitting constant*. The value of *k* is equal to 8.988×10^9 Nm^2c^{-2} for charges in free space. A convenient value of 9×10^9 Nm^2C^{-2} is normally used.

Force is in newtons(N), the charges in coulombs(C) and distance (r) in metres (m).

Coulomb (C) can also be expressed as:

1 coulomb = 10^6 micro coulombs

1 coulomb = 10^9 nano coulombs

Example 2.3

Suppose two point charges each with a charge of +1.0 C are separated by a distance of 1m. Determine the magnitude of the electrostatic force between them. Is the force attractive or repulsive? (Use $k = 9 \times 10^9$ Nm^2C^{-2}).

Data given

$$Q_1 = +1.0\ C, \quad Q_2 = +1.0\ C, \quad r = 1\ m$$

Since, $F = k\frac{Q_1 . Q_2}{r^2} = \frac{9 \times 10^9 \times 1.0 \times 1.0}{1^2}$ then,

$F = 9 \times 10^9$ N. The force is repulsive since it is from two similar charges.

Example 2.4

Two balloons are charged with an identical quantity and type of charge: -6.25 nC. They are held apart at a separation distance of 61.7 cm. Determine the magnitude of the electrical force of repulsion between them.

Take $k = 9.0 \times 10^9$ Nm^2/C^2.

Solution

$Q_1 = -6.25\ nC = -6.25 \times 10^{-9}\ C$

$Q_2 = -6.25\ nC = -6.25 \times 10^{-9}\ C$

$r = 61.7\ cm = 0.617\ m$

$$F = k\frac{Q_1Q_2}{r^2} = \frac{9 \times 10^9 \times 6.25 \times 10^{-9} \times 6.25 \times 10^{-9}}{0.617^2}$$

$$= 923.5 \times 10^{-9}\ N$$

Note:

When substituting, we drop the signs on the charges for the fact that the signs are only used to indicate where force is attractive or repulsive.

Exercise 2.3

Take $k = 9.0 \times 10^9 \, Nm^2/C^2$ and use it where necessary to answer questions.

1. (a) List two factors that affect the magnitude of the force between two charged objects.

   (b) State Coloumb's law.

2. Determine the force of attraction between two balloons with separate charges of $+3.5 \times 10^{-8}$ C and -2.9×10^{-8} C when separated a distance of 0.65 m.

3. Two balloons with charges of +3.37μC and -8.2μC attract each other with a force of 0.0626 N. Determine the distance between the two balloons.

4. A balloon with a charge of 4μC is held at distance of 0.7 m from the second balloon with the same amount of charge. Calculate the magnitude of the repulsive force.

5. Two balloons with charges of +3.37 μC and -8.21 μC attract each other with a force of 0.0626 N. Determine the separation distance between the two balloons.

6. Determine the electrical force of attraction between two balloons with charges of $+3.5 \times 10^{-7}$ C and -2.9×10^{-6} C when separated by a distance of 0.65 m.

7. Determine the force of attraction between two balloons that are charged oppositely with the same quantity of charge. The charge on the balloons is 6.0×10^{-5} C and they are separated by a distance of 0.50 m.

8. A helium nucleus has charge +2e and a neon nucleus +10e, where $e = 1.60 \times 10^{-19}$ C. With what force do they repel each other when separated by 3×10^{-9} m?

9. If two equal charges, each of 1 coulomb, were separated in air by a distance of 1 km, what would be the force between them?

10. Determine the force between two free electrons spaced 10^{-10} m apart.

    ($e = 1.60 \times 10^{-19}$ C)

11. What is the force of repulsion between two argon nuclei when separated by 10^{-9} m? The charge on an argon nucleus is +18e.

12. Two equally charged pith balls are 3 cm apart in air and repel each other with a force of 4×10^{-5} N. Compute the charge on each ball.

13. Two small equal pith balls are 3 cm apart in air and carry charges of $+3 \times 10^{-9}$ C and -12×10^{-9} C respectively. Compute the force of attraction.

14. A positive charge of magnitude 3.0×10^{-8} C and a negative charge of magnitude 4.0×10^{-8} C are separated by a distance of 0.02 m. Calculate the force between the two charges and state its direction.

2.4 Testing of charges

2.4.1 Gold leaf electroscope

Activity 2.9 **To identify the parts of a gold leaf electroscope**

(Work in groups)

Materials: • Gold leaf electroscope • Chart showing parts of an electroscope

Steps

In Unit 1 of this book, we came across the gold leaf electroscope.

1. What is an electroscope? Discuss.
2. Using the chart and device provided, draw a gold leaf electroscope. Label all the parts.
3. Discuss with your partner the functions of each part of the electroscope and how it works.

In your discussion, you should have discovered that a gold leaf electroscope is a *sensitive instrument that is used for detecting and testing small electric charges*. This instrument was invented by a clergy man called *Abraham Bennet* at the end of 18^{th} Century.

The gold leaf electroscope consists of an earthed metal case with a transparent plastic or glass windows. A brass rod is inserted through an insulated cork stopper. A brass disc or cap is mounted on the rod at the top and a thin metal leaf (aluminium or gold) is attached to the bottom of the rod. The enclosed case protects the leaf from air draughts. Fig. 2.9 shows a simplified version of a gold leaf electroscope. The inside of the electroscope is warmed with a burner or electric heater to achieve dry conditions.

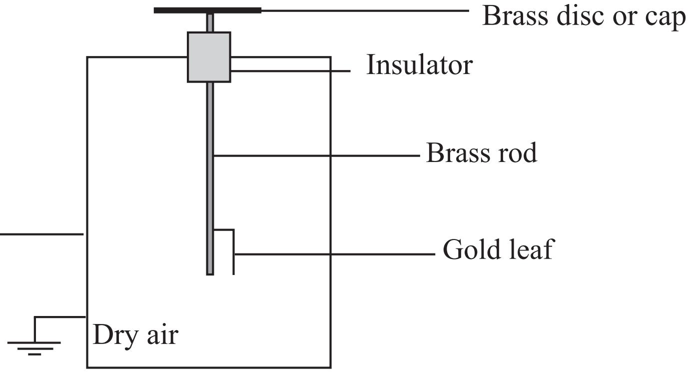


Fig. 2.9: A gold leaf electroscope

2.4.2 Charging and discharging a gold leaf electroscope

Activity 2.10 **To investigate the distribution of charges on an electroscope**

(Work in groups)

Materials

- A polythene rod
- A glass rod
- Silk cloth
- A gold leaf electroscope

Steps

Part 1: Charging an electroscope by contact

1. Take a negatively charged polythene rod and rub it on the cap a number of times and then withdraw it. Note what happens to the gold leaf of the electroscope (See Fig. 2.10).
2. Discuss your observations in step 1 with other groups in your class.

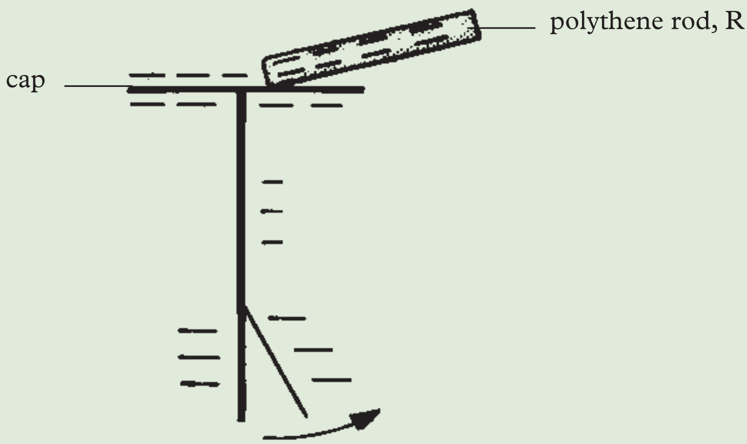
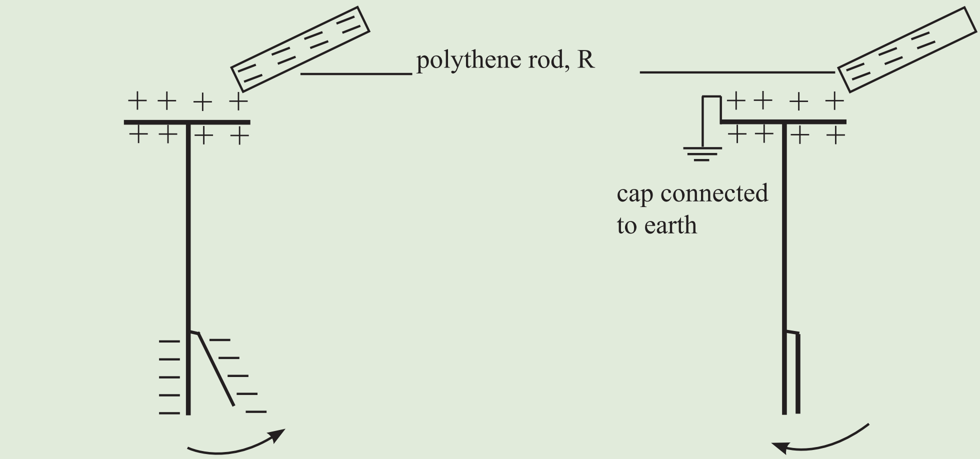


Fig. 2.10: Charging electroscope by contact

Part 2: Charging an electroscope by induction

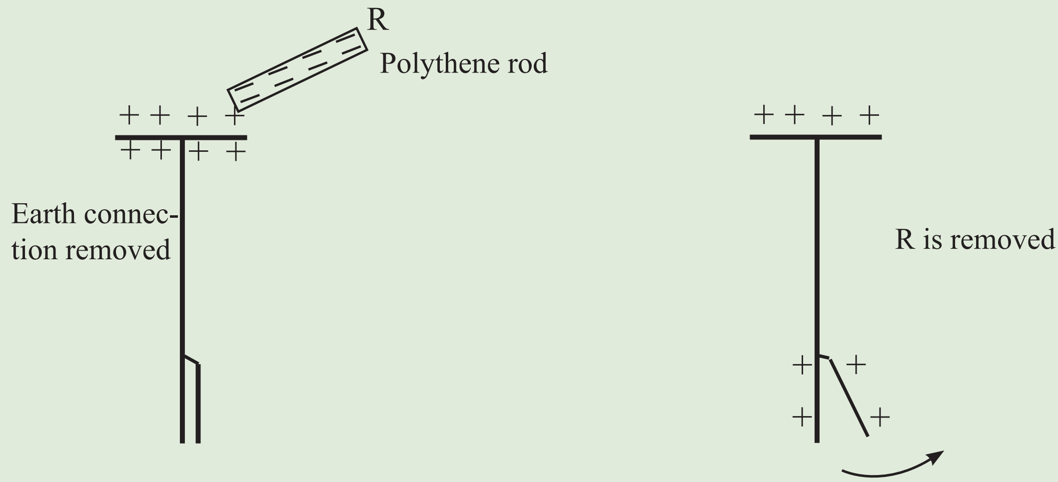
4. Bring a negatively charged polythene rod close to the cap. Note what happens to the gold leaf of the electroscope (Fig. 2.11(a)).
5. Without disturbing the rod, touch the cap with your finger and note again what happens to the gold leaf. (Fig. 2.11(b)).



(a) **(b)**

Fig: 2.11 (a) and (b): Charging a gold leaf electroscope

6. Keeping the rod in the same position, withdraw your finger. Observe and explain. What happens to the leaf ? (Fig. 2.12(a)).
7. Remove the polythene rod. Observe and explain what happens to the leaf (Fig. 2.12(b)).



(a) ***(b)***

Fig. 2.12 (a) and (b): Charging a gold leaf electroscope

Part 3: Discharging an electroscope

8. Touch the metal cap of a negatively charged gold leaf electroscope using your finger or wire. Observe what happens oto the gold leaf.
9. Now, touch the cap of a positively charged golf leaf electroscope with your finger or wire. Observe and explain. What happens to the gold leaf?

In Part 1, you should have observed that when the cap is being rubbed with the rod R, there is a divergence on the gold leaf. On withdrawing the rod, there is still some divergence.

During rubbing, the electrons are transferred from the rod to the cap, metal rod and the gold leaf. Since the rod and the gold leaf have acquired the same kind of charge, the gold leaf is repelled, hence there is a divergence. The gold leaf electroscope has been *negatively charged by contact.*

The gold leaf electroscope can also be charged by contact using a *charged metal rod with a rubber or polythene handle*. It is done by touching the metal cap with the charged metal rod.

In Part 2, you should have observed the following:

(i) In Step 4 the gold leaf diverges.

(ii) In Step 5 the gold leaf collapses.

(iii) In Step 6 the gold leaf stays the same.

(iv) In Step 7 the gold leaf diverges.

When the negatively charged polythene rod was brought close to the cap, the electrons from the cap were repelled to the gold leaf. The bottom end of the rod and the gold leaf acquired negative charges. The gold leaf was repelled, hence its divergence.

When the cap was touched (earthed), the excess electrons in the gold leaf and the rod escape to the earth. The gold leaf collapsed. The positive charges on the cap remain on it due to the force of attraction of the inducing rod.

There is no effect when the connection to the earth is removed. The gold leaf remains in the same position. When the polythene rod is moved away from the cap, some of the positive charges get redistributed by the electrostatic induction to the end of the rod and the gold leaf diverges again. The gold leaf electroscope is therefore positively charged by induction using a negatively charged rod.

Likewise, the gold leaf electroscope can also be charged negatively by using a positively charged glass rod.

In Part 3, you should have noted that there was no observable change on the gold leaf when it was touched with the uncharged glass rod in Step 1. However, the gold leaf diverged when the charged glass rod touched the metal cap in Step 2.

When the charged glass rod was removed from the metal cap, the gold leaf was still showing divergence, but it collapsed when the metal cap was touched with the finger.

The collapsing of gold leaf was due to the flow of the negative charges from the cap to the earth through a body.

Similarly, in Step10, the leaf collapsed because negative charges moved in from the earth through the finger/wire, into the electroscope and neutralised the positive charge.

This process of connecting a charged body to the earth using a conducting material is called *earthing*.

The symbol for earthing is s shown below.

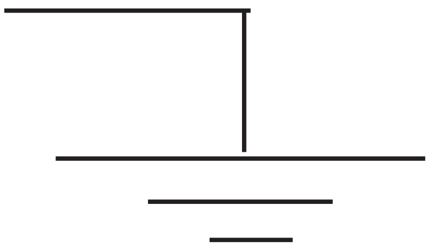


Fig.2.13: Symbol for earthing

If the charges are high, the charged body is earthed to a thick metal rod (Examples: water pipes or metal grills of a window).

If a negatively charged object is connected to the earth, *the excess electrons flow from the plate to the earth* and the plate becomes neutral. If a positively charged object is connected to the earth, *the electrons from the earth move to the plate* and neutralise the deficiency of electrons. Note that positive charges (protons) do not move. The plate becomes neutral.

CAUTION

High concentration of charge on a conductor or a device can cause electric shock. Be careful not to touch any electrical devices and charge generators. Obey warning signs like "Do not touch with bear hands".

2.4.3 Uses of a gold leaf elecroscope

(i) Testing presence of charges using an electroscope

Activity 2.11 **To identify the type of charge on a body**

(Work in groups)

Materials

- A charged electroscope
- A charged polythene rod
- A glass rod

Instructions

1. Using the set up in Fig. 2.14 below, explain how you would identify the charge on a body.
2. What happens to the divergence of the gold leaf when the body is:
   (a) negatively charged polythene rod.
   (b) posively charged glass rod.

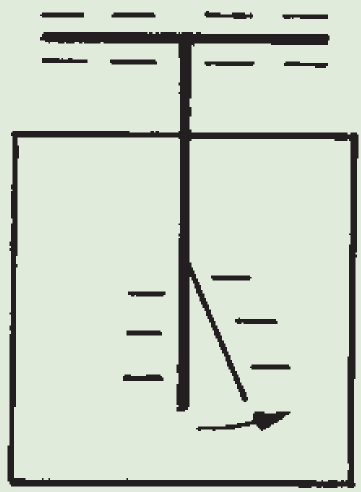


Fig. 2.14: A negatively charged electroscope.

3. Place your hand close to the metal cap of the electroscope. Note the position of the gold leaf.
4. Discuss your observations in cases 1 and 2 and summarise your discussion in a tabular form.

In Activity 2.11 Step 2(a), you should have noted that the divergence of the gold leaf increases. This is because the quantity of the charge on the gold leaf increases.

The increase in divergence of a charged gold leaf electroscope is due to the fact that the polythene rod brought near the cap has the same charge as the gold leaf of the electroscope, hence it repels more negative charges to the gold leaf. The leaf divergence increased. Therefore, the rod is negatively charged.

Similarly, you should have observed that the divergence of the gold leaf decreases in 2(b).
The divergence once again decreases on placing the hand close to the metal cap.

The positively charged glass rod attracted some of the electrons from the gold leaf to the cap. The quantity of charge on the gold leaf decreases. Hence the divergence decreased.

The hand is an uncharged body. When it was brought near the cap it acquired *positive charge by induction which attracted the electrons* from the gold leaf. The electrons moved from the gold leaf to the cap. The quantity of the charge on the gold leaf decreases (Fig. 2.15(b)). Hence divergence decreases. The decrease in divergence of the gold leaf is therefore not an evidence for the presence of a charged body.

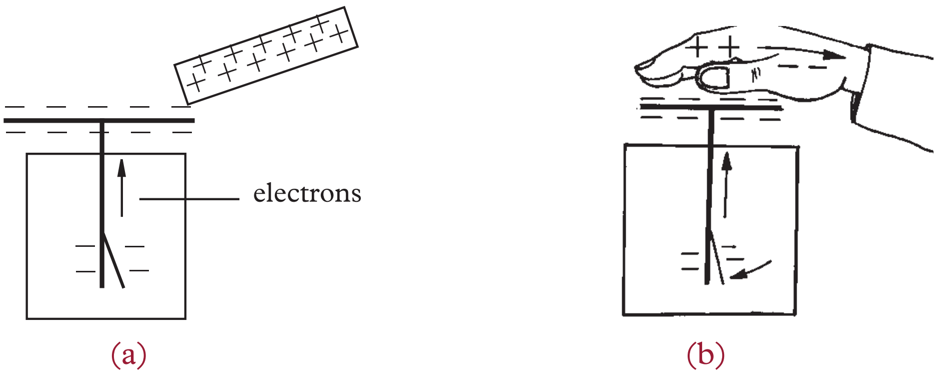


Fig. 2.15: Diagram to show decrease in divergence is not an evidence for presence of a charged body

Table 2.2 Summarises the effect on a gold leaf divergence when a charge (positive or negative) or uncharged body is brought near a cap of a gold leaf electroscope.

Table 2.2: Effect on the divergence of a gold leaf when a charged body is brought near the cap

Charge on gold leaf	Charge brought near a cap	Effect on leaf divergence
+	+	Increases
–	–	Increases
+	–	Decreases
–	+	Decreases
+ or –	Uncharged body	Decreases

(ii) To detect the presence of a charge on a body

The material to be tested is placed on or brought close to the cap of the electroscope. If the body is charged, the gold leaf diverges. If it is not charged the gold leaf does not diverge.

(iii) To identify conductors and insulators

Activity 2.12 **To identify conductors and insulators**

(Work in groups)

Materials

- A metal sphere
- Glass rod
- Stand and clamp
- Paper strip
- Copper wire
- Nail
- Insulating stand
- Cotton cloth
- stick
- Plastic strip

Steps

1. Suspend the glass rod with a string on the clamp. Charge the rod positively by rubbing it with the cloth.
2. Place the metal sphere on the insulating stand and charge it positively by rubbing it with the cloth.
3. Bring the metal sphere near the suspended charged glass rod. Observe and explain what happens to the rod (Fig 2.16 (a)).
4. Move the metal sphere away from the rod. Touch the surface of the sphere with your bare fingers and bring it back near the suspended rod Fig 2.16 (b). Note down any observation? Suggest an explanation.

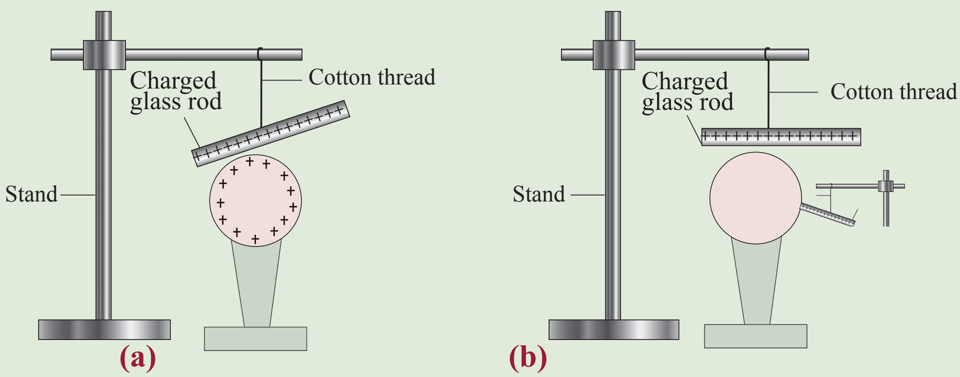


Fig. 2.16: Identifying conductors and insulators

5. Repeat steps 2 to 4 several times, each time holding a different material (copper wire, stick, papers and so on), and using it to touch the surface of the charged metal sphere. Note down the observation in each case.
6. Group the materials that lead to the same observation. How many categories of materials do you get based on the observations. Suggest the names of the categories.
7. Compare your observations with other groups in your class.

In Activity 2.12, you should have observed that the positively charged metal sphere repelled the suspended positively charged glass rod before being touched with any of the materials. When the charged sphere was touched with the hand, negative charges moved from the ground through your body and finger to the sphere neutralising it. Therefore, the sphere got attracted by the suspended rod. This shows that the human body is a *good conductor* of charge.

Similarly, when the charged sphere was touched with the copper wire, and nail, it also got discharged and got attracted byl the suspended rod. This shows that the copper wire, and nail are good conductors of charge.

However, when the charged sphere was touched with the stick, paper strip and plastic strip, it still repelled the suspended rod meaning that it was not discharged. This shows that negative charges were not able to flow through these materials to the metal sphere. Thus, the stick, paper strip and plastic strip are *insulators*.

Let us now discuss conductors and insulators in details.

Conductors

These are materials which allow the flow of charges (electrons) through them. They are made of atoms whose outer electrons in the atoms are loosely bound and free to move through the material. Some examples include; *copper, aluminium, gold, silver, aqueous solutions of salts and graphite. Human body, and living trees are also conductors*.

If a charged conductor is touched with another object, the conductor can transfer its charge to that object. The transfer of charge between objects occurs more readily if the second object is made of the same material as the conductor.

Insulator

They are materials which do not allow free flow of electric charges (electrons) from within them. Examples include most non-metals *glass, porcelain, plastic, dry air, paper, rubber, styrofoam, mica* and so on.

If charges are transferred to an insulator at a given location, the excess charges will remain at the initial location of charging.

Insulators play a critical role in real life. For example, conductors e.g electric cables are usually covered with insulators to protect us from electric shock.

2.5 Effects and applications of methods of charging

Activity 2.13 **To investigate real life effects of electrostatics**

(Work in groups)

Materials

- Two mirrors
- Wet cloth
- A dry cloth
- Chalk dust

Steps

1. Rub the first mirror with a dry cloth for some time.
2. Rub the second mirror with a wet cloth.
3. Bring both mirrors close to but not touching very fine chalk dust and observe what happens to the particles.
4. Where does the dust/ chalk stick so much? Explain your observation.

In Activity 2.20, you should have observed that when the mirror was rubbed within a dry cloth, it got charged by friction hence attracted the chalk dust particles. This is why most window glasses are usually dusty.

The following are some other effects of electrostatics:

1. One gets a shock on touching the metal knob of the door of a car while getting out of the car. Electric charges build up on the surface of a car due to friction with the road as well as with the air molecules. When the metal knob is touched, charges flow from the knob to the earth through the person. The discharging of the charges on the surface of the car through the person gives a mild shock. If a metal chain is attached to the car on the outside, the charges can pass easily to the earth and the charges cannot build up.

   It is for this reason that metal chains are attached to a petrol tanker. If large charges are allowed to *pile up* on the tanker, even a small spark produced can cause a fire and the tanker can explode.

2. When a mirror is cleaned with a dry cloth, both the mirror and the cloth get charged due to friction. The charged mirror acquires the attractive property. Dust, thin hair or fluffs can therefore stick to the mirror.

3. Cars are painted using a spray gun. The car is usually earthed and the paint droplets coming out of the spray gun are given a positive charge. The car attracts these charged droplets of paint uniformly.

4. Dust and smoke particles are extracted from the inside of the chimney by electrostatic attraction. This reduces the air pollution which is a health hazard.

5. Electrostatic induction is used in the photocopying machines.

6. Though rubber is an insulator, special materials called conductive rubber is used to make aeroplane tyres. The conductive rubber tyres reduce the risk of an explosion during refuelling the aircraft. When the metal spout of the fuel pipe touches the petrol tank sparks can be produced leading to an explosion.

Exercise 2.4

1. **(a)** What is meant by 'charging by contact'?
   (b) What is earthing?
   (c) What happens during earthing if an object is:
      (i) negatively charged?
      (ii) positively charged?
2. What is an electroscope?
3. Draw a diagram to show the important features of a gold leaf electroscope.
4. Copy the following diagrams and show the distribution of charges on the conductor BC placed on an insulated stand. I is a charged rod close to the end B (Fig. 2.17).

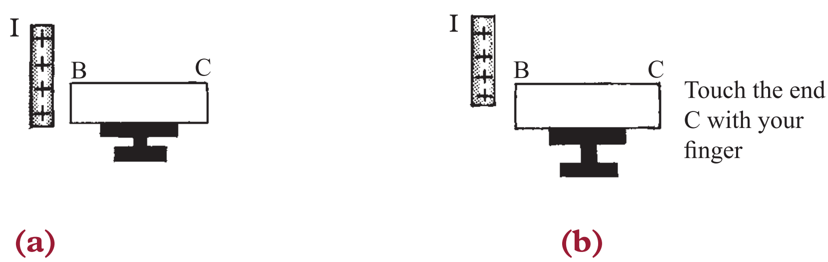
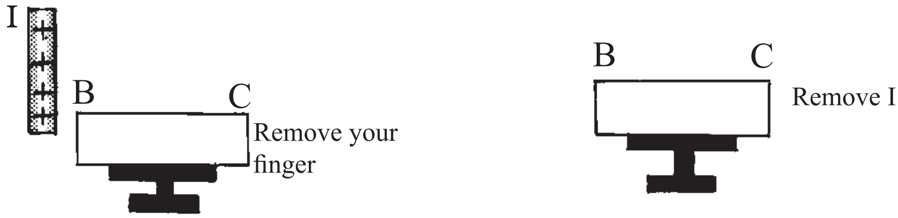


Fig. 2.17: Conductor BC placed on insulated stand



(c) (d)

Fig. 2.18: Conductor BC placed on insulated stand

5. A gold leaf electroscope is positively charged. Explain how to use this electroscope to test the charges on two rods, where one is negative and the other positive.
6. What are conductors and insulators? Give three examples of each.

2.6 Project work

Construction of a simple leaf electroscope

Materials

- A transparent conical flask or a tall glass jar having a narrow mouth
- Thin pieces of aluminium foil, a waxed cork
- A brass or copper rod bent into an L shape.

Steps

- Stick a thin piece of aluminium foil to the lower end of the rod.
- Place the L-shaped rod over the jar and then fit the waxed cork to insulate the rod from the glass jar. Fig. 2.19(a) shows the construction of a leaf electroscope and Fig. 2.19(b) shows an assembled leaf electroscope.

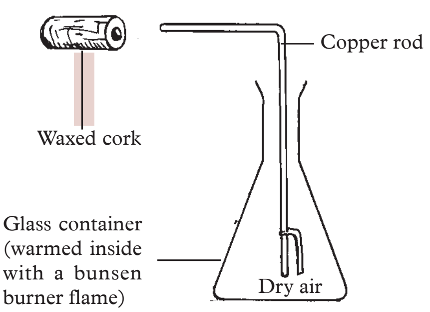


Fig.2.19(a): Construction of leaf electroscope

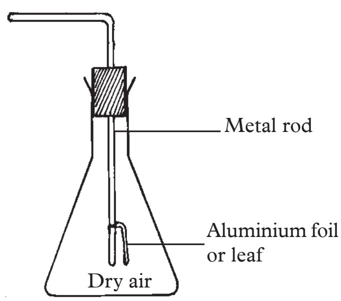


Fig. 2.19(b): Assembled leaf electroscope

Topic summary

- A charge is a characteristic of matter that expresses the extent to which matter has more or fewer electrons than protons and vice versa.
- Materials can be charged by rubbing. The charge acquired can be positive or negative.
- A body acquires negative charges if it gains electrons from the surface of the rubbing body. The body that looses electrons become positively charged.
- The law of electrostatic states that like charges repel and unlike charges attract.
- Coulomb's law states that two electrically charged bodies experience an attractive or repulsive force *F* which is inversely proportional to the square of the distance *d* between them and proportional to the product of charges Q_1 and Q_2 i.e

  $$F = k\frac{Q_1 . Q_2}{r^2}$$ where k is constant.

- SI unit of charge is coulomb (C).
- A gold leaf electroscope is used to:
  - detect presence of charges.
  - test insulating or conducting properties of a material.
  - test for the sign of a charge in a body.
- Charges are mostly concentrated at places where the surface is sharply curved or pointed.
- All substances can be classified as either conductors or insulators of electricity. Conductors allow electrons to flow through them freely, but insulators do not.
- Accumulation of charges at a pointed edge ionise the surrounding air.
- Ionisation means to remove or add an electron from an atom or to an atom.

Topic Test 2

1. When is a body is negatively charged?
2. A plastic rod is rubbed with a dry cloth and becomes positively charged. Explain why the rod becomes positively charged.
3. A glass rod is rubbed with silk. Explain how both the silk and the rod acquire charges.
4. What does the study of electrostatics deal with?
5. Two balloons inflated with air are tied with strings and held 2.25 metres apart. Both the balloons are rubbed with fur. Why do the balloons move apart when brought close together?
6. When a charged rod is held close to a metal sphere placed on an insulating stand, the charge distribution on the sphere is as shown in Fig. 2.20.

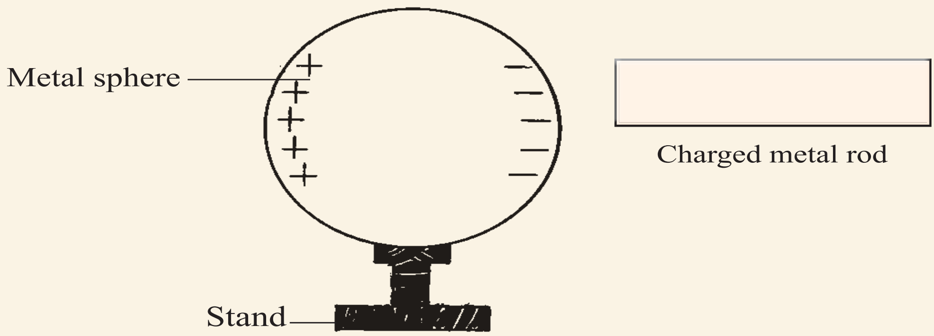


Fig. 2.20: Charge distribution on a sphere

(a) What is the sign of charge on the rod?

(b) Describe a simple method to charge the rod.

(c) Explain why the far side of the metal sphere has a positive charge.

(d) What happens to the charges on the metal sphere, if the charged rod is moved away from the sphere?

9. A container with dry chalk powder is covered with a clean glass plate. The top surface of the plate is rubbed with a piece of fur (Fig. 2.21).

State and explain the effects of:

(a) Rubbing the lid with fur.

(b) Touching the lid with a finger after sometime.

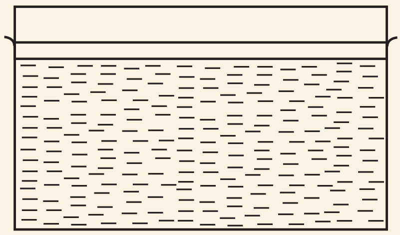


Fig. 2.21:

10. Explain, with aid of a suitable diagram, how to charge a gold leaf electroscope negatively, by induction.

11. A negatively charged polythene rod is placed on the pan of a balance. State and explain what happens to the balance reading if another charged polythene rod is brought closer to the first (Fig. 2.22).

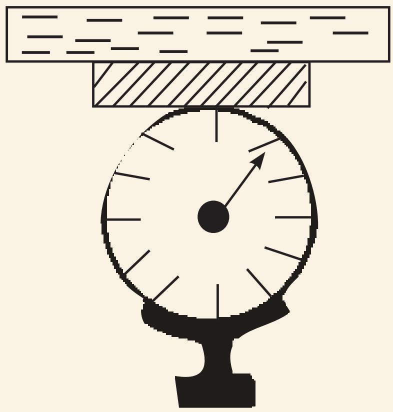


Fig. 2.22

12. Copy the following diagrams and show the charge on each metal sphere placed on insulated stands (Fig. 2.23).

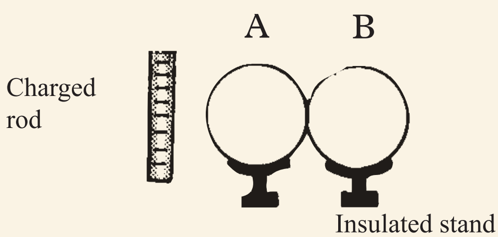


Fig. 2.23: (a) Two spheres touching each other

Fig. 2.23: (b) Sphere B is moved away from sphere A

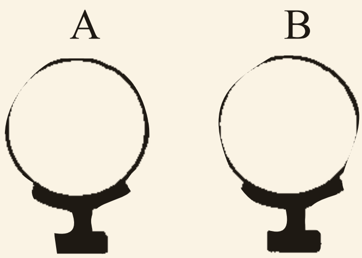


Fig. 2.23: (c) The charged rod is removed

Spheres A and B

Fig. 2.23

13. Why are metal chains attached to the trucks carrying petrol or other inflammable materials?

14. Determine the electrical force of attraction between two balloons that are charged with opposite type of charge but the same quantity of the charge. The charge on each balloon is 7.0×10^{-7} C and they are separated by a distance of 0.50 m.

15. Two balloons are charged with an identical quantity of charge; -6.25nC they are 61.7 cm apart. Determine the magnitude of the electrical force.

UNIT 3 Electricity

Topic 3: Current Electricity (II)

Topic 4: Basic Electronics

Learning outcomes

Knowledge and understanding

- Understand the nature of current electricity.
- Understand the effects of the internal resistance of a source of e.m.f. on the terminal potential difference and output power.

Skills

- Investigate the conditions for current flow using appropriate electric equipment to measure current.
- Verify Ohm's law experimentally.
- Design and connect circuits to include ammeter, switch, battery, fuses and lamps, test insulators and conductors and use the units ampere, volt, ohm.
- Solve problems in series and parallel circuits and apply the Kirchhoff's laws.
- Apply current electricity to electronics in semi-conductors.

Attitude and value

- Appreciate the importance and uses of electricity

Key inquiry questions

- Why do we study electric current?
- Why electrical appliances are always connected in parallel at home?
- How do we connect voltmeter in an electric circuit?
- How can we verify ohm's law?
- How do we differentiate the sources of e.m.f?

Topic 3 Current electricity (II)

Topic outlines

Introduction

In Secondary 1, we learnt how to make simple circuits and to measure current and voltage. In this topic, we will mainly learn how to determine the effective resistance to the flow of current offered by devices in a circuit.

3.1 Ohm's law

Activity 3.1 To investigate the variation of current (I) with change in potential difference (V) across a conductor

(Work in groups)

Materials

- Nichrome wire
- Ammeter
- Variable resistor
- Switch
- Cells (in a cell holder)
- Voltmeter

Steps

1. Using the nichrome wire, make a coil of as many turns as possible.
2. Connect the set-up as shown in Fig. 3.1.

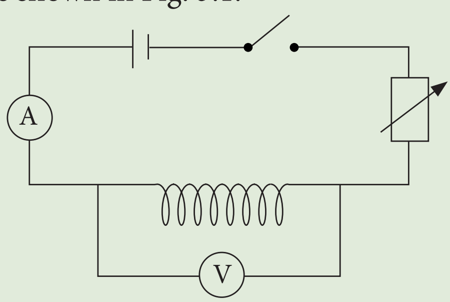


Fig. 3.1: Circuit to verify Ohm's law

3. Vary the potential difference (V) across the wire by adjusting the variable resistor. Observe what happens and answer the following questions.
   (a) What happens to the current reading when the potential difference is increased?
   (b) What happens to the current reading when the potential difference is reduced?
   (c) Using your observation in (a) and (b) summarise the relationship between (I) and (V).

You should have observed that as the potential difference (V) across the wire is increased the current also increases and vice versa. This observation is summarised by Ohm's law.

Ohm's law states that the current (I) flowing in a conductor is directly proportional to the potential difference (V) across it, if the temperature and other physical quantities of the conductor remains constant i.e. $I \propto V$ or $\frac{V}{I}$ is a constant.

The following activity will help us to verify Ohm's law.

To verify Ohm's law

Activity 3.2 To verify Ohm's law

(Work in groups)

Materials

- Dry cells, cell holder
- Variable resistor
- Ammeter
- 100 cm of nichrome wire
- Connecting wires
- Voltmeter and a switch

Steps

1. Connect the set-up as shown in Fig. 3.1 in Activity 3.1.
2. Close the switch and adjust the variable resistor so that the p.d across the conductor reads 0.5 V. Record the corresponding value of current as indicated by the ammeter.
3. Increase the voltage across the conductor at intervals of 0.5 V, each time noting and recording the corresponding values of the current through the conductor.
4. Record your results in a tabular form as shown in Table 3.1.

Table 3.1: Relationship between p.d and current

p.d across the conductor V (V)							
Current through the conductor I (A)							

5. Draw a graph of p.d (y-axis) against current, I.
6. Determine and compare the gradient/slope of the graph at different points. What do you notice? Discuss.
7. Suggest the relationship between voltage across the conductor and current through it.

The results show that as the potential difference across the conductor increases, the current through the wire also increases.

The graph of V against I is a straight line passing through the origin (Fig. 3.2).

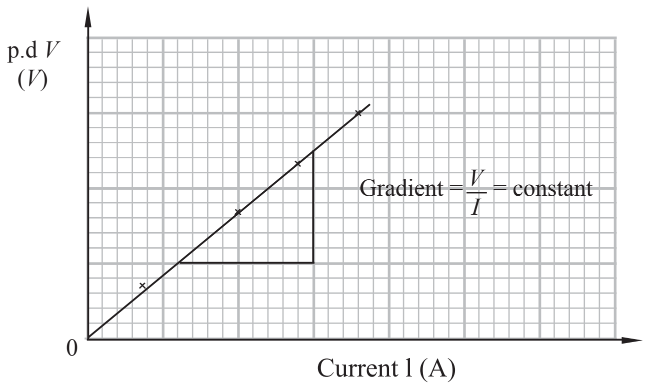


Fig. 3.2: Graph of p.d. (V) against current (I)

The graph in Fig. 3.2 shows that the current is directly proportional to the applied potential difference, i.e., $I \propto V$ or $V \propto I$. The gradient of the graph is also constant.

$$\text{Gradient} = \frac{\Delta V}{\Delta I} = \text{Constant}$$

$$\therefore \frac{V}{I} = \text{Constant}$$

Thus, Ohm's law is verified.

This constant is called the resistance (R) of the constructor, i.e

$$\frac{V}{I} = R$$

$$V = IR \Longrightarrow R = \frac{V}{I} \text{ and } I = \frac{V}{R}$$

The SI unit of resistance is the ohm (Ω). We will learn in details about resistance in our next subtopic.

The equation V = IR is the mathematical expression of Ohm's law named after a famous physicist George Simon Ohm. He was the first scientist to establish the relationship between current and potential difference.

Conductors that obey Ohm's law are called *ohmic conductors* and those materials whose current-potential graphs are not straight line graphs are said to be non-ohmic conductors. The nichrome wire used in Activity 3.2 is an ohmic conductor. When the experiment is repeated with a torch filament, a thermistor, a semiconductor diode, a thermionic diode and a copper sulphate (electrolyte) in place of the nichrome wire, the following graphs of current against voltage are obtained (Fig. 3.3).

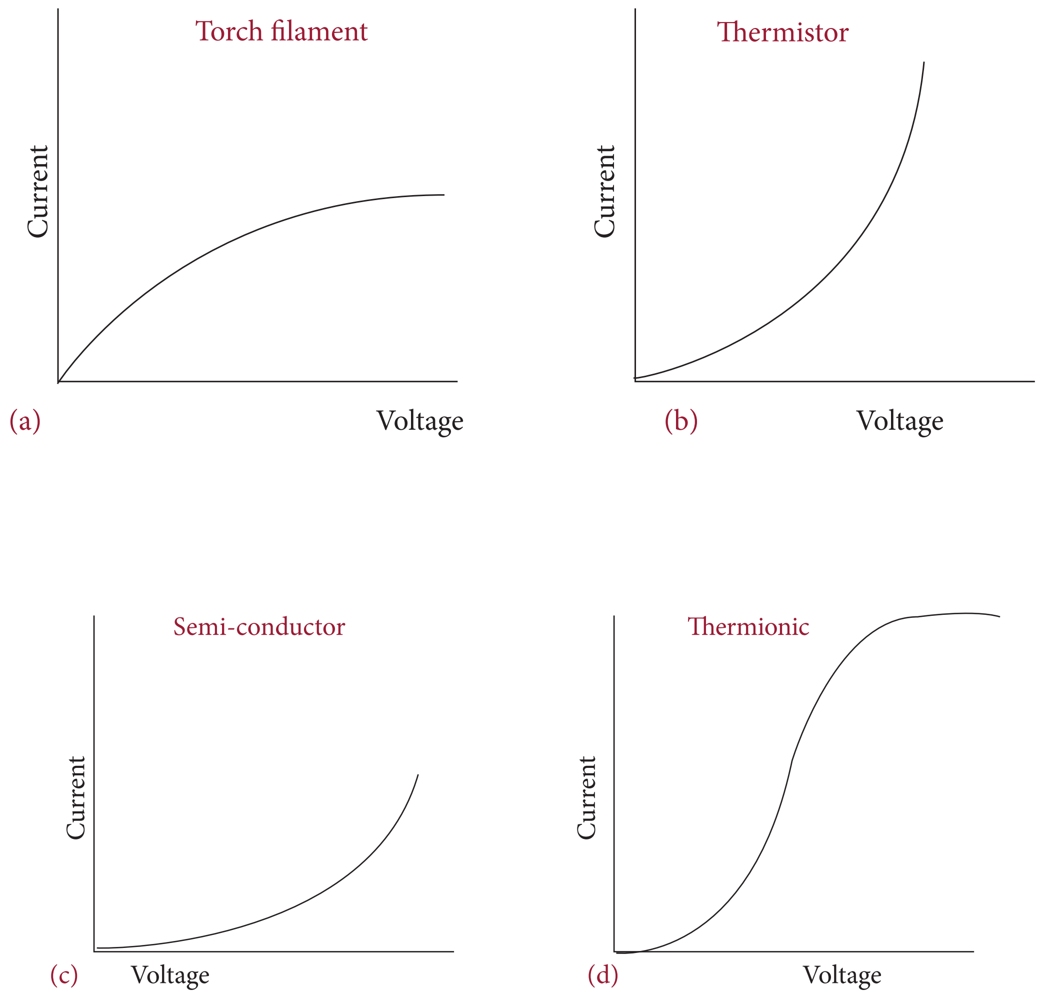


Fig. 3.3: Current against voltage graphs of various conductors

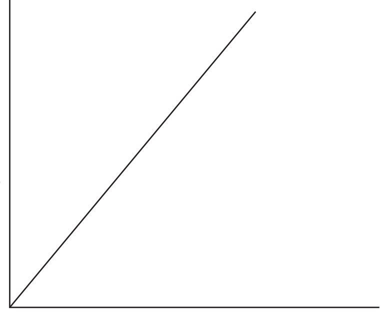


Fig. 3.4: Current against voltage graph for copper sulphate(electrolyte)

3.2 Electrical resistance

Activity 3.3 **Experiment to investigate the amount of current flowing through different materials under same conditions**

(Work in groups)

Materials

- Two dry cells rated 1.5 V and a cell holder
- Connecting wires
- An ammeter
- A switch
- Identical resistance wires of different materials e.g. copper, constantan, nichrome, tungsten etc.

Instructions

1. Using the materials provided above, carry out an investigation to find out the amount of current flowing through different materials such as copper, nichrome, tungsten and constantine wires of same length and cross-sectional area under the same conditions.
2. Write a procedure for your activity.
3. Draw a circuit diagram for measuring electrical resistance of the wires.
4. Complete the following table.

Table 3.2

Materials	Current(A)
Copper wire	
Tungsten wire	
Nichrome wire	
Constantine	

5. Compare the amount of current flowing through the three different wires. Compare the electrical resistances of the three wires,

- From the experiments we notice that the greatest current flows when copper wire is connected between points A and B in the circuit.
- The lowest current flows in the same circuit when nichrome is connected in place of copper.

This observation shows that different materials of the same dimensions allow different amounts of current to flow through them. In other words, different materials offer different amounts of opposition to the flow of electrical current through them. The opposition offered by a conductor to the flow of current through them is known as *electrical resistance*.

Different materials have different electrical resistances. From this experiment, we can say that copper offers a lower resistance than tungsten.

Measurement of electrical resistance

Electrical resistance of a conductor is measured using an instrument known as an *ohmmeter*. An ohmmeter, is connected across the component whose resistance is to be measured.

The symbol for an ohmmeter is shown in Fig. 3.5..

Fig. 3.5: A symbol of an ohmmeter

The resistance, R of a coil can also be found by direct application of the definition $R = \frac{V}{I}$ as shown in Activity 3.4.

Activity 3.4

Experiment to show how to determine the resistance of a resistor, R using Ohm's law

(Work in groups)

Materials

- Two cells and a cell holder
- Switch
- Coil of nichrome wire
- Ammeter
- Variable resistor

Steps

1. Set -up the circuit as shown in Figure 3.6.

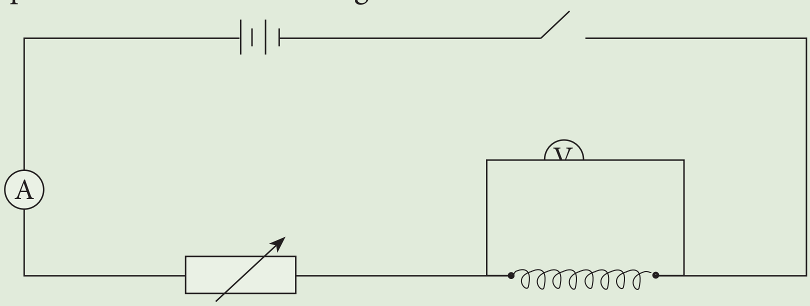


Fig. 3.6: Measurement of resistance

2. With the switch open, record the voltmeter reading,V and the corresponding ammeter reading, I.
3. Switch on the current and by adjusting the variable resistor, record at least five other values of V and the corresponding I.
4. Record your results in Table 3.3.

Table **3.3**

Voltage V (volts)	Current, I (A)

Compare value of V/I.

5. Plot a graph of V (vertical axis) against I. Note the shape of the graph.
6. Determine the slope (gradient) of the graph. Hence, state the resistance of the coil.

- When the switch is open, no current flows through coil R and therefore both the voltmeter and ammeter read zero. When it is closed, the current through the coil increases as the variable resistor is varied and the voltage across it also increases.
- An approximate value of the resistance of the coil is obtained by dividing the value of voltage across coil R by the corresponding current through it.
- The best value of R is found from the gradient of the graph plotted.

The graph of V against I is a straight line whose gradient gives resistance. The resistance obtained through calculation cannot be accurate since some little current is taken by the voltmeter thus not all of it flows through coil R.

Example 3.1

The voltage and current through a device in a circuit are 2 V and 0.02 A respectively. Calculate the resistance of the device.

Solution

$$\text{Resistance} = \frac{\text{Voltage}}{\text{Current}}$$

$$R = \frac{V}{I} = \frac{2\text{ V}}{0.02\text{ A}} = 100\ \Omega$$

$$V = IR$$

Example 3.2

A resistor rated 10 Ω allows a current of 2 A to flow through it in a simple circuit. The resistor is replaced with another one of 30 Ω. Calculate the amount of current passing through the 30 Ω resistor if the source of voltage is the same.

Solution

In the first case

$V = I_1 \times R_1 = 2\text{ A} \times 10\ \Omega = 20\text{ V}$

The voltage is the same in the second case.

$$V = I_2R_2 \Longrightarrow I_2 = \frac{20\text{ V}}{30\ \Omega} = 0.6667\text{ A}$$

Example 3.3

A current flows through a coil of wire of resistance 80 Ω when it is connected to the terminals of a battery. If the potential difference is 60 V, find the value of the current.

Solution

R = 80 Ω, V = 60 V

From Ohm's law,

$$I = \frac{V}{R} = \frac{60\ V}{80\ \Omega} = 0.75\ A$$

Exercise 3.1

1. State Ohm's law.
2. A p.d of 12 V is required to drive a current of 1.5 A to flow through a filament. Find the resistance of the filament.
3. A resistor of value 20 Ω allows a current of 0.3 A to pass through. Calculate the voltage across the resistor.
4. Fig. 3.7 is an ohmmeter connected in a circuit.

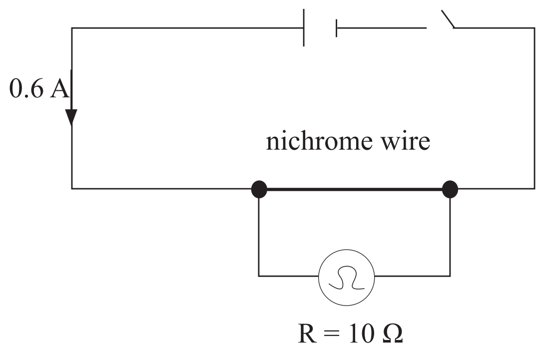


Fig. 3.7: A diagram of a circuit

   If the switch is closed, find the voltage across the nichrome wire.

5. The voltage and current through a device in a circuit are 2 V and 0.02 A respectively. Calculate the resistance of the device.
6. A current flows through a coil of wire of resistance 80 Ω when it is connected to the terminals of a battery. If the potential difference is 60 V. Find:
   (a) the value of the current
   (b) the number of electrons that pass through the coil per second. (Charge of an electron = 1.6×10^{-19} C).

3.3 Resistors

Activity 3.5 **To find out the types of resistors and their uses**

(Work in groups)

Materials

- Fixed carbon resistors
- A rheostat
- Piece of nichrome wire

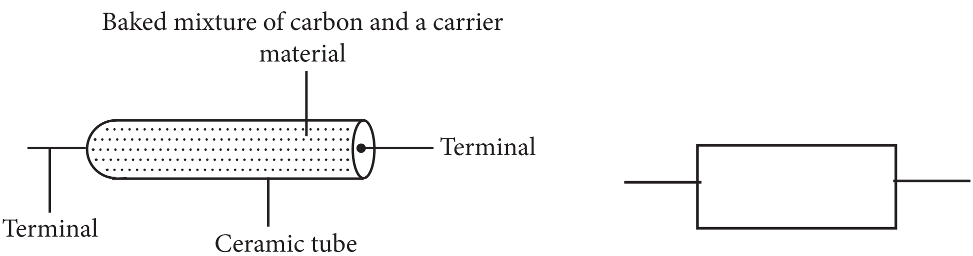
Steps

1. We have already learnt about resistance. What is a resistor.? What is it used for? Name any type of a resistor.
2. Now, take the resistors provided to you. Categorise them into two either fixed or variable resistance.
3. Sketch the symbols of fixed and variable resistors.
4. Look at the carbon resistors. What do you think the colour strips represent? How can you determine their resistance?

Devices specifically designed to offer resistance to the flow of current in a circuit are called resistors. There are mainly two types of resistors, i.e. fixed and variable resistors.

3.3.1 Fixed resistors

The term fixed resistor refers to resistors whose resistance is almost a constant. Fixed resistors are made from a variety of materials. Some are made from carbon and a carrier material. The two are mixed and baked. The baked mixture is then packed in a ceramic tube. These types of resistors are called carbon resistors (Fig. 3.8). These resistors are not bulky and are available in a wide range of values. They are widely used in electric circuits e.g. in radio and T.V circuits.



(a) A carbon resistor (b) A carbon resistor

Fig. 3.8: A carbon resistor

Colour code for carbon resistors

The value of the resistance for carbon resistors is indicated by four coloured bands painted round them.

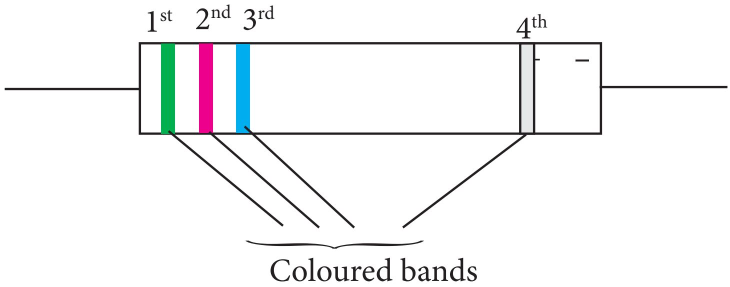


Fig. 3.9: Colour coated resistors

Each colour indicates a given value e.g. brown indicates 1. Using this colour code, the value and the tolerance (accuracy) of the resistor can be worked out. Table 3.4 gives the colour codes for resistance while Table 3.5 gives the colour codes for tolerance.

Table 3.4

Colour	Black	Brown	Red	Orange	Yellow	Green	Blue	Violet	Grey	White
Value	0	1	2	3	4	5	6	7	8	9

Table 3.5

Colour		Red	Gold	Silver	No colour
Tolerance	± %	2	5	10	20

If the value of resistance is ab × 10^n. The first band gives the first digit. The second band gives the second digit and the third band gives the power of ten. Tolerance, the maximum error in the value of the resistor is given by the fourth band. For example, the value of the resistor shown in Fig. 3.10 is $56 \times 10^5\ \Omega$ with a tolerance of 10%.

