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Junior Secondary
Physics

Student's Book

Form 2

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Dr Alnord D. Mwanza

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UNIT 1: Scientific Investigation

Success criteria

By the end of this unit, you must be able to:

- Design a scientific investigation.
- Carry out a scientific investigation

Introduction

In book 1, we discussed in details how the scientific method is used to study the natural sciences such as physics. In this unit, we will discuss how basic scientific investigations are carried out in the study of Physics.

In order to carry out a successful investigation, you will need to develop skills in:

1. **Making an observation**

   This involves critically looking at a natural phenomena as they take place.

2. **Proposing a hypothesis**

   A hypothesis is an idea that is suggested as a possible explanation of the observation made.

3. **Designing an experiment to test the hypothesis**

   This involves:

   - Identifying variables and quantities to be measured: -

     Controlled variables: These are variables that you keep constant so that they do not interfere with your test.

     Independent variables: These are the variables you control as you wish within suitable ranges of the investigation.

     Dependent variables: These are variables you measure every time you change your independent variables.

   - Outlining the apparatus and procedure or method to be followed.

4. **Methods of results presentation**

   This may include drawing tables to showing the quantities being measured and their units of measurement, drawing graphs, drawing bar charts etc.

5. **Drawing conclusions from the investigation**

   This involves comparing the hypothesis with the investigation with a view to accept or reject it.

6. **Evaluating the strength of the evidence**

When the hypothesis has been accepted, the limitations of the hypothesis must be indicated.

1.1 Strategies of planning an investigation

When you plan an investigation, you need to take into account: -

- *Safety measures* required in order to conduct an investigation successfully. In case of apparatus or chemicals which have a hazard factor to consider, you should take the measures outlined in book 1.
- *The apparatus and chemicals to be used.* The apparatus chosen should be appropriate for the measurement of the quantities involved. The sensitivity of the scales and their ranges should be appropriate for the investigation to be carried out. For example, it is not appropriate to measure the length and breadth of your classroom using a *centimetre scale*. A *metre* scale is good enough. It is not appropriate to measure the mass of a drawing pin using a *gram scale*. You need a *centigram scale* or a more sensitive one.

  The chemicals to be used must be handled as required, taking the necessary safety precautions as discussed in book 1. You must be conversant with how each and every apparatus you use is handled in order to produce the desired results at maximum safety. For example, one may choose to use plastic measuring cylinders as opposed to glass cylinders to avoid breakages and being cut by broken glass in case of an accident.
- *The procedure or method* to be followed should show clearly what quantities will be varied at will and quantities that vary as a result and how each will be measured. Quantities to be held constant and their values should be known in advance.
- *Repeated readings.* In order to improve the reliability of results obtained, very often, it is necessary to make repeated readings and find the average.

  For example, if you wish to determine your heart beat rate in number of beats per second, it is better to measure the number of beats in **1 minute** then divide the time obtained by 60.

  For example, if your heart makes 72 beats in 1 minute, then your heart beat rate is $\frac{72}{60} = 1.2$ beats per second.

  72 beats in one minute are easier to measure than 1.2 beats in one second.

1.2 The structure of a scientific investigation

The following is the general structure of a standard scientific investigation or experimentation.

- **Aim of the experiment:**

  This is a brief and concise statement of the objective of the experiment. It is derived from the hypothesis initially stated.

  For example, "*An experiment to show that the rate of cooling of a hot body is higher at higher temperatures than at lower temperatures*".

- **Apparatus/Equipment:**

  In this section, all the apparatus to be used are identified and listed.

- **Procedure/Method:**

  In this section, a step-by-step account of what is to be done, how it will be done and what quantities will be measured is outlined.

  A well-labelled diagram showing the setup of all the apparatus to be used is drawn in this section.

  The quantities to be varied, those to be measured and those that will be kept constant should be indicated together with their constant values clearly indicated in the procedure.

  Statements on how the results will be analyzed, for example, by drawing a graph or performing calculations are included.

- **Results:**

  Results of measurements (including tables, graphs and calculations) are shown in this section.

  The results of an investigation should, where convenient, be presented in table form showing all the quantities measured and the units used to measure them. If a graph is to be drawn, the columns of the independent and dependent quantities should be shown. If only calculations are required, the columns of the calculated quantities should be indicated.

- **Analysis:**

  The results of the investigation are discussed here. If a graph has been drawn, it should be discussed with the aim (objective) of the investigation in mind. The usual points of discussion of a graph are: -

  (i) *The trend of the graph:* For example decreasing or increasing curve or decreasing or increasing straight line graph.

(ii) *The gradient of the graph.* Sometimes the quantity you are investigating may be related to the gradient of the graph in same way.

(iii) *Area under the graph.* The area under the graph may sometimes be related to the quantity of investigation in some way.