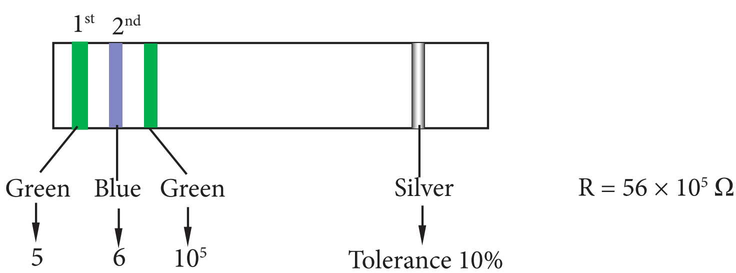


Fig. 3.10: Colour code for carbon resistors.

Example 3.4

A carbon resistor has a value of 20 MΩ ± 5%. What is the colour code for this resistor?

Solution

20 MΩ ± 5% = $20 \times 10^6\ \Omega$ ± 5%

2 — red; 0 — black; 6 — blue; 5% — gold

Therefore the colour code is as shown in Fig. 3.11.

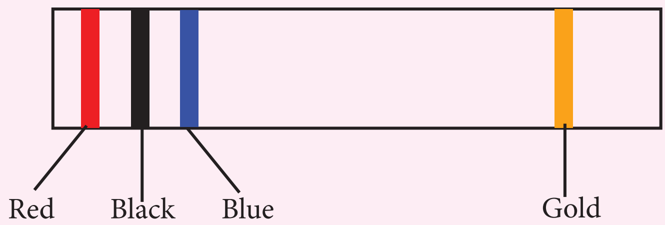


Fig. 3.11

3.3.2 Variable resistors

Resistors whose resistance can be varied are called variable resistors. Variable resistors are mainly of two types i.e. circular and the straight type. The circuit symbol for a variable resistor is shown in Fig. 3.12.

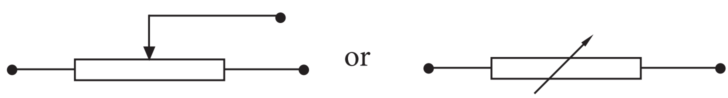


Fig. 3.12: Symbol for a variable resistor

Circular types of a rheostat

Fig. 3.13 shows a circular variable resistor. The metal slide connects the rotating arm to terminal 2. A knob is connected to the rotating arm. The function of the knob is to turn the rotating arm. The circular track is made of a thin carbon film for small current control or a coil of constantan wire for large current control.

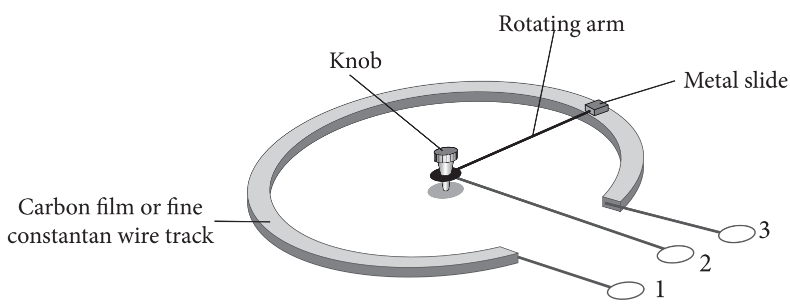


Fig. 3.13: Circular variable resistor

When terminals 1 and 3 are connected to the circuit, you get a maximum resistance which cannot be changed. However, when terminals 2 and 3 are used the resistance in a circuit can be varied. Minimum resistance can be obtained when the rotating arm is turned fully in a clockwise direction.

These types of resistors are used in electrical devices such as radios, iron boxes and light bulbs, to control sound, heat and brightness respectively.

Straight variable resistor (rheostat)

This is the one commonly used in the laboratories. Fig. 3.14 shows one type of straight variable resistor.

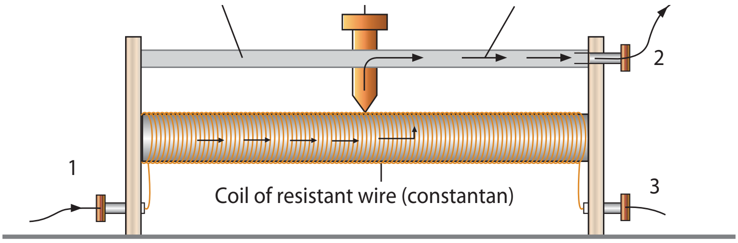


Fig. 3.14: A rheostat

Terminals 1 and 3 provide a fixed resistance while terminals 1 and 2 provide a variable resistance. The resistance is maximum when the slide is pushed near terminal 2 and minimum when the slide is near terminal 1.

Activity 3.6 **To vary the current in a circuit using a variable resistor**

(Work in groups)

Materials

- Ammeter
- Dry cell
- Connecting wires
- A variable resistor
- Bulb

Steps

1. Connect the circuit as shown in Fig. 3.15.

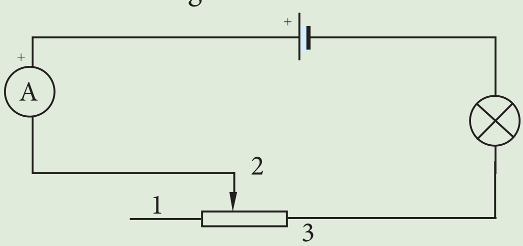


Fig. 3.15: Using a variable resistor

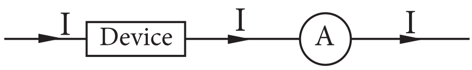
2. Position the slider (2) as close as possible to terminal 1.
3. Note the ammeter reading and the brightness of the bulb.

4. Slowly move the slider towards the other end and note what happens to both the ammeter reading and the brightness of the bulb.
5. Repeat the activity by connecting terminals 1 and 3 of the rheostat to the circuit.

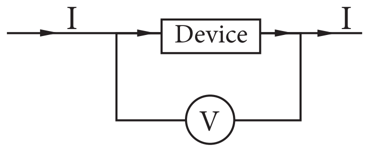
The ammeter reading and the brightness of the bulb increases. This shows that the resistance of the circuit decreases.

When terminal 1 and 3 are connected the ammeter records the lowest value. The resistance of the resistor is maximum.

Ammeters are designed to have negligible resistance so as not to interfere with the current to be measured. Similarly, voltmeters are designed to have very high resistance so that a negligible current passes through them. The potential difference across an ammeter is negligible while current through a voltmeter is also negligible (Fig. 3.16).



(a) Ammeter of negligible resistance



(b) Very high resistance voltmeter

Fig. 3.16: Effect of an ammeter and voltmeter in electric circuits

Exercise 3.2

1. Explain why carbon resistors are commonly used in radio and T.V circuits, despite the fact that they are not very accurate.
2. Describe how you would easily remember the order of the colours in the colour code.
3. Write the following using a colour code:

   (a) 63 000 Ω (b) 40 Ω (c) 1 000 Ω

4. Table 3.6 shows the current I through a carbon resistor and the corresponding potential difference applied across its ends.

Table 3.6

P.d V (V)	50	100	200	300	400
Current I (mA)	0.6	1.15	2.20	3.15	4.04

   (a) Draw a suitable graph to determine the resistance of the resistor.

   (b) For an applied p.d of 350 V, write the colour code for this resistor.

5. Suggest one reason why the colour codes are used on carbon resistors and not the actual values (numbers) of the resistance.

6. Explain the term 'tolerance' in relation to a carbon resistor.
7. With the aid of a labelled diagram show how a current in a circuit may be controlled by;
   (a) circular type of a rheostat (b) straight type of a rheostat.
8. Give two types of materials used in the construction of the coil of a variable resistor.
9. Explain why voltmeters have high resistance?
10. Describe how a variable resistor can be used to control the temperature of the element used in iron boxes.
11. Describe an experiment to show how a nichrome wire can be used in controlling a current in a circuit. What precautions should be taken?
12. Give two assumptions that are made in the determination of resistance of a resistor using an ammeter and a voltmeter method.

3.4 Arrangement of resistors in electric circuits

3.4.1 Resistors in series

Resistors are in series if they are connected end to end as shown in Fig. 3.17. Same (equal) current passes through each resistor.

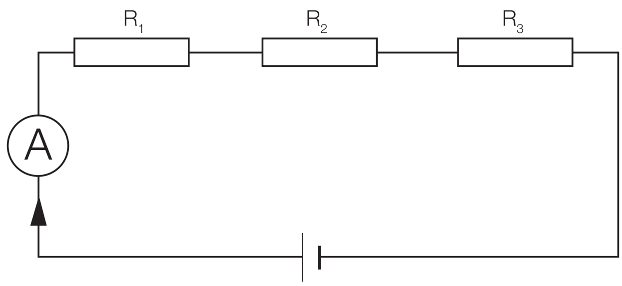


Fig. 3.17: Resistors in series

Activity 3.7 **Experiment to determine the total resistance for resistors in series**

(Work in groups)

Materials

- 2 resistors
- 3 voltmeters
- Ammeter
- 1 dry cell
- connecting wires
- a switch

Steps

1. Connect the two resistors in series as shown in Fig 3.17.
2. Close the switch and note the ammeter and voltmeter readings.

3. Calculate R_1 and R_2 using the equation which relates potential difference, current and resistance i.e.

   $V = IR$ which we shall learn later in this unit.

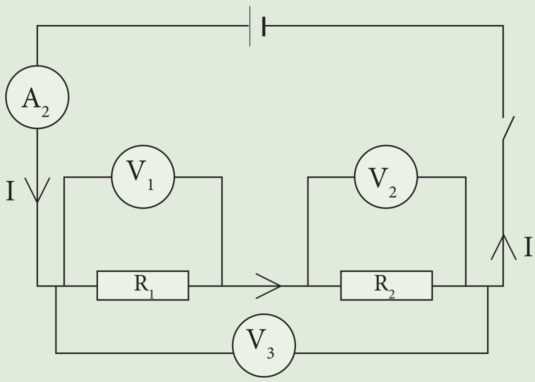


Fig. 3.18: Determine total resistance for resistors in series

We notice that current through R_1, is equal to current through R_2.

i.e $I = I_2. = I$

Also $V_3 = V_1 + V_2$

Current flowing through R_1 and R_2 is I.

$V = V_1 + V_2$, But $V = IR$

$I R_s = IR_1 + IR_2$, where R_s is the effective resistance

$R_s = R_1 + R_2$

If two or more resistors are connected in series, they give a higher resistance than any of the resistors alone. The total resistance, R_S is the sum of the individual resistances. Thus, if two or more resistors are in series, their combined resistance R_s is given by this equation.

$$R_S = R_1 + R_2 \ldots\ldots\ldots\ldots\ldots\ldots + R_n$$

Example 3.5

Work out the combined resistance for the resistors shown in Fig 3.18 (a) and (b).

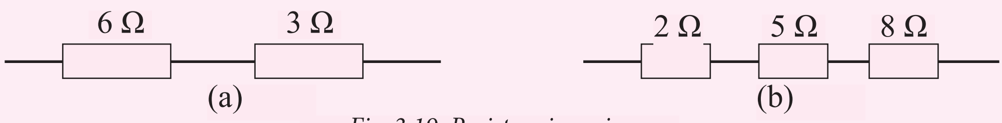


Fig. 3.19: Resistors in series

Solution

(a) $R_S = R_1 + R_2 = 6 + 3 = 9\ \Omega$ (read as 9 Ohms)

(b) $R_S = R_1 + R_2 + R_3 = 2 + 5 + 8 = 15\ \Omega$ (read as 15 Ohms).

Example 3.6

Find the value of resistor x if the combined resistance of the resistors in Fig. 3.19 is 21 Ω.

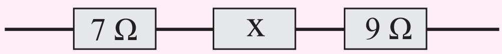


Fig. 3.20: Resistors in series

Solution

$$R_1 + R_2 + R_3 = R_s \Rightarrow 7\ \Omega + x + 9\ \Omega = 21\ \Omega$$

$$x = (21 - 16)\ \Omega$$

$$= 5\ \Omega$$

3.4.2 Resistors in parallel

In parallel connections, resistors are connected side by side and their corresponding ends joined together. The current divides itself into different paths depending on the resistance of the resistors.

Fig. 3.21 shows three resistors R_1, R_2 and R_3 connected in parallel.

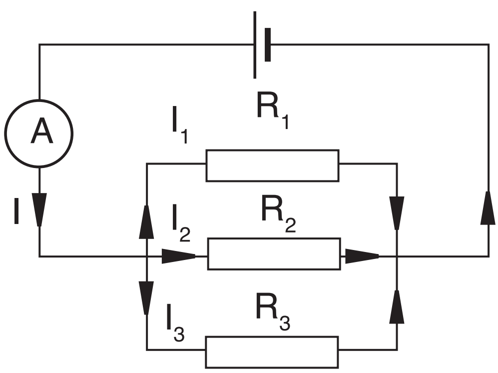


Fig. 3.21: Resistors in parallel

Activity 3.8 Experiment to determine the effective resistance when resistors are connected in parallel

(Work in groups)

Materials

- 3 resistors
- 4 voltmeters
- 1 dry cell
- 4 ammeters
- switch
- connecting wires

Steps

1. Arrange the three resistors in parallel as shown in Fig. 3.22.
2. Close the switch and note the ammeter and voltmeter readings.
3. Determine the values of resistances R_1, R_2 and R_3.

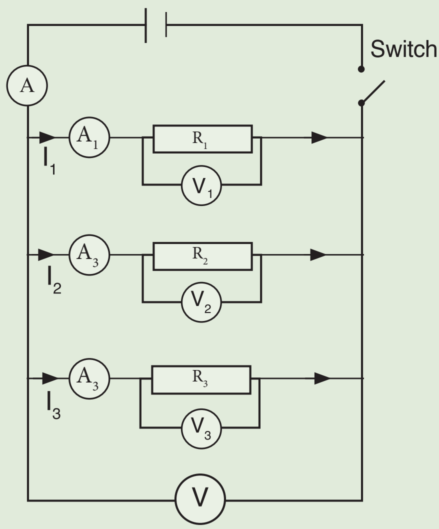


Fig. 3.22: Determining effective resistance for resistors in parallel

We observe that $V_1 = V_2 = V_3 = V$

This means that, $I = I_1 + I_2 + I_3$.

Voltage across R_1, R_2 and R_3 is V. But, $I = I_1 + I_2 + I_3$

From the equation, $V = IR \Rightarrow I = \dfrac{V}{R}$.

Therefore, substituting 'for I' we obtain $\dfrac{V}{R_p} = \dfrac{V}{R_1} + \dfrac{V}{R_2} + \dfrac{V}{R_3}$.

Dividing throug by V. We get $\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$ where R_p is the effective resistance of resistors in parallel in a circuit. To get R_p, we obtain the reciprocal of $\frac{1}{R_p}$.

If two or more resistors are connected in parallel, they give a lower resistance than the least resistor. Thus, if two or more resistors are in parallel, their combined resistance R_p is given by

$$\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots\ldots\ldots\ldots\ldots\ldots \frac{1}{R_n}$$

where, n =1, 2, 3, ...

Note: In parallel combination, effective resistance is always smaller than the resistance of the resistor with the smallest resistance in the combination.

Example 3.7

Calculate the combined resistance in each case of the resistors in Figure 3.23.

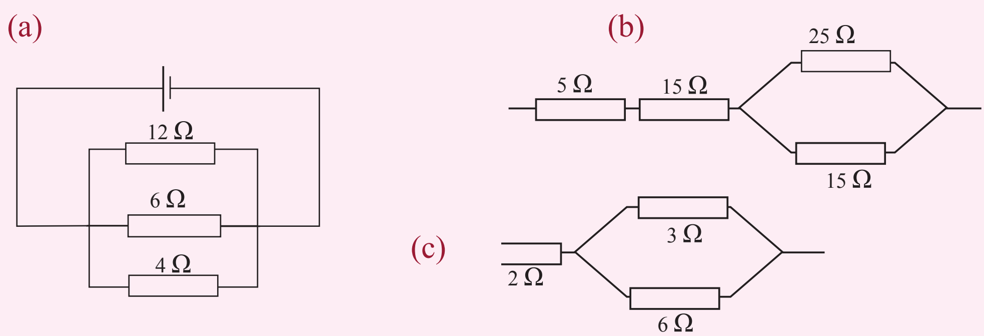


Fig. 3.23: Resistors in parallel

Solution

(a) For resistors in parallel

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

$$= \frac{1}{12} + \frac{1}{6} + \frac{1}{4} = \frac{6}{12}\ \Omega$$

$$R_p = \frac{12}{6} = 2\ \Omega$$

(b)

$$\frac{1}{R_p} = \frac{1}{15} + \frac{1}{25}$$

$$Rp = \frac{375}{40} = 9.375\ \Omega$$

$$Rp = (9.375 + 5 + 15)\ \Omega$$

$$= 29.375\ \Omega$$

(c) Starting with parallel circuit, we get

$$\frac{1}{R_p} = \frac{1}{6} + \frac{1}{3} = \frac{6+3}{18} = \frac{9}{18}$$

$$R_p = \frac{18}{9} = 2\ \Omega$$ (R_p is the equivalent resistance for the parallel connection)

Combining with 3 Ω i.e $R_s = 3\ \Omega$ (R_s is the equivalent resistance in series)

We obtain $R_T = 3 + 2 = 5\ \Omega$ (R_T is the total resistance in the circuit)

3.5 Kirchhoff's laws

Terms used to describe a circuit

- Circuit – a circuit is a closed loop with conducting path in which an electrical current flows.
- Path – a single line of connecting elements or sources.
- Node – a node is a junction, connection or terminal within a circuit were two or more circuit elements are connected or joined together giving a connection point between two or more branches. A node is indicated by a dot.
- Branch – a branch is a single or group of components such as resistors or a source, which are connected between two nodes.
- Loop – a loop is a simple closed path in a circuit in which no circuit element or node is encountered more than once.
- Mesh – a mesh is a single open loop that does not have a closed path. There are no components inside a mesh.

Fig. 3.24 shows nodes, branches and loops in a circuit.

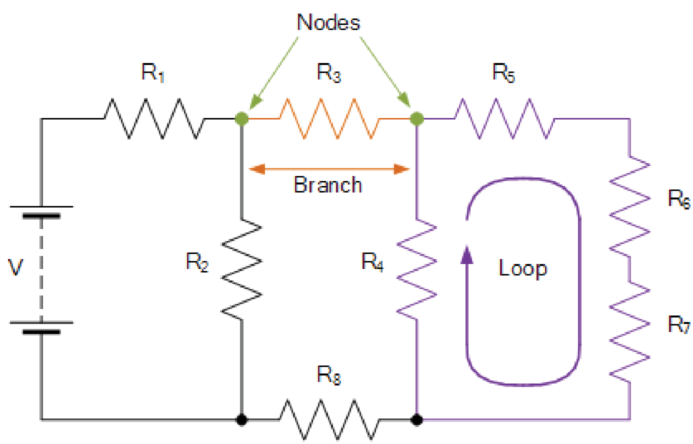


Fig 3.24

Activity 3.9 To investigate Kirchhoff's laws

(Work in groups)

Materials

- Batteries (12 V and 8 V)
- Ammeters (AM_1, AM_2 and AM_3)
- Resistors (1 k Ω, 2 kΩ and 3 kΩ)
- Connecting wires

Steps

1. Connect the circuit as shown in Fig. 3.25 with the position of the resistors as R_1 = 1 k Ω, R_2= 2 kΩ and R_3 = 3 kΩ.

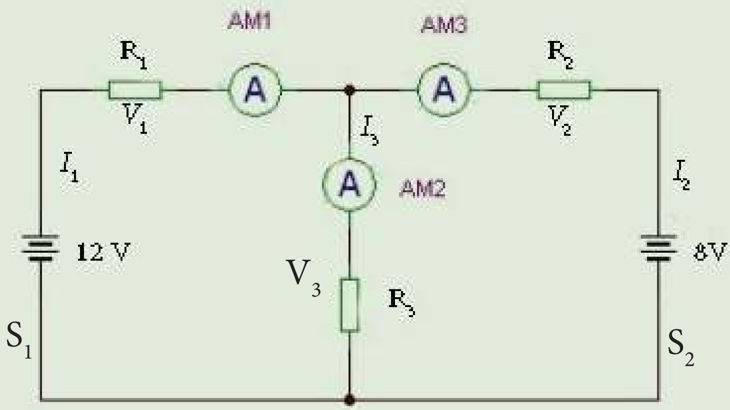


Fig: 3.25

2. (a) Switch on the power supply S_1 and S_2 and record the ammeter reading for I_1, I_2 and I_3 in Table 3.7. Calculate and record $I_3 = I_1 + I_2$ in the table.

Table 3.7

I_1 (A) (Measured)	I_2 (A) (Measured)	I_3 (A) (Measured)	$I_3 = I_1 + I_2$ (Calculated)	V_1 (V)	V_2 (V)	V_3 (V)

(b) Compare the measured and corresponding calculated values of I_3 . What do you notice?

3. (a) Determine the potential drops $V_1 = I_1R_1$, $V_2 = I_2R_2$ and $V_3 = I_3R_3$.

(b) Find the total sum of the potential differences in each loop, carefully considering the directions i.e

$12\ V + (-V_1) + (-V_3) = ...$

$8\ V + (-V_2) + (-V_3) = ...$

What do you notice?

4. Interchange the positions of the resistors as $R_1 = 3\ k\ \Omega$, $R_2 = 1\ k\Omega$ and $R_3 = 1\ k\Omega$ and repeat Steps 2 and 3.

5. Based on your observations in Steps 2, 3 and 4, with a general statement:

(a) Comparing the total current flowing into a node and with the total current flowing out.
(b) On the sum of all the voltage drops in a closed loop.

In 1845, a German physicist called Gustav Kirchhoff developed two laws, which deal with the conservation of current and energy within electrical circuits. The two rules are known as: Kirchhoff's Circuit Laws with the first one dealing with the current flowing Current Law, (KCL) while the other law deals with the voltage sources present in a closed circuit loop.

3.5.1 Kirchhoff's First Law – The Current Law, (KCL)

Kirchhoffs Current Law or KCL, states that the "total current or charge entering a junction or node is exactly equal to the charge leaving the node as it has no other place to go except to leave, as no charge is lost within the node".

In other words, the algebraic sum of ALL the currents entering and leaving a node must be equal to zero, $I_{(exiting)} + I_{(entering)} = 0$..

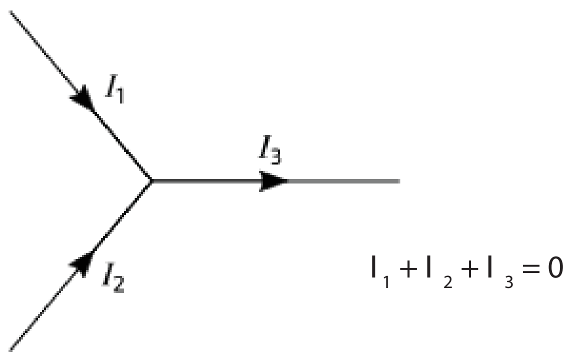


Fig: 3.26

This law shows that the charge in a $I_1 + I_2 = I_3$ circuit is conserved.

Example 3.8

What is the value of I in the circuit segment shown below?

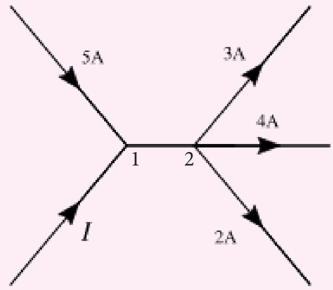


Fig: 3.27

Solution

Total current flowing out of the node 2 = total current coming out of node 1

= 2A + 4A + 3A = 9A

Total current coming into node 1 = total current coming out of node 1

5A + I = 9A

I = 5A – 9A = 4A

Example 3.9

Calculate the current flowing through R_3 in the circuit shown in Fig. 3.328

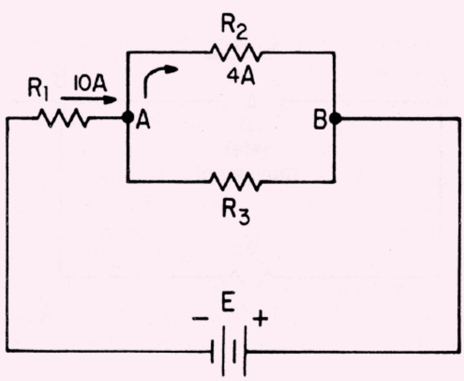


Fig: 3.28

Current into node A = current out of node a

$$10A = 4A + I_3$$

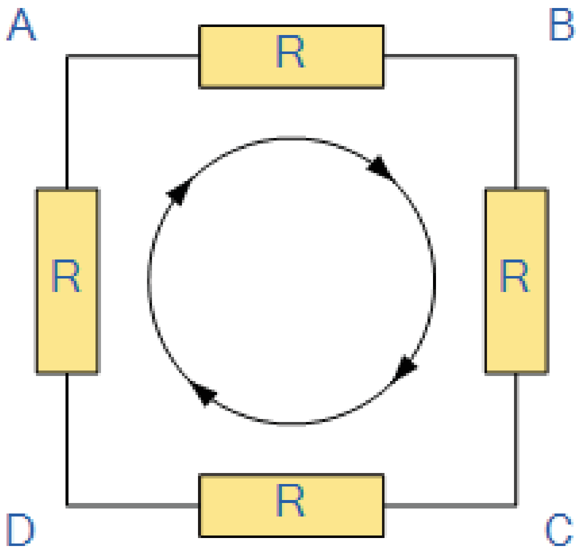
$$I_3 = 10A - 4A = 6A$$

3.5.2 Kirchhoff's Second Law – The Voltage Law, (KVL)

Kirchhoff's Voltage Law or KVL, states that "in any closed loop network, the total voltage around the loop is equal to the sum of all the voltage drops within the same loop" which is also equal to zero.

In other words the algebraic sum of all voltages within the loop must be equal to zero. This law supports the law of Conservation of Energy.

The sum of all the voltage drops around the loop is equal to zero



$$V_{AB} + V_{BC} + V_{CD} + V_{DA} = 0$$

Fig: 3.29

Starting at any point in the loop continue in the same direction noting the direction of all the voltage drops, either positive or negative, and returning back to the same starting point. It is important to maintain the same direction either clockwise or anti-clockwise or the final voltage sum will not be equal to zero. We can use Kirchhoff's voltage law when analysing series circuits.

Example 3.10

Find the value of E in the circuit in Fig. 3.30.

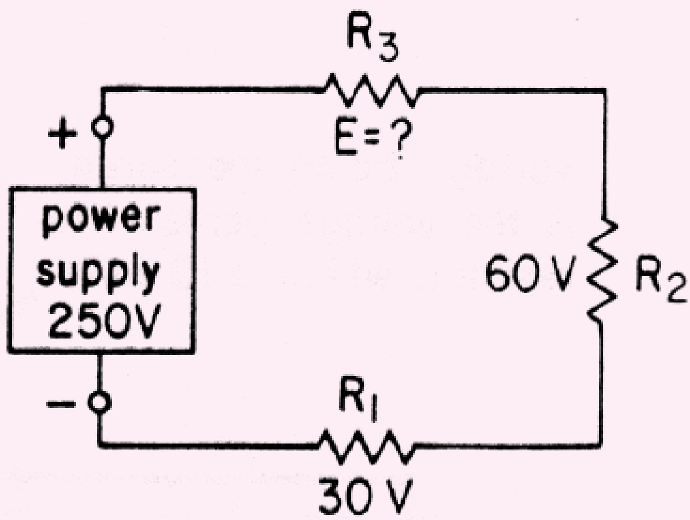


Fig. 3.30

Solution

Add the voltage drops considering their directions.

+250V – 30V – 60V – E = 0

We get: + 250V – 90V = E.

Thus, E = +160V

Example 3.11

Find the voltages V_A and V_B.

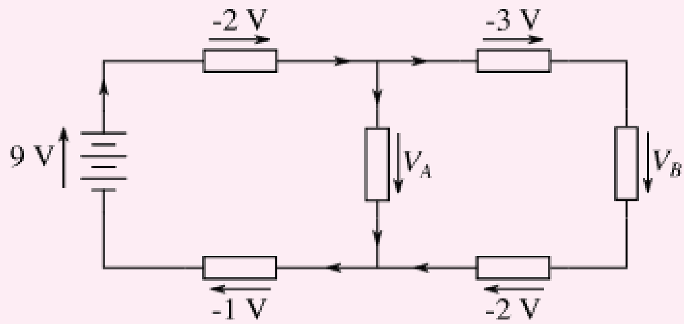


Fig. 3.31

Solution

In loop 1: $+9V - 2V - V_A - 1V = 0$

We get $V_A = 9V - 3V = 6V$

In loop 2: $-3V - V_B - 2V + 6V = 0$

We get $V_B = 6V - 5V = 1V$.

Example 3.12

Find the current flowing in the 40Ω resistor, R_3.

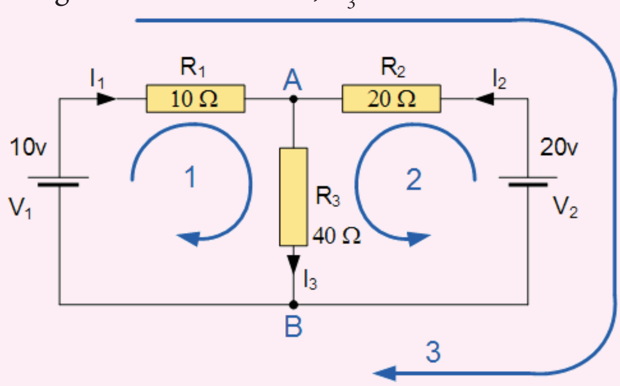


Fig. 3.32

Solution

The circuit has 3 branches, 2 nodes (A and B) and 2 loops.

Using Kirchhoff's Current Law, we get:

At node A : $I_1 + I_2 = I_3$..............(i)

At node B : $I_3 = I_1 + I_2$..............(ii)

Using Kirchhoff's Voltage Law and V = IR , we get:

Loop 1: $10 = R_1 I_1 + R_3 I_3 = 10I_1 + 40I_3$..............(iii)

Loop 2: $20 = R_2 I_2 + R_3 I_3 = 20I_2 + 40I_3$..............(iv)

Loop 3: $10 - 20 = 10I_1 - 20I_2$.........................(v)

Substituting $I_3 = I_1 + I_2$ in equations (iii) and (iv) we get:

$10 = 10I_1 + 40(I_1 + I_2) = 50I_1 + 40I_2$..............(vi)

$20 = 20I_2 + 40(I_1 + I_2) = 40I_1 + 60I_2$..............(vii)

Solving equations (vi) and (vii) simultaneously we get the values of I_1 and I_2 as

$I_1 = -0.143$ A and $I_2 = +0.429$

Substitution of I_2 in terms of I_1 gives us the value of I_2 as +0.429 Amps

Using $I_3 = I_1 + I_2$ we get I_3, current flowing in resistor R_3 as

$I_3 = -0.143 + 0.429 = 0.286$ A

And the voltage across the resistor R_3 is given as

$V_3 = I_3 R_3 = 0.286 \times 40 = 11.44$ V.

The negative sign for I_1 means that the direction of current flow initially chosen was wrong, but never the less still valid. In fact, the 20V battery is charging the 10V battery.

Exercise 3.3

1. State:

(a) Kirchohoff's Current Law

(b) Kirchohoff's Voltage Law.

2. Determine the current through each resistor in the circuit.

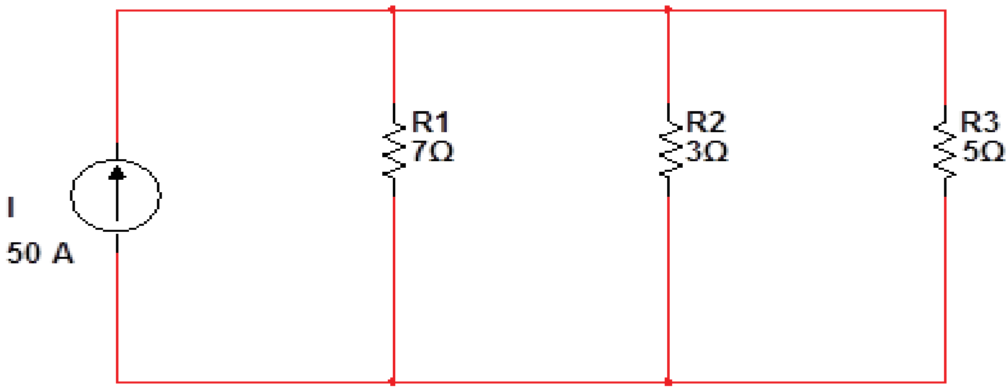


Fig. 3.33

3. Find the current through the resistor R_3 Fig. 3.34.

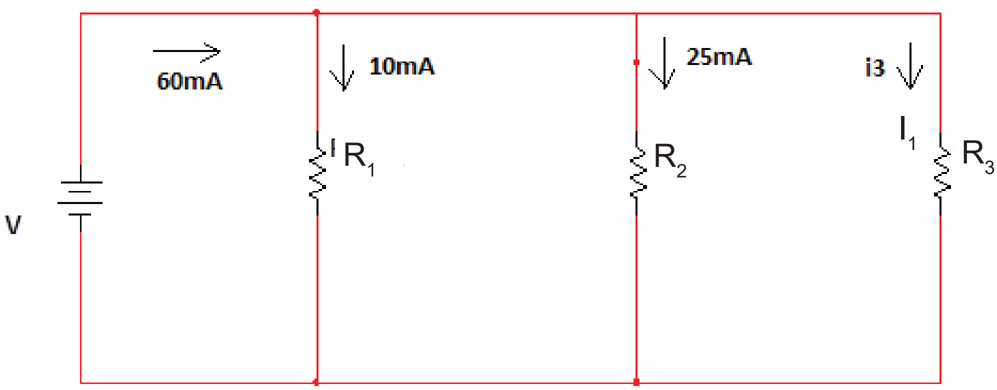


Fig. 3.34

4. Find the current in the circuit in Fig. 3.35

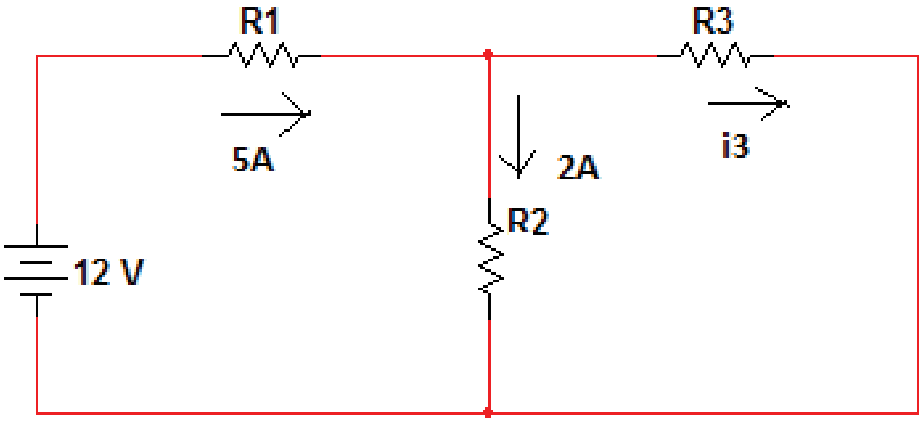


Fig. 3.35

5. A cell supplies a current of 0.24 A through two resistors of resistance 6 Ω and 3 Ω arranged in series. Calculate the:
   (a) p.d across each resistor.
   (b) Terminal voltage of the cell.

6. Three resistors of resistance 8 Ω, 10 Ω and 12 Ω are connected in series. A voltmeter connected across the 10 Ω resistor reads 6 V. Calculate the:
   (a) Current through the circuit.
   (b) Voltage across 12 Ω resistor.
   (c) Total voltage in the circuit.

7. Two resistors are connected in parallel as shown in Fig. 3.36. Calculate the:
   (a) Current that passes through R_1.
   (b) Terminal potential difference across the battery.

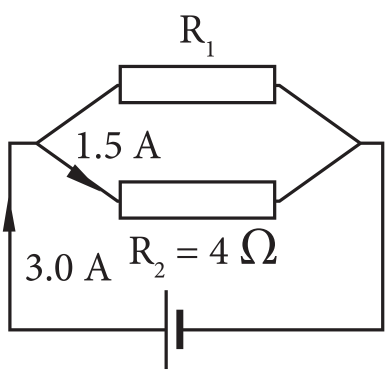
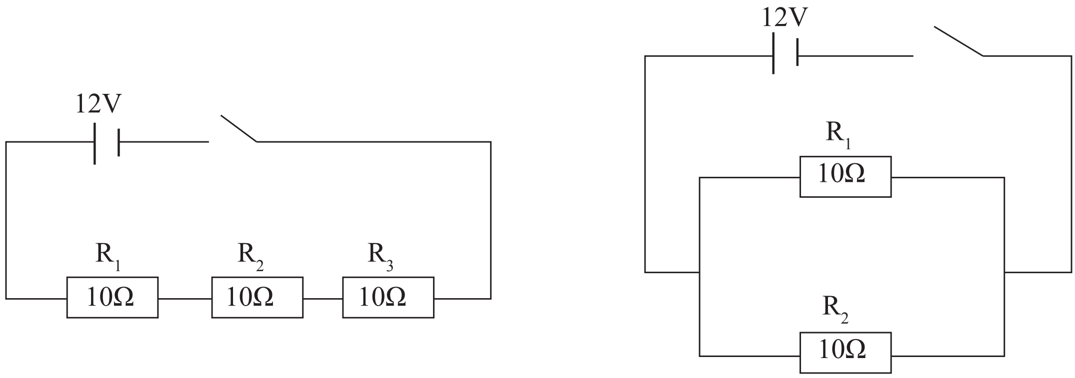


Fig. 3.36

8. Fig 3.37 shows circuit diagrams.



(a) (b)

Fig 3.37: Circuit diagrams

Calculate:

(a) The potential difference across each resistance in each circuit.

(b) Current through each of the resistors in circuits (a) and (b).

9. A p.d of 12 V is applied across two resistors of 10 Ω and 20 Ω connected in series. Find:

(a) The effective resistance for the circuit.

(b) The total current in the circuit.

(c) The current through each of the resistors.

(d) The voltage drop across each resistor.

10. Show that the effective resistance R of R_1, R_2 and R_3 when connected in parallel is given by:

$$\frac{1}{R} = \frac{1}{R_1} = \frac{1}{R_2} = \frac{1}{R_3}$$

11. Two resistors of 4 Ω and 2 Ω in parallel are connected in series to a 30 Ω resistor and a cell of e.m.f 1.5 V. Calculate:

(a) The effective resistance in the circuit.

(b) The current through each of the resistors and p.d across each.

3.6 Factors that affect resistance of materials (wires)

(a) Length of the wire

Activity 3.10 **To investigate how the resistance of a conductor depends upon the length.**

(Work in groups)

Materials

- Crocodile clips
- Ammeter
- Connecting wires
- Voltmeter
- 1.5 V dry cell
- Six pieces of nichrome wires of different lengths but same diameter

Steps

1. Take six different lengths of nichrome wire of the same diameter. Connect the smallest length in the gap AB using crocodile clips (Fig. 3.38).

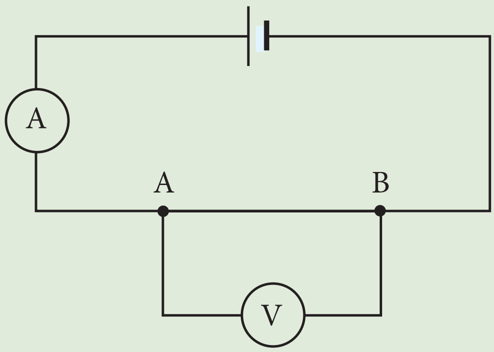


Fig. 3.38: Resistance depends on the length of a conductor

2. Record the values of the current passing through the wire and the potential difference across its ends. Repeat the activity by connecting the other lengths of the wire and complete Table 3.8.

Table 3.8

Length l (cm)	Current (A)	Voltage (V)	$R = \frac{V}{I}$ (Ω)
5.0			
10.0			
15.0			
20.0			
25.0			
30.0			

3. Plot a graph of resistance of the wire against its corresponding length.
4. Use your graph to describe the relationship between the resistance of a straight conductor and its length.

When the length of the wire increases, the resistance also increases.

Drawing a graph of resistance against length, l of the wire we get a straight line graph. (See Fig. 3.39), which is a straight line passes through the origin.

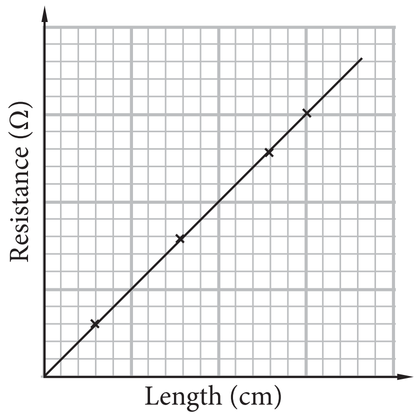


Fig 3.39: Resistance is directly proportional to length

From the graph, we can conclude *that the resistance (R) of a wire is directly proportional to its length l i.e.* $R \propto l$ *............... (i)*

(b) Thickness

Activity 3.11 **To investigate how the resistance of a wire varies with its thickness**

(Work in groups)

Materials

- Ammeter
- A voltmeter
- Six pieces of nichrome wires of different diameters
- Source of power
- Connecting wires

Steps

1. Set up the experiment as shown in Fig. 3.40. Connect various nichrome wires of the same length but of different diameters in the gap AB.

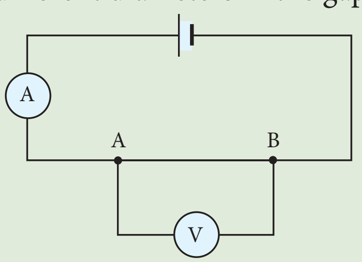


Fig. 3.40: Variation of resistance with thickness of conductors

2. Record the values of diameter (d) of the wire, current (I) and the potential difference (V) (Table 3.9).

Table 3.9

Diameter d (cm)	Voltage V(V)	Current I (A)	$R = \frac{V}{I}$ (Ω)	$A = \frac{\pi d^2}{4}$	$\frac{1}{A}$
0.04					
0.06					
0.08					
0.10					
0.12					

3. Plot a graph of R against $\frac{1}{A}$.
4. Use the graph to determine the relationship of a straight conductor and its cross-section area.

NB: A in this case is the area of cross-section of the wire given as $A = \frac{\pi d^2}{4}$ and not amperes (A).

- Resistance R, of a material decreases with an increase of the thickness or the diameter of the material.
- When a graph of R against $\frac{1}{A}$, is plotted, we get a straight line passing through the origin (Fig. 3.41).

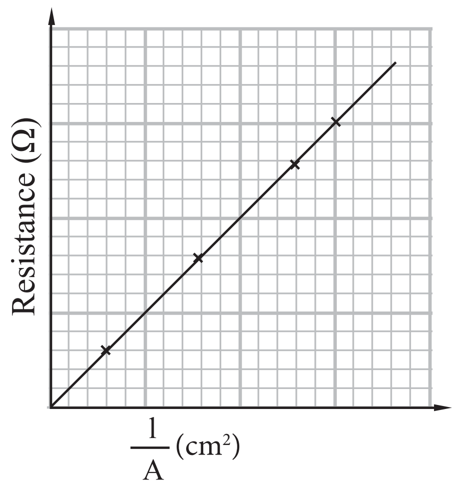


Fig. 3.41: Graph is resistance against inverse of cross-section area

The resistance, R is inversely proportional to the cross-section area, A i.e

$R \propto \frac{1}{A}$.

Thicker conductors offer less electrical resistance than conductors with smaller cross-section area.

Combining equations (i) and (ii), we conclude that

$$R \propto \frac{L}{A} \quad \text{.......................................} \quad (1)$$

Mathematically,

$$R = \rho \frac{L}{A}$$ where R is the resistance of material

L is the length of the conductor

A is the cross-section areas of the conductor

ρ is the resistivity.

Resistivity of a conductor is the ability of the material to offer opposition to the flow of current. It's symbol is ρ and given by

$$\text{Resistivity} = \frac{\text{Resistance} \times \text{cross-section area}}{\text{Length of conductor}}$$

$$\rho = \frac{RA}{L}$$

The SI unit of resistivity is the ohm – metre (Ω m).

Example 3.13

A wire of length 2 m and diameter 0.35 mm has a resistance of 10 Ω. What is the resistivity of the material of the wire.

Solution

$L = 2$ m $\qquad$ diameter $= \frac{0.35 \text{ mm}}{1000} = 0.00035$ m

$$A = \pi r^2 = \frac{22}{7} \times \left(\frac{0.00035}{2}\right)^2 = 9.625 \times 10^{-8} \text{m}^2$$

$$\rho = \frac{R \times A}{L}$$

$$\rho = \frac{10 \times 9.625 \times 10^{-8}}{2} = 4.8125 \times 10^{-7} (\Omega \text{ m})$$

(c) The nature of the material of a conductor

When the diameter of the nichrome wire is increased, the resistance decreases.

When a graph of R against $\frac{1}{A}$ for a certain material e.g. nichrome is drawn, the graph is found to be a straight line passing through the origin.

When the experiment is repeated with a wire of different material e.g. constantine, the slope of the graph changes (Fig. 3.42).

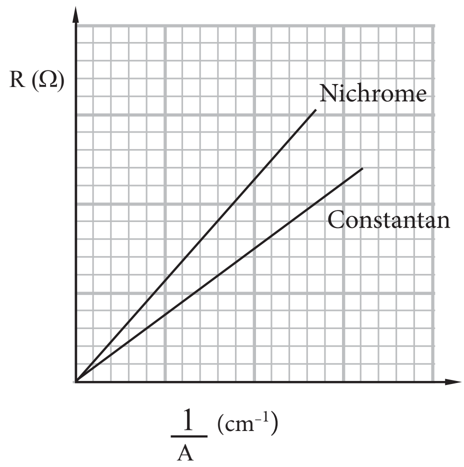


Fig. 3.42 Graph of R against $\frac{1}{A}$

This shows that *different materials offer different resistances to the flow of current*. i.e. some materials conduct electricity better than others.

This property makes it possible for different materials to be used for different purposes e.g. tungsten wire is used as a filament in bulbs, copper wires are used in electric motor and generator coils to minimise energy losses.

(d) Temperature

Activity 3.12 — **Experiment to investigate how the resistance of a wire varies with temperature**

(Work in groups)

Materials

- A voltmeter
- An ammeter
- A source of electricity
- Connecting wire
- A thermometer
- A source of heat

Steps

1. Setup the apparatus as shown in Fig. 3.43.

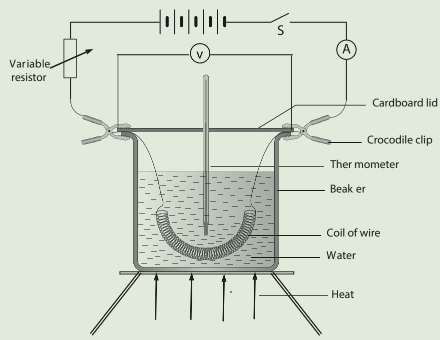


Fig. 3.43: Variation of resistance with temperature

2. Heat the bottom of the beaker as shown in Fig 3.43 and then record the ammeter and voltmeter readings at intervals of 20°C. Record the data in Table 3.10.

Table 3.10

Temperature	37° C	57° C	77° C	97° C
Voltage, V				
Current, I				
Resistance $\frac{V}{I}$ (Ω)				

Increase in the temperature of a conductor leads to an increase in the p.d across the conductor.

As the temperature increases, the electrons of the conductor vibrates more vigorously hence hindering the flow of current. This causes the resistance to increase i.e. Resistance α Temperature. ($R \propto \theta$).

In summary, the resistance of the materials (wires) depends on the following:

- the length of the conductor
- the cross-section area of the conductor
- the type of material the conductor is made of
- temperature.

3. Plot a graph of $\frac{V}{I}$ against temperature.
4. Use the graph to determine the relationship between resistance of a conductor and temperature.

Exercise 3.4

1. Explain three factors that affect the electrical resistance of a conductor.
2. An electrical conductor has a length of 100 cm and a resistance of 25 Ω. The conductor is cut into five equal pieces. Find the resistance of each piece.
3. What length of resistance wire of diameter 0.11 mm and resistivity 2.1×10^{-6} Ω m, would you cut from steel cable in order to make a 20 Ω resistor?
4. Two materials; A of resistivity 1.2×10^{-6} Ω m and B of resistivity 1.1×10^{-7} Ω m are used to make a resistor. Which material would you select to make a resistor of higher resistance? Explain.

5. In an experiment to investigate the V-I relationship for a conductor, the following results in Table 4.7 were obtained. (See Table 3.11.)

Table 3.11

P.d V (V)	2.0	3.0	4.0	6.0
Current (A)	1.0	1.5	2.0	3.0

(a) Plot a graph of I against the voltage V.

(b) Determine the resistance of the conductor.

(c) Comment on the nature of the conductor used.

6. Give two assumptions that are made in the determination of resistance of a resistor using the ammeter and voltmeter method.

3.7 Internal resistance, r

There seems to be some lost 'voltage' when a cell is driving a current round a circuit (Fig. 3.44). This is the voltage the cell uses in driving the current through itself. The resistance the cell offers to the flow of current inside the cell is called the internal resistance of the cell. It results from the properties of the substances used in the construction of the cell.

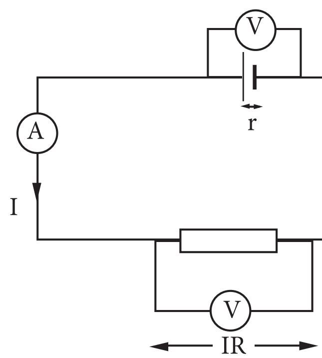


Fig. 3.44: Total e.m.f

Therefore, the total e.m.f available in the cell is used up in two ways:

1. Driving the current through the cell i.e. to overcome internal resistance (r).
2. Driving the current through external resistance R.

Hence, the total electromotive force (e.m.f = E) is given by e.m.f, E = p.d. across external resistance R (terminal voltage) + P.d. across internal resistance r (lost voltage).

$E = (IR + Ir) \Rightarrow E = I(R + r)$, since the current is the same.

Activity 3 13 **To determine the e.m.f. and the internal resistance of a cell**

(Work *in groups)*

Materials

- A voltmeter
- A rheostat
- A cell
- A fixed resistor
- An ammeter

Steps

1. Using a high-resistance voltmeter, determine the value of the e.m.f. (e) of the cell as shown in Fig. 3.45(a).
2. Connect the cell to a known resistance R as in Fig. 3.45 (b).

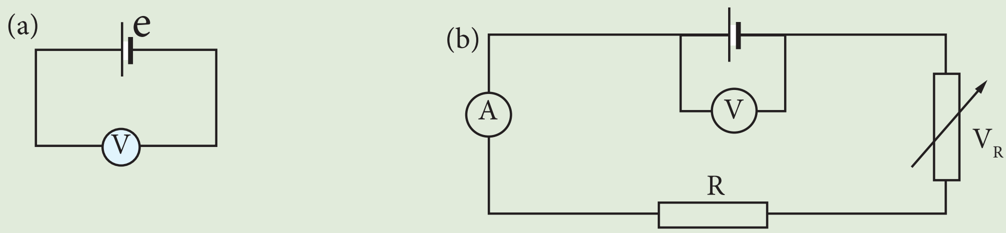


Fig. 3.45: Determining e.m.f and internal resistance of a cell.

3. Set the variable resistor at its maximum value. Record the ammeter and voltmeter readings (Table 3.12.)

Table 3.12

Voltmeter V (V)								
Ammeter I (A)								

4. Adjust the variable resistor by moving the sliding contact to change the resistance in the circuit and each time record the ammeter reading I and voltmeter reading V. What happens to the ammeter and voltmeter readings as the resistance is reduced?
5. Plot a graph of V against I and use it to determine the internal resistance of the cell guided by the equation

$$E = I(R + r).$$

The ammeter reading increases and the voltmeter reading decreases. A graph of voltage (V) against current (I) is as shown in Fig. 3.46.

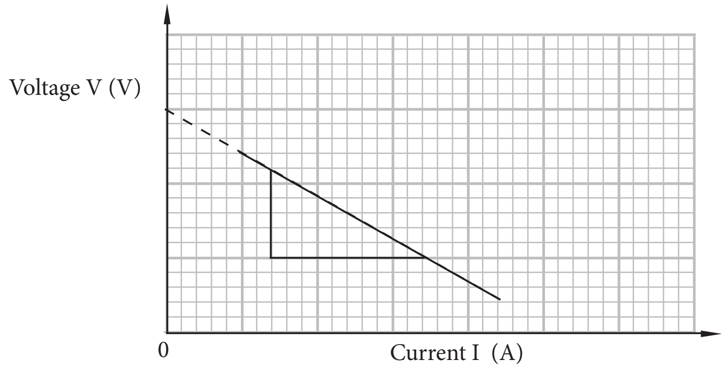


Fig. 3.46: Graph of voltage V against current I

Produce the line so as to meet the voltage axis as shown in Fig. 3.46. The value on the voltage axis at this point is the p.d. across the cell when the current is zero. The potential difference across the terminals of a cell when it is not driving a current is the e.m.f. of the cell. The value of the *intercept* therefore gives the e.m.f. of the cell.

$$E = IR + Ir$$

$$E = V_R + Ir$$

$$V_R = -rI + E$$

When this equation is compared with the general equation of a straight line i.e. $y = mx + c$, then the gradient of the line is equal to $-r$. The minus sign represents a negative slope. The slope of the graph gives the value of the internal resistance, r.

Example 3.14

An 'ideal' voltmeter is connected across the terminals of a cell. The voltmeter reads 1.5 V when the switch is open and 1.3 V when the switch is closed.

(a) What is the e.m.f of the cell?

(b) What is the terminal voltage of the cell?

(c) Calculate:

(i) the current in the circuit

(ii) the internal resistance of the cell.

Solution

(a) e.m.f of the cell = 1.5 V (no current is drawn from the cell).

(b) Terminal voltage of the cell = 1.3 V (the cell is in use).

(c) (i) p.d across the resistor = terminal voltage of the cell

$V = 1.3\ V;\ R = 2.6\ \Omega$

From Ohm's law, $V = IR$

$$I = \frac{V}{R} = \frac{1.3}{2.6} = 0.5\ A$$

Current in the circuit is 0.5 A.

(ii) Lost voltage inside = 1.5 V – 1.3 V = 0.2 V

$$V = Ir$$

$$r = \frac{V}{I} = \frac{0.2}{0.5} = 0.4\ \Omega$$

The internal resistance of the cell is 0.4 Ω.

Example 3.15

The 'ideal' ammeter in Fig. 3.47 reads 0.20A when the switch S is closed.

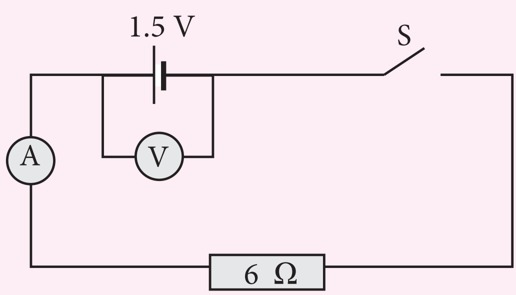


Fig. 3.47

Determine the internal resistance of the cell.

Solution

E.m.f of the cell = 1.50 V.

P.d across the resistor $V = IR$

$= 0.2\ A \times 6\ \Omega$

$= 1.20\ V.$

Thus terminal voltage = 1.20 V.

Lost voltage, V = 1.50 V – 1.20 V = 0.30 V.

$$V = Ir$$

$$r = \frac{V}{I} = \frac{0.3}{0.2} = 1.5\Omega.$$

The internal resistance of the cell is 1.5 Ω.

Exercise 3.5

1. The p.d across the terminals of a cell is 1.5 V when there is no current in the circuit. When there is a current of 0.50 A in the circuit, the p.d. falls to 1.3 V.
   (a) What is the e.m.f of the cell?
   (b) What is the terminal voltage of the cell?
   (c) Calculate the internal resistance of the cell.
2. Explain the term internal resistance of a cell. How does it arise?
3. The e.m.f. of a cell is given by the expression, $E = I(R + r)$. Explain the meaning of each term in the expression.
4. (a) Describe an experiment to determine the internal resistance of a cell.
   (b) Table 3.13 shows readings obtained in an experiment to determine the e.m.f, E and the internal resistance, r of an accumulator.

Table 3.13

External resistance R (Ω)	0.35	1.3	2.75
Current $I(A)$	2.5	1.0	0.5

   (i) Draw a suitable circuit diagram that can be used to get the above results.
   (ii) Plot a graph of $\frac{1}{I}$ against R. (reciprocal of I vs R)
   (iii) Determine the values of R and E.
5. A battery consisting of three cells in series, each of 1.5 V and internal resistance of 0.3 Ω is used to pass a current through a 1.8 Ω resistor. Calculate the current through the battery.

Topic summary

- An ammeter is an device used to measure current.
- A voltmeter is a device used to measure voltage.
- An ohmeter is a device used to measure electrical resistance of a body.
- Kirchhoff's current law states that, the total current entering a node is equal to the total current leaving the node.
- Kirchhoff's voltage law states that sum of all the P.d's in the circuit is zero.
- Electrical resistance is the opposition to the flow of electrical current in a conductor.

- Factors affecting electrical resistance include length, cross-section area, temperature and nature of conductor.
- The smaller the cross-sectional area of a wire, the higher the resistance to the flow of electric current.
- The thicker the conducting wire, the lower the electrical resistance.
- Increasing temperature of some conductors increases the resistance of the conductors.
- Voltmeters are connected in parallel while ammeters are connected in series to conductors in electric circuits.
- Ohm's law states that the current passing through a conductor is directly proportional to the potential difference applied across its ends provided that the temperature and other physical properties of the conductor remain constant:

$$V = IR$$

- Non-Ohmic conductors do not obey Ohm's law.
- Electromotive force (e.m.f) is the p.d at the terminals of a cell when the circuit is open.
- The instrument used to measure electrical resistance is called an ohmmeter.
- A resistor is a material that offers resistance to flow of electric current.
- There are two types of resistors: Fixed resistors and variable resistors. In a fixed resistor, the resistance is almost a constant while in variable resistor the resistance can be varied.
- Internal resistance is the resistance a cell offers to the flow of charges inside it.
- The electromotive force (E.m.f), $E = I(R + r)$, where R = total external resistance, r = Internal resistance

Topic Test 5

1. Calculate the resistance of a coil of wire through which a current of 3 A flows due to a potential difference of 12 V.

2. In the circuit shown in Fig. 3.48, the 12 V lamp glows when switch S is closed.

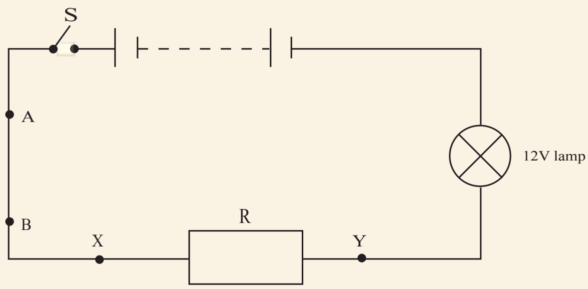


Fig. 3.48

What happens to the brightness of the lamp when another identical resistor R is connected between:

(a) Points A and B? (b) Points X and Y? Give a reason.

3. Figure 3.49 shows a battery with e.m.f. of 12 V supplying power to two identical lamps.

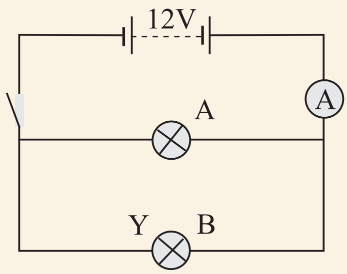


Fig. 3.49

The current in lamp B is 5 A. Calculate the:

(a) total current supplied by the battery when both lamps are on.

(b) current in lamp A.

(c) resistance of lamp A.

4. Figure 3.50 shows a battery of e.m.f 6V supplying current to two fixed resistors

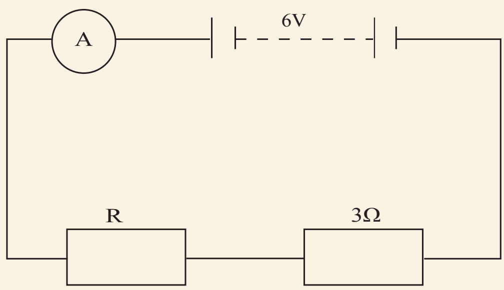


Fig. 3.50

When the current is switched on, the ammeter reads 0.5 A. Calculate the value of the unknown resistor R.

5. List two factors that affect the resistance of a conductor.

6. The set of readings shown in Table 3.14 were obtained in an experiment to investigate current and voltage.

Table 3.14

P.d (V)	0.2	0.5	1.0	2.0	4.0	6.0	8.0	10.0	12.0
Current (A)	0.12	0.15	0.22	0.23	0.32	0.36	0.40	0.44	0.51

(a) Plot a graph of voltage (V) against the current, I(A).

(b) Explain the shape of the graph.

(c) Determine the resistance of the bulb when the current is 0.25A and 0.60 A. Comment on the answer.

7. A battery is connected in series with an ammeter and a variable resistor R. The resistance, R is varied and the corresponding reading of the ammeter recorded in table 3.15.

Table 3.15

Resistance R (Ω)	1	2	3	4	5	6	10
Current I (A)	2.00	1.50	1.20	0.23	1.00	0.75	0.50

(a) Draw the circuit diagram used.

(b) Plot a graph of R against $\frac{1}{I}$ (reciprocal of I).

(c) What is the value of I when R is zero?

(d) Using your result in (c) above, find the internal resistance of the battery if its e.m.f = 6.0V.

8. Distinguish between Ohmic and non-Ohmic conductors. Give two examples of each.

9. Calculate the length of a nichrome wire of diameter 0.32 mm needed to give a resistance of 40 Ω given that the resistivity of nichrome is 1.1×10^{-6} Ω m.

Topic 4 Basic electronics

Topic outlines

4.1 Definition of electronics

Activity 4.1 **To define electronics**

(Work in groups)

Materials:

- Resistors
- Ordinary diode
- Bulbs
- Spring
- Beam balance
- Vernier calipers

Steps

1. Identify the electronic devices from the assorted devices provided. Suggest a reason for your choice.
2. Now, carry out research from Physics reference books and internet about the definition of electronics and electronic devices.
3. Name some other examples of electronic devices.

Electronics is a branch of Science that is concerned with the development of electrical circuits designed to process, store or transmit information. Concepts learnt in electronics are applied in the design of modern communication devices like televisions, calculators, radios, computers, burglar alarms, (CD) players, digital watches, Automated Teller Machines (cash dispenser), mobile phones, etc.

In this unit, we shall learn the basic principles of simple electronic circuits and components like diodes, transistors and their application.

4.2 Conductors, semiconductors and insulators

Activity 4.2 **To investigate conductors, semi-conductors and insulator materials**

Materials

- Copper • Iron • Zinc • Wood • Paper • Plastics • Silicon
- Connectivity wires • Bulb • Cell in cell holder • A switch.

Steps

1. Using connecting wires, bulb, cells in cell holder, and the switch provided, design a simple circuit as one shown in the following figure.

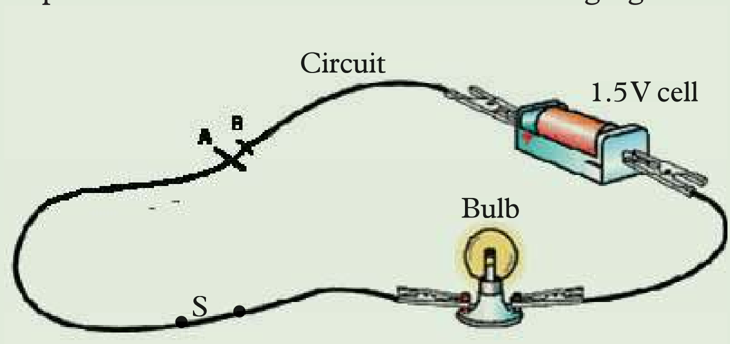


Fig. 4.1: Simple electric current diagram

2. Open the switch and in turn, connect the materials provided between terminals A and B to complete the circuit.
3. What observations do you make? Which materials are good conductors? Which ones are insulators?
4. Now carry out research from reference books or Internet on the structural differences between conductors, semi-conductors and insulators.
5. Using the knowledge from your research, in Step 4, make a suitable table with column of conductors, semiconductors and insulators.
6. Present your findings with the rest of the class.

Materials can be grouped according to their electrical conductivity properties. Materials that allow an electric current to pass through them easily are called *good conductors* e.g. copper, zinc, silver, mercury, etc. Those materials that do not allow electric current to flow through them at all are known as *insulators* e.g. paper, wood, plastics, etc. *Semiconductors* are those materials whose electrical conductivity lies between that of good conductors and insulators. Such materials include silicon and germanium.

The electrical conductivity of materials may be explained by studying how electrons are held or locked up in the crystal lattice. Many theories have been proposed to explain the electrical behaviour of materials. One such theory is the *band theory*.

Band theory

In this theory, materials are considered to contain two bands in which electrons may be found. These bands are the *valency band* and *conduction band* (Fig. 4.2).

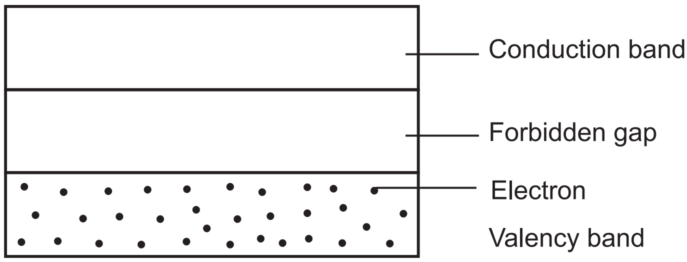


Fig. 4.2: Conduction and valency bands

The two bands are separated by a gap called *forbidden gap* (no electrons are allowed in this gap). For a material to conduct an electric current, electrons should be in conduction band. However, electrons strive to occupy the valency band as this is the lowest energy level. To move the electrons to the conduction band, energy is needed to cross through the forbidden gap. One way of providing the energy to cross the gap is to increase the temperature of the material.

Electrical conduction in conductors

In conductors, the valency and conduction bands overlap and hence no energy is needed to overcome the forbidden gap (Fig. 4.3).

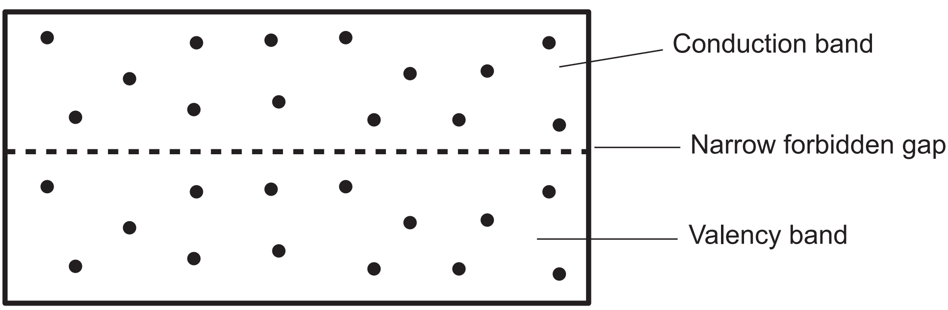
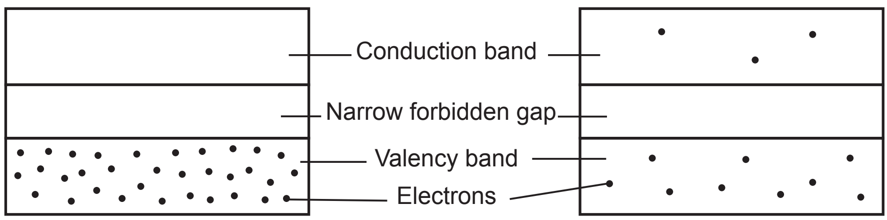


Fig. 4.3: Overlapping of bands in conductors

All the electrons are free and mobile to conduct electric current. If conductors are heated, the internal energy increases and the electrons move in all directions colliding with each other. This explains why metals become poor conductors as temperature increases.

Electrical conduction in semiconductors

In semiconductors, the forbidden gap is wider than in conductors (Fig. 4.4). At low temperatures, all the electrons are in the valency band. However, at room temperature some electrons gain thermal energy and cross the forbidden gap to the conduction band. The material then becomes a fair conductor. As the temperature is increased, more electrons move to the conduction band and hence its electrical conductivity is increased. This shows that the resistance of semiconductors decreases with increase in temperature.



(a) At low temperatures electrons are in the valency band

(b) At high temperatures some electrons move to the conduction band

Fig. 4.4

Poor electrical conduction in insulators

In insulators, the forbidden gap is so wide (Fig. 4.5) that any attempt, say by heating, to promote the electrons to the conduction band ends up breaking down the material. For example, if the material is paper, it burns off.

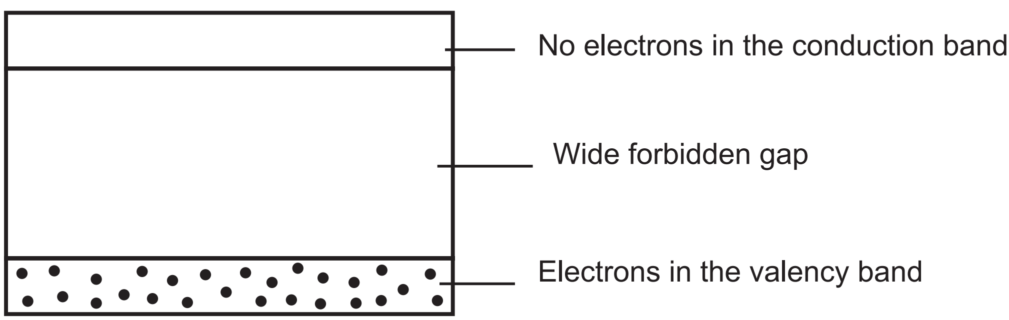


Fig. 4.5: The forbidden gap in an insulator

4.3 Intrinsic and Extrinsic semi-conductors

Activity 4.3: **To carry out research on semi-conductors**

Materials

- Reference books
- Resource persons
- Internet

Steps

1. Now conduct research from reference materials or internet on semi-conductors.

   In your research, find out:

   (a) The structural differences between intrinsic and extrinsic semi-conduciors and examples of ech category

   (b) How doping is done in semi-conductors.
2. Make a short report on your findings and present it to the whole class during class discussion.

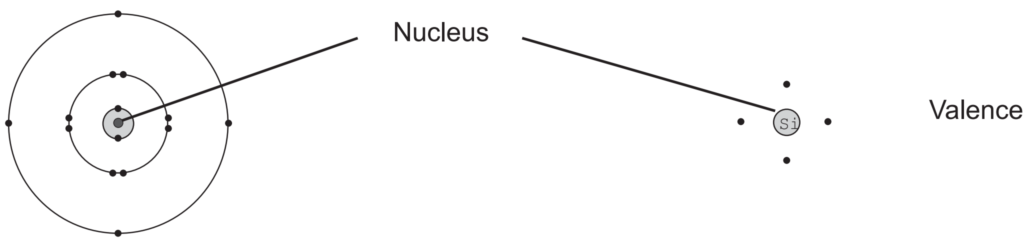
We have already learnt that semi-conductors are those materials whose electrical conductivity lies between those of good conductors and poor conductors. There are two types of semi-conductors.

(a) Intrinsic semi-conductors

(b) Extrinsic semi-conductors

4.3.1 Intrinsic semiconductors

Silicon and germanium are the most commonly used semi-conductors in electronic equipments. Fig. 4.6 (a) shows the electron configuration of a silicon atom. It has four electrons in the outermost shell (also called energy level). These electrons are called *bonding or valence electrons* (Fig. 4.6 (b)).

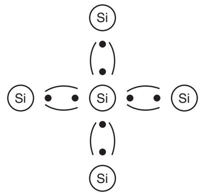


(a) Electron configuration of silicon

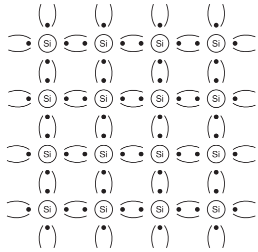
(b) Simplified silicon atom showing only valence electrons

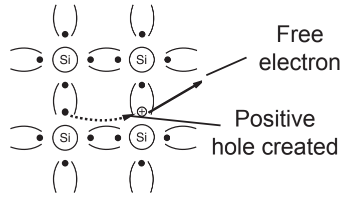
Fig. 4.6: Electronic configuration of a silicon atom

Fig. 4.7 (a) shows a silicon atom bonded with 4 other silicon atoms through covalent bonds. If the bonding is extended in all directions, the silicon lattice structure is formed (Fig. 4.7 (b)).



(a) Silicon atom bonded with 4 other silicon atoms


(b) Crystal lattice of pure silicon



(c) Thermal agitation in a pure semiconductor

Fig. 4.7: Bonding in a silicon crystal

At low temperatures, all the electrons are locked up in the covalent bonds i.e. they are in the valency band. At higher temperatures the electrons may gain thermal energy and move to the conduction band, in so doing, the bond is broken. These free electrons roam within the lattice and are thus available for conduction. These electrons are called *thermal electrons*. A free electron will leave a positive vacancy in the atom it came from. This vacancy is called *a hole* (see Fig. 4.7(c)) above. The atom becomes a positive ion and can attract an electron from the neighbouring atom.

When this process is repeated from one atom to another, *a positive hole seems to drift in the lattice*. If the semi-conductor is connected in a circuit containing a battery and a milliammeter, a small current is observed to flow (Fig. 4.8).

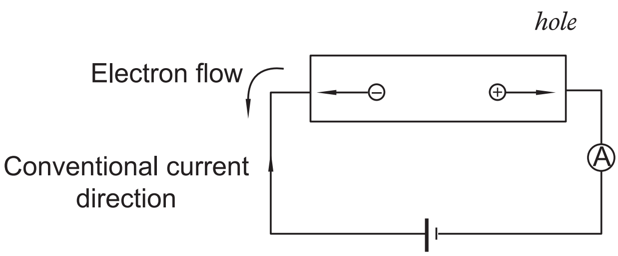


Fig. 4.8: A pure semiconductor in a circuit

Two types of charges seem to contribute to the conduction of the current i.e. the negative charge or electrons and the positive charge or holes. The electrons in the conduction band flow in one direction while the holes in the valence band flow in the opposite direction.

A material which increases its electrical conductivity from within itself (internally) is called *pure* or *intrinsic semi-conductor*. Silicon and Germanium are examples of intrinsic semi-conductors. Electrical conductivity in intrinsic semi-conductors is mainly due to electron-hole pair movement. In the intrinsic semi-conductors, the number of electrons is the same as the number of holes created.

A demonstration of hole movement

The *movement* of a hole may be likened to the apparent movement of an empty chair in a classroom (Fig. 4.9). When one student sitting on a chair moves, the chair is left empty (Fig. 4.9 (a)). The student behind can fill in the vacancy created and by so doing creates another vacancy (Fig. 4.9 (b)). This process is repeated until the last student moves (Fig. 4.9 (d)). In this analogy, the movement of the student represents the movement of electrons while the movement of the empty chair (vacancy) corresponds to the movement of holes.

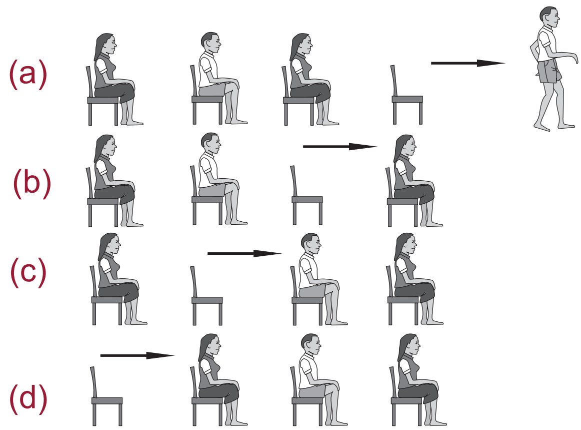


Fig. 4.9: Hole movement

4.3.2 Extrinsic semi-conductors

The electrical conductivity of a pure semi-conductor may be increased by adding or introducing a small and controlled amount of other materials (called *impurities)* into the pure semi-conductors. This process of introducing very small amounts of impurities into pure semi-conductors is called *doping*. A pure semi-conductor that has been doped externally is called an *extrinsic semi-conductor* (Fig. 14.10).

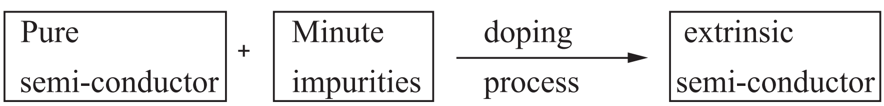


Fig. 4.10: Doping process

The impurities used in the doping process are elements whose atoms have either *three* valence electrons or *five valence electrons*. Examples of elements with *trivalent* atoms include *boron, aluminium, gallium and indium*. Examples of elements with *pentavalent* atoms include *phosphorous, arsenic, antimony* and *bismuth*.

4.3.3 Doping in semi-conductors

n-type semi-conductors

Consider an intrinsic silicon semi-conductor, doped with arsenic atoms. Each silicon atom has four valence electrons and therefore each atom has four neighbouring atoms bonded to it. Arsenic atoms will fit into this structure, but they have five valence electrons of which four participate in bonding with neighbouring atoms. The fifth electron is left free to roam within the lattice (Fig. 4.11). This electron is available for conduction. In this case, arsenic is said to be a *donor impurity*. The resulting semi-conductor has more electrons and is referred to as the *n-type* semi-conductor (n-for negative). In this semi-conductor, the *majority charge* carriers are the *electrons*.

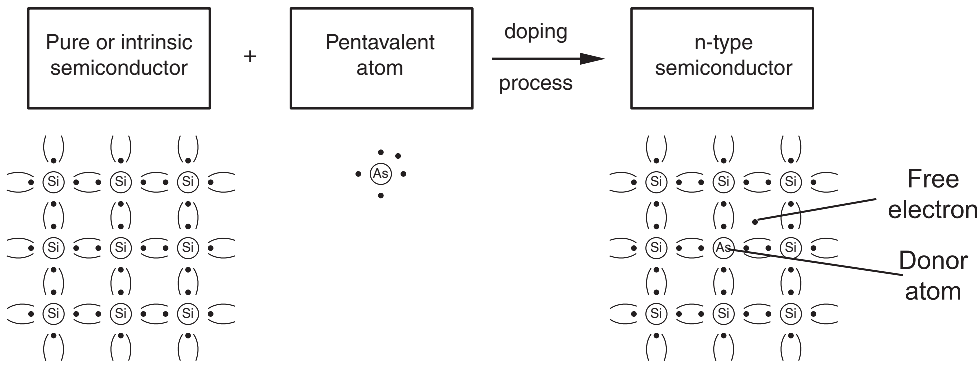


Fig. 4.11: Formation of n-type semi-conductor

p-type semi-conductors

Consider a crystal of silicon doped with a small amount of trivalent atoms e.g. boron. Boron has three valence electrons which participate in the bonding . This leaves a vacancy in the fourth bond called *hole*. This vacancy forms what is known as a hole in the fourth bond (Fig. 4.12).

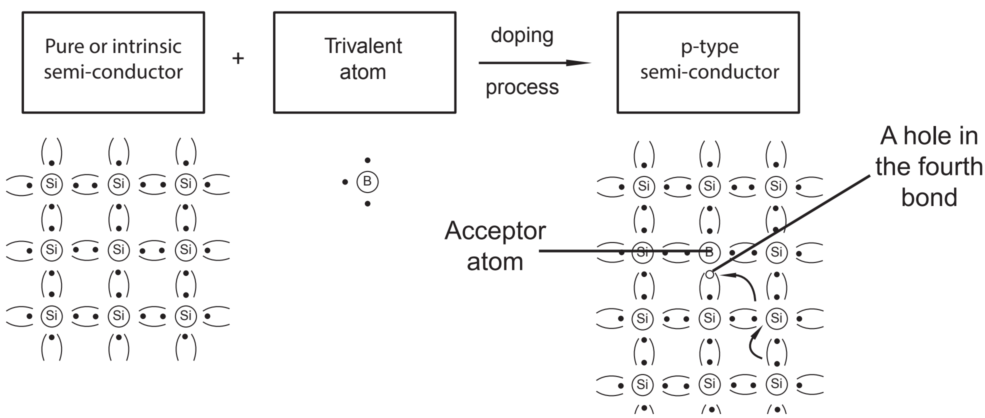


Fig. 4.12: Formation of p-type semi-conductor

When a bond is incomplete, it is possible for an electron in the neighbouring silicon atom to leave its electron-bond to fill the hole. The electron moving from the bond to fill a hole leaves a hole in its initial position. Hence, the hole effectively moves in the direction opposite to that of the electron. The hole, in its new position, may again be filled by an electron from another electron-pair bond making the hole move one more step in the direction opposite to the motion of the electron. *We get here a mechanism for the conduction of electricity, that does not involve the free electrons*. The atoms that introduce holes in the pure semi-conductors are called *acceptor atoms*. The resulting semiconductor has positive hole as charge carriers and is referred to as the *p-type semi-conductor* (p – for positive). In this type of semi-conductor, the *majority charge* carriers are the *holes*.

Exercise 4.1

1. Explain the following terms:
   (a) semi-conductors. (b) intrinsic semi-conductors.
   (c) extrinsic semi-conductors. (d) doping
2. Distinguish between semi-conductors and conductors. Give an example of each.
3. Describe how the following semi-conductors are made:
   (a) p-type (b) n-type
4. Draw the structure of a silicon crystal and show the bonding of electrons.
5. Explain the statement, 'at low temperatures the resistance of silicon is high, but decreases at high temperatures.'

4.4 p–n – Junction diode

4.4.1 The structure and working of junction diode

A p-type semi-conductor and a n-type semi-conductor of the same material e.g. silicon, can be 'joined' together to form what is called a *p-n junction* (Fig. 4.13).

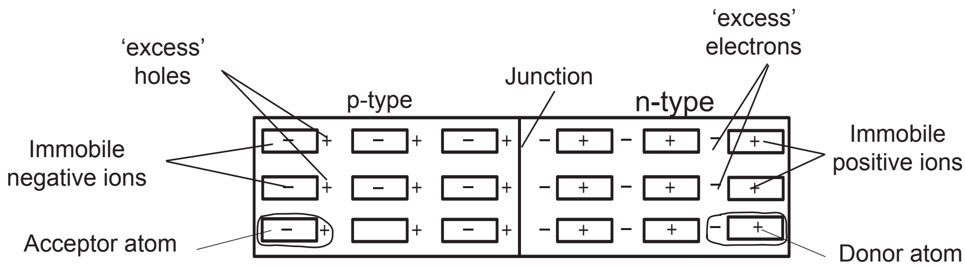


Fig. 4.13: p-n junction

As soon as this junction is formed, a charge movement begins only in the immediate vicinity of the junction until an equilibrium is reached. The charge movement can be likened to the diffusion of gases.

P-type and n-type regions are both electrically neutral. Charge movement results to holes combining with electrons thereby producing a net positive charge to the n-type region and leaving a net negative charge in the p-type region (Fig. 4.14). The net positive charge in the n-type prevents any further movement of the holes from the p-type to n-type. Also the net negative charge in the p-type stops any further movement of the electrons from the n-type to the p-type. A region is created which has lost all its free electrons and holes. This region is called *the depletion layer* (Fig. 4.14 (a).

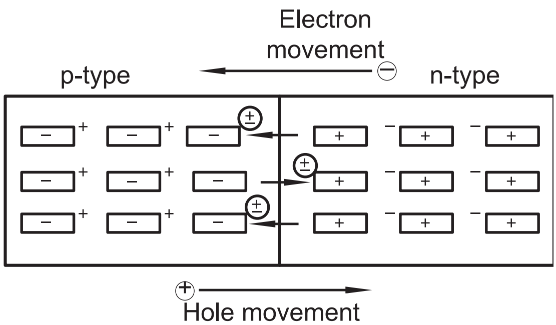
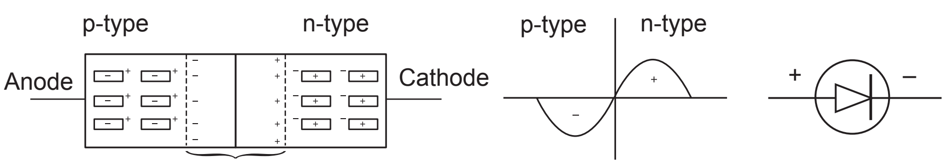


Fig. 4.14: Diffusion of holes and electrons

When the equilibrium has been achieved, the resulting device is known as *p-n junction diode*. Fig. 4.15 (c) shows the symbol of a junction diode.

Due to the movement of charges across the junction, a potential difference develops across the junction with its polarity such as to prevent further charge movement. This potential difference is called a *barrier potential difference* (Fig. 4.15 (b)). A lead connected to the n-type becomes a cathode while a lead on the p-type becomes an anode.



(a) Depletion layer *(b) Barrier potential difference* *(c) Symbol*

Fig. 4.15: A p-n junction diode

4.4.2 Working of a p-n junction diode

Activity 4.4 **To show that a p-n junction diode conducts only in one direction**

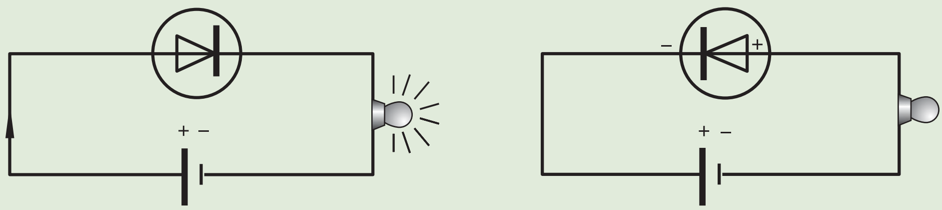
(Work in groups)

Materials

- Diode
- Dry cell
- Bulb
- Connecting wires

Steps

1. Connect a p-n junction diode as shown in Fig. 4.16 (a) with the negative end (n-type) connected to the negative terminal of the cell. What happens to the bulb? Explain this in terms of the effect of the applied p.d in the burner potential.



(a) *Forward biased diode* *(b)* *Reverse biased diode*

Fig. 4.16: Working of p-n junction diode

2. Reverse the connection of the diode and repeat the experiment (Fig. 4.16) (b). What happens to the bulb? Explain this items of the effect of the applied p.d on the burner potential.

- The bulb in Fig. 4.16(a) lights. This means that the current flows through the circuit.
- The bulb in Fig. 4.16(b) does not light.

The dry cell provides enough energy to overcome the barrier potential difference and to drive the electrons in the circuit. The holes are also able to move towards the junction and complete the circuit (Fig. 4.16 (b)).

When the diode is connected in this way)Fig. 4.17), it is said to be *forward biased*.

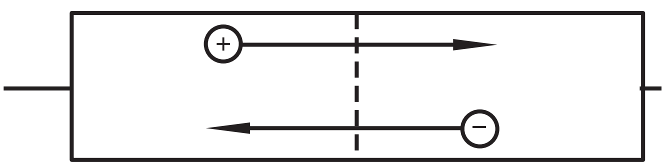


Fig. 4.17: Forward biased diode

When reverse based, the electrons and the holes are attracted to the opposite ends of the cell. This increases the width of the depletion layer (Fig. 4.18) and hence increases the barrier potential difference. No current can now flow through the diode.

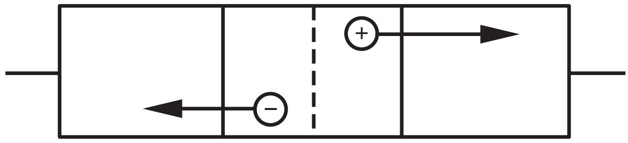


Fig. 4.18: Increased width of depletion region

When the diode is connected in this manner, it is said to be *reverse biased*. The diode behaves as an insulator.
The results of this experiment shows that a p-n junction diode is a device that conducts current in only one direction.

The characteristics of a p-n junction diode

Activity 4.5 **To investigate the relationship between the current through and the voltage across a p-n junction diode**

(Work in groups)

Materials

- Diode
- Switch
- Amination
- Cells
- Crocodile clip
- Connecting wires
- Resistance

Instructions

1. Use the set up in Fig. 4.19 to carry out an investigation into the relationship between current through and voltage across a p-n junction diode.
2. Write your procedure step by step.

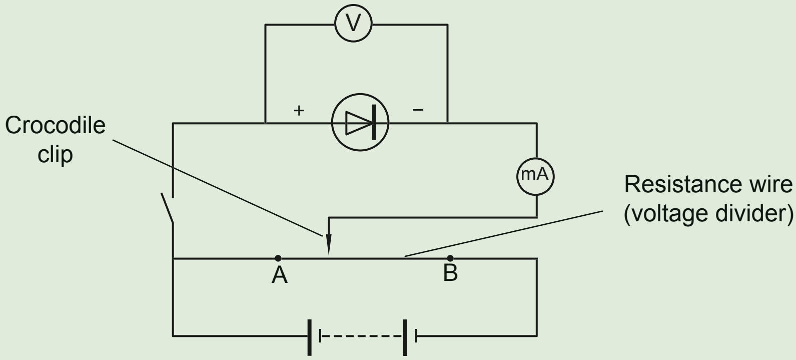


Fig. 4.19: Circuit to investigate the relationship between current, I and potential difference, V across a p-n junction diode

3. Repeat the experiment with a crocodile clip at other positions along AB.
4. Record, in each case, the values of potential difference and current.
5. Tabulate the results (Table 4.1).

Table 4.1

Potential difference (V)	Current (mA)

6. Reverse the connection of the diode and repeat the experiment.
7. Plot a graph of current against the potential difference. Explain the shape of the graph in terms of the effect of the applied p.d across the p-n junction diode.

On plotting the values of current against voltage, we get a graph similar to the one in Fig. 4.20.

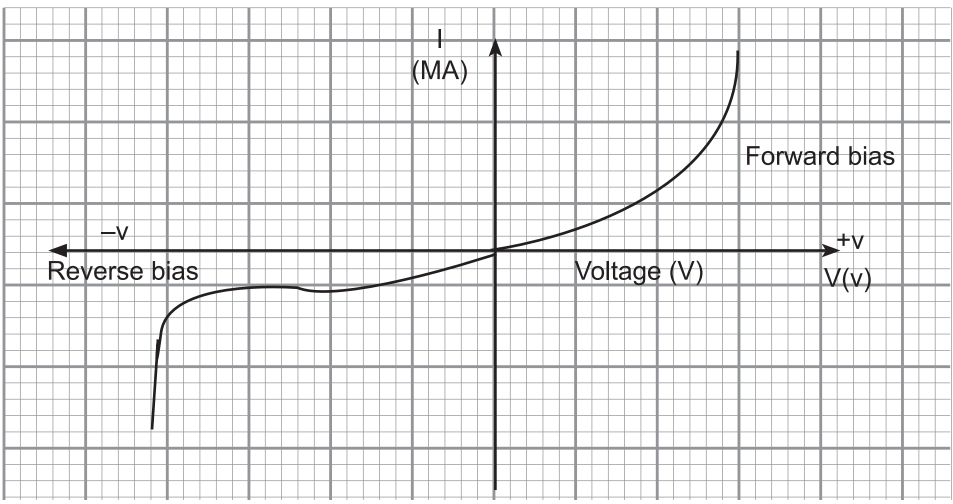


Fig. 4.20: Diode characteristics

The graph is called characteristics of a p-n junction diode. The small current in the reverse bias is due to the intrinsic conduction in the p-n junction diode.

The result shows that a p-n junction diode is a device that produces non-linear characteristics i.e. it does not obey Ohm's law. Such devices are called non-ohmic conductors.

4.4.4 Applications of p-n junction diodes

(a) Protecting electrical devices in a circuit

Some devices that operate on direct current (d.c), break down when large voltages are connected in reverse / opposite order to the supply terminals of the devices.

To protect such devices, a diode is usually connected in series with them and in reverse bias as in Fig. 4.21. It ensures that the device is protected by offering very high (almost infinite) resistance to the flow of the current in the reverse direction when the terminals are interchanged.

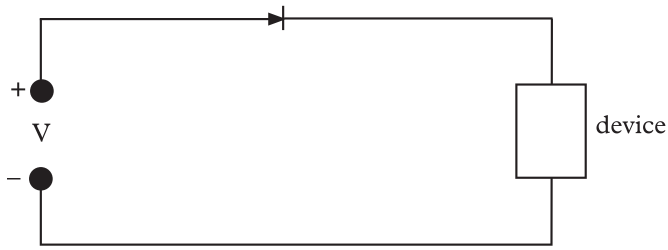


Fig. 4.21: Using a diode to protect a device.

(b) Zener diodes (in voltage stabilizer)

Some special types of diodes called Zener diodes are used to protect d.c devices by regulating the voltages applied across the devices. When the p.d (V) increases or abruptly surges to values that would damage the device C, the zener diode (Dz) breaks down and conducts. This protects the device by "short circuiting" it. When the p.d falls to normal the diode returns to normal. (See Fig. 4.22.)

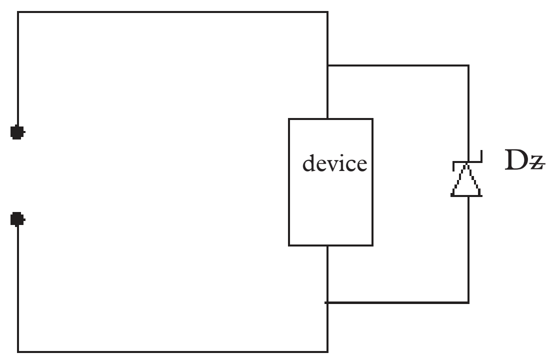


Fig. 4.22: Use of zener diode to protect d.c. devices

Note: Zener diode does not conduct at normal voltages since it is connected in the reverse bias mode. It is made to operate in such a way that, if the reverse p.d. connected to it increases beyond a certain value, it breaks down and conducts, offering almost zero resistance.

(c) Rectification

Not all electrical devices are operated by alternating current. Some need direct current to operate. It is therefore necessary to convert the alternating current to direct current. A p-n junction diode can be used for this purpose. The process of converting alternating current to direct current is called *rectification*.

(i) Half-wave rectification by a single diode

Activity 4.6 **To convert alternating current to direct current using a single diode**

Materials

- AC power supply
- Resistor
- Cathode ray oscilloscope
- Connecting wires
- p-n junction diode

Steps

1. Connect a load e.g. resistor to an a.c power supply.
2. Connect a cathode ray oscilloscope (C.R.O.) across the load as shown in Fig. 4.23 (a). Sketch the signal displayed in the CRO.
3. Now introduce a p-n junction diode as shown in Fig. 4.23 (b).

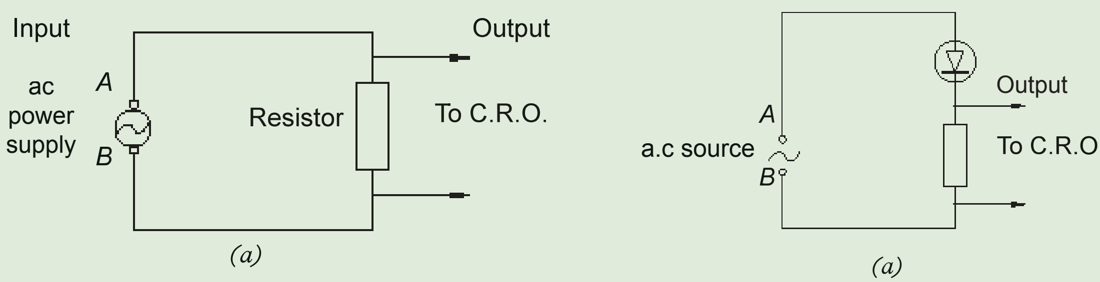


Fig. 4.23: Half-wave rectification

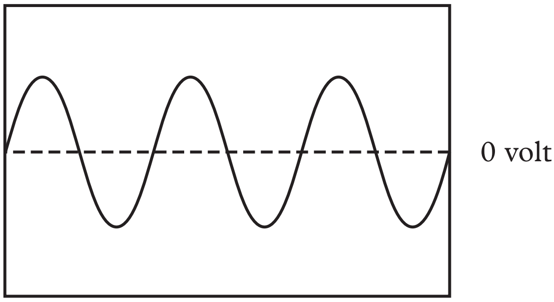
Explain the change in shape of the signal.

4. Reverse the connection of the diode and observe the reading of the cathode ray oscilloscope. Explain the change in shape of the signal.

The cathode ray oscilloscope shows how the voltage across the resistor varies as the current through the resistor changes direction.

It is observed that when terminal A is positive, the diode allows a current to flow. However, when A is negative the diode does not allow the current to flow (Fig 4.24).

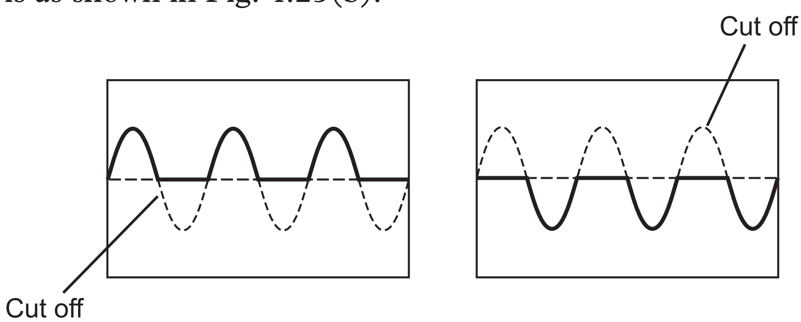
Terminal A is positive during a one half cycle and becomes negative during the next half cycle. When A is positive, a current flows from A through the resistor to terminal B. In the next half cycle, the terminal B becomes positive and the current flows from B through the resistor to A. The display follows a sine wave as shown in Fig. 4.24. During the first half cycle, the current flows in one direction. However, during the next half cycle, the current flows in the opposite direction.



C.R.O display

Fig. 4.24: Output from an ac power supply

When the diode is introduced, the signal is as shown in Fig. 4.25 (a). Only the positive half cycles appear on screen. When the diode is reversed, the signal is as shown in Fig. 4.25(b).



(a) C.R.O screen *(b) C.R.O screen*

Fig. 4.25: Half-wave rectification

The current flows in both circuits in only one direction. Half of the wave has been "cut off". This process of allowing only half of the wave to produce current that flows in one direction is called half-wave rectification. Although the alternating current has been converted into direct current, the magnitude varies from zero to a maximum value and from maximum to zero, with some intervals when no current flow at all.

Hence, a varying direct current is obtained across the resistor. In half-wave rectification, half of the input energy is wasted. To avoid this waste, full-wave rectification is required.

(b) Full-wave rectification using two diodes and a centre tapped transformer

Activity 4.7 To convert alternating current to direct current using two p-n junction diodes

Materials

- A.c power supply
- 2 p-n junction diodes
- Cathode ray oscilloscope
- Step-down transformer
- Connecting wires

Steps

- Connect the circuit as shown in Fig. 4.26 and observe the display in the cathode ray oscilloscope. What do you observe? Explain the change in shape of the signal displayed on the CRO from the normal a.c signal.

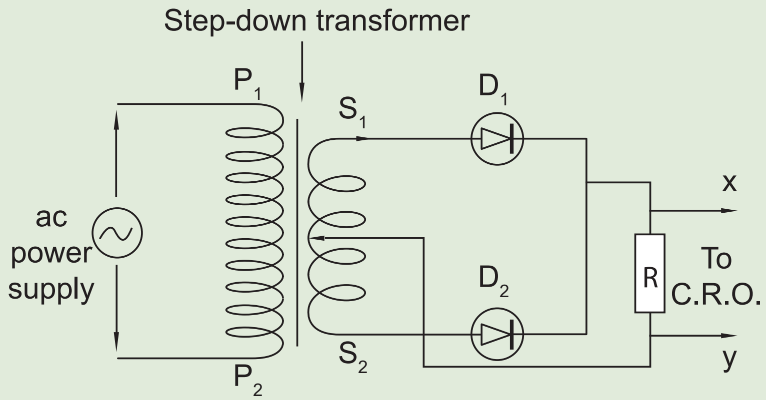


Fig. 4.26: Circuit diagram for rectification using two diodes

A wave pattern similar to the one shown in Fig. 4.27 is observed in the cathode ray oscilloscope.

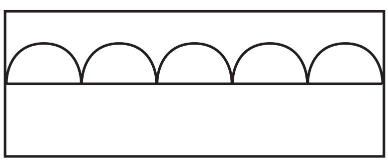


Fig.4.27: C.R.O display

During the first half cycle, S_1 is positive and diode D_1 is forward biased. However, during the second half cycle S_2 becomes positive and diode D_2 becomes forward biased with respect to diode D_1 which now will be reverse biased. In this case, irrespective of the polarities of input terminals, the current flows through the resistor continuously.

The alternating current has been *fully rectified* to a varying direct current

NB: Half of the input energy is wasted since only half of the transformer is in use in each cycle.

4.5 Transistors

4.5.1 The structure and working of a transistor

Activity 4.8 **To analyse the structure and describe the working of a transistor**

(Work in groups)

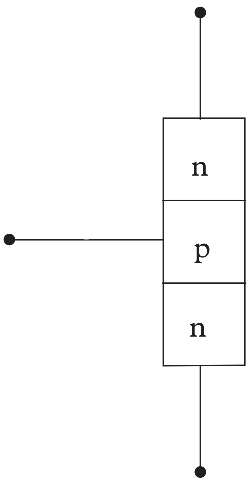
Materials

- Assorted transistors of different types and shapes.
- Motherboards of electronic devices like radios and televisions.
- Structural diagrams of transistors drawn on charts.
- Reference books, Internet.

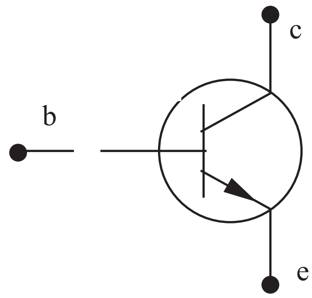
Steps

1. Research from reference books or Internet on the structure and working of different types of transistors.
2. Now look at motherboards/circuit boards provided by your teacher. Identify the transistors.
3. Look at the structural diagrams of the two types of transistors as drawn on the charts. Identify each type of transistor. What is the distinguishing feature?
4. Describe the working of each type of the transistor you have identified in Step 3.
5. Explain the role of transistors in radios, amplifiers and switching circuits.

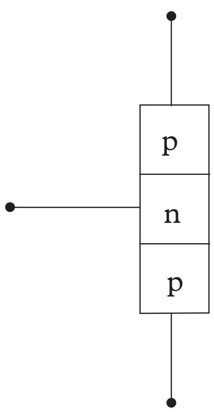
A transistor is a three terminal device formed by merging three pieces of extrinsic (doped) semi-conductors. The three terminals of a transistor are known as the *base (b)*, *collector (c)* and *emitter (e)*. The semi-conductors in the form n-p-n or p-n-p in Fig. 4.28 show the two types of transistors and their symbols.



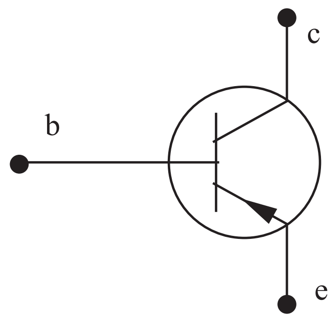
(a) n-p-n transistor



Symbol of n-p-n transistor



(b) p-n-p transistor



Symbol of p-n-p transistor

Fig. 4.28: Transistors and their symbols

In the symbols above, the arrows indicate the direction of convectional current flow when the transistor is operating normally. The *emitter (e)* emits electrons which pass through the *base (b)* to the *collector (c)*.

Note

n-p-n transistors are more commonly used than p-n-p because current moves faster in them. Transistors are assembled in different sizes and shapes. In most cases the emitter is marked by tags as shown in Fig. 4.29 (a) and (b).

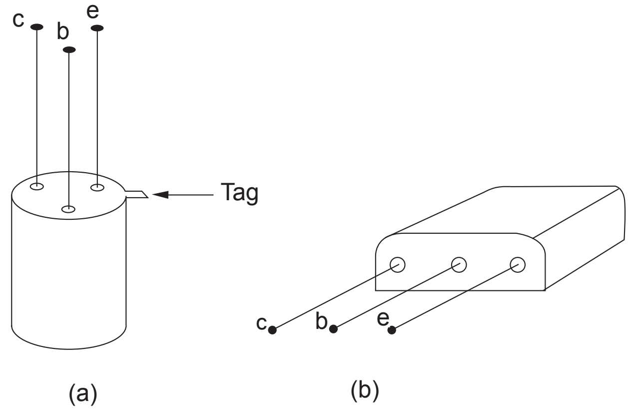


Fig. 4.29: Transistors of different sizes and shapes

Operation of a transistor

Fig 4.30 shows the *input* and *ouput* of a transistor. The emitter is connected to both the input (base) and the output (collector) side.

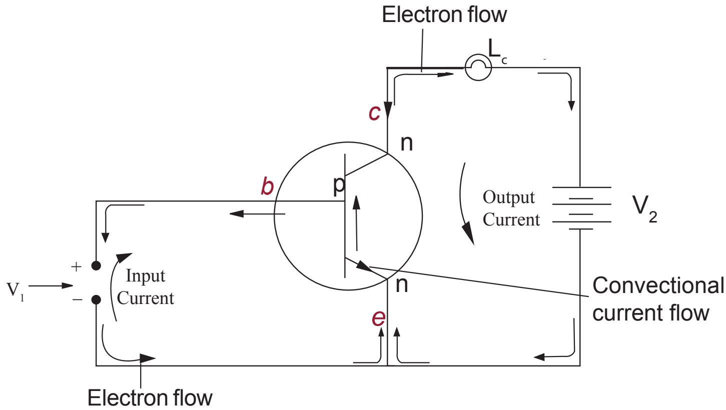


Fig. 4.30: Operation of a n-p-n transistor

When the output and input circuits are connected as shown in Fig. 4.30, the transmitter is said to be in *common-emitter* or (*CE) mode*. The n-type regions are the *emitter* and *collector* of the transistor; the p-type region is the *base*.

The output *of this transistor* (collector-base junction) reverse biased since the positive and negative terminals of V_2 are connected to the collector (n) and base (p) respectively, hence no current flows. The input (emitter-base junction) is forward biased since the positive and negative terminals of V_1 are connected to the base and emitter respectively, hence current flows. This current that flows through the input greatly reduces the 'current blocking effect' (overcomes barrier voltage) of the output (collector-base junction). When this happens, the output circuit starts to conduct and current flows between emitter and collector. Typically, a small current in the input (emitter-base junction) can cause a current many times larger to flow in the output (collector-base junction).

The transistor works in such a way that when the input side conducts i.e. current flows between base and emitter (base- emitter), then the output also conducts i.e. current flows between emitter and collector (collector-emitter) and so lamp L_C lights. When the input is off then the output is also off.

NB: For the input to be on, the V_1 must be equal or greater than a certain value.

4.5.2 Uses of transistors

There are very many uses of transistors most of which you will learn in other levels of your education. In most cases, several transistors are connected with other components such as diodes, capacitors and suitable resistors, they form devices called microchips which are core components in devices such as radios, computers, calculators, television, amplifiers etc.

(a) A transistor as a switch

In many circuits resistors are used as potential dividers. This is a circuit that proportionally divides a voltage in ratio of resistances. The potential divider shown in Fig. 4.30 has an input voltage of 6V.

In Topic 3, we learnt that in a series circuit, the sum of individual potential differences (p.d.) across a circuit is equal to the total p.d. of the battery. Thus $V_1 + V_2 = 6V$ since R_1 is in series arrangement with R_2 and X (Fig. 4.31).

We also learnt that in a parallel circuit, the potential difference across each resistor is the same. Therefore, R_2 and X have the same p.d. (V_2) because they are in parallel (Fig. 4.31).

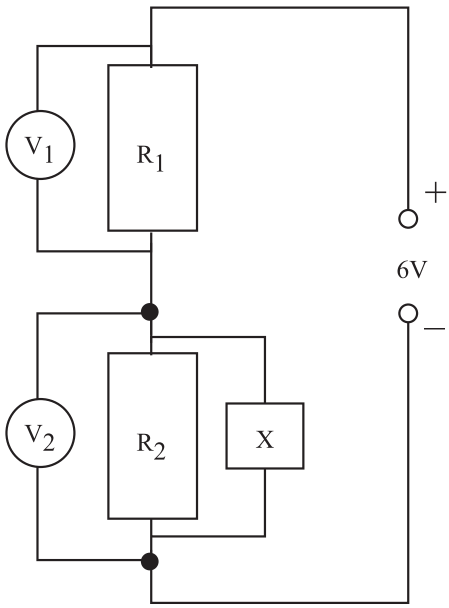


Fig. 4.31: Potential divider

We can extend the above concept to a transistor operated switch as we shall discuss in Activity 4.9.

Activity 4.9 **To show the use of a transistor as a switch**

(Work in groups)

Materials

- 2 resistors
- Protective resistor
- Transistor
- Lamp

Steps

1. Connect the components as shown in Fig. 4.32 using the following values:
   – R_1 and R_2 having about 10 kΩ each.
   – BC 108 or ZTX 300 transistor
   – 6 V, 100 mA lamp for L_C
   – 1 kΩ protective resistor in series with the base.

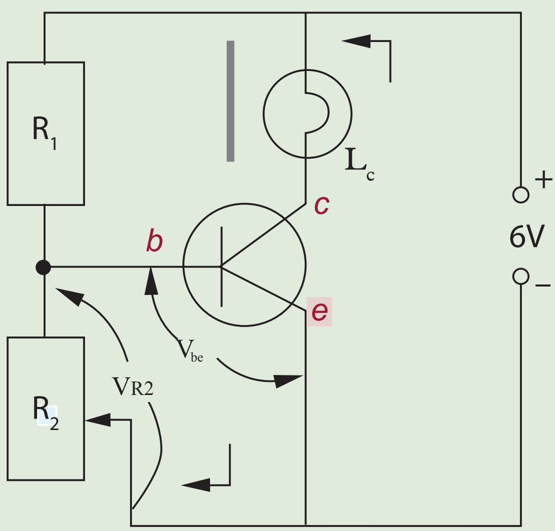


Fig 4.32: Transistor as a switch

2. Vary R_2 to zero and observe the behaviour of the lamp. What happens when the p.d across R_2 is increased?

It is observed that when the resistance of R_2 is zero then L_C is off and when the resistance of R_2 is high then L_C is on.

The p.d. across resistor R_2 i.e., V_{R2} is equal to the p.d. across the input (base), V_{be}, i.e. base-emitter voltage because they are in parallel arrangement. Since R_2 is a variable resistor, we can vary its value of resistance from zero to maximum. This in turn causes the voltage (V_{be}) between the base and emitter to change in a range from zero to a maximum value. When V_{be} is zero, no current flows through the output (collector) thus lamp L_c is off. When V_{be} is large enough, it forward biases the b-e junction to conduct and so current flows through the output, which makes lamp L_c to light on.

From this experiment, we can conclude that a transistor behaves as a switch, i.e. the input (base) controls the output (collector).

(b) A transistor operational amplifier

Activity 4.10 **To conduct research on operational amplifier**

(Work in groups)

Materials

- Reference books
- Internet
- Resource persons

Steps

1. Access reference books, internet or a resource person and do a research on operational amplifier.
2. In your research find out how it functions . How does it achieve the amplification?
3. Discuss your findings with your group members and write a brief report on operational amplifiers.
4. Present your report to the whole class during a class discussion.

An operational amplifier, commonly called OP-amp, is one of the basic building blocks of analogue electronic circuit. It is a *linear* device that has all the properties required for nearly ideal d.c amplification and is therefore used extensively in signal conditioning, filtering or to perform mathematical operations such as addition, subtraction, integration and differentiation.

An operational amplifier is basically a three-terminal device (Fig 4.33) which consists of two high impedance input, called the inverting input; marked with a negative or minus sign (-) and the other one called the non-inverting input marked with C positive or 'plus' sign (+). The third terminal represents the operational amplifier output port which can both sink and source either voltage or current.

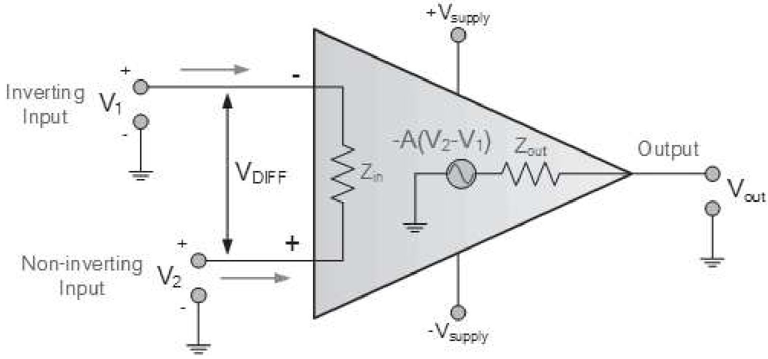


Fig 4.33: Operational amplifier

Working of the operational amplifier

An operational amplifier is fundamental voltage amplifier device designed to be used with external feedback components such as resistors and capacitors between its output terminals. Those feedback components determine the resulting function or 'operation' of the amplifier and by the virtue of different feedback configurations whether resistive, capacitive or both, the amplifier can perform a variety of different operations, hence the name of 'operational amplifier".

In a linear operational amplifier, the output signal is the amplification factor known as the amplifier gain. It is a multiplied value of the input signal and depends on the nature of these input and output signals.

Applications of operational amplifiers

1. An operational amplifier is used for amplification of input voltage or current on a circuit to required value especially in communication devices.
2. An operational amplifier is used to make comparator devices that are used to compare the voltage applied at one input to the voltage applied to the other input. A difference between the voltage even if it is small drives the Op-amp into saturation. When the voltage supplied to both the input are of the same magnitude and polarity, then the Op-amp output is zero volts.

   A comparator produces limited output voltages which can easily interface with digital logic even though compatibility needs to be verified.
3. They are used to make audio power amplifiers. The power amplifier is a component that can drive the loud speakers by converting the low-level signal into high level signal. The job of power amplifier is to produce relatively high voltage and high current. The power amplifiers have very low output resistance.

Exercise 4.2

1. (a) What is rectification?
   (b) Briefly explain how rectification is done using a single diode.

2. (a) What is a transistor?
   (b) Briefly explain the functioning and applications of a transistor.

3. (a) What is an operational amplifier?
   (b) Briefly explain the functioning and applications of operational amplifiers.

Topic summary

- Materials may be grouped into conductors, semi-conductors and insulators according to their electrical conductivities.
- Conductors have free and mobile electrons. The conductivity of a conductor decreases with the increase in temperature.
- Semi-conductors have electrons which are held loosely by its structure. The conduction in a semiconductor increases with the increase in temperature.
- Insulators do not have free and mobile electrons.
- Pure semi-conductors depend only on the thermal electrons produced within itself for conduction of a current are called intrinsic semi-conductors.
- Doping is a process of introducing minute impurities into a pure crystal of semi-conductor so as to boost the electrical conductivity of the semi-conductors.
- Semi-conductors obtained through doping process are called extrinsic semi-conductors.
- Atoms with three valence electrons are called acceptor atoms when used for doping.
- Atoms with five valence electrons are called donor atoms when used for doping.
- A p-type semi-conductor is obtained when a pure semi-conductor has been doped with trivalent atoms.
- An n-type semi-conductor is obtained by doping a pure semi-conductor with pentavalent atoms.
- In p-type semi-conductors, the majority charge carriers are the positive holes while in n-type semi-conductors, the electrons are the majority charge carriers.
- Operational amplifiers are the basic building block of analogue electronic circuits.

Topic Test 4

1. What is meant by "depletion layer" in a p-n junction diode?
2. Draw the symbol of a p-n junction diode. State one application of the diode.
3. Use circuit diagrams to distinguish between forward and reverse bias of a p-n junction diode.
4. A transistor is connected in a common-emitter mode,
   (a) Why is the input voltage necessary?
   (b) How does the current flow in the input circuit affect the output current.
5. Fig. 4.34 shows the use of a transistor as a switch. Study it carefully and answer the questions that follow.

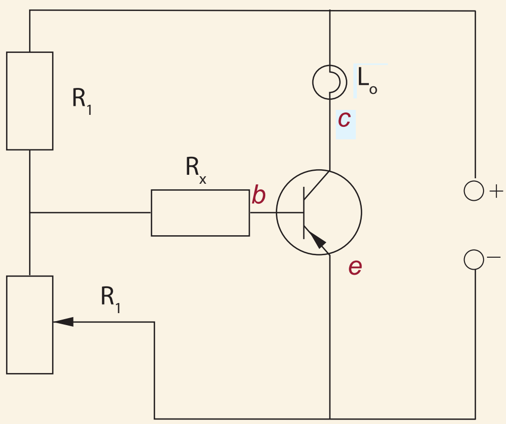


Fig. 4.34

   (a) State the meaning of the letters b,c and e.
   (b) What name is given to R_1 and R_2 combined, as used in the circuit?
   (c) What is the purpose of R_x?
   (d) What type of transistor is used in this circuit?
   (e) What would be the effect of adjusting R_2 to read zero?
6. Fig 4.35 shows a circuit that is used to switch a lamp automatically.

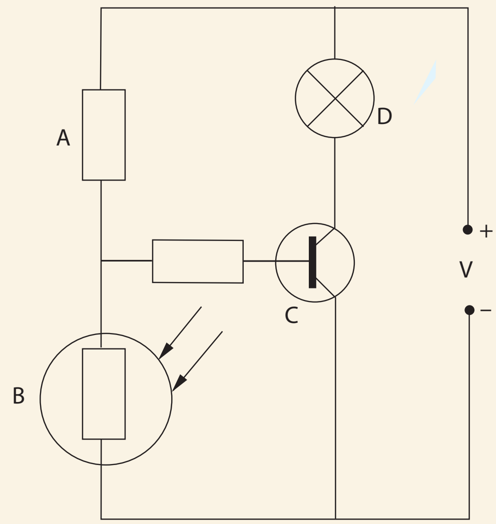


Fig. 4.35

(a) Write down the name of the components labelled A,B and D.

(b) Which of the four components A,B C or D acts as a switch?

(c) Explain why the lamp lights on as it falls dark.

7. Briefly explain the functioning and applications of operational amplifiers.

8. (a) Explain the term rectification.
   (b) Use a labelled diagram to explain how a full-wave rectification may be achieved by using a resistor and
   (i) two diodes. (ii) four diodes.

9. Fig. 4.36 shows a p-n junction diode connected in series with a power supply and a resistor.
   (a) What does the symbol ⊣▷⊢ stand for?
   (b) Draw the trace that would appear on a cathode ray oscilloscope screen when the cathode ray oscilloscope is connected across the:
   (i) power supply
   (ii) resistor.

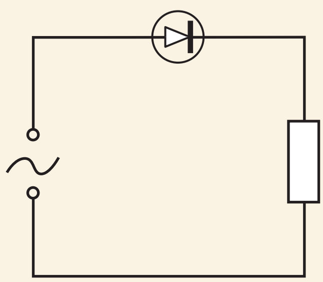


Fig. 4.36

10. You are provided with 12 V a.c power supply, four diodes and a resistor. Explain how these items may be used to provide a full-wave rectification.

12. With aid of a diagram explain how a capacitor can be used to obtain a smoothened full-wave rectification.

13. (a) What is meant by diode characteristics?

(b) Table 4.2 shows the variation of potential difference across a p-n junction and the current through it.

Table 4.2

Potential difference (V)	1.1	1.3	1.5	1.7	1.9
Current (mA)	3	10	20	33	61

(i) Draw a circuit diagram that may be used to obtain the results in the table.

(ii) Draw a graph of current against the potential difference.

(iii) Determine the resistance of a p-n junction diode when a current of 25 mA flows through it.

UNIT 4 Mechanics, motion and laws of linear motion

Topic 5: Mechanical properties of solids

Topic 6: Motion and momentum

Learning outcomes

Knowledge and understanding

- Understand the laws of linear motion.
- Understand the principles of kinematics and kinetics of particles.

Skills

- Investigate the application of vectors for the analysis of static equilibrium.
- Investigate frictional forces using shear force and bending moment diagrams.
- Analyse structural elements like trusses, frames and beams.
- Analyse planar rigid body kinematics and kinetics.
- Design and conduct experiments to test the rigidity of structures.

Attitude and value

- Appreciate the impact of the laws of motion.

Key inquiry questions

- How do we demonstrate the application of vectors for the analysis of static equilibrium?
- How do we analyse structural elements like trusses, frames and beams?
- How can we demonstrate an understanding of the principles of kinematics and kinetics of particles and planar rigid bodies?
- Why do we identify techniques for measurement using instrumentation with recognition of the principles of data collection?

Topic 5 Mechanical properties of solid

Topic outlines

5.1 Static Equilibrium

Activity 5.1 **To demonstrate static equilibrium**

(Work in groups)

Materials

- 1 rope
- 5 very strong girls
- 5 very small boys
- 5 very strong boys
- 3 spring balances
- Ring

Steps

Part 1

1. Let 5 boys and girls of equal strength gently pull a rope on either side. What would you observe? Explain why.
2. Let the 5 very strong girls pull a rope on one end and 5 small boys pull on the other end. Observe and explain what happens.
3. Discuss with your group members different situations where balanced and unbalanced forces are experienced.

Part 2

4. Hook three springs to the ring by means of loose loops of the string as shown in Fig 5.1 on the bench.

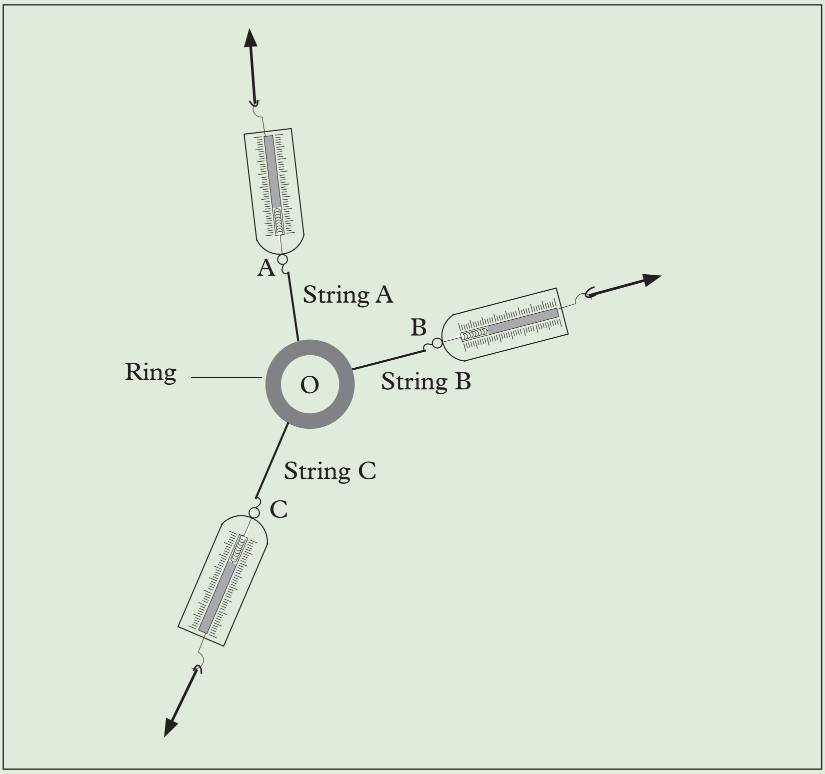


Fig. 5.1: Demonstrating equilibrium

5. Select 3 members of your group. Let each of them hold one of the springs, then they all pull gently at the same time. Let them balance their pulling forces until when the ring will not move in any direction.

   Describe the state of the ring at that point.

6. Let the group secretary record the readings on the spring balances. Are the readings necessarily the same? If not, explain why the balanced state of the ring has been achieved.

When all forces acting on an object are balanced, then the object is said to be in a state of *equilibrium*. In this state, *for each pair of opposite forces, the force in one direction is equal to the force in the opposite direction*. This however, does not mean that all the individual forces acting on the object are equal to each other as illustrated in Fig. 5.2.

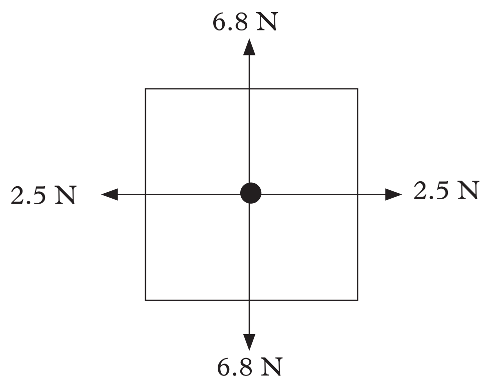


Fig. 5.2

The net force on an object at equilibrium is zero hence its acceleration is zero..

An object at equilibrium is either:

1. At rest and staying at rest or
2. In motion and continuing in motion with the same speed and direction.

If an object is at rest and is in this state of equilibrium, it is said to be in *static equilibrium*. Static means stationery or at rest.

In Activity 5.1, the ring was in static equilibrium. However, through the three forces acting on the ring through the springs were not be equal, their resolved components in opposite direction balanced. (Fig. 5.3)

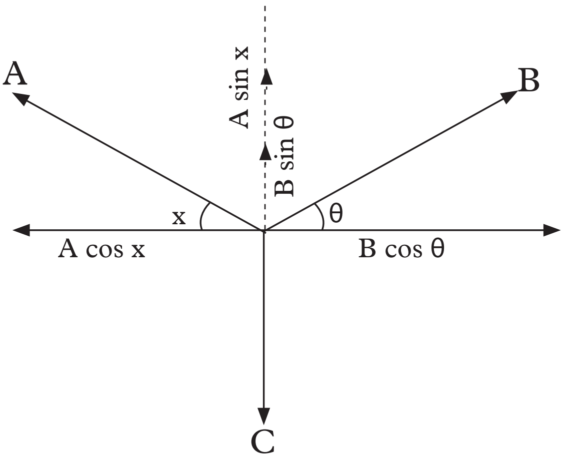


Fig 5.3

NB: $A \cos x = B \cos \theta$

$A \sin x + B \sin \theta = C$

In short, the two conditions for a rigid body to be in static equilibrium are:

1. The vector sum (sum of resolved) of all the forces acting on the body must be zero.
2. The vector sum of all forces (rotational moment of couples) must be zero.

Example 5.1

A boy is being pulled by a force of 50 N through a string as shown in Fig. 5.4 below but remains at rest.

(a) Determine the vertical and horizontal components in this force.

(b) Determine the static frictional force.

Fig. 5.4

Solution

(a) Vertical component, y $= 50 \sin 30^0$
$= 50 \times 0.5$
$= 25$ N

Horizontal component, x $= 50 \cos 30^0$
$= 50 \times 0.866$
$= 43$ N

(b) Frictional force = Horizontal component of 50 N.
$= 50 \times \cos 30^0$
$= 43.3$ N

The friction act in the reverse direction.

Example 5.2

Fig. 5.5 shows a lamp supported by two light strings AO and OB.

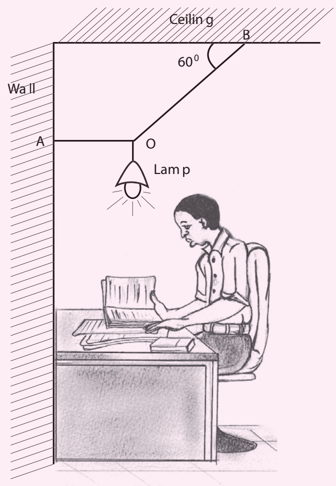


Fig. 5.5

(a) Draw and indicate the direction of forces acting at O.
(b) If the mass of the lamp and the bulb is 200 g, what is the tension in the string AO and OB?

Solution

(a)

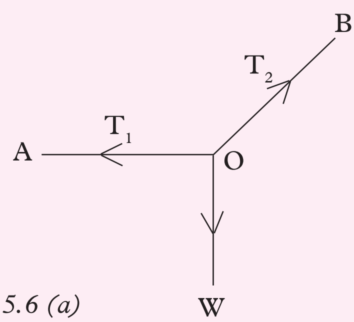


Fig. 5.6 (a)

T_1 is the tension in string AO.

T_2 is the tension in string OB.

W is the weight of the lamp.

$\frac{200}{1000} \times 10 = 2$ N

(b)

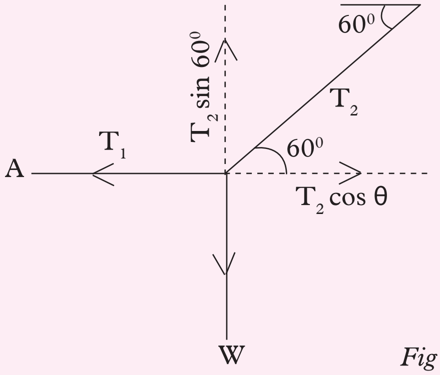


Fig 5.6 (b)

Since the lamp is in equilibrium

(i) $W = T_2 \sin 60^o$

$\therefore = T_2 = \frac{W}{\sin 60^o} = \frac{2}{0.860^o}$

$= 2.31\ N$

(ii) $T_2 \cos 60^o = 2.31 \times 0.5\ N$

$= 1.16\ N$

Example 5.3

A picture was hanged on a wall using two threads as shown in Fig 5.7.

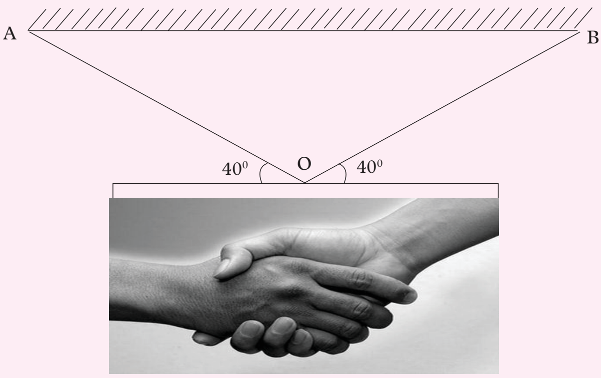
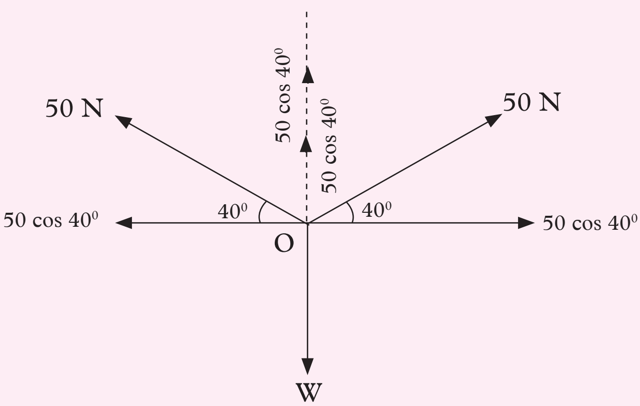


Fig 5.7

If the tension in each thread is 50 N and the angle that each thread makes with the horizontal is 40º. What is the weight of the picture?

Solution

Let us analyse the forces acting at point O.



$W = 50 \sin 40^O + 50 \sin 40^O$

$= 2 (\sin 40^O)$

$= 2 \times 50 \times 0.6428$

$= 64.28\ N$

Fig 5.8

Exercise 5.1

1. The following picture in Fig 5.9 is hanging on a wall. Use trigonometric functions to determine the weight of the picture.

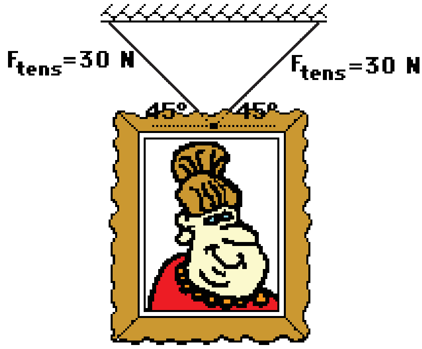


Fig. 5.9

2. After its most recent deriving, the infamous stork announces the good news. If the sign has a mass of 10 kg, what is the tension on each cable? (Use trigonometric functions.)

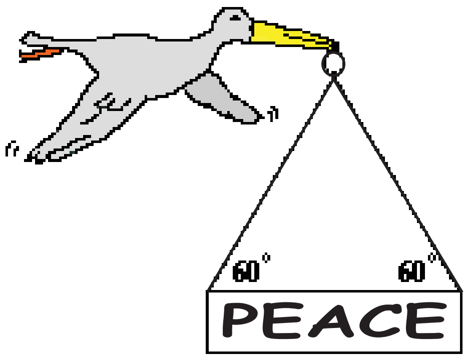


Fig 5.10

3. The sign in Fig 5.11 hangs outside the S3 Physics laboratory, advertisng the most important truth to be found inside. The sign is supported by a diagonal cable and digid horizontal bar. If the sign has a mass of 50 kg, determine the tension in the diagonal cable that supports its weight.

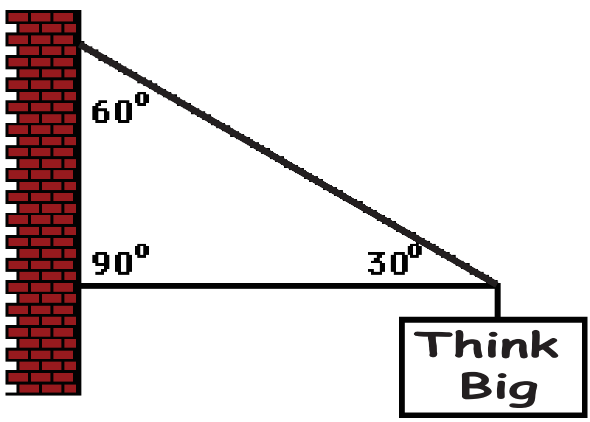


Fig. 5.11

4. A body of mass M kg is held in equilibrium by a string fixed to the wall and a horizontal spring balance as shown in Fig. 5.12. If the balance reads 20 N, determine:

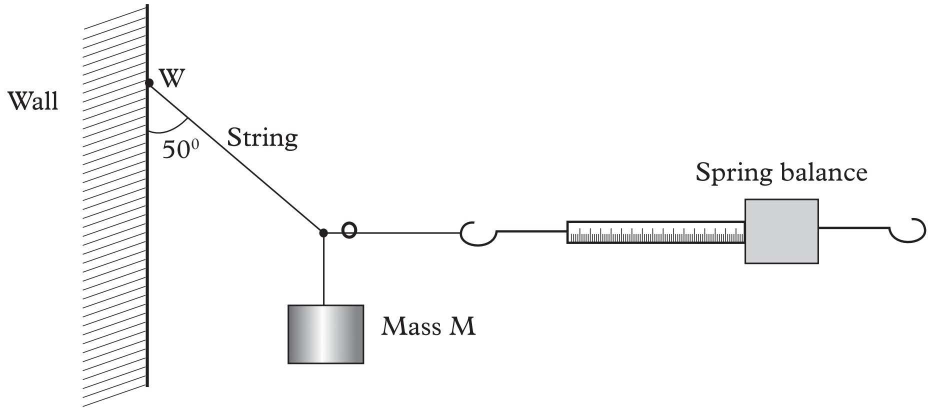


Fig 5.12

(a) the tension in the string
(b) the mass M of the body.

5.2 Bending of beams

A beam is a long block of material e.g. wood, metal or concrete primarily used to support a load. Beams are therefore very important parts of structures. They are used in buildings, bridges etc.

When a beam is supporting a load, it experiences compressional or tensional force due to that force exerted by the load. The beam is said to be under *stress*.

In diagrams, we use lines to show the line of action and the concentration of stress (force) on the beam. Such lines are called *stress lines*.

Activity 5.2 **To investigate what happens when a beam is loaded**

(Work in groups)

Instructions

1. Design and carry out an investigation with finding out what happens when a beam is loaded. Use the set up in Fig. 5.13.
2. Write your procedure.
3. Record all your findings.
4. Sketch the new shape of pattern of lines and explain the shape.

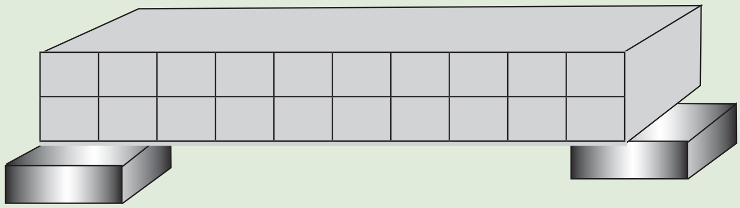


Fig. 5.13: To investigate what happens when a beam is loaded.

At the top of the block, the lines become shorter while those at the bottom become more spaced. The spacing of the lines remain unchanged at the middle (Fig. 5.14).

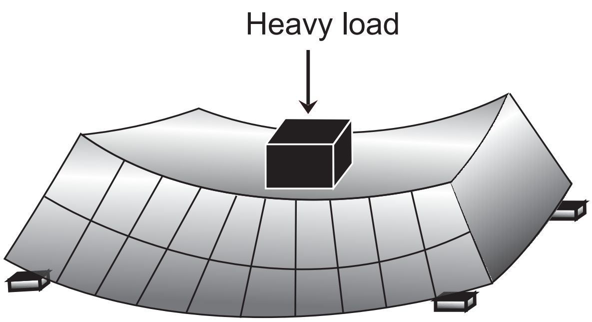


Fig. 5.14: Effect of a load on a beam

From the shape of the pattern of lines, we note that the *top part is under compression* since the lines are closer together while the *bottom part is under tension* since lines are further apart. At the centre there is no change in the spacing of lines hence, it is neither under compression or tension and is referred to as the *neutral layer* (Fig. 5.15).

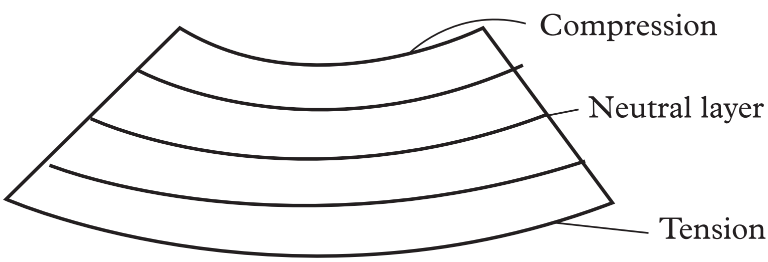


Fig. 5.15: Bending a beam to show tension, compression and neutral layer.

The moment or turning force produced by the force (load) applied to a structure e.g. beam that is fixed on both ends making it to bend is called a *bending moment*.

5.3 Shear force

Activity 5.5 **To demonstrate shear force**

Materials

- Two wooden block (a small one with a hook and a long one without
- Spring balance
- Glue

Steps

1. Smear the glue on the surface of the long wooden block
2. Place the small wooden block on the top of the smeared part.
3. Now hook the spring balance onto the smaller block and pull it towards the other end.
4. Record the force indicated on the spring balance just before the small block start moving out of the glued part.

By pulling one of the pieces of wood that have been glued together; the glue joint is being subjected to a shear loading (See Gig. 5.17).

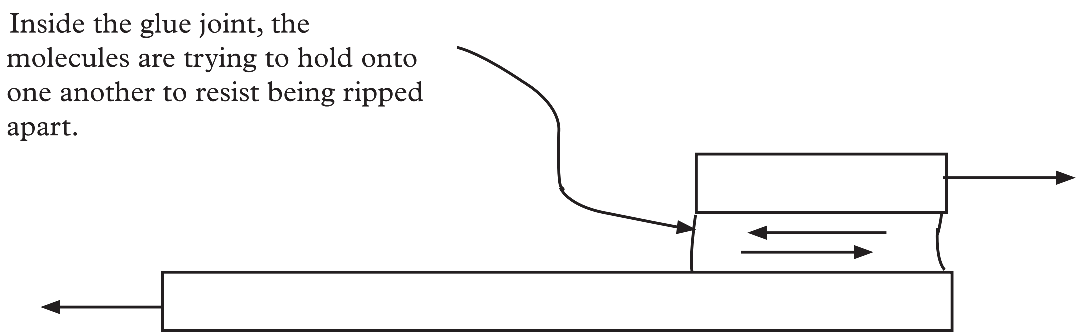


Fig. 5.17

5.4 Notch effect

Activity 5.6 **To investigate the notch effect**

(Work in groups)

Materials

- A rectangular block of rubber
- Knife or razor blade
- Ink pen

Steps

1. Draw close parallel lines on opposite sides of the rubber block.
2. By holding the rubber block at both ends with your hands, bend it. Observe and draw the shapes of the new pattern of lines. Explain why they are still parallel through bent.
3. Now cut a small V-shaped notch at the middle of the top surface. Repeat bending the block, observe and draw the new shape of the pattern of lines at the notch. Explain why they are concentrated at the notch, and what would happen if this would be done on a rigid structure like wood.
4. Now smoothen the notch by rounding the V-shaped end of the notch. Bend the blockage and observe the line pattern. Describe the distribution of the stressing force at the rounded notch.

Consider a uniform piece of wood (Fig. 5.18(a)). When a bending force is exerted on it, the stress is uniformly distributed along its length (Fig. 5.18(b)). When a small notch is cut on it and the same bending force applied on it, the stress is concentrated at the notch (Fig. 5.18(c)).

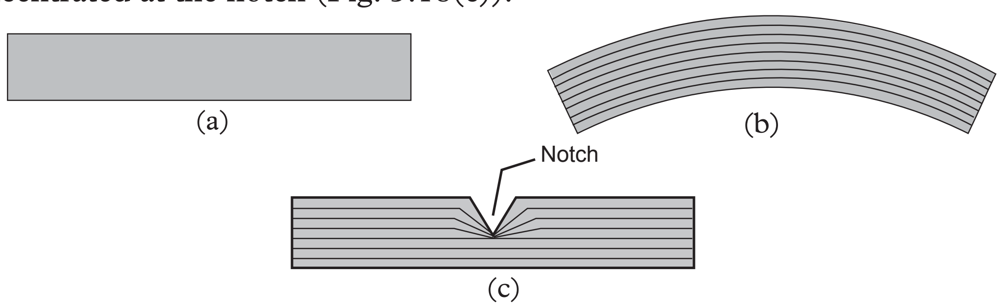


Fig. 5.18: Notch effect

The piece now breaks easily at the notch. This is known as the *notch effect.* Notch effect is applied when breaking firewood where we cut a small notch on the firewood and then break it easily. When cutting glass, the glass cutter makes a very tiny and almost invisible notch on the glass. A small force is then applied and the glass cuts smoothly along the notch.

To minimise the notch effect, the sharp point in Fig. 5.18 is rounded. The stress is now evenly distributed around the circular notch hence reducing the breaking effect (Fig. 5.19).

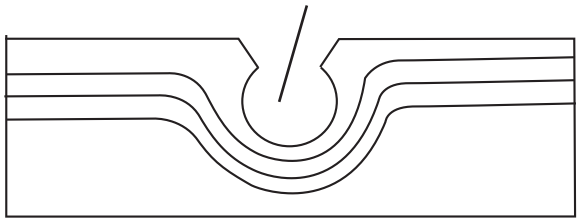


Fig. 5.19: Minimising notch effect

5.5 Struts and ties

Activity 5.6 **To find out what struts and ties are**

Materials

- 3 wooden blocks
- Nails
- Hammer
- Reference books
- Internet

Stops

1. Nail the three wooden blocks nails into a right-angled structure ABC (Fig. 5.20).
2. Fix the shorter side AB of the structure onto a wall or tree. Then, hang a load e.g. a stone on the structure at the acute-angled vertex C (Fig. 5.20).
   By observation, which of the three pieces are under:
   (a) compression
   (b) stress
   (c) not under either.

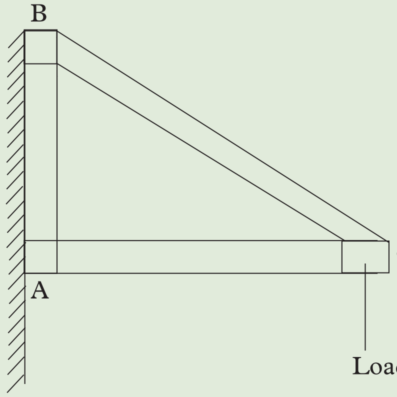


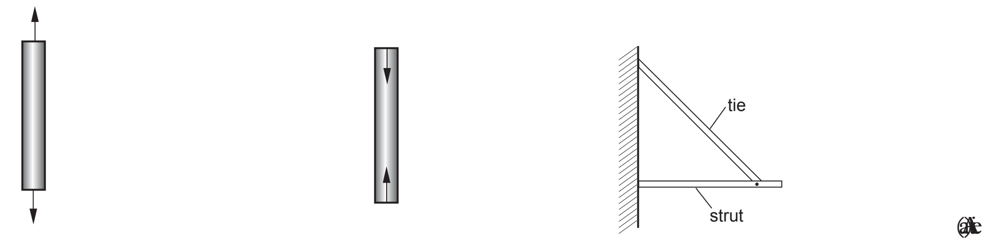
Fig. 5.20

3. Replace piece BC with a string and observe it when you suspend the load. Is the string under stress or compression? Justify your answer.

4. Now replace back piece BC with a wooden block and replace piece AC with a string. Observe piece AC when you suspend the load. Is the string under stress or compression?
5. What names are given to pieces AB, BC and AC?

A structure is a composition of pieces of materials joined together and collectively performing a task usually supporting a load. These pieces in a structure are collectively known as *girders.*

When supporting a load, some 5.21 pieces in the structure are under tensional force. These pieces are called *ties* (Fig. 20.18(a)). Others are under compressional forces and are called *struts* (Fig. 5.21(b)). A piece that is not under tension or compressional force is said to be *redundant*.



(b) A' strut (c)

Fig. 5.21: Girders

In order to identify struts and ties, in a structure, a piece (girder) is removed and replaced with a string while the rest remain in place. A force simulating the actual load is then applied on the structure. If the string straightens, the girder was a tie and if the string buckles, the girder was a strut. Otherwise, the piece was a redundant girder.

Example 5.2

Identify struts, ties and girders in the structure below (Fig.5.22).

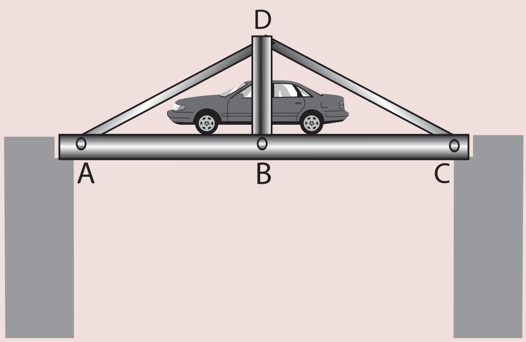


Fig. 5.22

Solution

AD and DC are ties (the string would tighten).

AC and DB is a strut (the string would buckle).

5.6 Shapes and strength of structures

There are many types and shapes of structures in common use. The type and shape of a structure determine its strength. Some common shapes used in structures are triangular, dome, T and L-shapes.

Activity 5.7 **To investigate the effect of shape on the strength of structures**

(Work in groups)

Materials

- Pins
- Drinking straws

Steps

1. Make a square with drinking straws and pins as shown in Fig. 5.23.

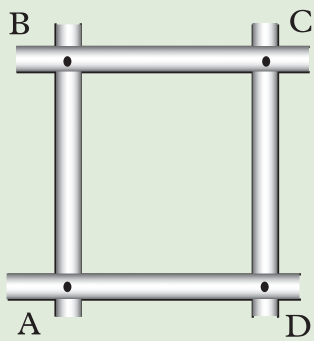


Fig. 5.23: Square structure

2. Place the structure vertically with corner D touching the bench. Then, apply a compressional force to the corner B that is opposite CD (diagonally) to D. Explain the observation.
3. Now fix in a diagonal piece BD using another straw (Fig 5.24). Again, apply the compressional force as in Step 2. What happens this time? Explain the change in the behaviour of the instructure.

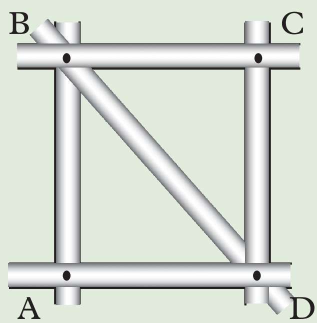


Fig. 5.24

Activity 5.8 **To design activities to investigate the strength of I, T, L - shaped, hollow and dome-shaped structures**

(Work in groups)

1. Using locally available materials design an activity to investigate the strength of:
   (a) I-shaped structures
   (b) T-shaped structures
   (c) L-shaped structures
   (d) Hollow-shaped structures
   (e) Dome-shaped structures
2. Make brief reports on the results of your investigations.
3. Present your results to the rest of the class.
4. Refine your results based on the class feedback on your presentation.

(a) Triangular-shaped structures

By putting the diagonal piece you form two triangles. A triangular structure is more stronger than a square or a rectangular one because it equally resists applied forces acting on all of its corners (Fig. 5.25). This makes the triangular structure the most popular.

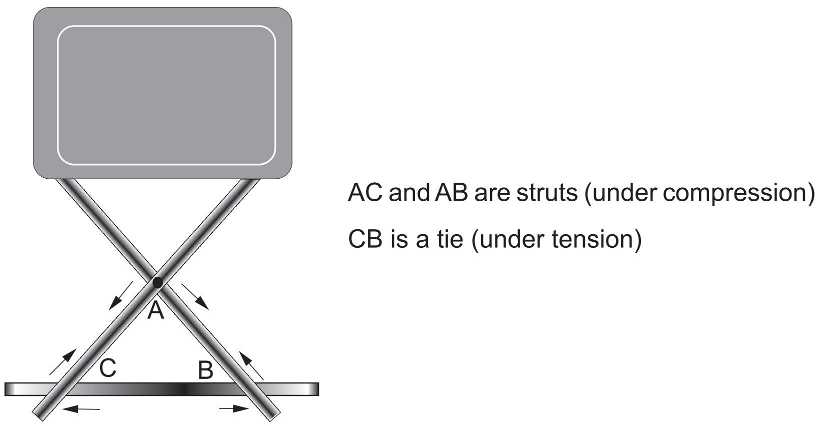


Fig. 5.25: Triangle structure

(b) I, T and L-shaped structures

As seen earlier, the stress in a beam when in use is concentrated at the top and bottom flanges. The middle layer is wasted because it does not resist either tension or compressional force. This makes the beam heavy, expensive and uneconomical. It is for this reason that the middle layer is sometimes removed to get an I-shaped beam (Fig. 5.26).

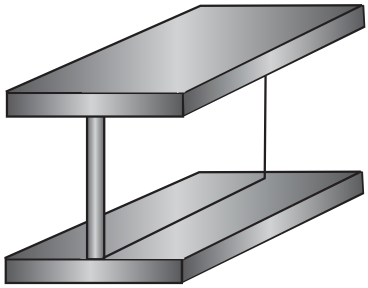


Fig. 5.26: I-shaped structure

The top flange of the I-shaped beam resists compressional force while the bottom flange resists tensional force. The I-shaped beam that is equally strong, lighter, economises on the material and is less expensive.

Other similar types of beam are the L-beams and T-beams (Fig. 5.27). A T-shaped beam is used in cases where only one type of force (either tension or compression) is being supported.

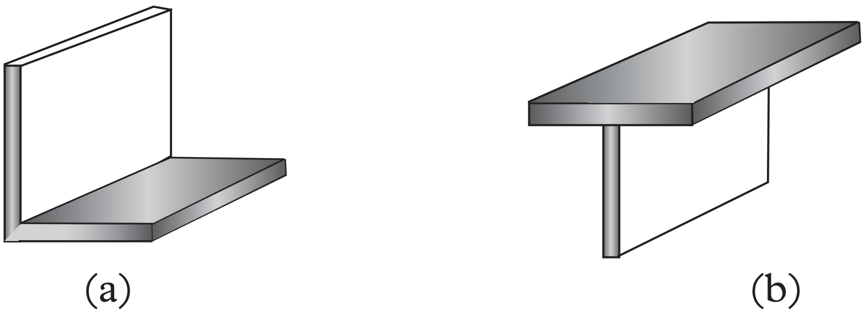


Fig. 5.27: L and T-shaped beams

(c) Dome-shaped structures

Dome shaped sructures are strong in that they distribute the stress through the curved sides to the foundations (Fig. 5.28). Domes are suitable when covering a large area e.g. a hall, a church or a stadium without having to put supporting walls in between.

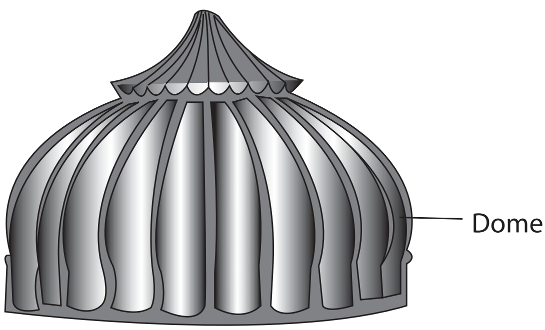


Fig. 5.28: Dome

(d) Hollow structures

Fig. 5.29 below shows a hollow tube.

Fig. 5.29: Hollow tube

Hollow tubes are also commonly used to support loads. One of the most common examples are culverts used to support weight on bridges (Fig. 5.30).

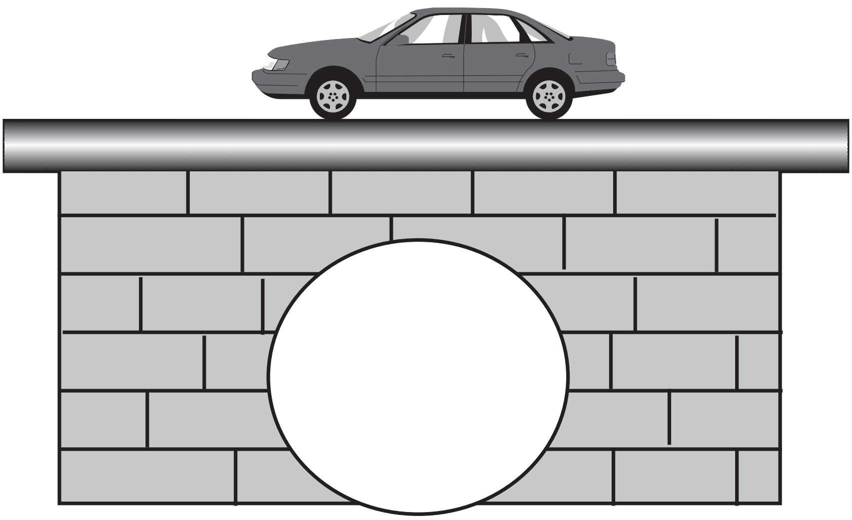


Fig. 5.30: A culvert

When supporting a load, the material ring of the hollow tube supports the compressional force exerted by the load. A hollow cylindrical structure is one of the most strong structures because it distributes the stress uniformly along its circular ring of material. If a solid cylindrical beam was used instead, the inner material would have been redundant and so wasted.

(e) Reinforced concrete

Concrete is a mixture of cement and stone aggregate. These are mixed with small amounts of water making the cement to hydrate and lock the aggregate into a rigid structure.

Concrete has a high resistance to compressive stresses. However, any appreciable tension on concrete e.g. due to bending, results in cracking and separation of the concrete. Actually, ordinary concrete is brittle. Such concrete must be well supported to prevent any development of tension.

Since concrete is strong under compression it is much used in pillars. If concrete is to be used in structures that need to resist compression and direct tensile action, then it needs to be reinforced. This involves incorporating steel bars, plates or fibers within concrete. The concrete is then referred to as *reinforced concrete*. The concrete therein resists compression while the steel bars resists the tension.

Reinforced concrete is used in slabs, walls, beams, columns, foundation and more. Fig 5.31 shows reinforced concrete used in the slabs and columns of a building.

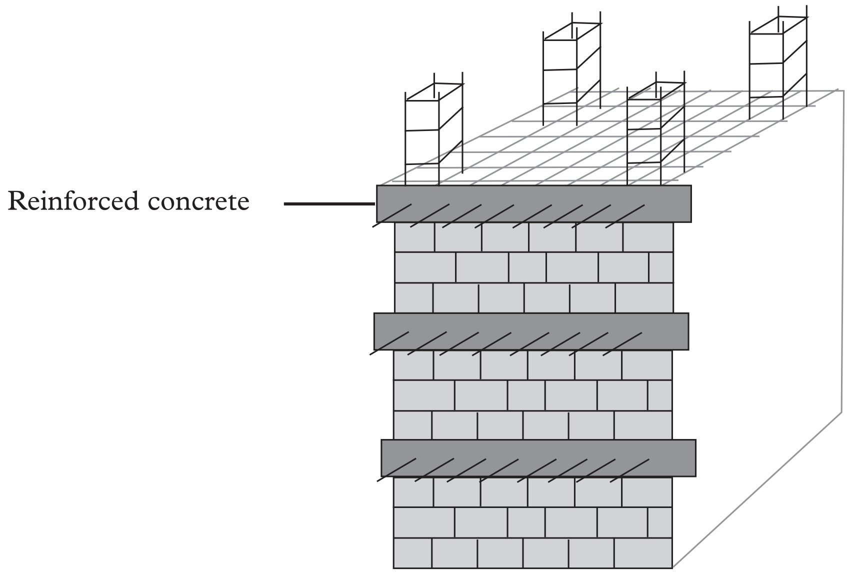


Fig. 5.31: Reinforced concrete in the slabs and beams

5.7 Application of mechanical properties of structures

Structures are all around us. They employ the various properties of matter and shape advantages that we have already looked at. Such structures in common use include roof support, water tank and bridges.

Bridges

Bridges make it possible to cross from one bank of a river to another. They also allow the movement of goods across a natural divide, over other roads, railways, deep gullies. There are various designs.

Beam bridge

This consists of a strong horizontal beam supported by a number of pillars. Its strength depends on the strength of the beam and the pillars (Fig. 5.32).

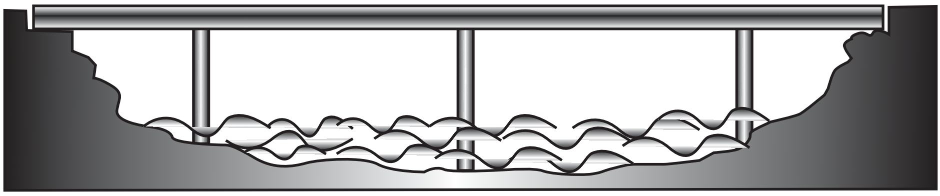


Fig. 5.32: Beam bridge

Cantilever

A cantilever type of bridge employs the use of struts and ties in the design of a truss (Fig. 5.33). It can cover a relatively wider area than the beam bridge without the intermediate beams.

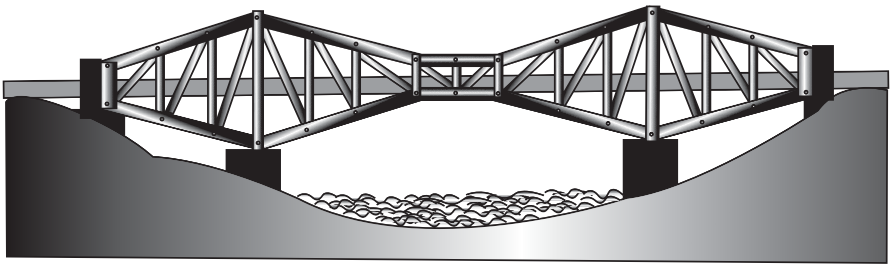


Fig. 5.33: Cantilever bridge

Arch bridge

An arch bridge employs the strength of circular structures under the beam (Fig. 5.34). Several arcs can be joined can be joined one after the other to cover longer distances.

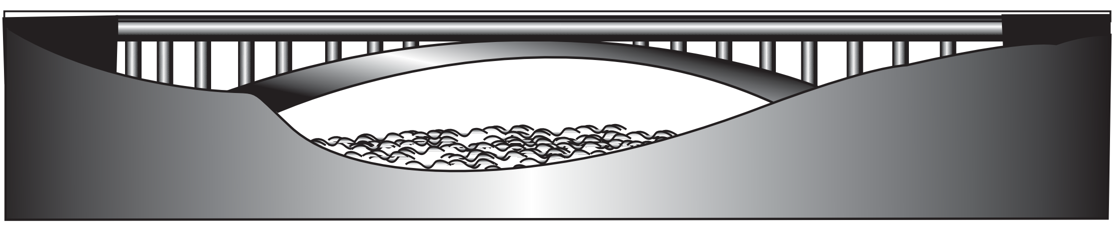


Fig. 5.34: Arch bridge

Suspension bridge

A suspended bridge also entails the use of circular support which rather suspend the bridge (Fig. 5.35). It can cover wider distances than any other bridge.

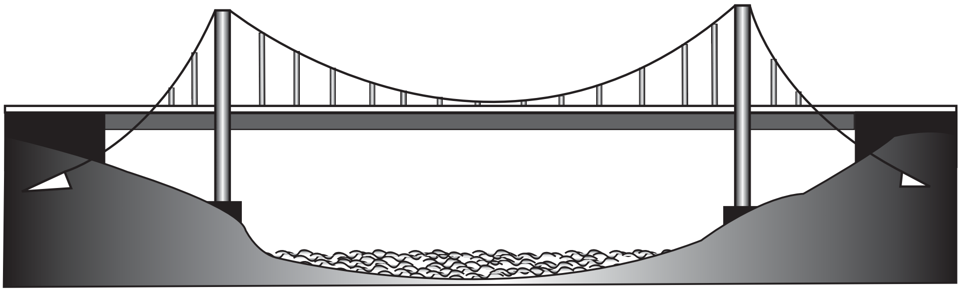


Fig. 5.35: Suspension bridge

Water tank supports

A water tank usually rests on a vertical structure that is reinforced by struts and ties (Fig. 5.36).The ties and struts distribute the weight to the ground.

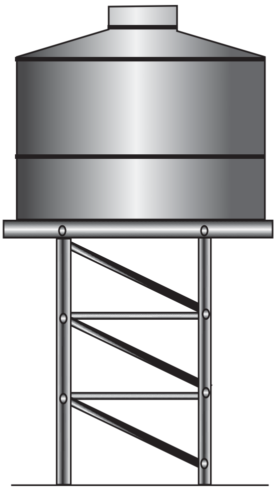


Fig. 5.36: Water tank

Roof top

A roof top consists of beams that are reinforced with struts and ties (Fig. 5.37). These girders make the top behave like one solid beam that resists sagging.

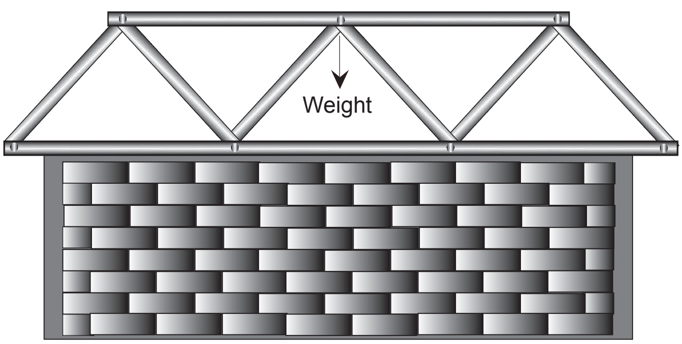


Fig. 5.37: Roof top

Exercise 5.2

1. Explain the term neutral axes.
   (a) Explain what struts and ties are in a structure.
   (b) Identify which of the girders are struts and which are ties in Fig. 5.38 (a), (b), (c), and (d).

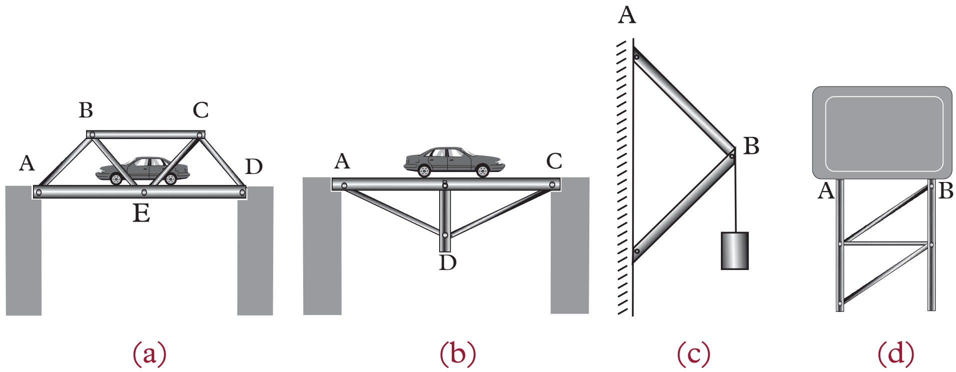


Fig. 5.39:

2. Briefly explain why a dome does not fall down.
3. Figure 5.36 below shows a television set resting on a shelf. Briefly explain the type of force experienced by pieces A, B, C & D.

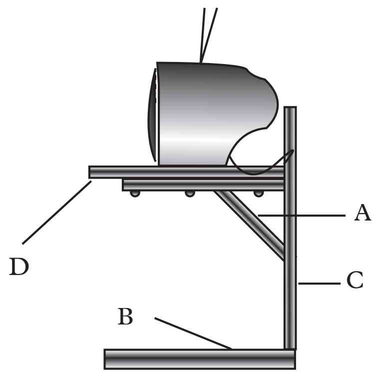


Fig. 5.39

4. Explain what bending moment of a beam is.

Topic summary

- Equilibrium is the state of an object when all forces acting upon it are balanced.
- State equilibrium is when an object is at test and in state of equilibrium.
- A beam is a long block of material usually used to support parts of the structures.
- A bending moment is a moment of force that causes bending of an object.
- A structure is a composition of parts of materials joined together in a collective manner to perform a particular task collectively supporting a load.
- Ties are parts of the structure that are under tensional force.
- Struts are parts of the structure that are under compressional forces.

Topic Test 5

1. Define the following terms and give examples where necessary.
   (a) Strength of forces on it. (b) Shear force. (c) Stress.
2. Explain factors that affect the strength of a material.
3. Using a diagram, describe the effect of a shear force on a body.
4. (a) Define the following terms:
   (i) Tension (ii) Compression
   (iii) a tie (vi) a strut
   (b) Fig 5.40 shows parts of a structure of a bicycle, under a force F.

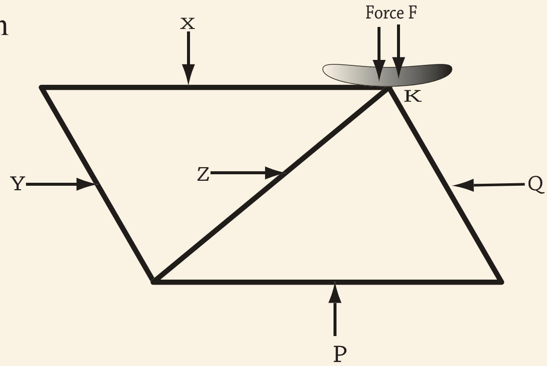


Fig. 5.40 : Type of forces on bicycle frame

Which of the parts X, Y, Z , P and Q would be under:
(i) tension force.
(ii) compression force, when a heavy load is applied at K in the direction shown?

5. Give four reasons why bicycle frames are made of hollow cylindrical structures.
6. (a) Fig 5.41 shows a roof structure.

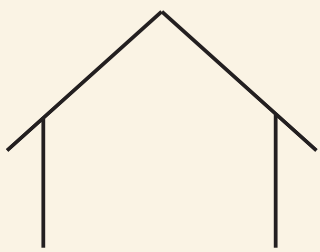


Fig 5.41: Roof structure

Show on the diagram how the structure can be strengthened by using two other girders.
   (b) State the three advantages of glass as a construction material.
7. (a) What is a notch effect?
   (b) Explain how a plunk of wood with a crack on one side can be placed to be a single wooden bridge across a stream.
8. (a) (i) What is the meaning of the term concrete?
   (ii) Explain how concrete can be reinforced.
   (iii) State why concrete is a good building material?
   (b) Explain why the lower part of the second floor of a building is made of reinforced concrete while the upper part is not reinforced.

Topic 6 Motion and momentum

Unit outline

Kinematics is the study of the motion of objects with no regard to the force which cause the motion.

Motion can be in a straight line or otherwise. Motion in a straight line is called *linear motion or rectilinear motion*. In this unit, we are going to study linear motion. We shall pay attention to the time taken, distance covered, speed, velocity and acceleration of the motion and their relationships.

6.1 Linear motion

There are two types of linear motion namely: uniform motion and non-uniform motion. In uniform motion, the speed of the moving object remains the same or constant.

In non-uniform motion, the speed of an object changes at a constant rate, a good example is the free fall.

(a) Distance and displacement

Activity 6.1 **To distinguish between distance and displacement**

(Work individually)

Materials: a tennis ball, rigid wall

Steps

1. Stand 2 m from a rigid wall.
2. Throw a tennis ball perpendicularly to a vertical wall.
3. Catch the ball when it bounces back.
4. Determine the distance and displacement covered by the ball.
5. Compare the two values. What is the difference? Use this difference to distinguish between distance and displacement.

Distance

Distance is *the total length of the path followed by an object, regardless of the direction of motion*. It is a scalar quantity and measured in units of length. The *SI unit* of distance is the *metre (m)*. Long distances may be measured in kilometres (km) while short distances may be measured in centimetres (cm) or millimetres (mm).

Displacement

Displacement is the object's overall change in position from the starting to the end point. It is the shortest distance along a straight line between two points in the direction of motion. The *SI unit* of displacement is the *metre* (m).

In Activity 6.1, you will find that the distance is 4 m while displacement is 0 m.

Suppose a boat starts at point A and moves 40 km East to point B followed by 30 m North to point C as shown in Figure 6.1.

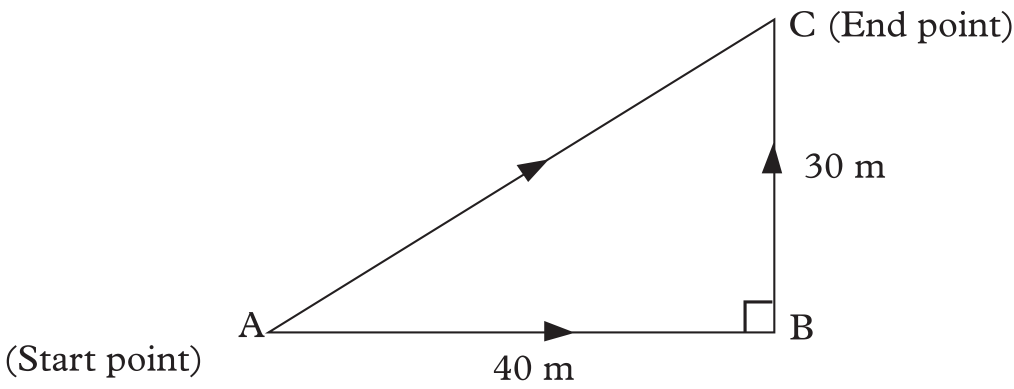


Fig. 6.1 Path followed by a boat

We can determine its distance and displacement covered as follows:

Distance = AB + BC = 40 m + 30 m = 70 m

Displacement = AC = $\sqrt{AB^2 + BC^2} = \sqrt{40^2 + 30^2}$ = 50 m.

6.1.2 Speed

Activity 6.2 **To establish the formula for speed**

(Work in pairs)

A car takes 20 s to travel a distance of 600 m between points A and B while a bicycle takes 300 s to travel the same distance.

1. Using a simple Mathematics approach, find the distance travelled by the:
   - **(a)** car in one second
   - **(b)** bicycle in one second.
2. Using the result in Step 1, discuss with your partner which of the two means of transport is faster than the other.
3. What is the name and SI unit of the quantity obtained in 1.
4. Write the formula for finding the quantity you have identified in Step 3.
5. Discuss with your partner how you can calculate the whole journey's speed for a body if the speed keeps on changing from one point to the other.
6. What is the name given to the quantity obtained in Step 1?

In your discussion, you should have established that the distance *moved by a body per unit time is called speed*. In this motion, direction is not considered. Thus,

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

The SI unit of speed is metres per second (m/s). Other units of speed such as kilometres per hour (km/h) and centimetres per second (cm/s) are also in common use.

When a body covers equal distances in equal time intervals, it is said to move with *uniform speed*.

Example 6.1

What is the speed of a racing car in metres per second if the car covers 360 km in 2 hours?

Solution

$$\text{Speed} = \frac{\text{Distance moved}}{\text{Time taken}} = \frac{360\text{ km}}{2\text{ h}} = 180\text{ km/h}$$

OR

$$\text{Speed} = \frac{\text{Distance moved}}{\text{Time taken}} = \left(\frac{360 \times 1\,000}{3600 \times 2}\text{ m/s}\right) = 50\text{ m/s}$$

As you travel in a car or bus, you notice that the speedometer of the car keeps on showing different values of speed. The speed at any given instant in your journey is called instantaneous speed.

The equivalent constant speed that the body would move at to cover the same distance in the same time is called avarage speed.

Average speed of a body is the total distance covered by the body divide by the total time taken i.e.

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

Example 6.2

A car moving along a straight road ABC as shown in Fig. 6.2 maintains an average speed of 90 km/h between points A and B and 36 km/h between points B and C.

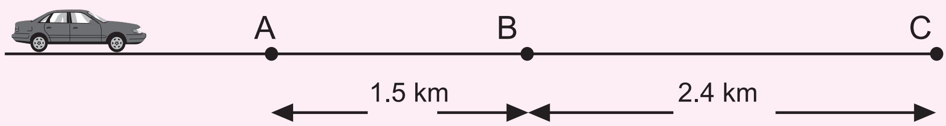


Fig. 6.2: Car moving along a straight line

Calculate the:

(a) Total time taken in seconds by the car between points A and C.

(b) Average speed in metres per second of the car between points A and C.

Solution

(a) $\text{Average speed} = \frac{\text{Total distance}}{\text{Time taken}}$

$$\text{Total time between A and B} = \frac{\text{Total distance}}{\text{Average speed}}$$

$$= \frac{1.5}{90}\text{ h} = \frac{1.5}{90} \times (60 \times 60)\text{ s} = 60\text{ s}$$

$$\text{Total time between B and C} = \frac{2.4}{36} \times (60 \times 60)\text{ s} = 240\text{ s}$$

$$\text{Total time between A and C} = 60\text{ s} + 240\text{ s} = 300\text{ s}$$

(b) Average speed $= \dfrac{\text{Total distance}}{\text{Time taken}}$

$= \dfrac{(1.5 + 2.4) \times 1\,000 \text{ m}}{300 \text{ s}}$

$= 13$ m/s

6.1.3 Velocity

Activity 6.3 To determine the speed in a specified direction

(Work in pairs)

Materials

- Playing ground
- Surveyor tape measure
- stopwatch

Steps

1. Mark three points, A, B and C on a straight line on the ground (Fig. 6.3).

Fig. 6.3: Marked points on a playground

2. Stand at point B. Start making forward steps to point C, as your partner does the timing and records the time you take.
3. Repeat the activity but now start at point B and move to point A.
4. Reverse your roles with your partner and repeat the activity.
5. Taking the distance covered in the forward direction (B to C) to be positive and the one on the reverse direction (B to A) to be negative, find your speeds in each case. What does the result you have found represent? Explain.
6. Suppose you are to describe your motions to somebody who was not at the venue. What aspects of the motion must you mention so that the person distinguishes the motions from B to C and B to A?
7. What name is given to a quantity that has both speed and direction.

The speed of a body in a specified direction is called velocity or velocity is the rate of change of distance in a particular direction with respect to time. Therefore,

$$\text{Velocity} = \frac{\text{Distance moved in a particular direction}}{\text{Time taken}} = \frac{\text{Displacement}}{\text{Time taken}}$$

The SI unit of velocity is *metres per second (m/s)*.

A negative sign in a value of velocity is commonly used to indicate movement in the appetite direction.

When describing velocity in a particular direction as constant, the velocity is referred to as *uniform velocity*.

In some cases, the velocity of a moving body keeps on changing. In such cases, the average velocity of the body is considered.

$$\text{Average velocity} = \frac{\text{Total displacement}}{\text{Time taken}}$$

Example 6.3

A car travelled from town A to town B 200 km east of A in 3 hours. It then changed direction and travelled a distance of 150 km due north from town B to town C in 2 hours. (Fig. 6.4). Calculate the average:

(a) Speed for the whole journey.

(b) Velocity for the whole journey.

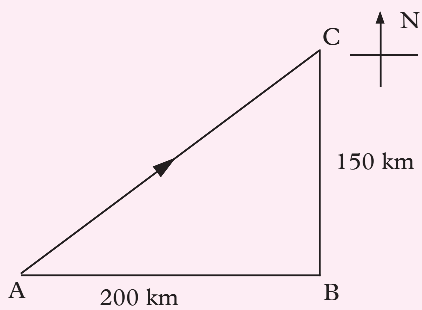


Fig. 6.4: Town A, B and C

Solution

(a) $\text{Average speed} = \frac{\text{Total distance}}{\text{Time taken}} = \frac{(200 + 150)\ \text{km}}{(3 + 2)\ \text{h}}$

$$= \frac{350}{5}\left(\frac{\text{km}}{\text{h}}\right)$$

$$= 70\ \text{km/h}$$

(b) $\text{Average velocity} = \frac{\text{Displacement, AC}}{\text{Time taken}} = \frac{\sqrt{200^2 + 150^2}\ \text{km}}{(3 + 2)\ \text{h}}$

$$= \frac{250}{5\ \text{h}}\ \text{km}$$

= 50 km/h, Direction is from A to C.

$$\text{In m/s} = \frac{50\ 000\ \text{m}}{3\ 600\ \text{s}}$$

$$= 13.89\ \text{m/s}$$

Exercise 6.1

1. Distinguish between:
   (a) Speed and velocity.
   (b) Distance and displacement.
2. Rusangwanwa cycles to school 2.5 km away in 5 minutes. What is his average speed in: (a) metres per second (b) kilometres per hour.
3. Nesa and Nshimiye decided to walk to a picnic site 12 km away. They walked the first 6 km at an average speed of 6 km/h and the rest at 5 km/h.
   (a) How long did the journey take?
   (b) What was their average speed for the journey?
4. The initial velocity of a motor cyclist riding on a straight road is 10 m/s. If the velocity was increasing by 5 m/s every second, find the:
   (a) velocity after (i) 1 s (ii) 2 s (iii) 5 s.
   (b) average velocity in 5 s.

6.1.4 Acceleration

Activity 6.4 **To determine the rate of change of velocity with time**

(Work in groups)

Materials: A long tape, carbon disk, a runway, ticker-tape timer, a trolley

Steps

1. Pass a long tape under the carbon disc of the ticker-tape timer and attach it to a trolley. Place the trolley on a horizontal runway. Ensure that the runway is friction compensated as in Fig. 6.5.

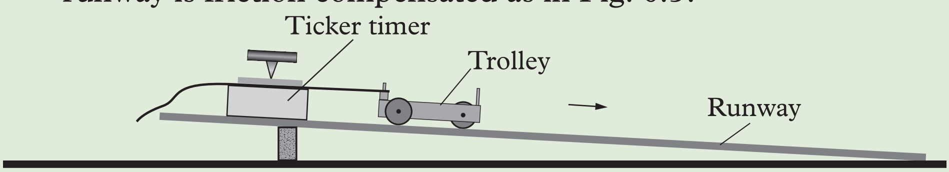


Fig. 6.5: To determine uniform velocity using a ticker-tape timer.

2. Now, increase the angle of inclination using the wooden block until the trolley is seen to be moving with increasing speed down the runway.
3. Release the trolley and start the ticker-timer. What do you notice about the separation of adjacent dots on the tape? Explain why.

4. Brainstorm with your members how the dots on ticker-tape will look like when the speed of trolley is reducing with time.

5. What quantity is used to refer to the change of velocity with time. Suggest its SI units.

It can be seen that the separation of the dots increases with time as shown in Fig. 6.6. Since the time between two successive dots is 0.02 s, the time between each 5 spaces length is 0.10 s.

Fig. 6.6: Ticker-tape for an accelerating body

This shows that the velocity of the trolley is not constant but changing with the time.

When the velocity of a body changes with time it is said to be *accelerating*. Acceleration is defined as *the rate of change of velocity* with time i.e.

$$\text{Acceleration} = \frac{\text{Change in velocity}}{\text{Time taken}}$$

The SI unit of acceleration is *metres per square second* or *m/s²*.

If the acceleration of a body is 4 m/s^2, it means that its velocity is increasing by 4 m/s every second. When the velocity of a body decreases, it is said to be decelerating or retarding. *Deceleration or retardation is negative acceleration*. This is usually shown with a negative sign before the value e.g – 4 m/s^2, is deceleration at 4m/s^2. A body moving with uniform velocity has zero acceleration since there is no change in velocity.

When the rate of change of velocity with time is constant, the acceleration is referred to as *uniform acceleration*.

Example 6.4

A car accelerates from rest to a velocity of 20 m/s in 5 s. Thereafter, it decelerates to a rest in 8 s. Calculate the acceleration of the car: (a) in the first 5 s, (b) in the next 8 s.

Solution

(a) Acceleration $= \frac{\text{Change in velocity}}{\text{Time taken}}$

$= \frac{\text{Final velocity} - \text{Initial velocity}}{\text{Time taken}}$

(rest means velocity is zero)

$= \frac{(20 - 0 \text{ m/s}}{5 \text{ s}}$

$= 4 \text{ m/s}^2$

(b) Acceleration =

$\frac{\text{Final velocity} - \text{Initial velocity}}{\text{Time taken}}$

$= \frac{(0 - 20) \text{ m/s}}{8 \text{ s}}$

$= \frac{-20 \text{ m/s}}{8 \text{ s}} = -2.5 \text{ m/s}^2$

or deceleration of 2.5 m/s^2

6.1.5 Equations of uniformly accelerated motion

Uniform and non – uniform motion can be described and represented by use of an equation called kinematic equation. There are four variables in these equations,displacement(and distance) velocity(and speed),acceleration and time.

.

Activity 6.5 **To describe the equations of uniform linear motion**

(Work in pairs)

Steps

1. From the expression $a = \frac{v - u}{t}$ where a is the acceleration, u is the initial velocity v is the velocity and t is the time taken. Make v the subject of the equation. The equation you obtain is known as *first equation of motion*.
2. Consider the following expressions:

   Distance covered (s) = Average velocity × t, where Average velocity = initial velocity (u) + final velocity (v). Substitute V from the equation you obtained above i.e v = u + at. Use the expression to derive the 2nd equation of motion in the form: $S = ut + \frac{1}{2}at^2$.
3. Use the first and second equations of motion to derive the third equation of motion in the form: $v^2 = u^2 + 2as$

Consider a body moving along a straight line with uniform (constant) acceleration (see Fig. 6.7)

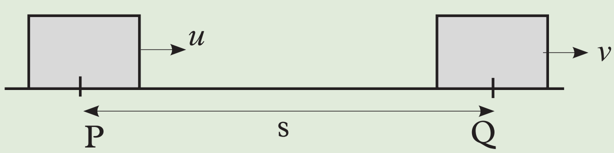


Fig. 6.7: A body moving with uniform acceleration

Let the initial velocity at point P be *u* and the final velocity at Q be *v*. The distance PQ travelled, in time *t* is *s*.

(a) Velocity and time

1. The acceleration of the body is given by

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

Making *v* the subject of the formula

$$\boxed{v = u + at}$$ …… 1^{st} equation of motion.

2. The average velocity of the body is given by

$$\text{Average velocity} = \frac{\text{Displacement}}{\text{Time taken}} = \frac{s}{t} \quad \ldots \text{(i)}$$

$$\text{But average velocity} = \frac{\text{Initial velocity + final velocity}}{2}$$

$$= \frac{u + v}{2} \quad \ldots \text{(ii)}$$

From equation (i) and (ii) $\frac{v + u}{2} = \frac{s}{t}$

$$s = \frac{(v + u)t}{2} \quad \ldots \text{(iii)}$$

Substituting v with (u + at) equation (iii) becomes

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

$$\boxed{s = \frac{2ut + at^2}{2} \text{ or } s = ut + \frac{1}{2}at^2}$$ …… 2^{nd} equation of motion

3. From the 1^{st} equation $t = \frac{v - u}{a}$. Substituting for *t* in the equation.

For average velocity

$$\frac{s}{t} = \frac{v + u}{2} \text{ we get } \frac{as}{v - u} = \frac{v + u}{2}.$$

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

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

$$\boxed{2as = v^2 - u^2 \quad \text{or} \quad v^2 = u^2 + 2as}$$ … 3rd equation of motion

Therefore, the equations $\boldsymbol{v = u + at}$, $\boldsymbol{s = ut + \frac{1}{2}at^2}$ **and** $\boldsymbol{v^2 = u^2 + 2as}$ are referred to as the equations of uniformly accelerated motion.

These equations can be utilised to predict unknown information about an object in motion if others are known. Each of the equations include four variables. If the values of three or four variables are known, then the value of the fourth variable can be calculated.

Example 6.5

A stone is thrown vertically upwards with a velocity of 20 m/s. After 4 s the stone returns to the same position with a velocity of 20 m/s downwards. Determine the acceleration of the ball during the first 2 seconds.

Solution

u = + 20 m/s, v = 0 m/s,

$$a = \frac{v - u}{t} = \frac{0 - 20 \text{ m/s}}{2 \text{ s}} = \left(\frac{-20}{2} \text{ m/s}^2\right)$$

$$= -10 \text{ m/s}$$

Example 6.6

A car on a straight road accelerates from rest to a speed of 30 m/s in 5 s. It then travels at the same speed for 5 minutes and then brakes for 10 s in order to stop. Calculate the:

(a) acceleration of the car during the motion.

(b) deceleration of the car.

(c) total distance travelled.

Solution

(a) *From* $v = u + at$, $a = \dfrac{v - u}{t}$

$$= \frac{(30 - 0) \text{ m/s}}{5 \text{ s}}$$

$$= 6 \text{ m/s}^2$$

(b) $\boldsymbol{a} = \frac{v - u}{t} = \left(\frac{0 - 30}{5}\right) m/s^2$

∴ deceleration is 6 m/s^2.

(c) There are three distinct sections of the journey.

(i) Section of acceleration: a = 6 m/s^2

$$\text{The distance, } s = ut + \frac{1}{2}at^2$$

$$= 0 + \frac{1}{2} \times 6 \times 5^2$$

$$= 75 \text{ m}$$

(ii) Section of constant velocity:

$$a = 0$$

$$\text{Distance, } s = 30 \times (5 \times 60)$$

$$= 9\ 000 \text{ m}$$

(iii) Section of deceleration a = –3 m/s^2 (from part (b))

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

$$= 30 \times 10 + \frac{1}{2} \times (-3) \times 10^2$$

$$= 300 - 150 = 150 \text{ m.}$$

Total distance travelled = 75 + 9 000 + 150

= 9 225 m

Example 6.7

The driver of a bus initially travelling at 72 km/h applies the brakes on seeing a crossing herd of cattle. The bus comes to rest in 5 seconds.

Calculate:

(a) the average retardation of the bus.

(b) the distance travelled in this interval.

Solution

(a) Velocity of 72 km/h in m/s is $\frac{72 \text{ km/h} \times 1\ 000 \text{ m}}{1 \times 3\ 600 \text{ s}}$

= 20 m/s

The quantities given are u = 20 m/s, v = 0 m/s and t = 5 s

From, $a = \frac{v - u}{t}$, $a = \frac{0\text{ m/s} - 20\text{ m/s}}{5} = {}^{-}4\text{ m/s}^2$

Since the question talked of average retardation, ignore the negative sign hence average retardation = 4 m/s^2

(b) From, $s = ut + \frac{1}{2}at^2$,

$$s = 20 \times 5 + \frac{1}{2} \times {}^{-}4 \times 5^2$$

$$= 100 - 50$$

$$= 50\text{ m}$$

or

From, $v^2 = u^2 + 2as$, $0^2 = 20^2 - 2 \times 4 \times s$

$$0 = 400 - 8s$$

$$= \frac{400}{8}$$

$$s = 50\text{ m}$$

Equations of motion under gravity

When a body is thrown vertically upwards with an initial speed u, it experiences a deceleration of 10 m/s^2 (ignoring air resistance) until its speed is reduced to zero at the maximum height reached. After this, the body falls downwards accelerating at 10 m/s^2.

How do the equations of linear motion already derived, apply to motion under gravity?

For motion upwards, acceleration, $a = {}^{-}g = {}^{-}10\text{ m/s}^2$.

Thus, the equation $v = u + at$ becomes $v = u - gt$ for motion upwards and $v = u + gt$ for motion downwards

If the maximum height above the starting point is H,

$s = ut + \frac{1}{2}at^2$ becomes $H = ut - \frac{1}{2}gt^2$ for motion upwards and

$H = ut + \frac{1}{2}gt^2$ for motion downwards.

Example 6.8

Derive the equations of linear motion for a body released from rest and falling under gravitational pull g from a height H in time t.

Solution

For the body falling freely under gravity $u = 0$, $a = g$ and $s = H$ downwards. Therefore,

$$v = u + at \text{ becomes } v = 0 + gt \text{ or } v = gt$$

$$s = ut + \frac{1}{2}at^2 \text{ becomes } H = 0 + \frac{1}{2}gt^2 \text{ or } H = \frac{1}{2}gt^2$$

$$v^2 = u^2 + 2as \text{ becomes } v^2 = 0 + 2gH \text{ or } v^2 = 2gH$$

It should be noted that gravity does not affect the velocity of a body horizontally. The motion of any body under gravity has zero acceleration in the horizontal direction.

Horizontally, the equation;

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

$$s = ut \text{ and } v^2 = u^2 + 2as \text{ becomes } v^2 = u^2 \text{ or } v = u.$$

Exercise 6.2

1. Define the term uniform acceleration of a body.
2. A racing car accelerates on a straight section of a road from rest to a velocity of 50 m/s in 10 s. Find:
   (a) the acceleration of the car
   (b) the distance travelled by the car in 10 s.
3. A motorcyclist accelerates from 10 m/s to 30 m/s in 20 s. Calculate:
   (a) the acceleration of the motorcyclist.
   (b) the displacement of the motorcyclist.
4. An object travelling at 10 m/s decelerates at 2.0 m/s^2. How long does the object take before coming to rest? Calculate the distance travelled by the object before it comes to rest.
5. The diagram in Fig. 6.8 shows a toy car accelerating down a straight incline.

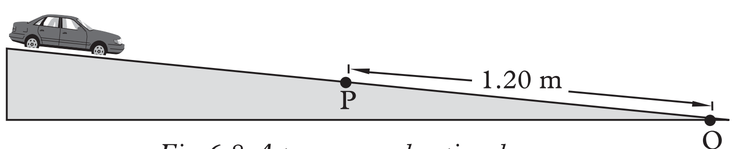


Fig. 6.8: A toy car accelerating down

(a) Explain how you would determine the average speed with which the toy car passes point P.

(b) It is found that the instantaneous speed of the car is 1.50 m/s at point P and 1.60 m/s at point Q. Point Q is 1.20 m from point P. Calculate the acceleration of the car between points P and Q.

6. A cyclist starts from rest and accelerates at 1.0 m/s^2 for 30 s. The cyclist then travels at a constant speed for 1 minute and then decelerates uniformly and comes to a stop in the next 30 s.

   (a) Find the maximum speed attained in

   (i) metres per second

   (ii) kilometres per hour.

   (b) Calculate the total distance covered in metres.

7. A bus decelerates from 18 m/s to rest in 10 seconds. Calculate:

   (a) the deceleration of the bus

   (b) the displacement of the bus.

8. A stone is let to fall vertically down from a window on the 10th floor of a building 40 m above the ground. Find the time taken by the stone to reach the ground.

9. An object is thrown vertically upwards with an initial velocity of 50 m/s. Find

   (a) the maximum height reached by the object.

   (b) the time taken to reach this height. (Neglect the effect of air resistance.)

10. A mass is dropped from a height of 50 m above the moon's surface. How long does the mass take to fall to the moon's surface if the moon's acceleration due to gravity is 1.7 m/s^2? Calculate the difference in time for the same mass when dropped 50 m above the earth's surface (Neglect air resistance.)

6.1.6 Graphs of linear motion

(a) Distance – time graphs

Activity 6.6 **To draw and interpret a distance-time graph**

(Work in groups)

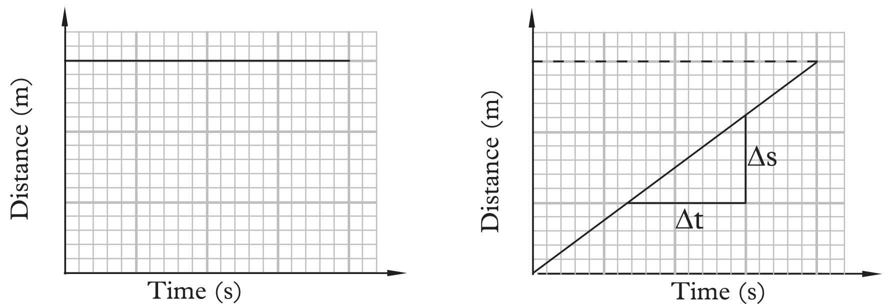
Materials

- Graph papers
- Pencil
- ruler

Steps

1. Discuss and sketch distance-time graphs for two bodies: one at rest and the other moving at a constant velocity.
2. Discuss and interpret each graph for each object.
3. Draw and analyse graphs of bodies whose speed is increasing or decreasing with time.
4. Suggest what the gradient represent in a distance-time graph.

In your discussion, you should have obtained Fig. 6.9(a) and (b) for the body at rest and one moving at a constant velocity respectively.



(a) Body at rest *(b) Moving body with constant velocity*

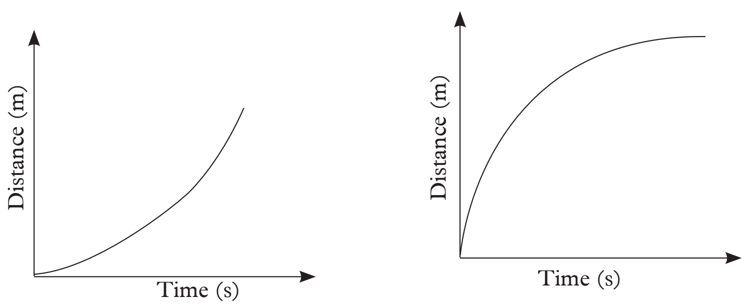
Fig. 6.9(a) and (b): Distance-time graph

The graph in Fig. 6.9(a) shows that the distance covered by the body is not changing with time. The body is therefore at rest (stationary).

The graph in Fig. 6.9(b) shows that the distance covered by the body is increasing with time.

The gradient of the graph is $\frac{\Delta s}{\Delta t}$ and represents the speed of the object. Thus, the graph represents the motion of the body moving with constant (uniform) speed.

In some cases, the speed of an object increases or decreases with time as shown by the graphs in Fig. 6.10.



(a): Speed increasing with time *(b): Speed decreasing with time*

Fig. 6.10: Distance - time graph

In Fig. 6.10(a) the gradient (representing speed) is increasing, implying that the object is accelerating. Examples of real-life settings where such motion is exhibited include a body rolling down an inclined plane and a car accelerating uniformly from rest. (graph with a smooth curve represent uniform motion.

In Fig. 6.10(b), the speed of the object is decreasing, implying that the object is decelerating. Examples of real-life setting where such motion is exihibited include a body thrown vertically upward, a body rolling uphill an inclined plane and a car decelerating uniformly.

Example 6.8

Fig. 6.11 shows a distance-time graph for a motorist. Study it and answer the questions that follow.

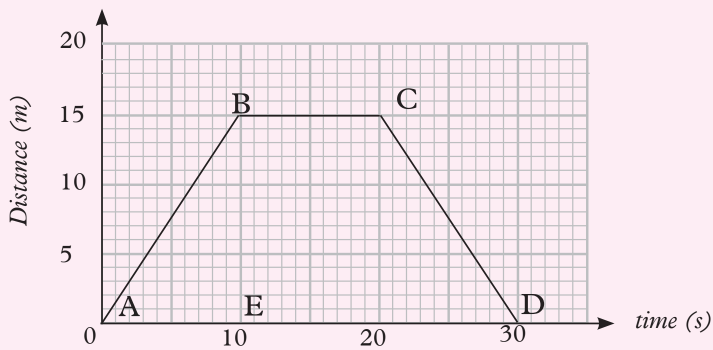


Fig. 6.11: Distance - time graph

(a) How far was the motorist from the starting point after 10 seconds?

(b) Calculate the average speed of the motorist for the first 10 seconds.

(c) Describe the motion of the motorist in regions: (i) BC (ii) CD

Solutions

(a) By reading directly from the graph, distance travelled in 10 s = 15 m.

(b) Slope of the graph = speed of the motorist.

$$\text{Slope} = \frac{\text{Change in distance}}{\text{Change in time}} = \frac{(15 - 0)\text{m}}{(10 - 0)\text{s}} = 1.5 \text{ m/s}$$

(c) (i) In the region BC, distance is not changing but time changes, hence the body is at rest (stationary).

(ii) In the region CD, the motorist is moving at a constant speed towards the starting point.

(b) Displacement-time graphs

Activity 6.7 **To draw and interpret a distance-time graph**

(Work in groups)

Materials

- Graph papers
- Pencil
- ruler

1. In groups of three, discuss and sketch the displacement-time graph for a body:
   - **(a)** whose displacement changes uniformly with time.
   - **(b)** at rest.
   - **(c)** whose rate of change of displacement with time is not constant.
2. In your group analyse and interpret the displacemnt-time graph in 1(a), (b) and (c).
3. Compare your graphs with those of other groups in a class discussion.

In order to describe the displacement of a body, a *reference point* is considered. The reference point is the point when the body is at zero displacement as shown in Fig. 6.12. The body may be moving from the left or right from the reference point.

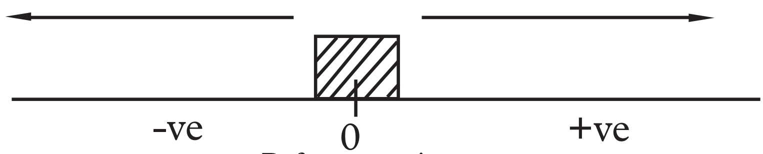
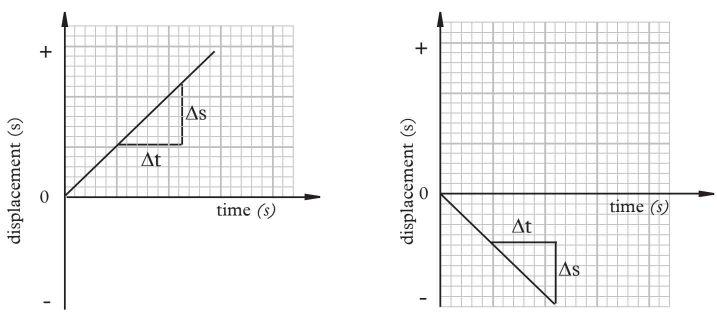


Fig. 6.12: Moving object

Let us consider a body moving in such a way that its displacement changes uniformly with time. Depending on the direction taken, two graphs can be drawn as shown in Fig. 6.13(a) and (b).



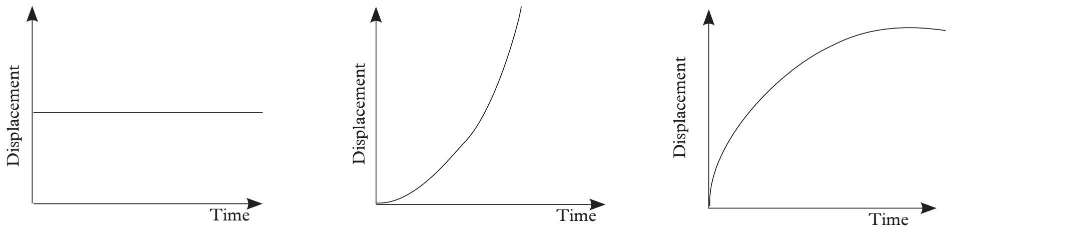
(a) A body moving forward with constant velocity

(b) A body moving in appropriate direction at constant velocity

Fig. 6.13: Displacement-time graphs for objects moving at constant velocities

As we have seen already, the gradient Δs/Δt of a displacement-time graph gives the velocity of the body. Thus, in Fig. 6.13(a), the body is moving forward at constant velocity while in Fig. 6.13(b), the body is moving in the reverse (opposite direction) at constant velocity.

Let us now sketch displacement-time graphs for a body at rest and for those whose rate of change of displacement with time (velocity) is not constant (Fig. 6.14).



(a) Object at rest.

(b) Displacement increases non-uniformly with time.

(c) Displacement decreases non-uniformly with time.

Fig. 6.14: Displacement-time graphs

In Fig. 6.14(a), the displacement does not change with time, hence the body is at rest. In Fig 6.14(b), the gradient (velocity) is increasing hence the body is accelerating. In Fig. 6.14(c), velocity (gradient) is decreasing hence the body is decelerating uniformly (since the curve is smooth.

(c) Speed-time graphs

Activity 6.8 **To draw and interpret a speed-time graph**

(Work in groups)

Materials:

- Graph papers
- Pencil, ruler

Steps

1. In groups of three, draw and interpret speed-time graphs for a body:
   (a) at rest.
   (b) moving with uniform and non –uniform speed.
   (c) moving with increasing speed.
2. Present and discuss your graphs to the whole class on the chalkboard/white board.

The gradient of a speed-time graph gives us

$$\frac{\text{Change in speed}}{\text{Change in time}} = \text{Acceleration.}$$

In Activity, you should have obtained the following:

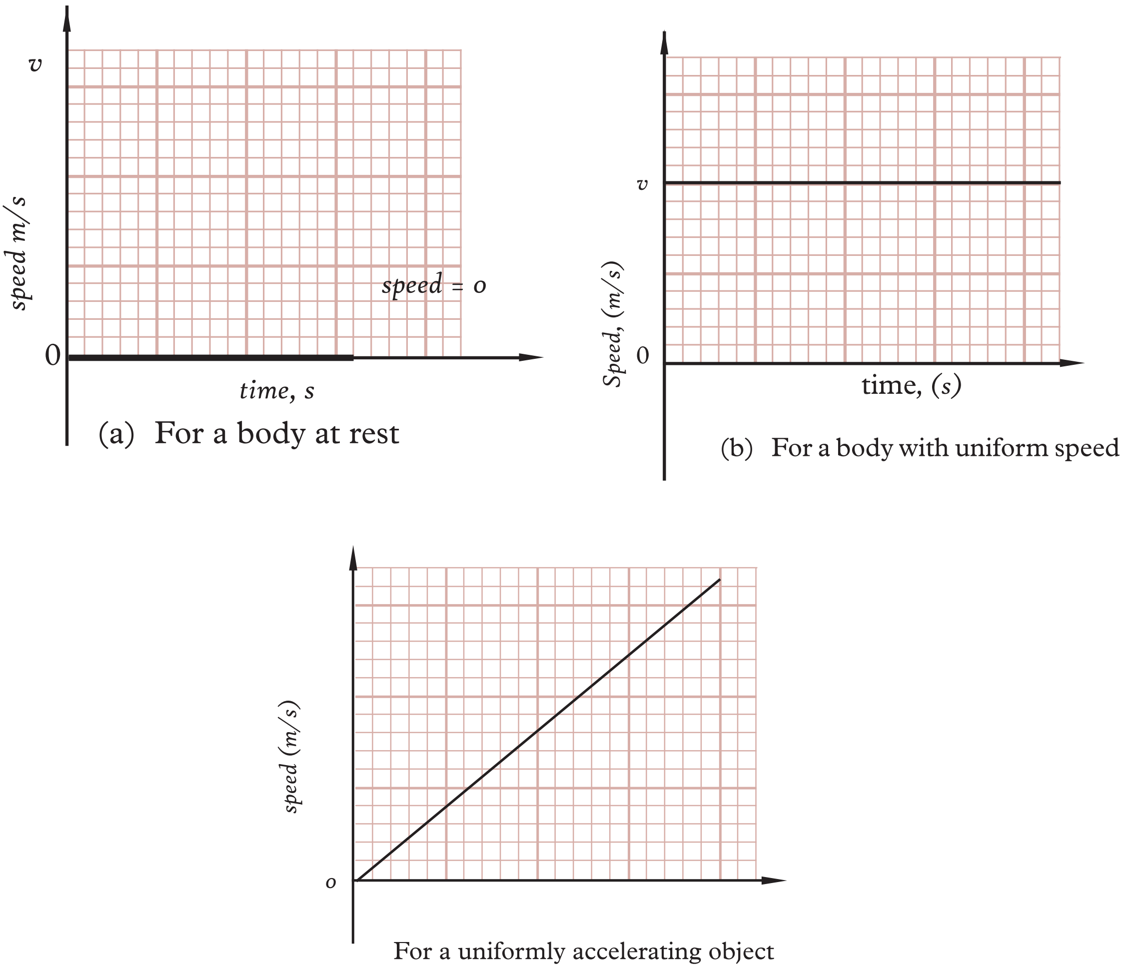


Fig. 6.15: Speed-time graph

In figures 6.15(a), gradient = 0.
Acceleration in this case is zero i.e $a = 0$ m/s^2

In this case (when the object is stationary) or moving at constant speed, the gradient is zero and so acceleration is zero.

Example 6.9

Fig. 6.16 shows a graph of speed against time for the motion of a car travelling from Ngumbo to Kator.
Determine:

(a) the acceleration of a car in the first 4 s.

(b) the distance travelled in the first 4 s.

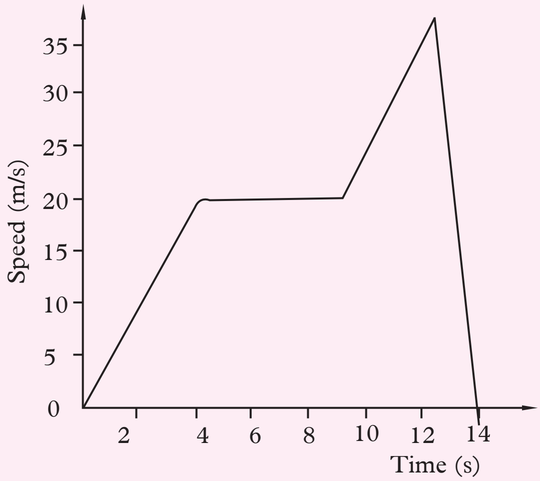


Fig. 6.16: Speed - time graph

Solution

(a) Acceleration $= \frac{\text{Change in speed}}{\text{Time taken}} = \frac{\Delta s}{\Delta t} = \frac{20 \text{ m/s}}{4\text{s}} = 5 \text{ m/s}^2$

(b) Distance travelled = Area under the graph $= \frac{1}{2}$ speed (m/s) × time (s)

$= \frac{1}{2} \times 20 \text{ m/s} \times 4\text{s}$

$= 40 \text{ m}$

(d) Velocity – time graphs

Activity 6.9 **To draw and interpret a speed-time graph**

(Work in groups)

Materials: • Graph papers • Pencils • Ruler

Steps

1. In groups of three, brainstorm on what a velocity-time graph is.

2. Suggest what the gradient of a velocity-time graph represents.

3. Draw and interpret velocity-time graphs for a body:

(a) moving with a constant velocity.

(b) accelerating from rest uniformly.

(c) decelerating uniformly.

(d) moving with non-uniform acceleration.

4. Discuss in your group what the area under a velocity-time graph represent.
5. Compare your graphs with those of other groups in your class. Did you get similar graphs? Discuss.
6. Present on the chalkboard/white board your findings to the rest of your class members.

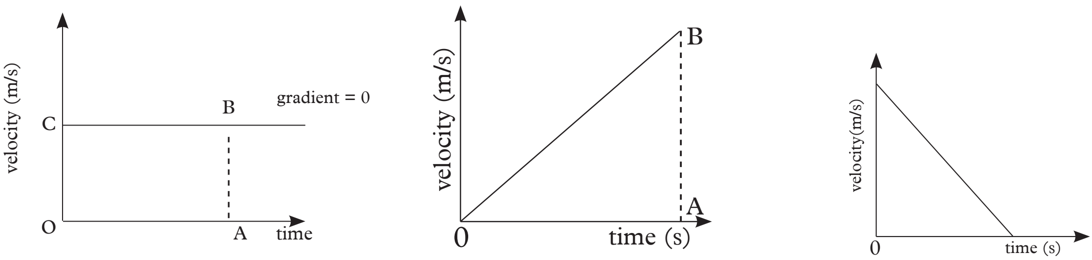
A velocity-time graph tells us how the speed and direction of an object changes with time.

The gradient of velocity-time graph represents the acceleration i.e.

$$\text{gradient} = \frac{\text{Change in velocity } (\Delta V)}{\text{Time taken } (\Delta t)} = \text{acceleration}$$

From Activity 6.8, you should have obtained the following line graphs:

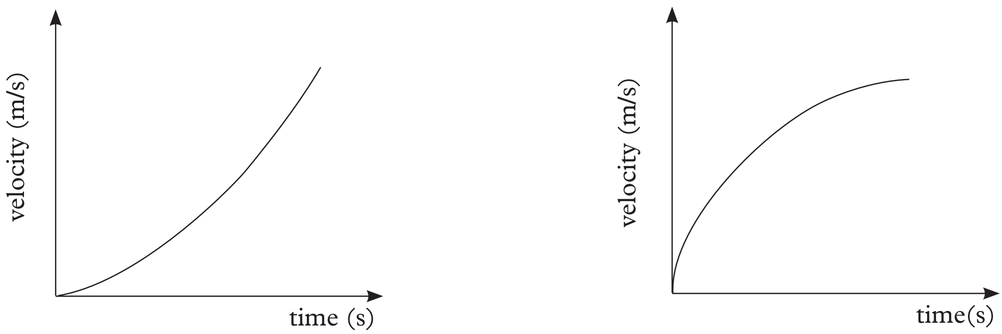
The velocity-time graph for a body moving at constant velocity is shown in Fig. 6.17.



(a) For a body at constant velocity *(b) For a body at constant acceleration* *(c) For uniform/constant deceleration*

Fig. 6.17: Velocity-time graph

In some situations, acceleration is not uniform; it may be increasing or decreasing. This can be represented by the graphs shown in Fig. 6.18 (a) and (b).



(a): Increasing acceleration *(b): Decreasing acceleration*

Fig. 6.18:Motion with uniform acceleration

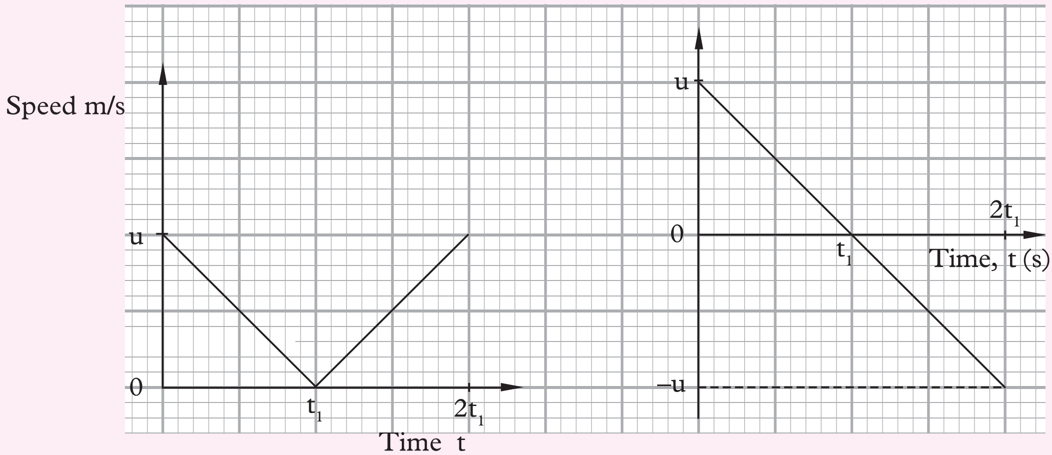
Example 6.10

A stone is thrown vertically upwards with an initial velocity u. Sketch its:

(a) speed-time graph.

(b) velocity-time graph for its motion up to the time it comes back to its original position.

Solution



(a) Speed-time graph of the stone (b) Velocity-time graph of the stone

Fig. 6.19: Motion of the body under gravity

The time taken to reach the maximum height is t_1.

The time taken by the body to fall back to its starting point is also t_1.

The total time of flight is $2t_1$.

Example 6.11

Table 6.1 shows the data collected to study the motion of a cyclist.

Table 6.1: Values of velocity and time

Velocity m/s	0	3	6	6	6	6
Time (s)	0	2	4	6	8	10

(a) Plot a graph of velocity (y-axis) against time (x-axis).

(b) Use your graph to determine the acceleration of the cyclist in the first four seconds.

Solutions

(a)

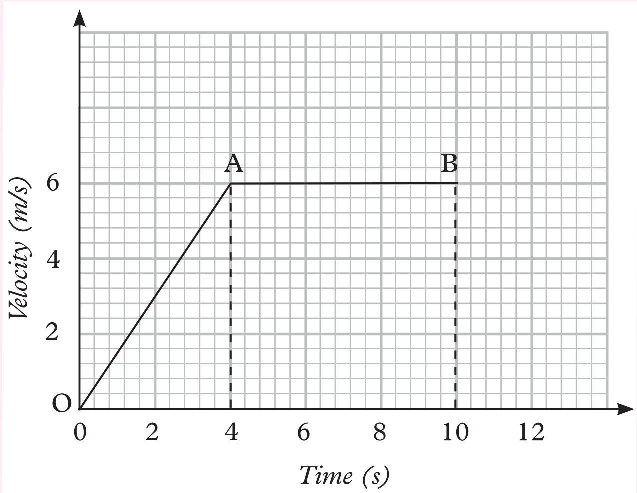


Fig. 6.20: Velocity-time graph

(b) Acceleration = slope of the graph

$$= \frac{\text{Change in velocity}}{\text{Change in time}}$$

$$= \frac{(6-0)\text{ m/s}}{(4-0)\text{ s}} = \frac{6\text{ m/s}}{4\text{ s}}$$

$$= 1.5\text{ m/s}^2$$

Exercise 6.3

1. Sketch the following graphs.

   (i) The speed-time graph for a body moving with uniform speed.

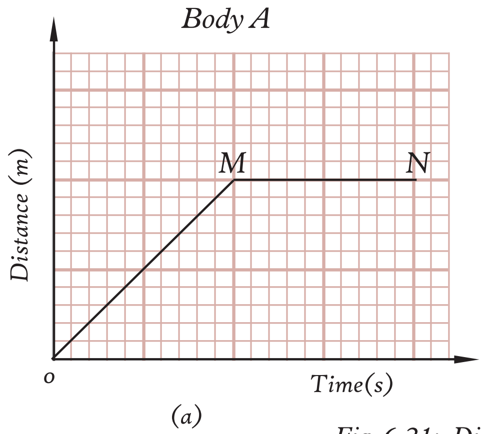
   (ii) The distance-time graph for a body moving with uniform speed.

   (iii) The speed-time graph for a body moving that is accelerating.

   (iv) The speed-time graph for a body moving with a decreasing acceleration.

   (v) The speed-time graph for a ball thrown upwards and then caught again.

2. Fig. 6.21 (a) shows the distance-time graph for body A while Fig. 6.21 (b) shows the speed-time graph for body B.



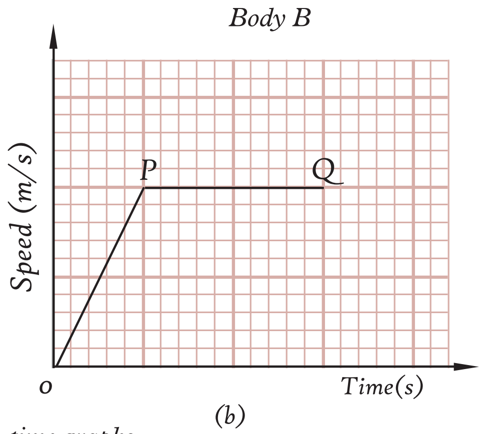


Fig. 6.21: Distance-time graphs

Describe fully the motion of the bodies in the following regions:

(a) OM **(b)** MN **(c)** OP **(d)** PQ

3. **(a)** Sketch a velocity-time graph for a car moving with uniform acceleration from 10 m/s to 30 m/s in 20 s.

(b) Use the graph to find the acceleration of the car and the total distance travelled by the car.

4. Fig. 6.22 shows the velocity-time graph of a car. Use the graph to find:

(a) acceleration of the car.

(b) deceleration of the car.

(c) total displacement of the car.

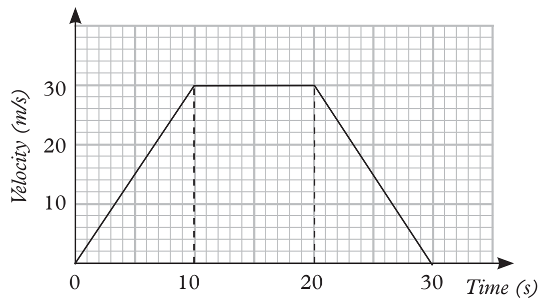


Fig. 6.22: Velocity-time graph

5. The graph in Fig. 6.23 shows the motion of a body falling freely under gravity.

(a) Determine the values of velocities at t = 1, 2, 3 and 4 s.

(b) Draw a graph of velocity(v) against time (t).

(c) Use your graph in (b) to find the value of gravitational acceleration.

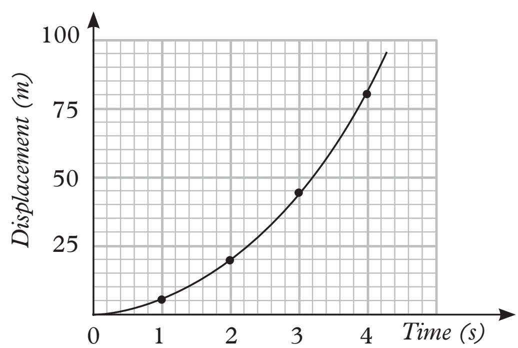


Fig. 6.23 Displacement-time graph

6. The sketches in Fig. 6.24 represent the motions of bodies in a straight line. Match each graph with appropriately description from the ones given.

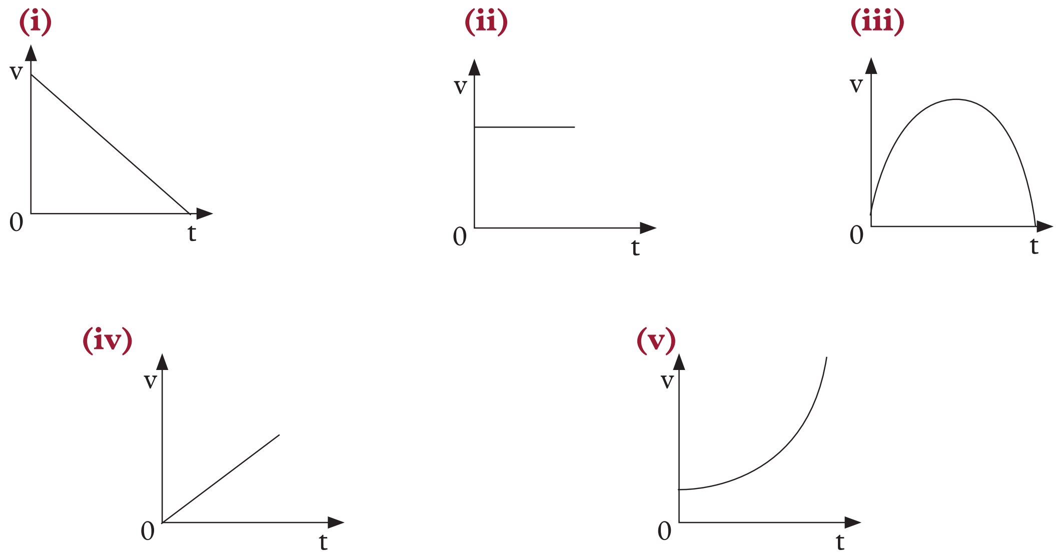


Fig. 6.24: Motion graphs

(a) Uniform acceleration of a body starting from rest.

(b) The body moves with constant velocity.

(c) Body decelerates uniformly, starting with finite positive velocity.

(d) A ball thrown to hit the ground and bounces back.

(e) Body moving with increasing acceleration.

7. Draw a graph of velocity against time for a car which starts with an initial velocity of 20 m/s and accelerates uniformly at 4 m/s^2 for 8 seconds, then slows down to rest in 20 seconds.

(a) How far does the car travel?

(b) What is the maximum velocity attained by the car?

(c) What is the retardation of the car as it comes to rest?

6. 2 Linear momentum and impulse

Activity 6.10 To illustrate linear momentum

(Work in groups)

Materials

- Two hammers (light and heavy)
- Two identical nails
- Wooden block

Steps

1. Take two nails and drive them into two pieces of wood using a light hammer.
2. Hit the first one gently and the second nail very hard. What happens in each case?
3. Repeat the activity using a heavy hammer (Fig. 6.25). What do you notice?.

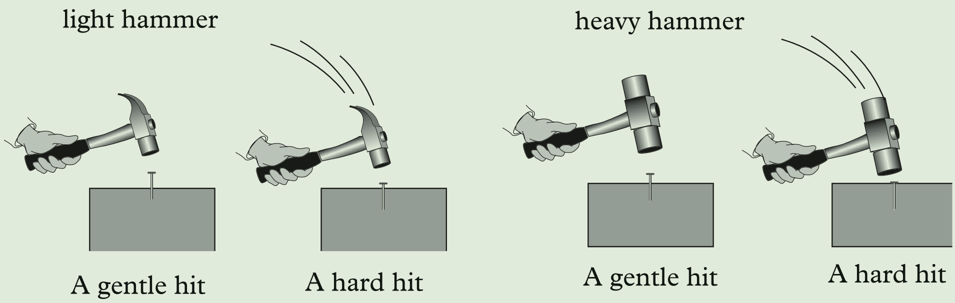


Fig. 6.25: Driving a nail into wood.

4. Highlight two factors on which the penetration distance of the nail depends.
5. Discuss with your classmate what the term 'linear momentum' means.
6. Explain the difference between impulse and momentum.

To drive a nail into wood, a certain rate of motion (velocity) and mass of the hammer is required. The quantity involving both motion and mass of a body is called *linear momentum*. It is denoted by the letter p and is called *momentum* in short.

Linear momentum of an object is defined as the product of the mass and the velocity of the object. i.e.

$$\text{momentum, } p = \text{mass} \times \text{velocity}$$
$$\text{In symbols} \quad p = m \times v$$

The *SI unit of momentum* is *kg m/s*. Momentum is a *vector quantity*. The direction of momentum is the same as that of velocity.

Example 6.12

A car of mass 600 kg moves with a velocity of 40 m/s. Calculate the momentum of the car.

Solution

Momentum = mass × velocity

= 600 kg × 40 m/s

= 24 000 kg m/s

Example 6.13

A body A of a mass 4 kg moves to the left with a velocity of 7 m/s. Another body B of mass 7 kg moves to the right with a velocity of 6 m/s away from each other. (Fig. 6.26).

Fig. 6.26

Calculate: (a) the momentum of A, (b) the momentum of B, (c) the total momentum of A and B.

Solution

Let us assign positive sign to indicate movement to the right and a negative sign to indicate movement to the left.

(a) Momentum of A = 4 kg × (–7) m/s = –28 kg m/s

(b) Momentum of B = 7 kg × (+6) m/s = +42 kg m/s

(c) Total momentum = (momentum of A) + (momentum of B)

= –28 kg m/s + 42 kg m/s

= +14 kg m/s

= 14 kg m/s to the right

When a force F acts on an object for a very short time t, it produces an impact, usually referred to as *impulse* on the object.

Impulse is defined as the product of force and time i.e.

Impulse = Force × time

In symbols: $I = Ft$

The SI unit of impulse is *newton second (N s)*.

When an impulsive force acts on an object, it produces a change in the momentum of that object. The velocity of that object changes from an initial value u to a final value v. Its mass m remains constant.

Experiments have shown that the impulse acting on the object is equal to the change in momentum it produces on the object.

Impulse = Change in momentum

$$Ft = mv - mu$$

Example 6.14

A hammer strikes a metal rod with a force of 20 N. If the impact lasts 0.4 s, calculate the impulse due to this force.

Solution

Impulse = Force × time

= 20 N × 0.4 s

= 8 Ns

Vertical linear motion

6.3 Newton's laws of motion

Everyday, we interact with forces. The forces can cause different effects such as change in motion, pressure as well as turning moments on an object. The effects of force on motion of a body are summarised by Newton's three laws of motion. In this unit, we will investigate each of these laws in details.

6.3.1 Newton's First law of motion

Activity 6.11 To demonstrate inertia using a coin and cardboard

Materials

- Table or bench
- A smooth cardboard
- Coin

Steps

1. Place the cardboard on the table with a small section of it extending beyond the edge of the table. Place the coin on the cardboard (Fig. 6.27).

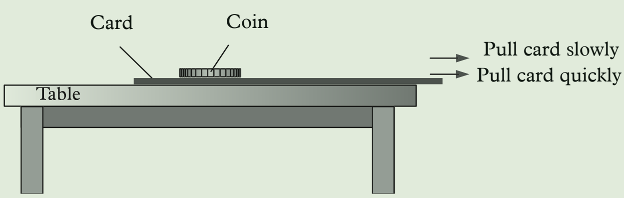


Fig. 6.27: A coin on top of a cardboard

2. Pull the cardboard gradually and observe what happens to the cardboard and the coin.
3. Return the cardboard and the coin to their initial position. Now pull the cardboard abruptly and observe what happens to the cardboard and the coin.
4. Explain your observations in Steps 2 and 3.
5. Discuss in your groups and make a presentation on the role of safety belts in a car.

The effects of a force on a body either at rest or in uniform motion is summed up under Newton's first law of motion which states that a body remains in its state of rest or uniform motion in a straight line unless acted upon by an external force.

Newton's first law of motion suggest that matter has an in-built reluctance to change its state of motion or rest. For instance, when a moving bus comes to an abrupt stop, the passenger lurches forward, i.e. tends to keep on moving. Likewise, when a bus surges forward, the passengers are jerked backwards, i.e. tend to resist motion.

This explains why cars have seat belts. The seat belts (see Fig. 6.28), hold passengers onto the seat incase the vehicle comes to a stop or decelerates suddenly, preventing them from lurching forward. This reduces any chances of serious injury incase of an accident.

Factors affecting inertia of a body

(a) Mass of a body

The mass of a body is a measure of its inertia. A large mass require a large force to produce a given acceleration or deceleration than a smaller mass. A larger mass therefore has a greater inertia.

(b) Acceleration of a body

As the acceleration of a body increases so does its tendency to continue at a constant velocity.

(c) Force applied on a body

When the force applied on a body is increased, its tendency to remain at rest is reduced. This would result to movement of the body from its resting state.

(d) Friction acting on a body

The law of inertia states that an on object / body will keep moving at a constant velocity unless a force is applied in it. An example of such a force is friction. It is a force that makes a body to slow down. Without it, the body would continue moving at the same velocity without slowing down.

Exercise 6.4

1. Define the term 'inertia.'
2. State the law of inertia.
3. Briefly explain why wearing safety belts in a moving vehicles is very important.

6.3.2 Newton's second law of motion

Activity 6.12 **To determine and state Newton's second law of motion**

(Work in groups)

Materials

- Two trolleys (heavier and light one)
- Spiral spring or rubber bands

Steps

1. Place the two trolleys on a smooth flat surface (floor or a table surface).
2. Connect the heavier trolley to the lighter one using a spiral spring or rubber bands provided.
3. Move the trolleys away from each other till they are about 1m apart.
4. Release them at the same time. Observe the difference in their velocities and acceleration. Which trolley accelerates faster?
5. Based on your observations in this activity, suggest relationship between the applied force, mass of an object and the acceleration produced by the force on the body.
6. Explain your observation using Newton's second law of motion in terms of momentum?
7. Compare your finding with those of other classmates.

As we have already learnt, one of the effects of a force is that it changes the state of motion of an object. i.e. it causes a body at rest to move and a moving body to accelerate or come to rest. Any change in the velocity of a body causes a change in its momentum.

Newton summarised this effect on a body in his second law of motion which states that *the rate of change of momentum is directly proportional to the resultant force on a body and it takes place in the direction of the force.*

Mathematically, the law is represented as follows:

$$\text{Force (F)} = \frac{\text{Change in momentum}}{\text{Time taken}}$$

$$\text{Force(F)} = \frac{\text{Final momentum} - \text{initial momentum}}{\text{Time taken}}$$

If m is the mass of the body and taking u and v to represent initial and final velocities respectively,

Initial momentum = mass × initial velocity (mu)

Final momentum = mass × final velocity (mv)

Change in momentum = final momentum – initial momentum

$$= mv - mu$$

$$\textit{Rate of change of momentum} = \frac{mv - mu}{t}$$

$$= m\left(\frac{v - u}{t}\right)$$

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

Therefore rate of change of momentum = m*a*.

Thus $F \propto ma$

or, $F = kma$ where k is a constant of proportionality.

Experiments show that k = 1. Therefore, F = ma.

This is the mathematical representation of Newton's second law.

The relationship F = ma shows that the greater the force applied on an object the more acceleration it causes on the object.

If mass is 1 kg and acceleration is 1 m/s^2, then the force is 1 N. This is the definition of 1 newton i.e. *1 newton is the force which produces an accerelation 1m/s^2 on a unit mass.*

Example 6.15

A truck of mass 2.5 tonnes accelerates at 7.5 m/s^2. Calculate the force generated by the truck's engine to attain this acceleration.

Solution

F = m*a*

= (2.5 × 1 000) kg × 7.5 m/s^2

= 18 750 N

Example 6.16

Calculate the acceleration produced by a force of 20 N on an object of mass 300 kg.

Solution

$$a = \frac{F}{m} = \frac{20 \text{ N}}{300 \text{ kg}}$$

$$= 0.066\ 7 \text{ m/s}^2$$

Example 6.17

Table 6.2 shows the values of force, *F*, and the acceleration, a, for the motion of a trolley on a friction compensated runway.

Table 6.2

Force F (N)	0.2	0.4	0.6	0.8	1.2
Acceleration, *a* (m/s^2)	0.90	1.8	2.7	3.5	5.3

(a) Plot a graph of force, *F* against acceleration, *a*.

(b) Use your graph to determine the force when the acceleration is 4.0 m/s^2

(c) Calculate the mass of the trolley, in grams, from your answer in (b).

Solution

(a) The graph is shown in Fig. 6.28.

(b) As shown in the graph, force, F = 0.88 N, when acceleration, a = 4.0 m/s^2.

(b) Since $F = ma$, $m = \frac{F}{a}$

$$= \frac{0.88 \text{ N}}{4.0 \text{ m/s}^2}$$

$$= 0.22 \text{ kg}$$

The mass of the trolley = 225 g.

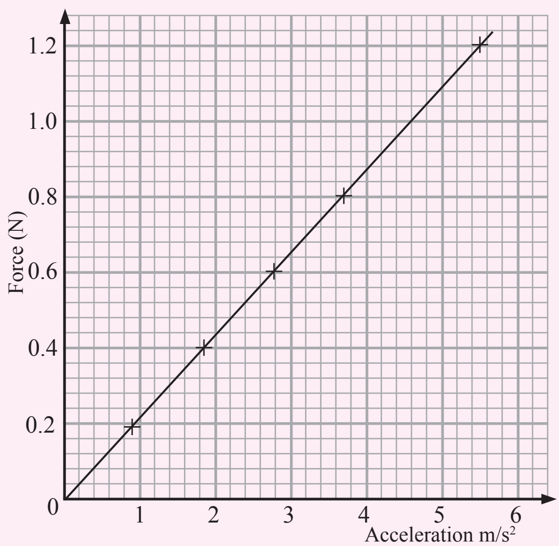


Fig. 6.28: A graph of acceleration against force

Note:

The slope of the graph of force (F) against acceleration gives the mass of trolley.

Exercise 6.5

1. **(a)** State Newton's second law of motion.
   (b) Use Newton's second law of motion to derive the equation F = ma.
   (c) Define the unit of force, 'the newton' using F = ma.
2. **(a)** What is meant by 'impulse of a force'?
   (b) What is the relationship between impulse and the change in momentum?
   (c) When a soccer goalkeeper is being trained on how to catch hard balls, he/she is taught how to pull back the hands while catching the ball. Explain how the technique works.
3. A 0.06 kg tennis ball drops freely from the left hand of a player. When in the air, it hits a racquet and leaves with a horizontal speed of 58 m/s.
   (a) Calculate the impulse produced on the ball.
   (b) If the time of contact with the racquet is 0.025 seconds, calculate the average force exerted on the ball.
4. A bullet of mass 7 g travels with a velocity of 150 m/s. It hits a target and penetrates into it. It is brought to rest in 0.04 s. Find the:
   (a) distance the bullet travels in the target.
   (b) average retarding force exerted on the bullet.
5. A ball of mass 45 g travelling horizontally at 30 m/s strikes a wall at right angles and rebounds with a speed of 20 m/s. Find the impulse exerted on the ball.
6. Fig. 6.29, shows a graph of the force on a tennis ball when served during a game. Find the mass of the ball if it leaves the racket with a velocity of 40m/s. (Assume the ball is stationary before it is struck.)

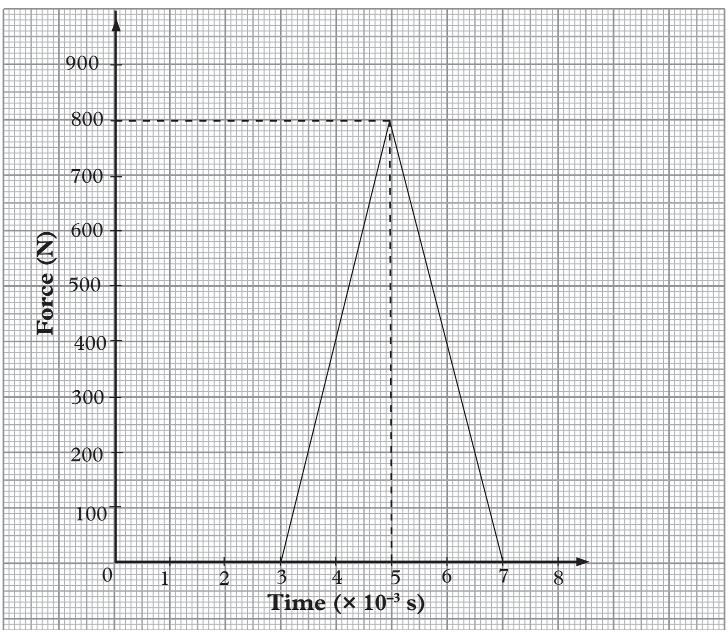


Fig. 6.29: A graph of force against time

7. A truck of mass 4 000 kg starts from rest on horizontal rails. Find the speed 4 seconds after starting if the impulsive force by the engine is 1 500 N.

6.3.3 Newton's third law of motion

Activity 6.13 **To demonstrate action and reaction force**

(Work in groups)

Materials

- Carton
- A large balloon
- Cellotape
- A straw
- 4 pins

Steps

1. Infillate a balloon, tie it and release it in the air. What happens?
2. Cut out one rectangular and 4 equal circular pieces from the carton to act as the body and wheels of a trolley respectively.
3. Pass the pins through the centre of the wheels to act as the shafts and fix the pins onto the body using cellotape. Ensure the wheels are able to rotate freely about the shafts.
4. Fix the straw into the mouth of the balloon using the cello tape and seal the mouth airtight. Fix the straw firmly onto the body of the trolley using cello tape as shown in Fig 6.30.
5. Inflate the balloon through the straw and then seal the mouth of the straw with the finger to prevent air from coming out. Place the trolley on a smooth horizontal surface
6. Remove the finger suddenly from the mouth of the straw so that air from the balloon comes out at once (Fig 6.30). Observe what happens to the trolley.

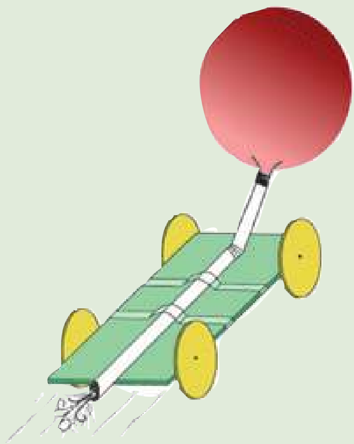


Fig. 6.30: A demonstration of action and reaction

6. In what direction does the air move as it leaves the mouth of the straw? In which direction does the trolley move? Explain the behaviour of the trolley. State the law that governs the behaviour of the trolley and other objects under similar conditions.

It is easier to study the effects of forces on an object by considering one force at a time. However, in reality, a single force cannot exist by itself. Two forces always occur when two objects push or pull each other. These forces are called *action* and *reaction* force.

Newton's third law of motion state that if a body *X* exerts a force on another body *Y*, *Y* exert an equal and opposite force on *X*. To every action force there is an equal and opposite reaction force.

Fig. 6.31 shows a real life example where action and reaction forces are experienced.

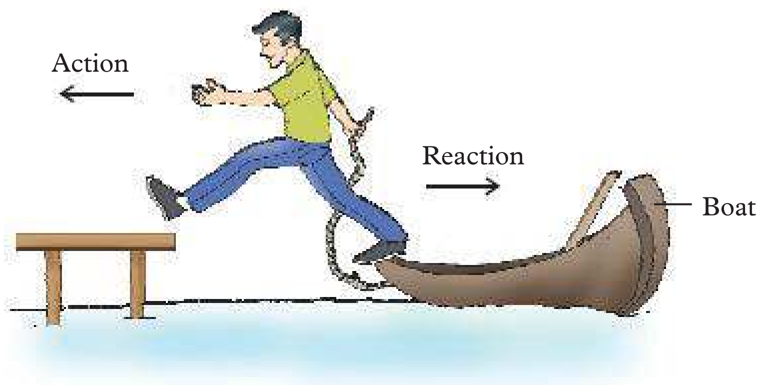


Fig 6.31: A person jumping from a boat

When one jumps off (action force) from a boat his/her forward force, exerts a backward force (reaction)on the boat. The boat moves backwards dragging with it his/her legs and then the person tends to fall into the water (See Fig. 6.31).

Topic summary

- Distance is the total length of the path travelled.
- Displacement is the shortest distance between two points in the direction of motion.
- Speed is the distance moved by the body per unit time.

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

- A body covering equal distances in unit time intervals is said to move with uniform speed.
- Velocity is the rate of change of displacement.

$$\text{Velocity} = \frac{\text{Change in displacement}}{\text{Time taken}}$$

- Instantaneous velocity is the velocity of a body at a specific moment in time.
- Acceleration is the rate of change of velocity

$$\text{Acceleration} = \frac{\text{Change in velocity}}{\text{Change in time}}$$

- The gradient of a velocity-time graph represents acceleration
- The area under a velocity-time graph represents displacement.
- The gradient of a displacement-time graph represents velocity
- Equations of motion

  $v = u + at$; $s = ut + \frac{1}{2}at^2$; $v^2 = u^2 + 2as$
- If the motion is due to gravity (moving upwards), the equations of motion becomes:

  $v = u - gt$ $\quad h = ut - \frac{1}{2}gt^2$ $\quad v^2 = u^2 - 2gh$
- All bodies near the earth's surface experience acceleration due to gravity. Its value is 9.8 m/s^2 or approximately 10 m/s^2 near the earth and is directed towards the earth's centre.
- Newton's first law of motion states that a body continues in its state of rest or uniform motion in a straight line unless compelled to act otherwise by some external force.
- Momentum is the product of mass and velocity of a body.

  (p = m × v)
- Impulse = force (N) × time(s) = Ft
- Impulse = change in momentum **(Ft = mv – mu)**
- The law of conservation of momentum states that when one or more bodies collide, their total momentum remain constant provided no external forces are acting.

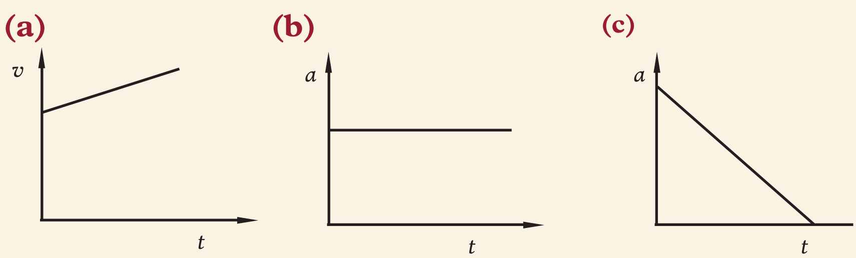
  $\mathbf{m_A u_A \times m_B u_B = u_A v_A \times m_B v_B}$

- Newton's second law of motion states that the rate of change of momentum is directly proportional to the force on a body and takes place in the direction in which the force acts.
- Newton's third law states that for every action there is an equal and opposite reaction.

Topic Test 6

(Where necessary take $g = 10\ m/s^2$.)

1. Define the following terms:
   (a) Distance (d) Velocity (b) Displacement
   (e) acceleration (c) Speed
2. A cyclist travelling at a uniform acceleration of $2.5\ m/s^2$ passes through two points P and Q in a straight line. Her speed at point P is 20 m/s and the distance between the points is 100 m. Calculate her speed at point Q.
3. A car increases its speed steadily from 8.0 m/s to 30 m/s in 10 s. How far does it travel in this time?
4. Ntwali runs 100 m race in 12.0 s. Find his average velocity.
5. A racing cyclist starts from rest and accelerates uniformly to a velocity of 20 m/s in 4 s.
   (a) What is the acceleration of the cyclist?
   (b) What is the distance covered in the 4 s?
6. Uwase threw a ball vertically upwards while playing in the school field. Sketch:
   (a) a speed-time graph for the motion of the ball.
   (b) a velocity-time graph for the motion of the ball.
7. Which one of the following motion-time graphs represent a body moving with uniform acceleration from rest? (Fig. 6.32.)



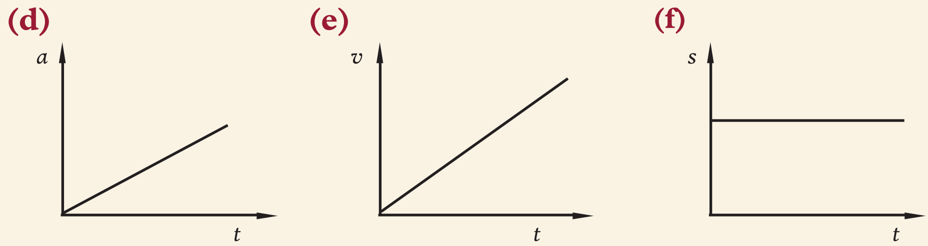


Fig. 6.32 Motion-time graphs

8. The velocity-time graph in Fig. 6.33 shows the movement of a toy car on a straight path. Use the information to find:

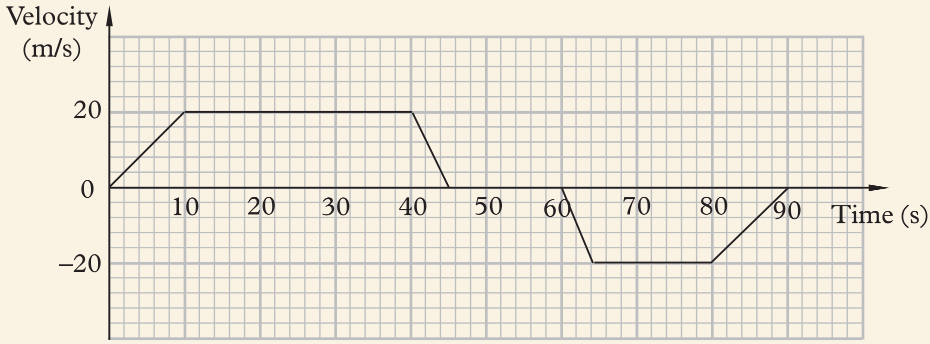


Fig. 6.33: Velocity-time graph

(a) the initial acceleration of the car.

(b) the total time the car was not moving.

(c) the total distance travelled by the car.

(d) the displacement of the car from the starting point.

9. Fig. 6.34 shows a displacement-time graph of the motion of a body over a period of 14 s. Use the graph to determine:

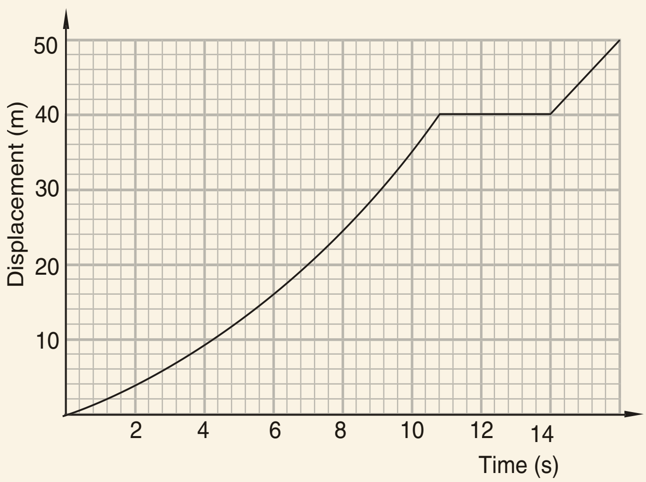


Fig. 6.34: Displacement-time graph

(a) the velocity when t = 3 s and t = 7 s.

(b) the acceleration of the body between 3 s and 7 s.

(c) the time, in seconds, the body was stationary.

10. (a) Explain why Newton's first law is also called the law of inertia.

(b) Describe an experiment to illustrate Newton's first law of motion.

11. Table 6.3 shows the values of the resultant force, *F*, and time, *t*, for a bullet travelling inside the gun barrel after the trigger is pulled.

Table 6.3

Force (N)	360	340	300	240	170	110
Time (10^{-3} s)	3	4	8	12	17	22

(a) Plot a graph of force, F, against time, t.

(b) Determine from the graph:

(i) the time required for the bullet to travel the length of the barrel. Assume that the force becomes zero just at the end of the barrel.

(ii) the impulse of the force.

(c) Given that the bullet emerges from the muzzle of the gun at a velocity of 240 m/s, calculate the mass of the bullet.

UNIT 5 Thermal energy

Topic 7: Thermal energy

Learning outcomes

Knowledge and understanding

- Understand thermal energy, heat capacity of a substance, carry out energy calculation.
- Understand the rise in temperature of a body in terms of an increase in its internal energy.

Skills

- Investigate using appropriate equipment, the specific heat capacity of a substance.
- Design practical investigations to determine the heat capacity, specific heat capacity, latent heat and specific latent heat capacity of a substance.
- Apply the relationship thermal energy = mass ×specific heat capacity ×change in temperature to new situations.
- Derive the mathematical expression of thermal energy.

Attitude and value

- Develop conceptual thinking about thermal energy.

Key inquiry questions

- How can we determine the heat capacity and latent heat of a substance?
- Why the internal energy of a substance changes?
- How could we use knowledge of quantity of heat to explain the factors that affect the boiling point and melting point?

Topic 7: Thermal energy

Topic outline

Introduction

In Secondary 1 and 2, we learnt about the effect of heat on substance and how it is transferred from one substance to another. In this unit, we will learn how to determine the quantity of this heat through practical investigations.

7.1 Heat capacity and specific heat capacity

Activity 7.1 **To show that the heat energy required to produce a certain change in temperature depends on the mass of the substance**

(Work in groups)

Materials

- A beaker
- An immersion heater
- A thermometer
- Water
- A measuring cylinder
- Stop watch

Steps

1. Take 200 g of water in a beaker and note its initial temperature θ_1. Heat the water with an immersion heater for 3 min (Fig. 7.1 (a)). Note the final temperature θ_2 and calculate the change in temperature, $\Delta\theta = \theta_2 - \theta_1$.
2. Repeat (a) above by taking 400 g of water in the same beaker and same initial temperature θ_1 (Fig. 7.1 (b)). Note the time taken to produce the same change in temperature as before.
3. Compare the time taken to produce the same change in temperature in parts (a) and (b). What is your conclusion?

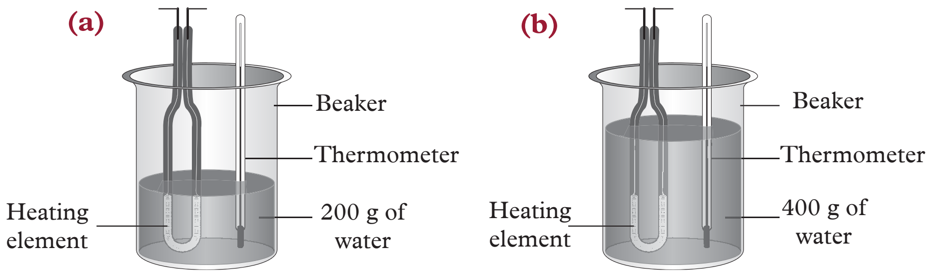


Fig. 7.1: Relationship between heat energy and mass of the substance

The larger the mass, the longer the time needed to change its temperature. This means the larger the mass, the more heat is supplied to change the temperature by one degree. Hence the quantity of heat energy, Q, gained by a substance through a certain temperature change is directly proportional to its mass, m. Therefore,

Heat energy is proportional to mass that is;

$Q \propto m$, when temperature change is constant.

Activity 7.2 **To show that the heat energy required by a substance of a given mass depends on the change in temperature**

(Work in groups)

Steps

1. Repeat Activity 7.1 step 2 with 200 g of water, but this time, heat to produce twice the change in temperature. Note the time taken for this to happen.
2. Which case takes more time, heating up to a given temperature or up to double that temperature?
3. What relationship does this observation show between quantity of heat and change in temperature?

The longer the time of heating, the more heat energy supplied and the greater the temperature change.

Heat energy, Q is proportional to change of temperature, $\Delta\theta$, when mass of a substance is constant. $Q \propto \Delta\theta$.

7.1.1 Heat capacity

Heat capacity of a substance can be therefore defined as *the heat energy required to raise the temperature of a substance by 1 K*.

Mathematically,

$$\text{Heat capacity (c)} = \frac{\text{Amount of Heat supplied (Q)}}{\text{Temperature change }(\Delta\theta)}\ \text{J/K}$$

The SI unit of heat capacity is joule per kelvin (J/K)

Example 7.1

Calculate the quantity of heat required to raise the temperature of a metal block of capacity of 520 J/K from 9 °C to 39 °C.

Solution

Quantity of heat Q = Heat capacity × temperature change

$$Q = C \times \Delta\theta$$
$$= 520 \times (39 - 9)$$
$$= 15\ 600\ \text{J}$$

Example 7.2

The quantity of heat required to raise the temperature of water from 10 °C to 65 °C is 6 200 J. Calculate the heat capacity of water.

Solution

$$Q = C\Delta\theta \quad \therefore\ C = \frac{\theta}{\Delta\theta}$$

$$= \frac{6\ 200\ \text{J}}{(65 - 10)\text{K}} = 112.73\ \text{J/K}$$

The heat capacity of water is 112.73 J/K.

Exercise 7.1

1. The heat capacity of water depends on the mass of the water being heated. TRUE or FALSE? Justify your answer.
2. Calculate the heat capacity of tea when 400 J of heat are supplied to change its temperature from 25 K to 40 K.
3. Calculate the amount of heat energy given out when the temperature of a metal block of heat capacity 520 J/K dros from 60 °C to 20 °C.

7.1.2 Specific heat capacity

From activities 7.1 and 7.2 we learnt that.

Quantity of heat, $Q \propto$ mass, m and

$Q \propto$ change in temperature, $\Delta\theta$

$$Q \propto m\Delta\theta \text{ or}$$
$$Q = mc\Delta\theta \textit{ where c is a constant}$$

When the mass of the substance is 1 kg (i.e. m = 1 kg) and the change in temperature is 1K (i.e. $\Delta\theta$ = 1 K), then Q = *c* and *c* is referred to as the *specific heat capacity* of the substance.

The specific heat capacity, c of a substance is defined as the *heat energy required to change the temperature of mass 1 kg of a substance by 1 Kelvin*.

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

Therefore,

Quantity of heat = mass × specific heat capacity × temperature change

$$Q = mc\Delta\theta$$

where, $\Delta\theta$ = final temperature – initial temperature

The SI unit of specific heat capacity is joule per kilogram per Kelvin (J/kg K).

Example 7.3

Calculate the heat energy required to raise the temperature of 2.5 kg of aluminium from 20 °C to 40 °C, if the specific heat capacity of aluminium is 900 J/kg K.

Solution

Heat energy required = mass × specific heat capacity × temperature change

$$Q = mc\Delta\theta$$
$$= 2.5 \times 900 \times (40 - 20)$$
$$= 45\ 000 \text{ J}$$

Example 7.4

To raise the temperature of a solid of mass 5 kg from 10 °C to 50 °C, 180 000 J of heat energy is supplied. Calculate the specific heat capacity of the solid.

Solution

$$c = \frac{Q}{m\Delta\theta}$$
$$= \frac{180\ 000 \text{ J}}{(50 - 10)\text{K} \times 5 \text{ kg}}$$
$$= 900 \text{ J/kg K}$$

Example 7.5

Find the final temperature of water if 12 000 J of heat is supplied by a heater to heat 100 g of water at 10 °C.

(Take specific heat capacity of water and 4 200 J/kg K.)

Solution

$$Q = mc\Delta\theta \quad \therefore \ \Delta\theta = \frac{Q}{m \times c}$$

$$= \frac{12\,000\ \text{J}}{(0.1 \times 4\,200)\ \text{J/K}}$$

$$= \frac{12\,000\ \text{J}}{420}$$

$$= 28.57\,^\circ\text{C}$$

$\Delta\theta = \theta_f - \theta_i$, where θ_f – final temperature, θ_i – initial temperature

$\therefore \quad = \Delta\theta + \theta_1 = 28.57\ ^\circ\text{C} + 10\ ^\circ\text{C}$

$\theta_f = 38.57\ ^\circ\text{C}$

The final temperature is 38.57 °C.

Exercise 7.2

1. If 45 000 J of heat are supplied to 5 Kg of aluminium initially at 25°C, what is its final temperature? (Take the specific heat capacity of aluminium as 900 J/kgk).
2. What is the difference between heat capacity and specific heat capacity?
3. Suppose 24 000 J of heat energy is supplied to raise the temperature of a substance of mass 6 kg from 12 °C to 48 °C, calculate the specific heat capacity of the substance.

7.1.3 Comparison of specific heat capacities of the three states of matter

Activity 7.3 **To show that different substances have different specific heat capacities**

(Work in groups)

Materials

- Two thermometers
- A lid with two holes

- Two boiling tubes (one containing cooking oil and the other water)
- A hot water bath

Steps

1. Pour equal volume of liquids (cooking oil and water) into two identical test tubes. Place identical thermometers in each test tube (Fig. 7.2).

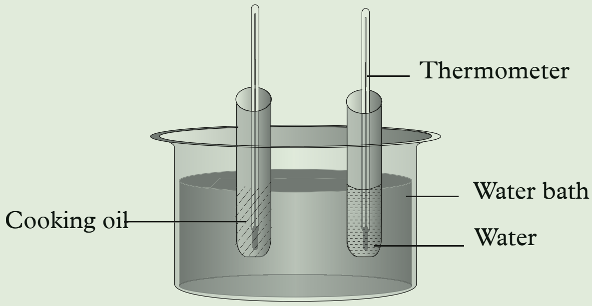


Fig. 7.2: Set-up to show different specific heat capacities

2. Heat the test tubes in a hot water bath for the same time. Observe and compare the temperature changes in the two cases. Explain the difference if any.

Different substances have different specific heat capacities. Solids require more heat energy than liquids and gases. This means that solids have higher specific heat capacity than liquids and gases. Gases have the lowest specific heat capacity. (energy for water)

Two different substances of the same mass when subjected to the same quantity. of heat, acquire different changes in temperature. Table 7.1 shows that different substances have different specific heat capacities. This is true for solids and liquids but not in gases

Table 7.1: Values of specific heat capacities of solids

Substance	Specific heat capacity (c) J/kg K
Aluminium	900
Brass	370
Copper	390
Cork	2000
Glass	670
Ice	2100
Iron	460
Lead	130
Silver and tin	230

7.2 Methods of determining specific heat capacity

Activity 7.4 **To determine the specific heat capacity of a solid by the electrical method**

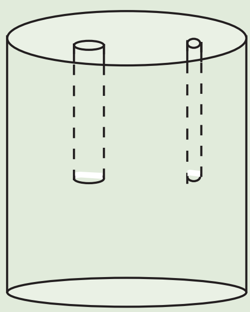
(Work in groups)

Materials

- Electric circuit
- Metal cylinder
- Variable resistor
- Aluminum foil
- Heating element
- Thermometer
- Cotton wool
- Wooden container
- Solid metal blocks in the form of a cylinder, with 2 holes

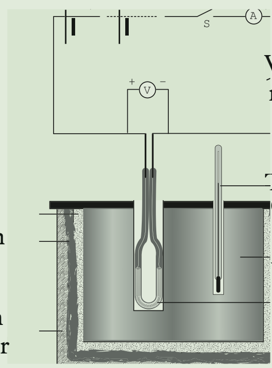
Steps

1. Measure and record the mass, m, of the metal cylinder.
2. Insert an electrical heater in position in the metal block through the larger hole and a thermometer through the other hole.
3. Note the initial temperature of the metal block θ_1.
4. Cover the solid with cotton wool or felt material and wrap a aluminium foil around cotton wool.
5. Place the set up a wooden container. Complete the electrical circuit as shown in Fig. 7.3.



(a) Metal solid cylinder

(a) Metal solid cylinder



(b) Circuit diagram

Fig. 7.3: Specific heat capacity of a by solid-electrical method.

6. Close switch S and start a stop watch at the same time.
7. Use the variable resistor to maintain a steady current passing through the heater.
8. Note the current I through the heater with the ammeter and the potential difference, V across the heater with the voltmeter.
9. Pass this steady current for some time so that the rise in temperature in the solid is about 8 °C.

10. Note the time t, when the final temperature of the solid is θ_2.
11. Calculate the change in temperature $\Delta\theta = \theta_2 - \theta_1$.
12. Show the relationship between electrical energy used and the heat energy gained by the metal and hence calculate the specific heat capacity of the metal cylinder.
13. How much electrical energy has been spent in this time? What has happened to this energy? What is the purpose of cotton wool or felt material, aluminium foil and the wooden container?

Electrical energy E, spent by the heater in a time, t , is given by E = VIt. This energy is converted into heat energy and has been absorbed by the metal solid cylinder. Heat energy gained by the metal

$$Q = mc\Delta\theta$$

Assuming no energy from the heater is lost to the surrounding,

electrical energy used = heat energy gained by the metal cylinder.

$$\therefore\ VIt = mc\Delta\theta$$

from which the specific heat capacity, c, of the solid can be calculated as

$$\therefore\ c = \frac{VIt}{m\Delta\theta}$$

Example 7.6

The following data was obtained from an experiment similar to that of Activity 7.25. Mass of copper l block = 200 g, initial temperature of the block = 22°C, ammeter reading = 0.5 A, voltmeter reading = 3.0 V, final temperature of the block = 30 °C, time of heating = 7 minutes. Use the data to calculate the specific heat capacity of copper. What does this value mean?

Solution

Electrical energy spent is given by, E = VIt.

Assuming no energy from the heater is lost to the surrounding,

heat energy gained by the metal block = mcΔθ.

$$\mathrm{m}c\Delta\theta = \mathrm{VIt}$$

$$\therefore\ c = \frac{\mathrm{VIt}}{\mathrm{m}\Delta\theta} = \frac{3.0 \times 0.5 \times (7 \times 60)}{0.200 \times (30 - 22)}$$

$$= \frac{3.0 \times 0.5 \times 420}{0.200 \times 8}$$

$$= 393.75 \text{ J/kg K}$$

$\therefore$ specific heat capacity of copper = 394 J/kg K

This means that to raise the temperature of 1 kg of copper by 1 K(or by 1°C), 394 Joules of heat energy are required.

Example 7.7

Calculate the heat energy required to raise the temperature of 5.0 kg of aluminium from 60 °C to 90 °C, if the specific heat capacity of aluminium is 900 J/kg K.

Solution

Heat energy required, $Q = mc\Delta\theta$

$= 5.0 \times 900 \times (90 - 60)°C = 5.0 \text{ x } 900 \text{ x } 30 °K$

$= 135\ 000$ J

Activity 7.5 **To determine the specific heat capacity of water by the method of mixtures**

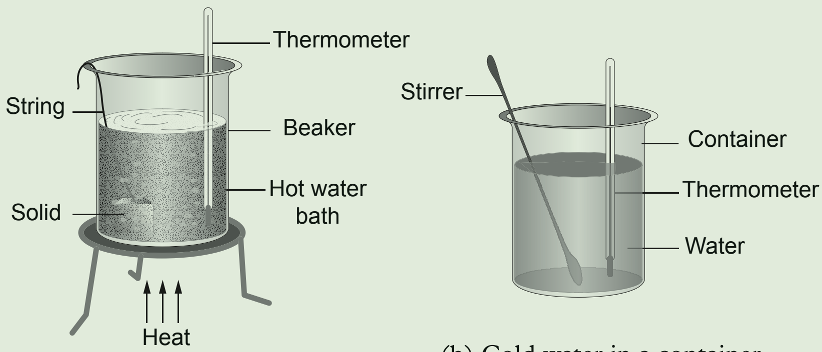
(Work in groups)

Materials

- A solid of known specific heat capacity (c_s)
- Weighing machine
- Thermometer
- Stirrer
- Tripod stand
- Water bath
- Beaker
- Heating source

Steps

1. Take a solid of known specific heat capacity (c_s) and measure its mass (m_s).
2. Heat it in a water bath till the water starts boiling, as shown in Fig. 7.4 (a).
3. In the meantime, take an empty, clean and dry container of known specific heat capacity (c_c) and measure its mass (m_c).
4. Put water into the container, say to half of the container, and measure the total mass.
5. Calculate the mass of water (m_w) whose specific heat capacity (c_w) is to be determined.
6. Find the initial temperature (θ_1) of water and the container (Fig. 7.4 (b)).
7. When water in the water bath has started boiling, note the temperature of the solid (θ_s) in the water bath.
8. Quickly transfer the hot solid into cold water in the container and observe the temperature of the mixture. (Shake off the heat water before transfer.



(a) A solid being heated

(b) Cold water in a container

Fig. 7.4: Specific heat capacity of water by method of mixture.

9. Stir the contents gently to distribute the heat uniformly throughout the mixture and note the final maximum steady temperature of the mixture (θ_2).
10. What happens to the cold water and the container when the hot solid is transferred into the container?
11. Using all the data you have collected, calculate the specific heat capacity of water using the equation:

    Heat lost by solid = heat gained by water
12. What precautions have to be taken to ensure accuracy in the experimental procedure?
13. Highlight the assumptions for this activity.

The temperature of the solid has decreased from θ_s to θ_2, showing that the solid has lost heat energy. The temperature of the cold water and the container has increased from θ_1 to θ_2 showing that they have gained heat energy.

Quantity of heat energy lost by the hot solid = $m_s c_s(\theta_s - \theta_2)$

Quantity of heat energy gained by the container and cold water

$$= (m_c c_c + m_w c_w)\,(\theta_2 - \theta_1)$$

Assuming no energy is lost to the outside;

Energy lost by the hot solid = heat energy gained by the container and cold water.

$$\therefore\ m_s c_s(\theta_s - \theta_2) \quad = \quad (m_c c_c + m_w c_w)\,(\theta_2 - \theta_1)$$

from which the specific heat capacity of water (c_W) can be calculated.

As a precaution, the container has to be covered with wool or felt and aluminium foil wrapped round the cotton wool. Note; the whole arrangement has to be placed inside a wooden container before the hot solid is transferred into the cold water in the container and a litre. These precautions ensure that minimum heat energy is lost from the mixture to the surroundings.

Experiments show that specific heat capacity of water is 4 200 J/kgK. This means that we need 4 200 Joules of heat energy to raise the temperature of 1 kg of water by 1K. Note that this value is about 10 times more than that of copper or iron. Once water is heated it retains the heat energy for a long time due to its high specific heat capacity.

Example 7.8

In an experiment, to calculate the specific heat capacity of water, the following metal data was obtained. Mass of the metal solid = 50 g, specific heat capacity of the solid = 400 J/kg K, initial temperature of the hot solid = 100 °C, mass of the container = 200 g, specific heat capacity of the material of the container = 400 J/kg K, mass of water = 100 g, initial temperature of the water and the container = 22 °C.

When the hot solid was transferred into the cold water in the container, the temperature of the mixture was 25 °C.

Use the data to calculate the specific heat capacity of water.

Solution

Let the specific heat capacity of water be c_w.

Heat lost by the hot solid $= mc\Delta\theta = 0.050 \times 400 \times (100 - 25)$

$= 1\ 500$ J

Heat gained by the container and water $= (mc\Delta\theta)_{container} + (mc\Delta\theta)_{water}$

$= 0.200 \times 400 \times (25 - 22) + 0.100 \times c_w\ (25 - 22)$ J

$= 80 \times 3 + 0.1\ c_w \times 3$

$= 3\ (80 + 0.1\ c_w)$ J

Assuming no energy losses to the surroundings

Heat lost = heat gained

$1\ 500 \text{ J} = 3\ (80 + 0.1\ c_w)$

$500 = 80 + 0.1\ c_w$ (on dividing by 3 both sides)

$420 = 0.1\ c_w$

$\therefore\ c_w = 4\ 200$ J/kg K

Activity 7.6 To determine the specific heat capacity of a liquid by electrical method

(Work in groups)

Materials

- Calorimeter
- Heater
- Variable resistor
- Stirrer
- A liquid
- Themometer
- Electrical circuit

Steps

1. Measure and record the mass, m_c, of an empty, clean and dry copper container with the stirrer of the same specific heat capacity, c_c.
2. Gently pour the liquid of known mass, m_l, into the container. Let the specific heat capacity of the liquid be c_1.
3. Note the initial temperature of the liquid and the container, θ_1.
4. Complete the electrical circuit as shown in Fig. 7.5 with the heater fully immersed in the liquid without touching the base or the sides of the container.

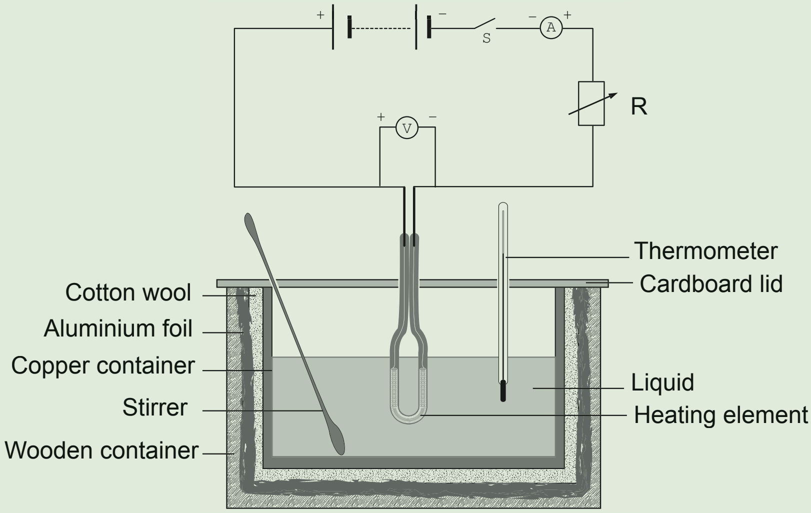


Fig. 7.5: Finding specific heat capacity of a liquid by electrical method.

5. Close the switch *S* and start a stop watch at the same time.
6. Use the variable resistor *R* to maintain a steady current passing through the heater.
7. Note the current I through the heater with the ammeter and a p.d *V* across it with the voltmeter. Pass this steady current for some time so that the rise in temperature of the liquid and the container is about 5 °C.
8. Keep stirring the liquid gently throughout the experiment. Note the time, t, taken when the final temperature of the liquid and the container is θ_2.

Calculate the change in temperature $\Delta\theta = (\theta_2 - \theta_1)$.

9. How much electrical energy has been spent in this time?

10. What has happened to this energy?

11. Using all the data you have collected, calculate the specific heat capacity of the liquid.

(Hint: Electrical energy supplied = heat energy gained by liquid)

12. What precautions have to be taken during the experiment?

Electrical energy spent = heat energy gained by the liquid, the container and the stirrer.

$$\therefore VIt = m_c c_c(\theta_2 - \theta_1) + m_l c_l (\theta_2 - \theta_1)$$

$$VIt = (m_c c_c + m_l c_l)\,\Delta\theta$$

From this equation, the specific heat capacity of the liquid c_l can be calculated.

Different liquids have different specific heat capacities. Table 7.2 shows the specific heat capacities of some liquids

Table 7.2

Substance	Specific heat capacity (c) J/kg K
Castor oil	2 130
Coconut oil	2 400
Glycerol	2 400
Mercury	140

Substance	Specific heat capacity (c) J/kg K
Olive oil	2 000
Paraffin oil	2 130
Sulphuric acid	1 380
Water	4 200

Example 7.9

In an Activity similar to 7.6, the following data was obtained. Power of electric heater = 30 W, mass of the calorimeter and the stirrer = 200 g, specific heat capacity of the calorimeter and the stirrer = 400 J/kg K, mass of water in the calorimeter = 100 g, specific heat capacity of water = 4 200 J/kg K.

Use the data to calculate the time taken by the heater to rise the temperature of water, container and the stirrer from 20 °C to 23 °C. What assumption have you made in your calculations?

Solution

Assuming that all the electrical energy is absorbed by the container, stirrer and water,

Electrical energy used = Heat energy gained

$VIt = m_{cal} C_{cal} \Delta\theta + m_w c_w \Delta\theta$

As electrical power P = VI and the time taken is t,

$Pt = m_{cal} c_{cal} \Delta\theta + m_w c_w \Delta\theta$

$\therefore$ 30 t = 0.200 × 400 × 3 + 0.100 × 4 200 × 3

30 t = 3(0.200 × 400 + 0.100 × 4 200)

30 t = (80 + 420)3

$\therefore$ t = 50 seconds

Exercise 7.3

Where necessary, take specific heat capacity of water = 4 200 J/kg K.

1. Define: (a) heat capacity (b) specific heat capacity of a substance

2. Calculate the:

(a) heat energy required to raise the temperature of 200 g of gold of specific heat capacity 130 J/kg K by 1 000 °C.

(b) heat energy given out when a piece of hot iron of mass 2 kg cools down from 450 °C to 25 °C, if the specific heat capacity of iron is 460 J/kg K.

3. Describe an activity to determine the specific heat capacity of a solid by the method of mixtures. State the necessary precautions to be taken during the activity.

4. Define specific heat capacity of water. How would you determine the specific heat capacity of water by the method of mixtures?

5. An electric kettle rated 2 kW is filled with 2.0 kg of water and heated from 20 °C to 98 °C. Calculate the time taken to heat the water assuming that all the electrical energy is used to heat the water in the electric kettle and the kettle has negligible heat capacity.

6. A hot solid of mass 100 g at 100 °C is quickly transferred into 100 g of water in a container of mass 200 g at 20 °C. Calculate the resulting temperature of the mixture. Specific heat capacity of the solid and the container is 400 J/kgK.

7. An electric heater rated 1 500W is used to heat water in an insulated container of negligible heat capacity for 10 minutes. The temperature of water rises from 20 °C to 40 °C. Calculate the mass of water heated.

8. A piece of metal of mass 200 g at a temperature of 150 °C is placed in water of mass 100 g and temperature 20 °C. The final steady temperature of the water and the piece of metal is 50 °C. Neglecting any heat losses, calculate the specific heat capacity of the metal.

9. Describe an experiment to determine the specific heat capacity of a liquid by electrical method.
10. A piece of iron of mass 200 g at 300 °C is placed in a copper container of mass 200 g containing 100 g of water at 20 °C. Find the final steady temperature of the mixture, assuming no energy losses. The specific heat capacities of copper and iron are 390 J/kg K and 460 J/ kg K, respectively.
11. A class of Physics students decided to determine the specific heat capacity of water in a waterfall. They used a sensitive thermometer to find the difference in temperature of water at the top and the bottom of the waterfall and obtained the following results; height of the waterfall = 52 m, temperature of water at the top = 21.54 °C. Temperature of water at the bottom = 21.67 °C. Stating any assumptions made, calculate a value for the specific heat capacity of water.

7.3 Latent heat and specific latent heat of fusion

7.3.1 Latent heat of fusion

Heat is either absorbed or given out at a constant temperature when a substance is changing its state. When a substance changes from a solid state to a liquid state, heat is absorbed. This heat is called the ***latent heat of fusion*** of a substance. The *latent heat of fusion of a substance is defined as the quantity of energy required to change the substance from solid state to the liquid state without change in temperature at a constant pressure*.

When the mass of the substance undergoing change is 1 kg, the absorbed heat is called ***specific latent heat of fusion***. *The specific latent heat of fusion of a substance is defined as the quantity of heat energy required to change 1 kg of the substance from solid state to the liquid state without change in temperature at a constant* pressure.

The latent heat of fusion required (Q) is directly proportional to the mass of the substance i.e.

$$Q \propto m$$

$$Q = lm$$

Where l_f is constant called *specific latent heat of fusion* of the substance.

$$\therefore l_f = \frac{Q}{m}$$

SI units of specific latent heat of fusion is *Joule per kilogram (J/kg)*.

Specific latent heat of fusion of ice

Since pure ice melts at 0 °C under standard atmospheric pressure, the specific latent heat of fusion of ice (l_{ice}) is defied as *the quantity of heat energy required to change 1 kg of ice at 0 ºC to 1 kg of water at 0 ºC under standard atmospheric pressure*.

Activity 7.7 **To design and conduct an investigation to determine the specific latent heat of fusion of ice by electrical method**

(Work in groups)

Materials

- Pure ice
- Stand & clamp
- Filter funnel
- Electrical circuit
- Heater
- Stopwatch

Instructions

1. In this activity, you will design and carry out an investigation to determine the specific latent heat of fusion of ice by electrical method.
2. By modifying the set-up, we used in Activity 7.6,with the materials provided to help you conduct this investigation. Sketch the new set-up.
3. Write a brief procedure for your investigations, keenly considering the qualities you need to measure.
4. Execute the procedure carefully, measuring the quantities you identified in Step 3 and recording them down.
5. By applying the relevant formulae and relationships, determine the specific latent heat of fusion of ice.
6. Compare your values in steps with the known exact value.

   Suggest some possible sources of errors in your investigation and how they can be reduced. Write a report for your investigation and present to the rest of the class.

Heat energy gained by ice at 0 °C in time t is given by $Q = ml_{f(ice)}$, where $l_{f(ice)}$ is the specific latent heat of fusion of ice. Assuming no electric energy is lost from heater, Electrical energy supplied = latent heat gained by ice in melting

$$VIt = ml_{f(ice)}$$

From which $l_{f(ice)}$ can be calculated.

Experiments show that the specific latent heat of fusion of ice is 3.36×10^5 J/kg. This means that we need 336 000 joules of energy to convert 1 kg of ice at 0 °C to water at 0 °C under standard atmospheric pressure.

Example 7.10

An electric heater rated 1.5 kW is used to melt 1.5 kg of ice at 0 °C. Calculate the specific latent heat of fusion of ice, if it takes 7.6 minutes for the heater to melt all the ice at 0 °C.

Solution

Electrical energy spent in time, t = VIt

= Pt (since electrical power, P = VI)

Heat energy gained by ice to change its state $Q = ml_{f(ice)}$

Assuming no energy losses,

$$Pt = ml_{f(ice)}$$

$$l_{f(ice)} = \frac{P \times t}{m} = \frac{1\,500 \times (7.6 \times 60)}{1.5}$$

$$= 336\,000 \text{ J/kg}$$

Activity 7.8 **To determine the specific latent heat of fusion of ice by the method of mixtures**

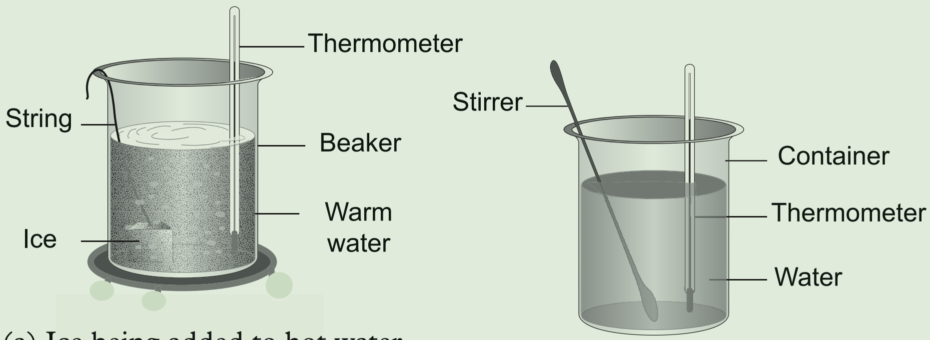
(Work in groups)

Materials

- Container with known specific heat capacity
- Warm water
- Ice
- Heat capacity
- Thermometer
- Weighing machine

Steps

1. Take an empty, clean and dry container of known specific heat capacity (c_c) and measure its mass (m_c).
2. Add some warm water at a temperature that is a few degrees above room temperature to the container and note its temperature (θ_1).
3. Measure the mass of the container with warm water and calculate the mass of water (m_w).
4. Dry small pieces of ice with a blotting paper and gently immerse them into the warm water, without splashing out any water. (Fig 7.6)



(a) Ice being added to hot water

(b) Mixture in a container

Fig. 7.6: Specific heat capacity of water by method of mixtures.

5. Keep adding the small pieces of dried ice till the temperature of the mixture is a few degrees below room temperature.
6. Note the temperature of the mixture (θ_2). Find the mass of the mixture.
7. Calculate the mass of ice (m_{ice}) which has been added.
8. Using the data you have collected, determine the latent heat of fusion of ice..

   (**Hint:** Heat gained by ice to melt = heat lost by warm water)

Assuming no energy losses; heat energy given out by the container and warm water = heat energy used in melting ice at 0 °C + heat energy used in rising the temperature of the melted ice from 0 °C to θ_2 °C.

$$\therefore\ m_c c_c (\theta_1 - \theta_2) + m_w c_w(\theta_1 - \theta_2) = m_{ice}\, l_{ice} + m_{ice}\, c_w\, (\theta_2 - 0_1)$$

where c_w is the specific heat capacity of water and l_{ice} is the specific latent heat of fusion of ice. From the above equation we can calculate l_{ice}.

7.4 Latent heat and specific latent heat of vaporisation

7.4.1 Latent heat of vaporisation

When a liquid changes into gas the temperature remains constant till all the liquid has changed its state to gas. This shows that heat is absorbed to change the state from liquid to gas state. The heat is called the *latent heat of vaporisation* of the liquid. *The latent heat of vaporisation of a liquid is the amount of heat energy required to change the substance from the liquid state to gaseous state at a constant pressure without change in temperature*.

When the mass of the substance undergoing change is 1 kg, the heat is called *specific latent heat of vaporisation*. The specific latent heat of vaporisation of a substance *is* *the quantity of heat energy required to change 1 kg of the substance from the liquid state to the gaseous state at a constant pressure without change in temperature*.

The quantity of heat energy required to change a liquid of mass, m, into gas is given by,

$$Q = ml$$

where l is called the *specific latent heat of vaporisation* of the liquid

Specific latent heat of vaporisation of water or steam

Specific latent heat of vaporisation of water (l_{water}) is the quantity of heat energy required to change 1 kg of water at 100 °C to 1 kg of steam at 100 °C under standard atmospheric pressure.

Activity 7.9 To determine the specific latent heat of vaporisation of water by electrical method.

(Work in groups)

Materials

- Beaker
- Insulated container
- Stopwatch
- Heater electrical circuit
- Tube T
- Stopper
- Cold water
- Thermometer

Steps

1. Take some water in a glass container which is well insulated from the outside with a rubber/cork stopper at the top and bottom and a lagging material like cotton wool around it.
2. Insert a long glass tube T and a condenser as shown in Fig 7.7, with the electric heater fully immersed in water.
3. Complete the electrical circuit as shown.
4. Close the switch *S*. Let a steady current, *I*, flow through the heater for sometime till water boils.
5. Adjust the variable resistor so that a steady current flows through the heater.

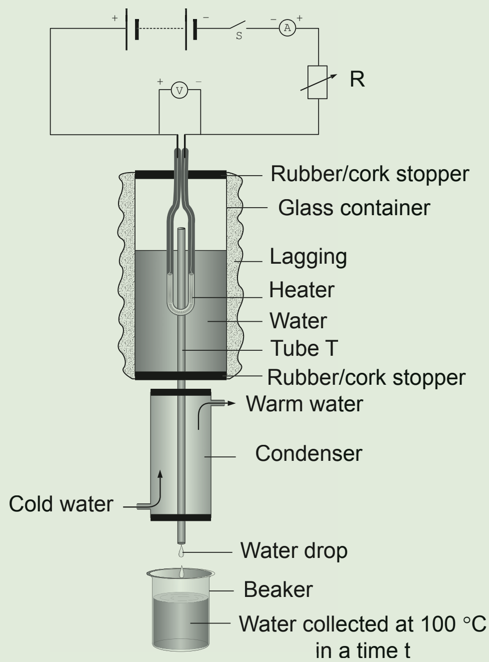


Fig. 7.7: Specific latent heat of vaporisation

6. Take an empty, clear and dry beaker and find its mass, m_1.
7. Place the beaker under the condenser, where cold water is being circulated, and start a stopwatch when the first drop of water is collected.
8. Collect enough water in the beaker. Note the time taken, t, to collect this mass of water.
9. Find the mass of the beaker again with the water collected, m_2 and calculate the mass m of water collected, i.e the mass of steam at 100 °C which has condensed $m = (m_2 - m_1)$.
10. Assuming that there is no energy loss,calculate the latent heat of vapourisation using the data you have obtained.

How much electrical energy has been spent in this time, t? What has happened to this energy?

Electrical energy spent = VIt

Heat energy gained by water at 100°C = energy used to form steam at 100˚C which condenses into water.

The heat energy is given by the equation;

$Q = ml_v$

Where l_v is the specific latent heat of vaporisation of water or steam.

Assuming no energy losses,

$VIt = ml_v$

Hence $l_v = \frac{VIt}{m}$

Experiments show that the specific latent heat of vaporisation of water l_w is 2.26×10^6 J/kg. This means that 2.26×10^6 Joules of energy are needed to convert 1 kg of water at 100 °C to 1 kg of steam at 100 °C under standard atmospheric pressure.

Example 7.11

An electric kettle rated 1500 W is used to boil 500 g of water into steam at 100 °C. Calculate the time required to boil off the water, if the specific latent heat of vaporisation of water is 2.26 MJ/kg. Why is the correct time likely to be longer than your calculated time?

Solution

Let the time taken to boil off water be t (s)

Electrical energy spent = VIt = Pt ...(i)

Heat energy required to boil off 500 g of water = ml_v...(ii)

From (i) and (ii), ml_v = Pt

$$\therefore t = \frac{ml_v}{P}$$

$$= \frac{0.500 \times 2.26 \times 10^6}{1\ 500}$$

$$= 753 \text{ s}$$

The correct time is likely to be more than the calculated time, as no allowance has been made for the energy loss from the heater to the outside or the energy gained by the kettle itself.

Example 7.12

The graph in Figure 7.8 shows how temperature varies with time when 1 kg of ice at –10 °C is converted into 1 kg of steam at 100 °C under standard atmospheric pressure. Calculate the heat energy required to convert ice into steam given: Specific heat capacity of ice = 2 100 J/kg K, specific heat capacity of water = 4 200 J/kg K, specific latent heat of fusion of ice = 3.36×10^5 J/kg, specific latent heat of vaporisation of water = 2.26×10^6 J/kg.

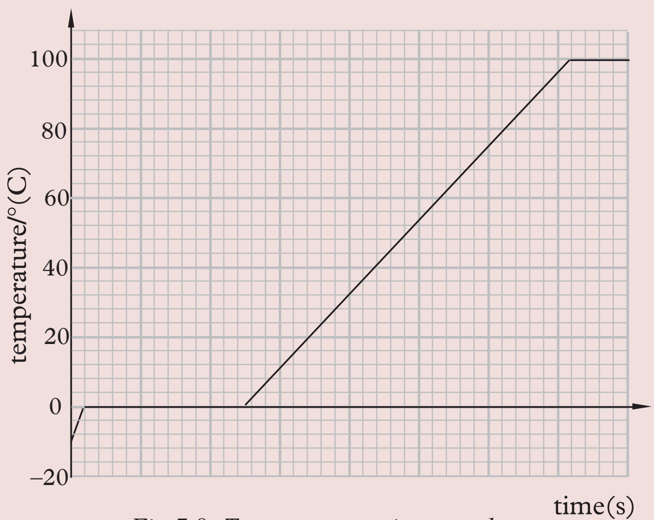


Fig 7.8: Temperature – time graph

Solution

Heat energy required to:

1. Raise the temperature of ice from ⁻10 °C to 0 °C is given by

$$Q_1 = (mc\Delta\theta)_{ice} = 1 \times 2\ 100 \times 10 \text{ J} = 21\ 000 \text{ J}$$

2. Convert ice at 0 °C to water at 0 °C is given by

$$Q_2 = (ml_f)_{ice} = 1 \times 3.36 \times 10^5 \text{ J} = 336\ 000 \text{ J}$$

3. Raise the temperature of water from 0 °C to 100 °C is given by

$$Q_3 = (mc\Delta\theta)_{water} = 1 \times 4\,200 \times 100 \text{ J} = 420\,000 \text{ J}$$

4. Convert water at 100 °C to steam at 100 °C is given by

$$Q_4 = (ml)_{water} = 1 \times 2.26 \times 10^6 \text{ J} = 2\,260\,000 \text{ J}$$

∴ Total heat energy required to convert ice into steam is given by

$$Q = Q_1 + Q_2 + Q_3 + Q_4$$

$$= 21\,000 + 336\,000 + 420\,000 + 2\,260\,000 = 3.04 \times 10^6 \text{ J}$$

Example 7.13

Calculate the ratio of $l_{v(w)}$ to $l_{f(\text{ice})}$, if when the same electrical heater is used throughout the experiment, the time taken to convert ice at 0 °C to water at 0 °C is 168 s and the time taken to convert water at 100 °C to steam is 1 130 s.

Solution

Assuming electrical energy spent = heat energy gained

$$VIt = ml_{f(ice)}$$

$$\therefore Pt_1 = ml_{f(ice)} \quad \ldots\text{(i)}$$

$$\text{Similarly } Pt_2 = ml_{v(w)} \ldots \text{(ii)}$$

Dividing equation (ii) by (i) $\dfrac{Pt_2}{Pt_1} = \dfrac{ml_{v(w)}}{ml_{f(ice)}}$

$$\therefore \frac{l_{v(w)}}{l_{f(\text{ice})}} = \frac{1\,130}{168} = 7.73$$

Exercise 7.4

Where necessary, take:

Specific heat capacity of ice = 2 100 J/kg K

Specific heat capacity of water = 4 200 J/kg K

Specific latent heat of fusion of ice = 3.36×10^5 J/kg K

Specific latent heat of vaporisation of water = 2.26×10^6 J/kg K

1. Define the terms: melting, boiling, melting point, boiling point.

2. Sketch a graph to show how temperature varies with time when ice at $^-8$ °C is converted to water at 16 °C.
3. **(a)** Define: (i) the latent heat of fusion (ii) latent heat of vaporisation of a substance.
   (b) Why do we use the term 'latent' heat?
4. **(a)** Define the term specific latent heat of fusion of ice.
   (b) With the aid of a diagram, describe an experiment you could conduct in order to determine the specific latent heat of fusion of ice.
5. Calculate the amount of heat energy required to convert 2.5 kg of ice at 0 °C to water at 0 °C.
6. **(a)** How much heat energy is required to convert 2.0 kg of ice at –10 °C to water at 20 °C?
   (b) If an electric heater rated 1.0 kW is used, calculate the time taken to heat ice at –10 °C to water at 20 °C? State the assumption you have made in arriving at your answer.
7. **(a)** Define the term specific latent heat of vaporisation of water.
   (b) With the aid of a circuit diagram describe an experiment you would conduct to determine the specific latent heat of vaporisation of water.
8. An electric kettle rated 2.5 kW is used to boil 2.0 kg of water at 100 °C into steam at 100 °C. Calculate the mass of water converted into steam if the kettle was used for 6 minutes.
9. An electrical kettle rated 1.5 kW is used in an experiment to convert 200 g of ice at –5 °C to steam at 100 °C under standard atmospheric pressure. Calculate the time for which the kettle has to be used in the above experiment.

7.5 Applications of specific heat capacity

Activity 7.10 **To identify and describe the application of specific heat capacity in our daily lives**

(Work in groups)

Materials

- Reference books
- Resource person
- Internet

Steps

1. You have learnt about specific heat capacity. How is it useful in our daily lives?
2. With the help of the Internet and reference books, conduct research on the

application of specific heat capacity. Identify those that are not highlighted in this book. Note them in your notebook.

3. Represent your findings to the whole class

Specific heat capacity has many applications in our daily life. The following are a few examples:

(a) A material with high specific heat capacity absorbs a lot of heat with only a small rise in temperature. This accounts for the efficiency of water as a coolant in a car radiator and of hydrogen gas in enclosed electric generators.

(b) Substances with low specific heat capacities are quickly heated up; they experience a greater change in temperature after gaining a small amount of heat energy. For this reason, they are used to make cooking utensils such as frying pans, pots and kettles.

(c) Sensitive thermometers are made from materials with low specific heat capacity in order to detect and accurately show rapid change in temperature, even for small amounts of heat energy.

(d) Materials with high specific heat capacity are suitable for making handles of heating devices like kettles, pans and oven covers. This is because they do not get very hot easily when they absorb high amounts of heat energy.

7.6 Internal energy of a system

Activity 7.11 **To demonstrate and explain internal energy of a system**

(Work in groups)

Materials:

- Reference books
- Internet
- Transparent container
- Marbles of two different colours

Steps

1. Open the transparent container and drop the marbles of one colour followed by by those of the other colour.
2. Shake the container and observe the marbles. What do you see? Did the marbles remain at the same position?

3. Suppose the container is the system and the marble is the internal energy. Explain how internal energy flows inside a substance.
4. Now conduct research from the internet or reference book on the definition of internal energy.
5. Compare and discuss your findings with other groups in class.
6. Write down your findings in your note book.

The internal energy of a system is identified with the random, disordered motion of molecules. The total (internal) energy in a system includes:

- translational kinetic energy
- vibrational and rotational kinetic energy
- potential energy from intermolecular forces

The symbol for internal energy change is ΔU.

Note that same quantities of substances at the same temperature do not necessarily possess the same amount of internal energy. For example, one gram of water at 0°C compared with one gram of copper at 0 °C do not have the same internal energy. This is because, though their kinetic energies are equal, water has a much higher potential energy causing its internal energy to be much greater than the copper's internal energy.

The following activities will help us to derive the mathematical expression of the thermal energy.

Activity 7.12 Verify the laws of conservation of energy

(Work in groups)

Materials:

- Beaker
- Water
- Bunsen burner
- Thermometer

Steps

1. Put some water in a beaker and dip the thermometer in the water. Note the temperature of the water.

2. Place the beaker on a bunsen burner and observe what happens as you continue to heat.
3. Observe what happens to the water particles as the water boils.
4. Describe energy transformation taking place in the set up during heating and at boiling point.
5. State the law that governs the energy transformations in this activity.

We have already learnt about the law of conservation of energy which states that energy can neither be created nor destroyed but can be converted from one form to another. This law is obeyed by all systems.

The law of conservation of energy governs the energy transformations that involve applying heat and internal energies. In such systems for example, the heat applied (external energy) and the work done by the environment onto the system are converted to internal energy.

Mathematically, it can be represented as

Change in internal Energy of a system = heat dissipated or absorbed by the system + Work done by or to the system

$$\Delta U = Q + W$$

Note:

(a) The absorption of heat by the system tends to raise the energy of the system and vice versa.

Therefore, in the equation, we take heat (Q) to be positive if it is supplied to the system and negative if heat is dissipated (removed) from the system.

(b) The performance of work by the system requires use of energy by the system hence lowers the energy of the system, and vice versa.

Therefore, in the equation, we take work done as positive if it is done to the system and negative if it is done by the system.

Example 7.14

A gas in a system has constant pressure. The surroundings lose 49 J of heat to the system and does 316 J of work onto the system. What is the change in internal energy of the system?

Solution

Let us first consider the relationship between the system and the surroundings.

The surrounding loses heat and does work onto the system. Therefore, we take Q and W as positive in the equation.

Therefore,

$$\Delta U = Q + W$$

$$\Delta U = 49\ J + 316\ J$$

$$= 365\ J$$

Example 7.15

In a certain process, 450 J of work is done on the system. If the system gives off 124 J of heat, what is the change in internal energy of the system?

Solution

We take the heat (Q) as negative because it is given off by the system.

We take the work done (W) as positive because it is done on the system.

Therefore,

$$\Delta U = Q + W$$

$$= -124\ J + 450\ J$$

$$= 326\ J$$

Example 7.16

In a certain process, 523.6 J of heat is added to a system. The system does work equivalent to 78I.4 J by expanding against the surrounding atmosphere. What is the change in internal energy for the system?

Solution

We take the heat (Q) as positive because it has been added the system.

We take the work done (W) as negative because it is done by the system

Therefore,

$$\Delta U = Q + W$$

$$= 523.6\ J - 781.4\ J \text{ (In this case, W is negative)}$$

$$= -257.8\ J$$

$$= -257.8\ J$$

Exercise 7.5

For questions 1 - 3 select the most appropriate response from the choices given.

1. Which has more internal energy?
   - **A.** Bathtub full of cool water
   - **B.** Cup of hot water
2. If a piece of aluminum is placed in contact with both a bathtub full of cool water and a cup of hot water connected to the aluminium, which way will heat flow?
   - **A.** From the cup to the bathtub
   - **B.** From the bathtub to the cup
3. A system has 30 J of heat added to it and in doing so, it does 25 J of work. Its change in internal energy will be:
   - **A.** +25 J **B.** + 5 J **C.** -5 J
   - **D.** -30 J **E.** -25 J

Fill in the blank spaces.

4. Besides kinetic energy, molecules have rotational kinetic energy, potential energy due to forces between molecules and more. The total of all energies inside a substance is called ___________?
5. If heat flows from a cup of hot water to a bathtub full of cool water, the water in the cup will have a ___________ in internal energy while the water in the tub will have an ___________ in internal energy.

7.7 The processes of melting and solidification

7.7.1 Melting

Activity 7.13 To show the process of melting

(Work in groups)

Materials:

- Thermometer
- Glass beaker
- Crushed ice
- Tripod stand
- Bunsen burner and wire gauze.

Steps

1. Take pure crushed ice at about -10 °C and put it in a beaker placed on wire gauze on a tripod stand as shown in Fig. 7.9.

2. Note the initial temperature of the ice.
3. Light a Bunsen burner and adjust the blue flame to a small low temperature.
4. Note the temperature of ice at 30 seconds interval until the temperature of the water is about 10 °C.
5. Record your results as shown in Table 7.3.
6. What happens to the amount of ice as heating continues?
7. Plot a graph of temperature against time.
8. Explain the shape of the graph.

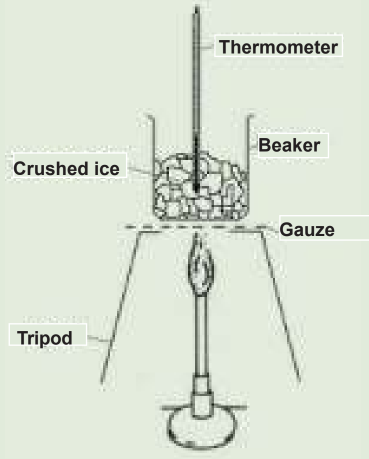


Fig. 7.9: Set up to show heating of ice

Table 7.3

Time (s)	0	30	60	90	120
Temperature (°C)					

Melting is the change of state from a solid to a liquid. Melting of a pure substance occurs at a particular constant temperature called *melting point*.

Fig 7.10 shows a graph of temperature against time for ice.

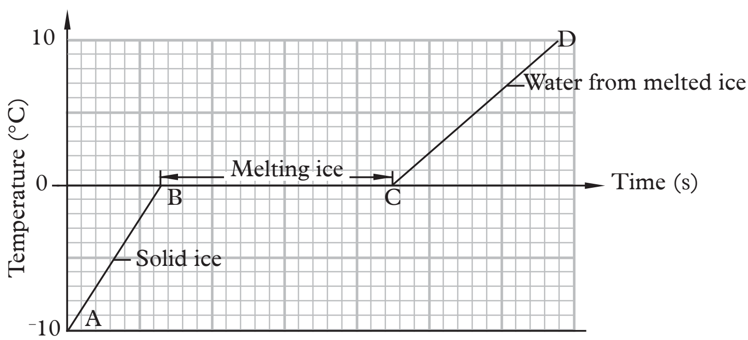


Fig. 7.10: Melting process of ice

The graph shows that:

1. The temperature of ice rises steadily from -10°C to 0°C. During this time, along AB, the ice remains as solid.
2. At 0°C, along the line BC, the temperature remains constant for a period of time. During this period, the ice is melting. During the melting process, solid and liquid exist in equilibrium.

Step by step process of what happens during melting:

(i) Heat energy is absorbed by the solid particles.

(ii) Heat energy is converted to kinetic energy.

(iii) The kinetic energy of the particles increases and the particles in the solid vibrate faster.

(iv) At melting point, the particles have gained enough energy to overcome the attractive forces between particles.

(v) Particles starts to move away from their fixed position.

(vi) Liquid is formed.

(vii) The cause for constant temperature during melting: The absorbed heat energy during melting is used to weaken the attractive forces between particles and not the kinetic energy of the particles.

3. After all the ice has melted, the temperature of water starts rising again as seen along the line CD of the graph.

4. The line AB of the graph is steeper than the line CD of the graph showing that the time taken to raise the temperature of ice by 10 °C is less than the time taken to raise the temperature of water by 10 °C. It is easier to raise the temperature of ice than water. This means that the specific heat capacity of ice is less than that of water.

Activity 7.10 shows that when a substance is changing its state from solid to liquid, heat is required. Thermal energy absorbed during the melting process is called latent heat. There is no change of temperature, as shown in the part BC of the graph, until all the ice has melted. Conversely, if water at 0 °C freezes to ice at 0 °C, it must give out the same heat energy.

If pressure remains constant, a solid substance melts or freezes at a specific temperature. The melting point of ice is 0°C under standard atmospheric pressure.

7.7.2 Solidification

Fig 7.11 Shows the cooling curve for water.

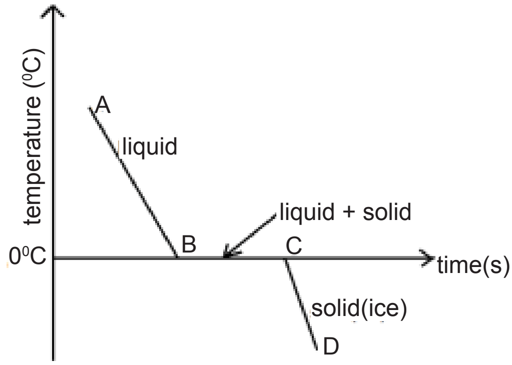


Figure 7.11. A cooling curve for water

The graph shows that:

1. The line AB represents water still in liquid state where molecules are free to move in random directions, colliding with each other and the walls of the container. The temperature of water falls steadily between points A and B.
2. At 0 °C, along the line BC, the temperature remains constant for a certain period of time. During this time, there is a mixture of a liquid and solid i.e. water is observed to freeze (solidify). At C all the water has completely (frozen) changed to ice.
3. After all the water has solidified, the temperature of ice starts reducing again as seen along the line CD of the graph.

Note: Activities with other substances show a similar behaviour. This shows that kinetic theory can be applied to all substances.

Solidification is the change of state from a liquid to a solid. It is also known as freezing. A pure substance freezes at a temperature equal to its melting point. Freezing of a substance occurs at a particular constant temperature called the freezing point.

7.7.3 Factors that affect melting/freezing point

(a) Pressure

Under standard atmospheric pressure, a pure substance always melts at a definite temperature. The melting point however changes with the change in pressure acting upon a substance. The change in the melting point due to change in pressure is however not large.

Activity 7.14 **To show the effect of pressure on the melting point of ice.**

Work in groups

Materials:

- Wire
- 2 cement blocks
- 2 Equal weights
- Soft pad
- Block of ice

Steps

1. Rest a large block of ice at 0 °C on two stools or two cement blocks.
2. Hang a thin copper wire around the block and attach two equal heavy weights to the ends of the wire as shown in Fig. 7.12. Observe and record what happens to the wire and the block of ice as time progresses.

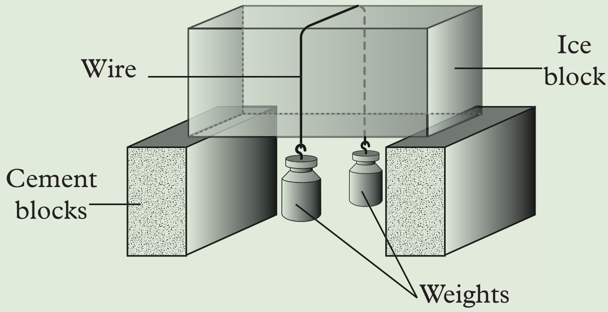


Fig. 7.12: Effect of pressure on melting point of ice

The wire completely cuts through the block of ice and the weights fall to the soft pad on the floor. Is the ice in one piece or two pieces?

In the above experiment, it is observed that initially as the pressure of the wire on the ice increases, the melting point of ice decreases and so the ice melts. The water flows above the wire. The latent heat of fusion required for the melting of ice comes from the copper wire. The water above the wire is no longer under pressure. As the pressure is released, the water which is at a temperature below zero freezes again binding the two pieces of ice together. During freezing heat is given out by water and this heat is conducted down through the copper wire. This provides heat for further melting of the ice under the wire. At some point, the wire cuts right through the block of ice and falls to the floor, leaving ice still in a solid block.

This phenomenon in which ice melts when pressure is increased and again solidifies (freezes) when the pressure is reduced is called *regelation* (re-again: gelare-freeze). This is melting under pressure and freezing again when this pressure is reduced.

Ice contracts on melting. An increase in pressure would help it in its contraction and hence we should expect a decrease in the melting point of ice as pressure on its surface is increased. *The melting point of ice decreases with the increase in pressure*.

For substances like wax, gold, silver etc. which expand on melting, an increase in pressure would make its expansion difficult. These substance have to be heated more in order to melt. As a result, we should expect an increase in the melting point, as pressure is increased. For such substances, *the melting point increases with the increase in pressure*.

Impurities

Experiments show that *impurities decrease the melting point of a substance*. Though pure water freezes at 0 °C, salty water remain as water even at –1 °C. The extent to which the freezing point is lowered depends on the concentration of impurities dissolved into the liquid. For example, when salt is added to ice, its melting point is reduced to a value as low as –10 °C This method is used to defreeze roads in cold countries during winter. Antifreeze material is added to the water in the car radiators to stop water from freezing when temperature falls below 0 °C.

Exercise 7.6

1. State two reasons why you should understand the concept of heat capacity.
2. State the mathematical expression of the thermal energy.
3. Explain the following processes:

   (a) Melting   **(b)** Solidification
4. Using a sketch graph describe the process of heating a solid ice till it becomes steam.
5. Use the correct words from the following to answer questions that follows:

   decreases, increases, heat, specific heat, insulator, condensation, internal energy.

   (a) _______ is the process of changing from gas to liquid.

   (b) ______________ is the name for energy that is transferred only from a higher temperature to a lower temperature.

   (c) The measure of the amount of disorder in a system is called ______________?

Topic summary

- Heat capacity of a substance is the quantity of heat energy required to change the temperature of the substance by 1 K.
- Specific heat capacity of a substance is the quantity of heat energy required to change the temperature of 1 kg of the substance by 1 K. Whenever there is

a change in temperature of a substance, the quantity of heat energy involved is given by, $Q = mc\Delta\theta$.

- Latent heat of fusion of a substance is the quantity of heat energy required to change the substance from the solid state to the liquid state without any change in temperature at a constant pressure.
- Specific latent heat of fusion of a substance is the quantity of heat energy required to change 1 kg of a substance from the solid state to the liquid state without any change in temperature at a constant pressure.
- Specific latent heat of vaporisation of a substance is the quantity of heat energy required to change 1 kg of a substance from the liquid state to the gas state without any change in temperature at a constant pressure.
- Whenever there is a change of state of a substance at constant temperature, the quantity of latent heat involved, $Q = ml$.
- The internal energy of a system is identified with the random, disordered motion of molecules.
- Melting is the change of state from a solid to a liquid. Melting of a pure substance occurs at a particular constant temperature called melting point.
- Solidification is the change of state from a liquid to a solid it is also known as freezing. A pure substance freezes at a temperature equal to its melting point

Topic Test

1. Define the terms:

(a) heat capacity **(b)** specific heat capacity of a substance

2. Calculate the heat capacity if 8 000 J of heat is replaced to cool a solid from 80 °C to 20 °C.

3. Calculate the;

(a) the heat energy required to raise the temperature of 200 g of gold of specific heat capacity 130 J/kg K by 1 000 °C.

(b) the heat energy given out when a piece of hot iron of mass 2 kg cools down from 450 °C to 25 °C, if the specific heat capacity of iron is 460 J/kg K.

5. In experiments requiring storage of heat energy, water is preferred to other liquids. Give two reasons for this.

6. Calculate the heat energy required to raise the temperature of 400 g of water from 25 °C to 45 °C. Specific heat capacity of water = 4 200 J/kg °C.
7. Find the initial temperature of aluminium if 2 400 J of heat is used to raise the temperature of 50 g of aluminium to 62 °C. Specific heat capacity of aluminium is 900 J/kg K.
8. 620 000 J of heat energy is supplied to raise the temperature of a solid of mass 10 kg from 40 °C to 75 °C. Calculate the specific heat capacity of the solid.
9. Calculate the heat required to heat 0.5 kg of ice at –8 °C to steam at 100 °C. (Specific heat capacity of ice = 2 100 J kg/K. Specific heat of fusion of ice is 3.34×10^5 J/kg and specific latent heat of vaporization of water = 2.26×10^6 J/kg K.
10. A mass of 700 g of copper at 98 °C is put into 800 g of water at 15 °C contained in a copper vessel of mass 200 g and the final resulting temperature of the mixture is found to be 21 °C. Calculate the specific heat capacity of copper.
11. A refrigerator converts 1 kg of water at 25 °C into ice at –5 °C in 2.5 hours. Show that the rate at which heat is extracted from the refrigerator is about 50 J/s.
12. It takes 15 minutes for an electric kettle to heat a certain quantity of water from 0 °C to 100 °C. It requires 80 minutes to convert all the water at 100 °C into steam. Calculate the specific latent heat of vaporisation of water.
13. In a certain process, 600 J of work is done on the system which gives off 250 J of heat. What is the change in internal energy for the system?
14. How much work does a heat engine do if it takes in 2 500 J of heat and expels 1 500 J?
15. The graph in Figure 7.13 shows how 400 g of ice at –10 °C would change with time, if it were to be heated at a steady rate of 600 W.
    (a) Explain in molecular terms, what has happened to the energy being supplied at 0 °C.
    (b) Use the graph to determine the specific latent heat of fusion of ice.

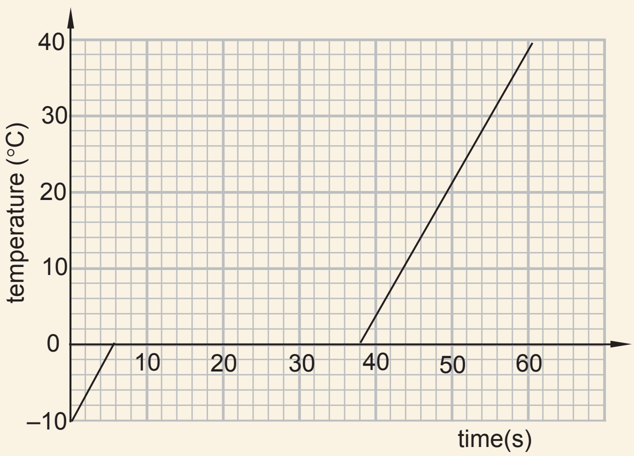


Fig. 7.13

16. A hot solid of mass 100 g at 100° C is quickly transferred into 100 g of water in a container of mass 200 g at 20 °C. Calculate the resulting temperature of the mixture. (Specific heat capacity of the solid and the container is 400 J/kg K.

17. A gas enclosed in a cylinder occupies 0.030 m^3. It is compressed under a constant pressure of 3.5×10^5 Pa until its final volume is exactly one-third of its initial volume.

(a) What was the change in the gas volume? ________________

(b) The gas lost 5.0×10^3 J as heat during the compression process. Did the internal energy of the gas increase or decrease? By how much?________

18. A steel marble at room temperature was placed in a plastic-foam cup containing ice and water at 0 °C. After thermal equilibrium was reached, the temperature of the ice-water mixture and marble was 1 °C.

(a) Which object lost heat energy?

____

(b) Did the internal energy of the marble increase or decrease? What was the measurable effect of this change?

____

(e) Did the internal energy of the system consisting of the water-ice mixture and the marble increase or decrease?

____

19. State and explain factors that affect the melting point of a substance.

20. Give a reason why the thermal energy of a substance changes.

6 Bulk properties of solids and fluids

Topic 8: Bulk properties of solids and fluids

Learning outcomes

Knowledge and understanding

- Explain the bulk properties of solids and fluids and their application.
- Understand Hooke's law.

Skills

- Investigate by performing experiments individually in groups about the bulk intensive and extensive properties.
- Design practical investigations on viscosity, the rate of change of shear, strain, and the coefficient of viscosity.
- Derive the equation of continuity and Bernoulli's equation, and apply them to solving problems.

Attitude and value

- Appreciate the bulk properties for either chemical mechanical ,etc.

Key inquiry questions

- What is meant by bulk material?
- How do we need to find bulk density of solid?
- How can we work out the density, specific weight, specific volume and specific gravity of fluid?
- Why fluid has compressible and incompressible property?

Topic 8 Bulk properties of solids and fluids

Topic outlines

8.1 Definition of bulk, intensive and extensive properties

Activity 8.1 **To define bulk, intensive and extensive properties of matter**

(Work individually)

Materials

- Reference books
- Internet
- Resource persons

Steps

1. Conduct research from reference books or Internet on the definition bulk, intensive and extensive properties of materials. Explain difference between intensive and extensive properties. Give examples of each.
2. Present your findings to the class during the class discussion.

Bulk properties of materials are those properties that depend on the types of particles (atomic and molecular) and how the particles are distributed in the material. These properties can either be intensive and extensive..

Intensive properties are bulk properties which only depend on the type of matter in a sample but not on the amount of matter that is present. Examples include:

- Boiling point
- Density
- State of matter
- Hotness
- Colour
- Melting point
- Odour
- Ductility
- Temperature
- Refraction index
- Lustre
- Malleability

Extensive properties depend on the amount of matter that is present in a sample.

- Length
- Size
- Mass
- Volume
- Weight

The ratio of two extensive properties of the same object or system is an intensive property. For example, the ratio of an object's mass and volume, which are two extensive properties, is the density, which is an intensive property.

While extensive properties are great for describing samples, they aren't helpful in identifying it because they can change according to sample size or conclusion.

The following activity will help us to distinguish between intensive and extensive properties of matter.

Activity 8.2 **To investigate intensive and extensive properties of matter.**

Materials

- Measuring cylinder
- One 250 ml beaker
- One 100 ml beaker
- Two thermometer
- Two bunsen burners
- Two tripod stands
- Water
- Weighing balance

Instructions

In this activity:

1. Design and carry out an investigation to proof that boiling point is an intensive property of liquids.
2. Design and carry out an investigation to confirm mass is an intensive property.
3. For each investigation:
   (a) write down the procedure.
   (b) measure and record data accurately
   (c) analyse the data.
   (d) draw logical conclusions
   (e) suggest possible sources of errors and how they can be minimised.

Exercise 8.1

1. Differentiate by giving three examples between intensive and extensive properties of water.
2 (a) Is weight intensive or extensive property? Explain.
  (b) Briefly explain how density is independent of the mass of a system.

8.2 Bulk properties of solids

In construction, manufacturing and the informal metal works industries, many types of materials are used. These materials vary greatly in their mechanical properties. The mechanical properties of a material determines its suitability to a particular use. As future engineers, contractors and metal work artisans, we need to understand these properties of materials. They include elasticity,strength, stiffness, ductility and brittleness.

8.2.1 Stretching of materials

Robert Hooke did a lot of research work on stretching of materials. He performed different experiments involving:

1. stretching of spiral springs,
2. stretching of wires, and
3. loading horizontal beams fixed at one end.

From these experiments, he discovered the relationship between the *applied force* and *the extension* of the material used. This relationship is referred to as *Hooke's law*.

Activity 8.3 **To investigate the relationship between the extension produced in a spring and the force applied**

(Work in groups)

Materials

- A metre rule
- A stand with clamp
- A spiral spring
- Seven 50 g masses

Steps

1. Set up the apparatus as shown in Fig. 8.1. Note the initial position (x) of the pointer before the weight is loaded.
   The initial pointer reading x = ________cm

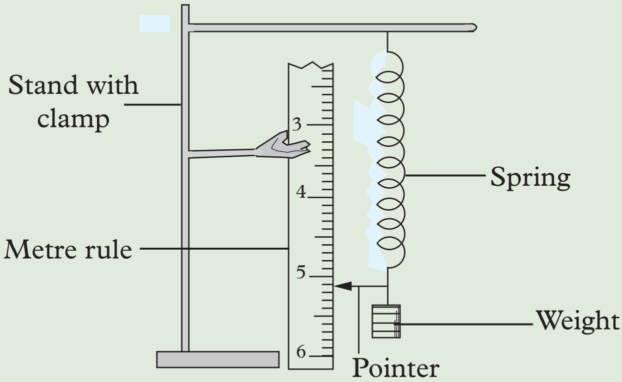


Fig. 8.1: Stretching a spring.

2. Load the spring with a 50 g mass and record the new pointer reading. Unload the spring and observe what happens to the pointer.
3. Repeat Step 2 with 100 g, 150 g, 200 g, 250 g, 300 g, 350 g masses and record the readings in a table (Table 8.1).

Table 8.1

Mass (g)	**Force (N)**	**Final reading y**	**Extension, e y – x (cm)**
50			
100			
150			
200			
250			
300			
350			

5. Draw a graph of applied force against extension produced.
6. From the graph, find the:
   (a) Force that produces an extension of 2 cm
   (b) Extension produced by a force of 2.8 N.
   (c) How does the extension change if force is doubled?
7. Determine the gradient of the graph. What quantity does the gradient represent? What does this quantity tell us?
8. How do you expect the quantity you determined in Step 7 to change?
   If: **(a)** You use a stronger spring?
   (b) You use a weaker spring?

Fig. 8.2 shows the graph of Force (N) against extension (cm) for an elastic material.

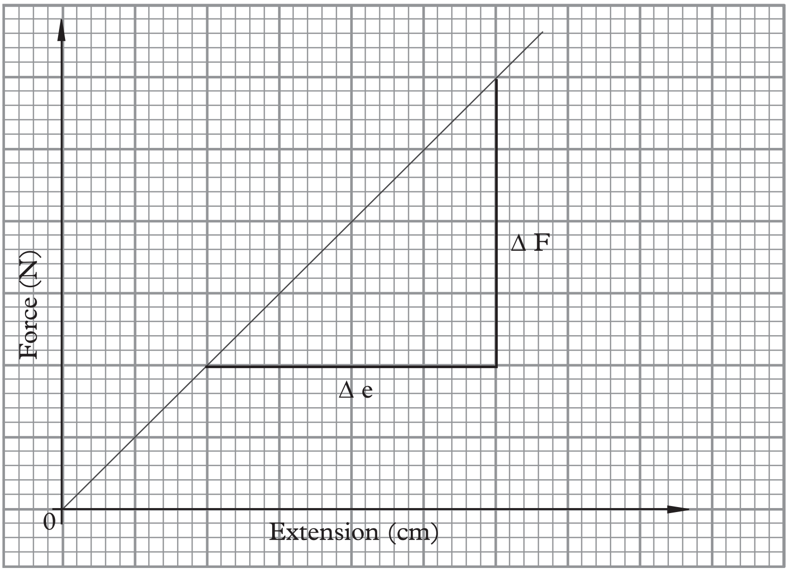


Fig. 8.2: Force-extension graph for a spring.

It is a straight line graph passing through the origin.

$\frac{\Delta F}{\Delta e}$ = gradient of a graph of force against extension is known as the *spring extension (k)*.

$\therefore$ the spring constant, (k) $= \frac{\Delta F}{\Delta e}$.

It can be seen from the graph that *the extension produced is directly proportional to the force applied*. Each time the spring is unloaded the pointer returns to its original position.

Materials that are able to recover their original shape and size after unloading are said to be *elastic*.

If more weights are added to the spring in Activity 8.3, a point is reached where the extension is no longer proportional to the applied force. This point is called *the elastic limit* (Point E in Fig. 8.3.)

The pointer does not return to the original position when the load is removed once the elastic limit is exceeded. The spring is said to have been *permanently deformed* i.e. it acquires a permanent extension.

Fig. 8.3 shows the graph of force against extension after the spring has been permanently deformed.

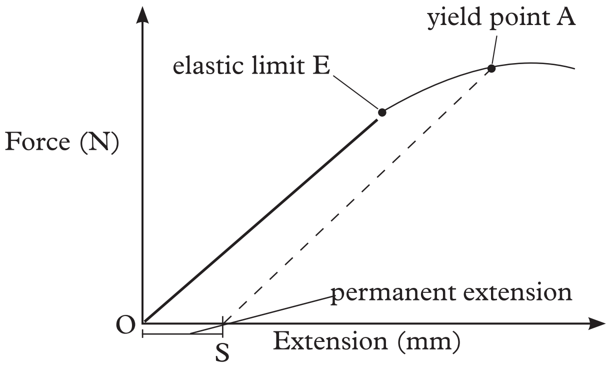


Fig. 8.3: Force-extension graph showing permanent deformation

The spring is said to undergo *elastic deformation* along OE. When a material is undergoing elastic deformation it is said to be obeying Hooke's law.

The spring is said to undergo *plastic deformation* along EA. Hooke's law is no longer obeyed beyond point E. If the weights are further added, a point is reached beyond which the material loses its elasticity. This is called the *yield point* (Point A in Fig. 8.3).

Hooke's law states that provided the elastic limit is not exceeded, the extension of a spring is directly proportional to the load applied on the spring.

Mathematically, the applied force, F, is directly proportional to the extension, e, i.e. $F \propto e$.

Therefore:

$$F = ke$$

where k is a constant of proportionality called *the spring constant*. Hence

$$k = \frac{F}{e}$$

The SI unit of the spring constant, k, is the *newton per metre* N/m.

If Activity 8.2 is repeated with a spring of different number of turns the spring constant changes. Springs of different materials or dimensions have different spring constants. When the activity is repeated by compressing the elastic material, similar results are attained where the compression force is directly proportional to the compression.

The spring constant is a measure of *the stiffness* of the spring; the stiffer the spring the larger the value of its *spring constant*.

If Activity 8.2 is repeated with a *rubber band*, by increasing the load (forces) beyond elastic limit a graph shown in Fig. 8.4 is obtained.

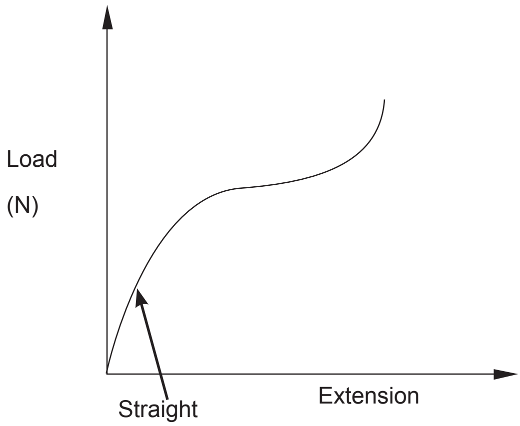


Fig 8.4: A load against extension of the rubber band

Application of Hooke's law

Calibration of spring balance

Hookes's law is applied in the making of spring balances which are used to measure weights of various substances. (Fig. 8.5).

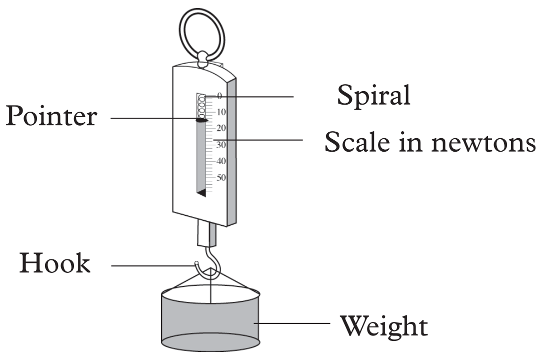


Fig. 8.5: A spring balance

Other applications of Hooke's law

- Elasticity in materials e.g springs is applied in making spring beds, diving boards etc.
- Stretching and compressing of spiral springs help in designing spring shock-absorbers or shock breakers used in car suspensions.
- Elastic materials are used in making rubber bands, rubber shoes etc.
- Elastic materials are used in making catapult used for hunting birds.

- Elastic materials are used to make equipments used in trampoline games. Fig. 8.6 shows children playing trampoline games.

Fig. 8.6: Children playing on a trampoline

> Care should be taken when jumping on trampolines to avoid jumping sideways as this can cause injuries.

Example 8.1

A sack containing drugs and narcotic substances intercepted by the police, was weighed on the spring balance and the spring balance stretched by 3 cm. The owner was arrested and finally jailed after a court case. If the sack had a mass of 200 g, calculate the spring constant of the spring balance.

Solution

$F = ke \quad \therefore \quad k = \frac{F}{e} = \frac{mg}{e}$

$= \frac{(200 \div 1\,000) \times 10}{(3 \div 100)} = 66.67 \text{ N/m}$

> Avoid drugs and narcotic substances. They are addictive and harmful to your health. Besides, taking them is a criminal offence punishable by the law.

Example 8.2

A spring has a spring constant of 200 N/m. If it is compressed by 0.06 m. Calculate the compressing force.

Solution

$k = 200 \text{ N/m}, e = 0.06 \text{ m}$

$F = ke = 200 \text{ N/m} \times 0.06 \text{ m}$

$= 12 \text{ N}$

Example 8.3

Fig. 8.7 is a graph of force against extension drawn from an experiment to verify Hooke's law.

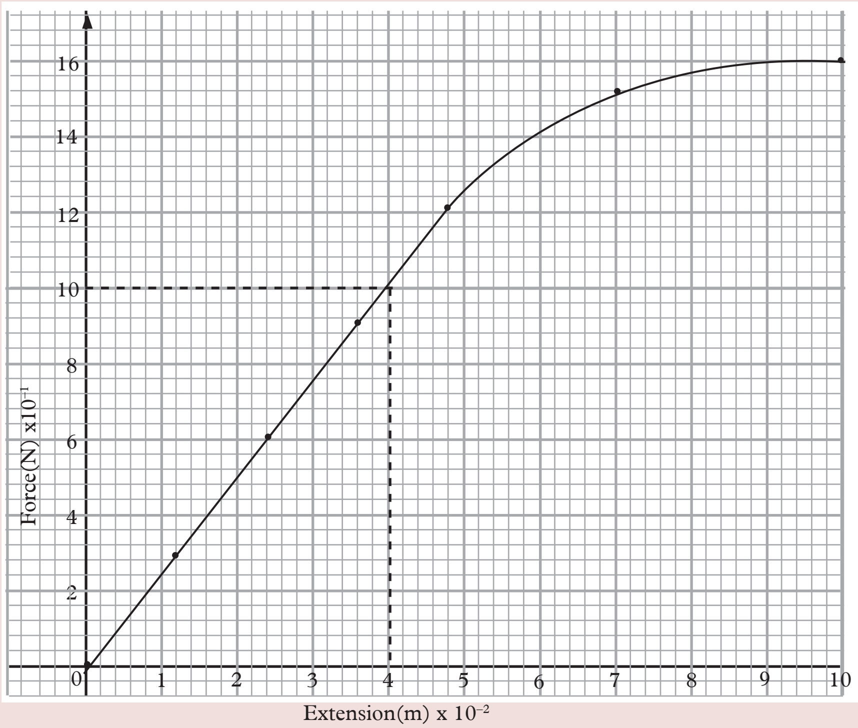


Fig. 8.7: A graph of force against extension

(a) Use the graph to determine the spring constant.

From Hooke's law, $k = \frac{F}{e}$. Thus, in a graph of F against e,

Spring constant = Gradient of the graph

$$= \frac{(10 - 0) \times 10^{-1}\ \text{N}}{(4 - 0) \times 10^{-2}\ \text{m}} = 25\ \text{N/m}$$

(b) Use the graph to find the length of the spring when a mass of 0.05 kg is hung from it. Assume that the length of unloaded spring is 80 mm.

Extension for 0.5 N = 2 mm

Length of spring = 80 mm + (0.02 × 1 000)

= 100 mm

(c) State with a reason whether or not Hooke's Law is obeyed.

Hooke's Law is obeyed up to the 12 N force because the graph is a straight line from the origin. It is not obeyed beyong 12 N.

Example 8.4

A force of 12 N extends a spring by 8 mm. Calculate the extension that is produced by the same spring if a force of 25N is hanged on it. (Assume the elastic limit is not exceeded.)

Solution

$$k = \frac{F}{e} = \frac{12\ \text{N}}{8\ \text{m}}$$

$$= 1.5\ \text{N/mm}$$

$$\text{Extension, } e = \frac{F}{k} = \frac{25\ \text{N}}{1.5\ \text{N/mm}}$$

$$= 16.67\ \text{mm}$$

Exercise 8.2

1. What is an elastic material?
2. Explain the following terms:
   (a) Stiffness **(b)** Extension **(c)** Spring constant
3. State Hooke's Law.
4. A force of 20N is used to compress a spring through 0.25 cm. Calculate the spring's constant in SI unit.
5. A spring with a constant of 100 N/m stretches through 0.5 m. Calculate the force causing the stretch.
6. Fig. 8.8 shows a spring balance. Its spring constant is 50 N/m. The scale extends over a maximum distance of 10 cm.

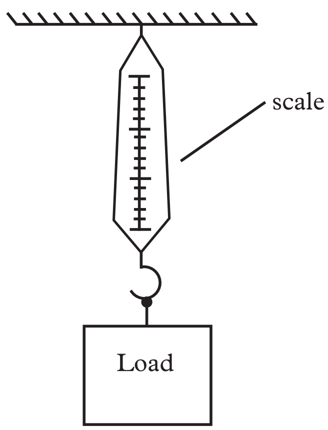


Fig. 8.8 Measuring weight using a spring balance

What is the maximum weight that it can measure?

8.2.2 Strength of materials

Activity 8.4 **To investigate the strength of materials**

(Work in groups)

Materials

- 2 stands and clamps
- Cotton and steel threads
- A table
- Slotted masses

Steps

1. Clamp a cotton thread and a steel thread of the same length and thickness on two separate stands as shown in Fig. 8.9.
2. Suspend masses of 50 g on each thread as shown in Fig. 8.9(a) and (b).

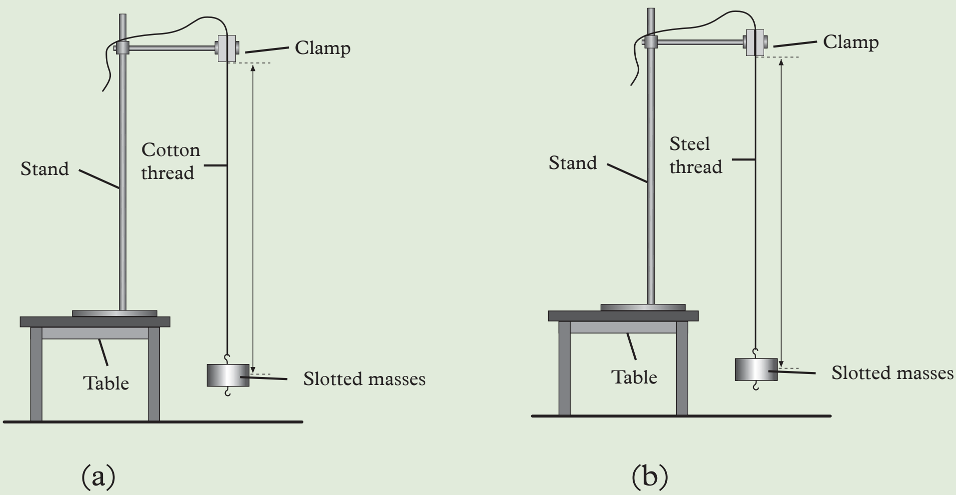


Fig. 8.9: Comparing the strengths of cotton and steel threads

3. Continue adding equal masses to both set-ups. Which thread breaks first? Explain your observation.

Strength is the *ability of a material to withstand an external force without breaking*.

When few slotted masses are suspended from the cotton thread, the thread snaps. However, the steel thread is able to support more masses than the cotton thread before breaking.

Although the materials are of the same length and thickness, the steel wire is *stronger* i.e. it is able to withstand a larger external force than the cotton thread. This external force puts the material under *tension* hence the material is said to have *tensile strength.*

8.2.3 Stiffness

Activity 8.5 **To investigate the stiffness of materials**

(Work in groups)

Instructions

1. Design an activity to investigate the stiffness of aluminium and steel rods. Use the set up below (Fig. 8.10).
2. Write your procedure.
3. Which of the two rods is easier to bend?

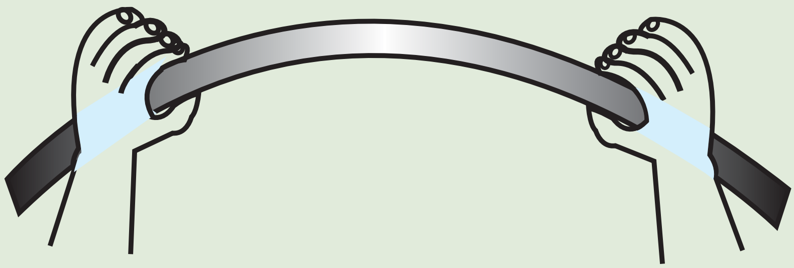


Fig. 8.10: To investigate the stiffness of materials.

Stiffness is the *ability of a material to oppose distortion of its shape or size or both by an applied force*. The distortion may be due to bending, stretching or compression. Materials that are stiff are less flexible.

The aluminium rod is easier to bend than the steel rod. A material bent only a little by a large force can reasonably be said to be *stiff*. However a material can be stiff but not strong e.g. biscuits and chalk. An example of a material that is both strong and stiff is steel.

8.2.4 Ductility

Activity 8.6 **To demonstrate ductility of a material**

(Work in groups)

Materials

- Plastic pipe

Steps

1. Repeat Activity 8.5 using a plastic pipe. What do you notice?
2. Discuss with your classmate what ductility of a material is.

Ductility is the *ability of a material to sustain great plastic deformation before reaching elastic limit*. A ductile material can be hammered, rolled, bent or stretched into useful shapes. The force against extension graph for ductile materials is shown in Figure 8.11.

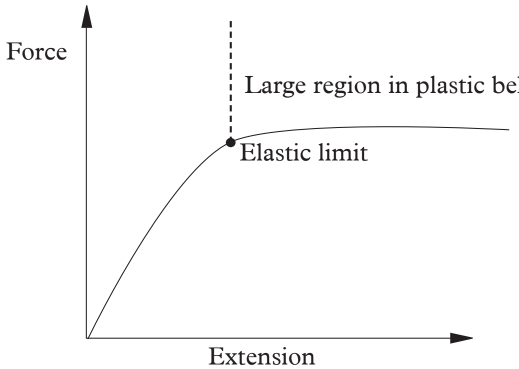


Fig. 8.11: A graph of force against extension for a ductile material

Common metals can be ranked from the least to the most ductile as follows: gold, silver, platinium, iron, nickel, copper, aluminium, zinc, tin and lead

The ductility of steel, an alloy of iron and carbon, varies depending on relative quantities of its different constituents. Increasing the quantity of carbon decreases ductility.

Ductility of materials is an important consideration in metal work. Materials that crack or break easily under external forces cannot be reshaped through metal shaping processes like hammering, rolling, bending, stretching and drawing into wires.

8.2.5 Brittleness

Activity 8.7 **To demonstrate brittleness of a material**

(Work in groups)

Materials

- A piece of chalk

Steps

1. Take a piece of chalk and try to bend it. What do you observe?
2. Discuss with your classmate what brittleness of a material is.

Brittleness is the *ability of a material to undergo little or no plastic deformation before breaking when an external force is applied*.

Thus, brittle materials break immediately they reach their elastic limit. They break with a sharp cracking sound in such a way that the broken ends can fit together again (Fig. 8.12).

Fig. 8.12: Brittle fracture

Some examples of brittle materials include glass, crockery, crisps, chalk and bricks.

However, *brittle materials can be toughened*. For instance, an inter-layer of polyvinyl butyral that absorbs growing cracks is placed between two sheets of glass. These toughened glass is referred to as *laminated glass* and is commonly used for windscreens in cars (Fig. 8.13).

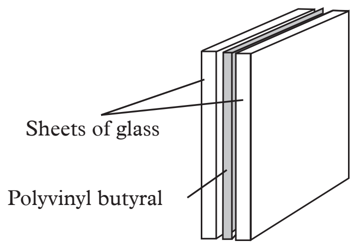


Fig. 8.13: Laminated glass

When a graph of force against extension is plotted for a brittle material like ceramic, it shows little or no plastic deformation (Fig. 8.14).

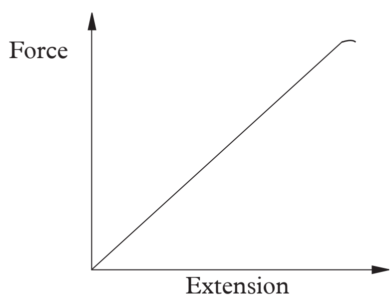


Fig. 8.14: A graph of force against extension for a brittle material

8.2.6 Stress, strain and Young's modulus

Activity 8.8 **Conduct research on Young's modulus**

(Work individually)

Materials

- Reference books
- Resource person
- Internet

Steps

1. Conduct research from reference books and the internet and define stress, strain and Young's modulus.
2. In your research, find out the definition of each, their mathematical expression and SI units and how you can use them.
3. Derive the mathematical expression for Young's modulus from stress and strain of the materials.
4. What is the significance of each of those three qualities to the materials used in a structure?.
5. Discuss your findings with your classmates and present to the rest of the class..

Stress

From Hooke's law, we learnt that the load applied to an elastic object is directly proportional to the extension of the material, provided that the elastic limit is not exceeded. This applied force keeps the string under tension, hence it is referred to as the *tensional force* (Fig. 8.15).

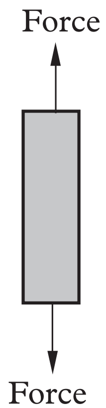


Fig. 8.15: Material under tensile stress

Although not all materials obey Hooke's law, most materials extend when under the action of tensional forces. Such extension does not only depend on the force applied but also on its length and cross-sectional area.

The *tensile force per unit cross-sectional area of a material is referred to as tensile stress* i.e,

$$\text{Tensile stress} = \frac{\text{Tensile force (N)}}{\text{Cross-sectional area } (m^2)}$$

SI unit for tensile stress is Nm^{-2}.

It is not in all cases where tensile force act on materials e.g a force to compress or shorten a material and the resulting effect is called compressive stress. In other cases, the force tend to shear the material and therefore, called shearing stress is resulted.

Example 8.5

A force of 1×10^4 N is acting on a circular rod with diameter 10 mm. Calculate the stress on the rod.

Solution

$$\text{Stress} = \frac{\text{Force}}{\text{Cross-section Area}}$$

$$= \frac{1 \times 10000 \text{ N}}{3.14 \times (5 \times 10^{-3})^2 \text{ m}^2}$$

$$= 1.27388\,535 \times 10^8 \text{ N/m}^2$$

Strain

Strain is deformation of solid due to stress. It is of two types namely:

1. Normal (tensile) strain which is due to elongation or contraction.
2. Shear strain which is due to change in angle between line segment originally perpendicular.

For now, we will learn in detail about tensile strain.

During the extension of a material, each unit length of the material extends by the same amount. *The extension per unit length is referred to as tensile strain* i.e,

$$\text{Tensile strain} = \frac{\text{Extension}}{\text{Original length}}$$

Tensile strain has no units since its a ratio of lengths.

Fig 8.16 shows a typical stress versus strain curves for different materials.

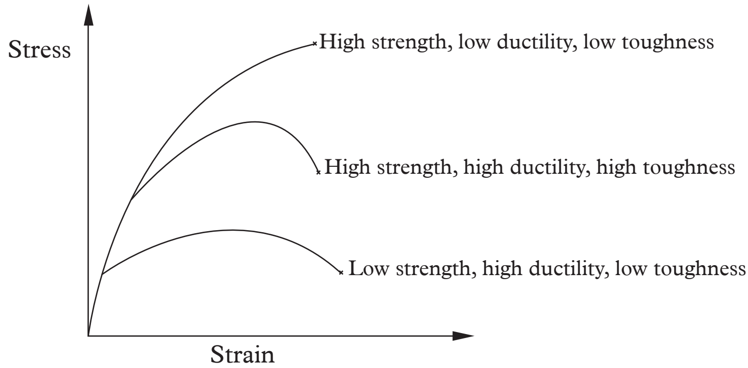


Fig. 8.16: Graphs of stress against strain for different materials

Example 8.6

The length of a spring when supporting no mass is 12 cm. A 50 g mass was hanged on the spring and its length becomes 21.5 cm. Calculate the tensile strain of the spring.

Solution

Original length = 12 cm

Extension = 21.5 cm – 12.0 cm

= 9.5 cm

$$\text{Tensile strain} = \frac{\text{Extension}}{\text{Original length}}$$

$$= \frac{9.5 \text{ cm}}{12.0 \text{ cm}}$$

$$= 0.79167$$

Young's modulus

Young's modulus (named after physicists, Thomas Young) describes the elastic properties of a solid undergoing tension or compression in only one direction.

It is a measure of the ability of a metal to withstand changes in length when under tension or compression. It is sometimes referred to as the modulus of elasticity. It is the ratio of stress to strain.

Consider a metal bar of cross-sectional area A being pulled by a force F at each end. The bar stretched from its original length L_o to a new length L (see Fig 8.17).

Fig. 8.17

We have already learnt that stress is the quotient of the tensile force divided by the cross-sectional area, i.e F/A. We also learnt that strain or relative deformation is the change in length $(L - L_o)$ divided by the original length, that is $(L\text{-}L_o)/Lc$ Thus, Young's modulus may be expressed mathematically as:.

$$\text{Young's modulus} = \frac{\text{Stress}}{\text{Strain}} = \frac{F}{A} \div \frac{(L - L_o)}{L_o} = \frac{FL_0}{A(L - L_o)}$$

The SI unit of Young's modulus is newton per square metre (N/m^2).

Example 8.7

A rectangular metal bar of length 8 cm and area 48 cm^2 was subjected to a force of 600 N from its both ends. If the new length after the longitudinal stress was 9.3 cm, calculate the Young's modulus of the metal bar.

Solution

$$\text{Stress} = \frac{F}{A} = \frac{600\text{ N}}{\left(\frac{48}{10\,000}\right)\text{ m}^2}$$

$$= \frac{600 \times 10000}{48}\text{ N/m}^2$$

$$= 125\,000\text{ N/m}^2$$

$$\text{Strain} = \frac{\text{Extension}}{\text{Original length}},$$

Extension = 9.3 cm – 8cm , Original length = 8
= 1.3 cm

$$\text{Strain} = \frac{1.3\text{ cm}}{3\text{ cm}} = 0.433$$

$$\text{Young's modulus} = \frac{\text{Stress}}{\text{Strain}} = \frac{(125000 \text{ N/m}^2)}{0.433}$$

$$= 288.7 \text{ N/m}^2$$

Bulk modulus

Bulk modulus is a numerical constraint that describes the elastic properties of a sand or fluid when it is under pressure on all surface.

The applied pressure reduces the volume of a material, which returns to its original volume when the pressure is removed. Sometimes referred to as the *incompressibility*.

Bulk modulus can therefore be defined *as a measure of the ability of a substance to withstand changes in volume when under compression on all sides*. It is equal to the functions of the applied pressure divided by the relative deformation of stress.

In this case, the relative deformation (strain) is the change in volume divided by the original volume. Thus, if the original volume Vo of the material is reduced by the applied pressure, P to a new volume Vn, then the strain may be expressed as the change in volume, $V_o - V_n$, divided by the original volume or $\frac{(V_o - V)}{V_o}$. Therefore, the bulk modulus can be expressed mathematically as

$$\text{Bulk modulus} = \text{Pressure/(Strain)} = \frac{PV_o}{(V_o - V)}.$$

The SI units of bulk module is newton per square metre (N/m²) or pascals.

Example 8.8

Calculate the bulk modulus of a material where volume changes from 200 cm³ to 120 cm² when SI pressure of 2 500N/m² is applied to it.

Solution

$V_o = 200 \text{ cm}^2 \qquad V = 120 \text{ cm}^3 \qquad P = 2\,500 \text{ N/m}^2$

$\quad = 0.000\,2\text{m}^3 \qquad\quad = 0.00012 \text{ m}^3$

$V_o - V = 0.0002 \text{ m}^3 - 0.00012 \text{ m}^3 = 0.0008 \text{ m}^3$

$$\text{Bulk modulus} = \frac{\text{Pressure}}{\text{Strain}} = \frac{(PV_o)}{(V_o - V)}$$

$$= \frac{(2500 \text{ N/m}^2 \times 0.002 \text{ m}^2}{0.0008 \text{ m}^2}$$

$$= 6259 \text{ N/m}^2$$

Exercise 8.3

1. Define the following terms as used in this topic
   (i) Stress (ii) Ductility
   (iii) Stiffness (iv) Strain
   (v) Strength (vi) Bulk modulus
   (vii) Young's modulus (viii) Elasticity
2. (a) A force of 150N is applied to a circular metal plate whose diameter is 49 mm. Calculate the tensile stress of the plate.
   (b) If the strain of the metal plate in 2 (b) is 0.678, calculate the Young's modulus of this plate.
3. A student was preparing an experiment in the laboratory using a spiral spring metre ruler and some masses. She noticed that the length of the spring increases by 6.4 cm when a mass of 100 g is hang on it. Calculate the strain of the spring if its length without any mass is 16.3 cm.
4. A solid material is under pressure of 5500N/m^2. If its volume changes from 320 cm^2 to 195 cm^3, calculate its bulk modulus.

8.3 Bulk properties of fluids (liquids and gases)

Properties of fluids determine how fluids can be used in engineering and technology. They also determine the behaviour of fluids in fluid mechanics.

The following are some of the important bulk properties of fluids.

1. Density
2. Specific volume
3. Viscosity
4. Pressure
5. Specific gravity
6. Temperatures
7. Specific weight

Let us now look into each property in details.

8.3.1 Density, specific weight and gravity

We have already learnt that density is an intensive property. We also learnt how to determine it in solids. How can you determine the density of a fluid (e.g water)? The following activity will help us to ensure this question.

Activity 8.9 **To determine the density of water**

(Work in groups)

Materials

- Water
- Measuring cylinder
- Beam balance.

Steps

1. Place an empty measuring cylinder on the beam balance and determine its mass call it m.
2. Pour water into the measuring cylinder to say 40 ml level.
3. Place the measuring cylinder with water on the beam balance. Record the new mass call it m_2.
4. Determine the mass of water of volume 40 ml, that is $m_2 - m_1$.
5. Repeat Steps 2 to 4 for different volumes of water and record your result in table 8.2.

Table 8.2

Volumes of water V						
Mass of water						
Mass/Volume						

6. Calculate the ratio $\frac{\text{mass}}{\text{volume}}$ of each column and record it in Table 8.2.∫ What do you notice?
7. Now, discuss with your classmate what specific volume and specific weight of a fluid are.

Density is the mass per unit volume of fluid. In other words, it is the ratio between mass (m) and volume (V) of a fluid.

Density is denoted by the symbol. 'ρ'. Its SI unit is kg/m³.

$$\text{Density, } \rho = \frac{\text{Mass (kg)}}{\text{Volume m}^3}$$

Specific volume

Specific volume is the volume of a fluid (v) occupied per unit mass (m). It is the reciprocal of density.

Specific volume is derived by the symbol 'v'. Its SI unit is m^3/Kg.

$$\text{Specific volume, } V = \frac{V\ (m^3)}{m\ \ (kg)}.$$

Example 8.9

The density of a unit mass of alcohol is 0.79 g/cm^3. Calculate its specific volume.

Solution

$S = 790\ kg/m^3$

$$\text{Specific volume, } V = \frac{I}{(\text{Density})} = \frac{I}{790}$$

$$= 0.0012658\ m^3/Kg$$

Specific weight

Specific weight is the weight per unit volume of a fluid. It is denoted by 'W'. Its SI unit is N/m^3.

Specific weight varies from place to place due to the change of acceleration due to gravity (g).

$$\text{Specific weight, } w = \frac{\text{Weight}}{\text{Volume}} \left(\frac{N}{m^3}\right)$$

Example 8.10

The weight of a gas in 1 cm^3 balloon is 0.000125 N. Determine its specific weight.

Solution

$$\text{Volume} = \frac{1}{1000\ 000\ m^3}$$

$$\text{Specific weight, } w = \frac{\text{Weight}}{\text{Volume}} = \frac{0.000125}{\frac{1}{1000\ 000}} = 125\ N/m^3$$

Specific gravity

Specific gravity is the ratio of specific weight of the given fluid to the specific weight of standard fluid. It is knocked by the letter 's'. It has no unit.

$$\text{Specific gravity, s} = \frac{\text{Specific weight of given fluid}}{\text{Specific weight of standard fluid}}$$

Specific gravity may also be defined as the ratio between density of the given fluid to the density of standard fluid.

$$s = \frac{\text{Density of a given fluid}}{\text{Density of a standard fluid}}$$

Temperature and pressure of a fluid

Temperature of the fluid is the property that determines the degree of hotness or coldness or the level of intensity of a fluid.

Temperature is measured using temperature scales. The three commonly used temperature scales include:

Kelvin scale

Celcius scale

Fahrenheit scale

Kelvin scale is widely used. This is because, the scale is independent of properties a substance.

Pressure

We have already learnt about pressure in our previous level (secondary 1 unit 2) pressure of a fluid is the force for unit area of the fluid. In other words, it is the ratio of force on a fluid to the area of the fluid held perpendicularly to the direction of the force.

$$\text{Pressure} = \frac{\text{Force}}{\text{Unit area}}$$

7.3.2 Viscosity

Activity 8.10 **To show that fluids offer resistance to motion of objects through them**

Materials

- 2 measuring cylinders
- Water
- Stop watch
- 2 identical ball bearings
- Glycerine

Steps

1. Pour water in one of the measuring cylinders and glycerine on the other.
2. Allow identical ball bearing to fall though a certain height *h* in air, water and glycerine (Fig. 8.18).

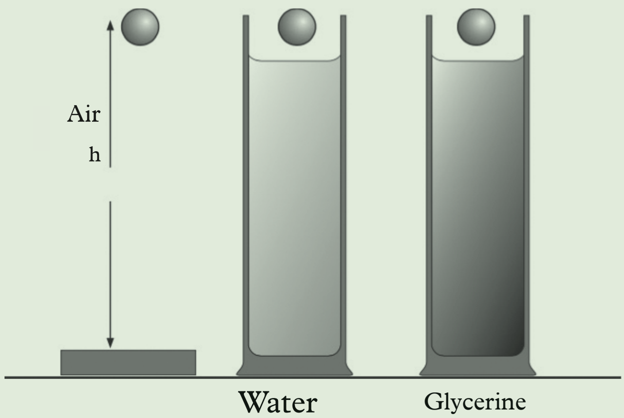


Fig. 8.18: Frictional forces in fluids

3. Measure the time taken for the ball bearing to move through this height, *h*.
4. Compare the times in the three cases.
5. Suggest what will happen if hot water and glycerine were to be used. Will time taken will be longer or shorter?
6. Discuss with your classmate what viscosity is.

The time taken by the ball to fall in air is shorter than the time it takes to fall in water. The time taken for the ball to fall in water is shorter than in glycerine.

This shows that liquids *offer resistance to the movement of objects* in them. *This resistance differs from liquid to liquid.*

Viscosity is the fluid property that determines the amount of resistance of the fluid shear stress. It is the property of the fluid due to which the fluid offers resistance to the flow of one layer of the fluid over another adjacent layer.

In a liquid, viscosity decreases with increase in temperature. In gases, viscosity increases with increase in temperature.

Frictional force in liquids is due to the *viscocity* of the liquid. If the frictional force is comparatively low, as in water, the viscosity of the liquid is low. If the frictional force is large as in glycerine, the viscosity of the liquid is high. Air has a very low viscosity. The resistance due to fluids is called the *viscous drag*.

Coefficient of viscosity and terminal velocity

Terminal velocity is the maximum downward velocity possible for a body falling through a fluid. The following experiment will help us determine terminal velocity and coefficient of viscosity in a fluid.

Activity 8.11 To determine terminal velocity and coefficient of viscosity

(Work in groups)

Materials

- A long tube filled by a fluid (glycerine density = 1.26 g/cm^3)
- Spherical steel ball (density = 7.77 g/cm^3)
- Micrometer screw gauge
- Stop watch

Theory: The equation for the coefficient of viscosity of the liquid is given by:

$$\eta = \frac{2r^2(\rho - \theta)g}{9v_t} \quad \text{where}$$

η = Coefficient of viscosity

r = Radius of the object used

ρ = Density of the object used

θ = Density of the fluid used

v_t = Terminal velocity

g = Gravitational pull

Steps

1. Measure the radius of the sphere using a screw gauge. Record it down.

   $r = \frac{d}{2} = \_\_\_\_\_$

2. Fix some rubber bands around a long tube at equal distances.
3. Drop a small steel ball bearing into the long tube containing glycerine (Fig. 8.19).
4. Measure the time taken by the ball to move through the equal intervals.
5. Determine the velocity of the ball as it descends into glycerine. What can you say about the velocity of the ball?

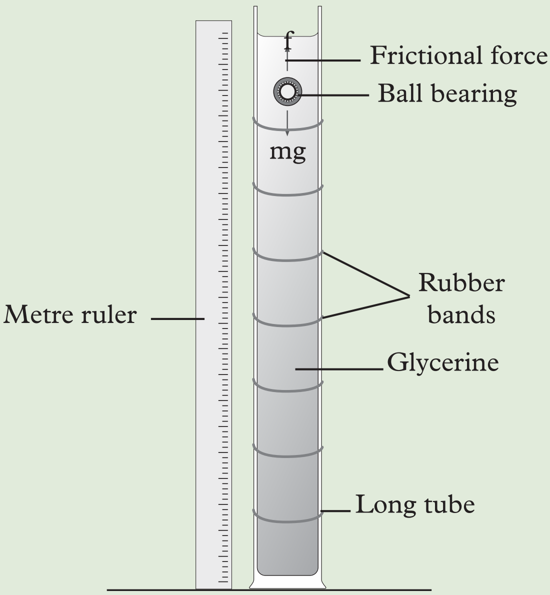


Fig. 8.19: Determination of terminal velocity

6. Repeat Steps 3 to 5 and get the average terminal velocity (v_t).

   $v_t. = \_\_\_\_\_\_\_\_\_\_$ cm/s

7. Now calculate the coefficient of viscosity using the formula:

$$\eta = \frac{2\pi^2(\rho - \theta)g}{9\, v_t}$$

8. Suggest two possible sources of errors in your activity.

You must have observed that the velocity of the ball starts from zero and accelerates to a maximum value and then remains constant at this value, as the ball continues falling.

When a body is falling in a fluid, three forces act on it (Fig. 8.20).

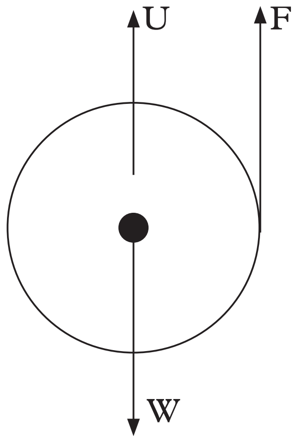


Fig 8.20: A body falling in a fluid

These forces are:

(i) weight of the body (W)

(ii) upthrust (U)

(iii) viscous drag (fluid friction F).

The fluid friction increases with increase in speed of the falling body.

Initially, W > (U + F) hence the body accelerates downwards.

As fluid friction (F) increases, it reaches a point where U + F = W.

There being no resultant force, the body moves at uniform (constant) velocity. This constant velocity is called *terminal velocity.* (V_t).

Terminal velocity is therefore defined as the maximum downward velocity possible for a particular object falling through a fluid.

If the velocity of the object is plotted against time, a graph similar to the one in Fig. 8.21 is obtained.

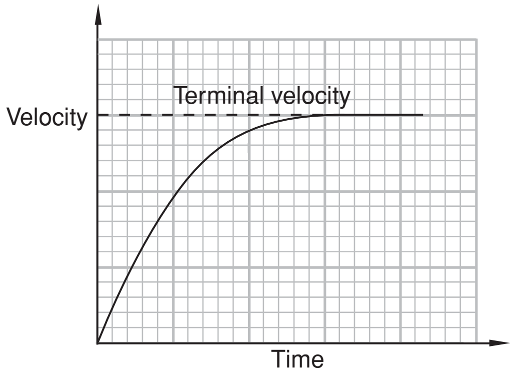


Fig. 8.21: Graph of velocity against time

8.4 Air resistance

When running, we experience the backward pushing by air even without the pressure of wind. The same resistance is experienced by moving vehicles. Thus, air offers resistance to movement. Air resistance is also referred to as air friction. i.e. friction opposing a moving body in air. It is a form of dynamic friction. Moving objects waste a lot of energy in overcoming air resistance. For a vehicle, this leads to high fuel consumption. To reduce air resistance, bodies of cars and planes are streamlined. i.e they have smoothened, rounded and pointed bodies.

Example 8.11

A car of mass 1000 kg is travelling under the action of forces as shown in Fig 8.23.

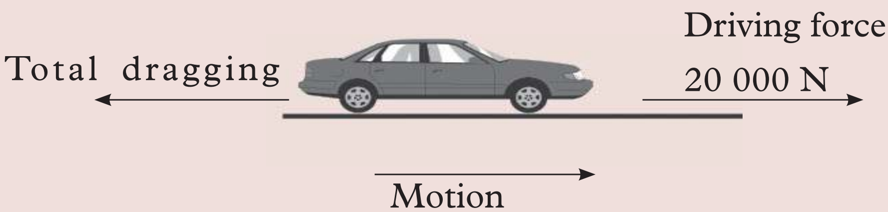


Fig. 8.22: Forces on a moving car

(a) State the size of the drag force when the car is travelling at a constant speed.

(b) If the car accelerates at 5 m/s^2, work out the total dragging force.

(c) The car continues accelerating at 5 m/s^2 but eventually reaches the highest constant speed. Explain.

Solution

(a) At constant speed, resultant force = 0 N.

$\therefore$ Total dragging force = Driving force = 20 000N

(b) According to Newton's second law,

Resultant force = mass × acceleration

Driving force – total drag force = ma

$20\ 000 - F = 1\ 000\ \text{kg} \times 5\ \text{m/s}^2$

$F = 20\ 000\ \text{N} - 5000\ \text{N}$

$= 15\ 000\ \text{N}$

(c) As the speed of the car increases, air resistance increases. At some point the total drag equals the highest driving force, hence the car cannot accelerate any further.

Exercise 8.4

1. State three bulk properties of fluid.
2. The specific weight of a gas is 650 N/m^3. If the weight of the gas is 0.000345 N, calculate its volume.
3. Define the following terms:
   (a) Specific gravity
   (b) Specific volume
   (c) Viscosity
   (d) Terminal velocity
   (e) Coefficient of viscosity
4. (a) Sketch a diagram to illustrate all forces acting on a spherical ball dropped in a liquid.
   (b) In an experiment to determine the coefficient of viscosity a student used a liquid of density 0.96 g/cm^2, a spherical iron ball of density 8.8g/cm^3 and radius of 0.2 cm. If the terminal velocity was 10 cm/s, calculate the value of coefficient of viscosity the student got.

8.4 Fluids in motion

Activity 8.12 **To conduct research on fluid flow**

(Work in groups)

Materials

- Floating object
- A river or stream near your school or home
- Stop watch

Steps

1. Identify a river or a stream near your place (at school or home)
2. Go nearby and study keenly how water flow at different parts along the river or stream.
3. Identify the places where the water is flowing very fast and where it moves slowly (almost stationary)
4. Place the floating object on the surface of water where the flow is slow, estimate the time taken to move a distance of about 1m. Repeat with the place where the flow is fast.
5. Discuss with your classmates what a streamline and turbulent flow of fluids are.
6. Summarise the points from your discussion.

The study of motion of fluids is called *hydrodynamics*. Example of motion of fluid flow include the flow of water in rivers, sea water breaking against the seashore, flow of smoke moving up from chimneys etc.

8.4.1 Streamline flow of fluids

Consider the motion of water flowing in a pipe as shown in Fig 8.23 If the motion of water is smooth and steady, each and every molecule of water in the pipe travels in the same direction with the same velocity. Such a smooth flow of a liquid through a pipe is called the *streamline flow*.

A streamline flow is one where, at a given point, each and every molecule of the fluid travels in the same direction and with the same velocity.

The lines indicating the path of the particles having a streamline flow are called the streamlines. The streamlines are parallel to each other. In Fig 8.23 there are six streamlines.

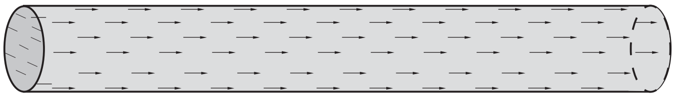


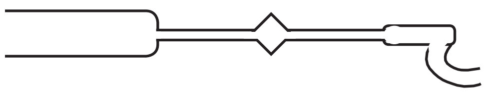
Fig. 8.23: Streamline flow

It should be noted that due to frictional resistance between (a) the liquid molecules and the walls of the pipe and (b) the *viscosity* of the liquid (a property which arises due to the internal friction between the molecules of a liquid), the velocity of the liquid is not the same at every point in any cross section of the pipe. It is maximum along the axis and gradually decreases towards the walls of the pipe. It is therefore necessary to assume that the liquid is non-viscous so that the velocity at all points in any section of the pipe is the same. We should also assume that the liquid is *incompressible* so that the density of the liquid is the same at each point.

8.4.2 Turbulent flow

If the pipe through which a fluid flows is not of uniform cross-section (Fig. 8.24 (a) and (b)), the velocity of the fluid will not be uniform. The velocity of the fluid becomes large at the constrictions in the pipe. This causes the fluid to change its direction too abruptly or sharply.

(a)



(b)

Fig. 8.24: Velocity of fluid is high at constriction

The stream line flow is broken and *eddies* and *whirls* are formed. The streamline flow changes to a churning motion called a *turbulent flow* (Fig. 8.25).

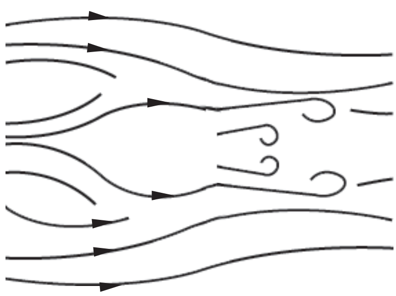


Fig. 8.25: Turbulent flow

8.4.3 Rate of flow of a fluid

The *rate of flow of a fluid* is defined as the volume of the fluid flowing through any section in one second.

Consider a pipe of uniform cross sectional area, A, and length, l. Let v be the velocity of the fluid (Fig. 8.26).

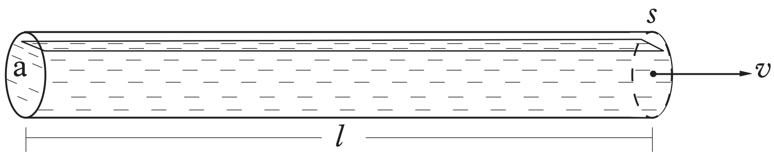


Fig. 8.26: Rate of flow of a fluid

If the time taken by the fluid to cover the length l is t, then the velocity of the fluid, v is given by

$$v = \frac{l}{t} \quad ; \qquad \text{or} \qquad l = vt.$$

The volume, V of the fluid which passes through any section is given by

Volume, V, = area of cross section, a, × length, l, i.e.

$$V = Al = avt$$

$$\text{Hence the rate of flow} = \frac{\text{Volume of the fluid}}{\text{Time taken}}$$

$$= \frac{Avt}{t}$$

$$= Av$$

The rate of flow of a fluid = cross-sectional area × velocity.

The SI unit of the rate of flow of a fluid is m^3/s or m^3s^{-1}.

For streamline flow the rate of flow of the fluid through any section of the pipe is uniform.

8.4 Equation of continuity

Consider a fluid flowing through a pipe of varying diameter. Let a_1 and a_2 be the cross sectional areas of the pipe at two points P and Q respectively (Fig. 8.27).

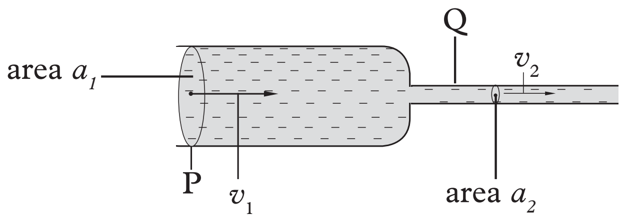


Fig. 8.27

For streamline flow, the volume of the fluid flowing across any section in a time t must be the same, i.e. the rate of flow of the fluid is constant. The rate of flow of the fluid through the section at P = $A_1 v_1$. The rate of flow of the fluid through the section at Q = $A_2 v_2$

Hence $A_1 v_1 = A_2 v_2$

This is the equation of continuity for a fluid having streamline flow.

At the point P, the cross sectional area of the pipe is more and hence the velocity of the fluid is low while the reverse is the case at Q.

Thus,

$$\frac{v_1}{v_2} = \frac{A_2}{A_1}$$

This equation shows that *for streamline flow, the velocity of the fluid at any point is inversely proportional to the cross sectional area of the pipe at that point.*

Equation of continuity considering mass flow

If 'mass flow' of the fluid is considered then the mass of the fluid crossing any section in each second is the same.

Let the mass of the fluid crossing the sections at P and Q be m_p and m_Q respectively.

$m_P = m_Q$ But mass = volume × density

(Volume × density)$_P$ = (Volume × density)$_Q$

$(A_1 l_1 \times \rho_1)_P = (A_2 l_2 \times \rho_2)_Q$ where ρ is the density.

The mass of the fluid crossing each section in 1 second = $\frac{\text{Mass}}{\text{Time}}$

$$\frac{A_1\ l_1\ \rho_1}{t} = \frac{A_2\ l_2\ \rho_2}{t}$$

$$A_1 v_1 \rho_1 = A_2 v_2 \rho_2 \qquad \text{since } \frac{l}{t} = v$$

As the fluid is assumed to be incompressible, density of the fluid is constant: i.e. $\rho_1 = \rho_2$

Hence $\quad A_1 v_1 = A_2 v_2$ —— equation of continuity

Example 8.12

Water flows through a pipe of length 0.20 m and of uniform cross sectional area 20 cm^2 in 2 s. Calculate the rate of flow of water in: (a) cm^3/s (b) m^3/s

Solution

(a) Volume of water in the pipe is given by

$$\begin{aligned} V &= \text{area} \times \text{length} \\ &= 20\ \text{cm}^2 \times 20\ \text{cm} \\ &= 400\ \text{cm}^3 \end{aligned}$$

$$\text{Rate of flow of water} = \frac{v}{t} = \frac{400\ \text{cm}^3}{2\text{s}}$$

$$= 200\ \text{cm}^3/\text{s}$$

∴ The rate of flow of water is 200 cm^3/s

(b) 1 m^3 = 100 cm × 100 cm × 100 cm = 1 × 10^6 cm^3.

$$\text{The rate of flow of water} = \frac{200}{1 \times 10^6}\ \text{m}^3/\text{s}$$

$$= 2 \times 10^{-4}\ \text{m}^3/\text{s}$$

Example 8.13

A mass of 600 g of water flows through a tube of uniform cross sectional area of 20 cm^2 in 10 s. Calculate the rate of flow of water in m^3/s if the density of water is 1 000 kg/m^3.

Solution

$$\text{Volume} = \frac{\text{Mass}}{\text{Density}}$$

Volume of water flowing through the pipe $= \frac{0.6 \text{ kg}}{1\,000 \text{ kg/m}^3}$

$= 6 \times 10^{-4} \text{ m}^3$

Rate of flow of water $= \frac{\text{Volume}}{\text{Time}} = \frac{6 \times 10^{-4}}{10} = 6 \times 10^{-5} \text{ m}^3\text{/s}$

Example 8.14

Water flows along a horizontal pipe of cross sectional area 36 cm². The speed of the water is 6 m/s, but this increases to 9 m/s in a constriction in the pipe. What is the area of this narrow part of the pipe?

Solution

Assuming streamline flow through the pipe, the rate of flow of water through any section of the pipe is uniform.

$$A_1 v_1 = A_2 v_2$$
$$36 \text{ cm}^2 \times 6 \text{ m/s} = A_2 \times 9 \text{ m/s}$$
$$A_2 = 24 \text{ cm}^2.$$

The area of the narrow part of the pipe is 24 cm².

Exercise 8.5

1. Define the terms: fluid, streamline flow, turbulent flow
2. Prove that the rate of flow of a fluid through a pipe = cross-sectional area of the pipe x velocity of the fluid.
3. Water flows through a tube of length 40 cm and of cross-sectional area 10 cm² in 4s. Calculate the rate of flow of water in m³/s.
4. For a non-viscous, incompressible fluid having streamline flow, the equation of continuity states that $a_1 v_1 = a_2 v_2$. Explain the meaning of the symbols used. Use a neat labelled diagram.
5. A liquid flows along a horizontal pipe of cross-sectional area 24 cm² with a speed of 3 m/s. The speed increases to 9 m/s where there is a constriction. Calculate the diameter of the constriction.
6. In Fig. 8.28, calculate the speed of water, having streamline flow, at the point P. The diameter of the pipe at P is 2 cm and at Q is 6 cm, and

the speed of water at Q is 0.3 m/s.

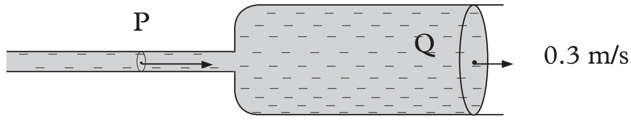


Fig. 8.28

8.5 Bernoulli's equation

Activity 8.13 **To conduct research into Bernoulli's equation**

Materials

- Reference books
- Resource persons, internet.

Steps

1. Conduct a research from reference books, internet or resource persons on the Bernoulli's principles and equation. How does it state?
2. In your research, identify the component in the Bernoulli's equation.
3. Discuss with your classmate how to derive the equation.
4. Make summarised notes on how to derive the equation and present it to the class during a whole class discussion.

Daniel Bernoulli (1700 – 1782) formulated the famous equation for fluid flow that bear his name.

The Bernoulli's equation is essentially more general and mathematical form of Bernoulli's principle that also takes into account changes in gravitational-potential energy.

The equation denotes pressure, speed and height of any two points (say 1 and 2) in a steady streamline flowing fluid of uniform density. Bernoulli's equation is usually expressed as follows

$$P_1 + \tfrac{1}{2}\rho v_1^2, + \rho g h_1 = P_2 + \tfrac{1}{2}\rho v_2^2 + \rho g h_2$$

The variables P_1 v_1 and h_i are pressure, speed, and height of the fluid at point 1 respectively whereas P_2 v_2 and h_2 are also pressure, speed and height at point 2 respectively.

Let us now learn how to derive Bernoulli's equation.

8.6.1 Deriving the Bernoulli's equation

Consider the Fig 8.29 where water flows from left to right in a pipe that changes both cross-sectional area and height.

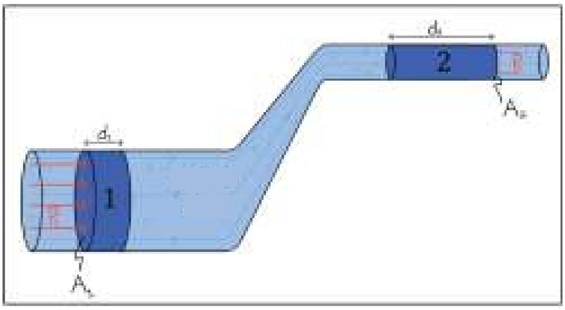


Fig. 8.29

The water will speed up and gain kinetic energy, K at constrictions in the pipe, since the volume flow rate must be maintained for incompressible fluid even if those constricted sections of the pipe move upwards.

The constrictions will cause the water to move upward hence gaining both gravitational potential U and kinetic energy, K. we assume the fluid flow is streamline, non-viscous and there are no dissipative forces affecting the flow of the fluid, then any extra energy (i.e Δ (K + U) added to the system will be caused by external work done on the fluid from the surrounding external force.

This can be expressed mathematically as,

External = Δ(K + U) system ....(i)

First, let us find the external work, done on the water. The external work will not come from within the system (i.e between points 1 and 2) but from the pressure P_1 and P_2 applied to the system (see Fig...).

Let the pressure P_1 applied to the right to be in positive direction and pressure P_2 to be in negative direction. We can therefore calculate the external work as follows

$W = F \times \mathrm{d}$

But $P = \dfrac{F}{A} \implies F = PA$ substituting we get

$W = PAd$ so the positive work done in our system near point 1 will be

$W_1 = P_1 A_1 d_1$ ....(ii) and the work done by water near point 2 will be

$W_2 = -P_2 A_2 d_2$ ....(iii). Note it is negative because of opposite direction.

Substituting equations (ii) and (iii) into left side of equation (i) i.e

$W = \Delta(K + U)$ system.

We get:

$P_1 A_1 d_1 - P_2 A_2 d_2 = (K + U)$ system..... (iv)

But the terms A_1 d_1 and A_2 d_2 in equation (iv) have to be equal since they represent volume of fluid displaced near point 1 and 2 that is

$V_1 = A_1 d_1 = A_2 d_2 = V_2$. Note that the assumption we have made here is that the fluid is compressive, hence equal volume of fluid must be displaced at any point within the system.

Since $V_1 = V_2$, we can just write the volume terms in equation (iv) simply as V, that is:

$P_1 V - P_2 V = \Delta(K + U)$ system......(v)

The left side of equation (i) is now done. We have to deal with the right side to complete the equation. In this case, we assume that the flow of the fluid is steady. By steady flow we mean the speed of the fluid passing through at any particular point in the pipe doesn't change.

Fig 8.30 will help us to complete the right side of equation (v).

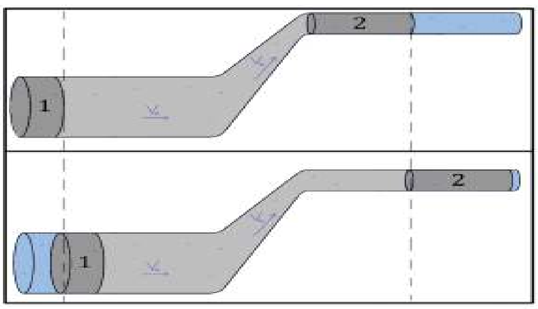


Fig. 8.30

In the first diagram, the system has some amount of total energy (K + U) initial. In the second diagram, the entire system had work done on it, gain energy, shifts to the right, and now has some different total energy (K + U) final.

On the overall this means that the total change in the energy of the system can be found by simply considering the energies of the end points. That is, we can take the kinetic energy and potential energy (K_2 + U_2) that now exists in volume 2 after the work was done and subtract the kinetic and potential energy (K_1 + U_1) that no longer exist behind V_1 after the work was done. In other words.

$$\Delta(K+U)\text{ system} = (K_2 + U_2) - (K_1 + U_1) \ \ldots\ldots\ldots\text{(vi)}$$

Plugging equation (vi) in equation V, we got

$$P_1V - P_2V = (K_2 + U_2) - (K_1 + U_1) \ \ldots\ldots\ldots\ldots\text{(vii)}$$

Now substitute in the formulas of kinetic energy, K = ½ mv^2 an gravitational potential energy U = mgh in equation (vii) to got.

$$P_1V - P_2V = (\tfrac{1}{2} m_2v^2{}_2 + m_2gh_2) - (\tfrac{1}{2} m_1v_1{}^2 + m_1gh_1) \ \ldots\ldots\text{(viii)}$$

But since we are assuming the fluid is incompressible then the displaced masses of volume 1 and 2 must be subscript on the M's we got,

$$P_1V - P_2V = (\tfrac{1}{2} mv^2{}_2 + mgh_2) - (\tfrac{1}{2} mv^1{}_2 + mgh) \ \ldots\ldots\text{(ix)}$$

We can divide both sides by V we got

$$P_1 - P_2 = \frac{(\tfrac{1}{2} mv^2{}_2)}{V} + \frac{mgh_2}{V} - \frac{(\tfrac{1}{2} mv_1{}^2)}{V} - \frac{mgh_1}{V} \ \ldots\ldots\text{(x)}$$

We can simplify this equation by noting that the mass of the displaced fluid divided by volume of the displaced fluid is the density of the fluid $= \frac{m}{V}$. Substituting $\frac{m}{V} = \rho$ we get:

$$P_1 - P_2 = \tfrac{1}{2} \rho v^2{}_2 + \rho gh_2 - \tfrac{1}{2} \rho V_1{}^2 - \rho gh_1 \ \ldots\ldots\ldots\text{(xi)}$$

Now, we're just going to rearrange equation (xi) to get

$$P_1 + \tfrac{1}{2} \rho v_1{}^2 + \rho gh_1 = P_2 + \tfrac{1}{2} \rho v_2{}^2 + \rho gh_2 \ldots\text{(xii)}$$

Equation (xii) is called Bernoulli's equation. Since the quantity P + ½ pv^2 + Pgh is the same at every point in the streamline fluid flow, another way of writing Bernoulli's equation is

$$P + \tfrac{1}{2} \rho v^2 + \rho gh = \text{constant}\ldots\ldots\text{(xiii)}$$

Example 8.15

Water is flowing in a fire hose with a velocity of 1.0 m/s and a pressure of 200000 Pa. at the nozzle the pressure decreases to atmospheric pressure (101 300 Pa), there is no change in height. Use the Bernoulli's equation to calculate the velocity of the water existing in the nozzle. Take density of water = 1000 kg/m^3 and g = 9.8 mls^2).

Solution

$P_1 + ½\,\rho v_1^2 + \rho g h_1 = \rho_2 + ½\,\rho v_2^2 + \rho g h_2$

Since the height does not change ($h_1 = h_2$), the height terms can be subtracted from both sides to get.

$½\,\rho v_1^2 + P_1 = ½\,\rho v_2^2 + P_2$

Rearranging the equation to solve for v_2 we get,

$$v_2 = \sqrt{\frac{2}{p}(½\,\rho v_1^2 + P_1 - P_2)} = \sqrt{\frac{2}{1000}(½ \times 1000 \times 1^2 + 200\,000 - 101300)}$$

$$= 14.1 \text{ m/s}$$

Exercise 8.6

1. Write down Bernoulli's equation and state what each variables in the equation stands for.
2. Explain how you can derive the Bernoulli's equation.
3. State two reasons why it is important to understand the Bernoulli's s equation.
4. A U-tube manometer containing water is connected to a nozzle of air tunnel that discharges to the atmosphere as shown in Fig 8.31. The area ratio is $\frac{A_2}{A_1} = 0.25$. For given operational conditions the level difference in the manometer is h = 94 mm. Take the density of water $\rho_w = 1000$ kg/m³ and the air density $\rho_{air} = 1.23$ kg/m³. Calculate the average air velocity at the exit, v_2 of the nozzle?

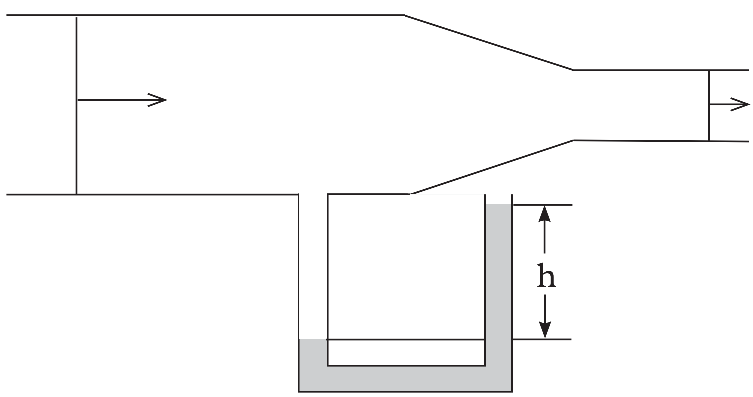


Fig. 8.31

Topic summary

- An intensive property is a physical quantity whose value does not depend on the amount of the substance for which it is measured. Examples are temperature, density, hardness, elasticity, pressure, viscosity etc.
- An extensive property is a physical quantity which is the sum of the properties of separate non-intersecting subsystem that compose the entire system.
- Some material stretch when subjected to a force and regain their original state after the force is removed. Materials that behave in this manner are called elastic materials.
- The extension (e) produced in elastic materials is directly proportional to the force applied (F) within the elastic limit. This is called Hooke's law; mathematically expressed as F = ke, where k is the spring constant.
- The spring constant of an elastic material is force per unit extension.

  Elastic limit is a point beyond which a material loses its elasticity.
- Bulk properties of solids include strength, stiffness, ductility, brittleness.
- Bulk properties of fluids include: Density, specific volume temperature, pressure, specific weight, viscosity and specific gravity.
- Terminal velocity is the constant velocity with which the body moves in a liquid after acceleration.
- Every fluid has a property called viscosity. This is an internal property of the fluid that offer resistance to the movement of particles through it.
- For streamline flow, each and every molecule of the fluid travels with same velocity, in the same direction and the streamline are parallel.
- The line indicating the path of the particles having streamline flow is called the streamline.
- For turbulent flow, the streamlines are not parallel and there is turbulence. The velocity of the molecules and the direction of flow change abruptly.
- The rate of flow of a fluid = cross-sectional area x velocity of the fluid.
- For streamline flow, the rate of flow of the fluid through any section of the pipe is uniform.
- The equation of continuity for a fluid having streamline flow is $a_1 v_1 = a_2 v_2$.
- Form Bernoulli's principle; for a fluid having streamline flow, the pressure is inversely proportional to the velocity.
- The equation $P_1 + ½ PV_1^2 + Pgh = P_2 + ½ V_2^2 + Pgh_2$ is called Bernoulli's equation.

Topic Test 5

1. Define the following terms:
   (a) Intensive property
   (b) Extensive property
   (c) Viscosity
   (d) Specific gravity.
2. State Hooke's law.
3. Discuss how you can derive Bernoulli's equation.
   $P_1 + ½ \rho v_1^2 + \rho g h_1 = P_2 + ½ \rho v_2^2 + \rho g h_2$
4. A liquid flows along a horizontal pipe of cross-sectional area 24 cm^2 with a speed of 3 m/s. The speed increases to 9 m/s where there is a constriction. Calculate the diameter of the constriction.
5. A square iron bar of side 12.6 cm was subjected to a force of 136N from one side. If the side on which the force acted increased by 2.9cm, calculate the Young's modulus of the metal box.
6. (a) Draw a labelled diagram of the apparatus to be used to investigate how the extension of a spiral spring varies with the stretching force.
   (b) In such an experiment, the following reading were taken (Table 8.5).

Table 8.5

Force (N)	1	2	3	4	5	6	6.5
Extension, *e* (mm)	20	40	60	80	104	122	174

   (i) Plot a graph of extension (y-axis) against the force (x-axis).
   (ii) Mark on the graph the elastic limit of the spring used.
   (iii) Use the graph to determine the force required to produce an extension of 48 mm.
   (iv) A similar spring is used to make spring balance. What is the maximum weight that could be measured with this balance?
7. In Fig. 8.32, the liquid has streamline motion. Calculate the diameter of the narrow part of the pipe, if the radius of the larger pipe is 4 cm.

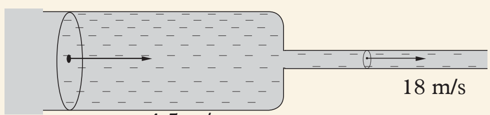


Fig. 8.32

8. Through a refinery, fuel ethanol is flowing in a pipe at velocity of 1 m/s and a pressure of 101300 Pa. The refinery needs the ethanol to be at a pressure of ratio(202 600 Pa) on the lower level. How fair must the pipe drop in height in order to achieve this pressure? Assume the velocity does not change. (Hint: Use the Bernoulli's equation. The density of ethanol is 789 Kg/m^3 and gravity is 9.89 m/s^2.