- **Conclusion:**

  The results of the analysis are carefully stated, noting the limitations (boundary conditions) of the experiment. Sources of error should also be discussed and improvements suggested. Finally, the conclusion should discuss the extent to which the aim (and the hypothesis) has been achieved.

1.3 Sample scientific investigation 1

In order to clearly show and explain how each of the above skills is acquired, we will consider an observation made by a F1 student and show how it can be investigated following the steps above.

- *Observation:* A Senior 1 student observed that when he put two firmly closed glass bottles full of water in the fridge: one in the freezer compartment and the other in the cooling compartment, the bottle in the freezer compartment was broken and the water had frozen to ice while the bottle in the other compartment was intact though the water had cooled down below room temperature.

  The student decided to apply what he had learnt about expansion and contraction of solids and liquids when they are heated and cooled, respectively, and realized that there was a contradiction between his observation and the expectation. He expected the volume of water in each bottle to decrease as the water cooled. His observation seemed to suggest that the water in the bottle had expanded as it turned to ice.

  He came up with following hypothesis

- *Hypothesis:* Water expands as it turns to ice and occupies a greater volume than when it was in liquid state.

  The student designed and conducted an experiment and filled the following report:

Experiment 1.1: To show that water expands when it freezes and becomes ice.

Apparatus:

- Two identical plastic measuring cylinders with 20 cm^3 of water each.
- A refrigerator

Method/Procedure:

- Fill two $25cm^3$ plastic measuring cylinders with water to the $20\ cm^3$ level at room temperature and put one in the freezer compartment of the fridge and the other in the lower cooling compartment of the fridge.
- Close the fridge and allow the water to cool until all the water in the freezer compartment turns to ice.
- Remove both cylinders at the same time and note the volume of the water in each of them.

Results

1. The water level in the cylinder from the lower compartment decreased slightly to below the $20\ cm^3$ mark.
2. The volume of the ice in the other cylinder from freezer compartment was more than $20\ cm^3$, as the level of the ice level had increased above the $20\ cm^3$.

Analysis

Since no water was added or removed from either cylinder while they were in the fridge, the fact that the level of the ice had risen showed that the volume of the original water had increased on freezing. This means that the water expanded on freezing.

Conclusion

The results obtained in this experiment supports the hypothesis

This leads to the conclusion that *water expands on freezing to ice.*

Strength of the evidence

This experiment was conducted only for water. There is no evidence to suggest that all other liquids behave the same way.

1.4 Sample scientific investigation 2

Senior 2 students were given an exercise to practice the use of a mass balance to measure mass and measuring cylinder to measure the volume of each of 4 different liquids. Their teacher recommended that they measure the mass and the volume of each liquid at least 4 times using different volumes of each liquid. The liquids were water, a salt solution, cow milk and a fruit juice.

While carrying out the exercise, two students noticed that for each liquid, the ratio $\frac{\text{mass}}{\text{volume}}$ was nearly the same for all portions of the liquids they used, and they alerted their teacher. The teacher suggested that they investigate this hypothesis with this help.

The formulated the following hypothesis:

Hypothesis

The ratio $\frac{\text{mass}}{\text{volume}}$ of a liquid is a constant for that liquid at a constant temperature.

They designed and conducted an experiment to investigate the hypothesis for water and filled the following report:

Experiment 1.2 To show that the ratio $\frac{\text{mass}}{\text{volume}}$ of water is a constant at room temperature.

Apparatus:

- A beaker
- A measuring cylinder
- A weighing balance
- Water

Procedure:

1. Determine the mass (m_e) of the empty measuring cylinder using the mass balance (Fig. 1.1).

Fig. 1.1: Measuring the mass

2. Add about 40 cm^3 of water to the measuring cylinder and determine the total

mass (m_t) of the cylinder together with water.

3. Determine the mass of water (m_w) put in the measuring cylinder using $m_w = m_t - m_e$
4. Repeat steps 1 – 3 for seven readings of volume by increasing the volume with about 40 cm^3 each time.
5. Record the results in a table as shown in Table 1.1.
6. Calculate the ratio of mass to volume i.e. $\frac{\text{mass}}{\text{volume}}$ for each set of values and enter in the table.
7. Draw a graph of mass against volume.
8. Determine the slope (gradient) of the graph.

Table of results

Average room temperature was 24°C.

Volume (cm^3)	Mass (g)	$\frac{\text{mass}}{\text{volume}}$ (g/cm^3)
41	41.9	1.02
80	81.3	1.02
122	123.9	1.02
161	162.8	1.02
201	203.2	1.01
244	249.9	1.02
281	283.2	1.01

Table 1.1

They obtain the straight line graph shown in Fig. 1. 2.

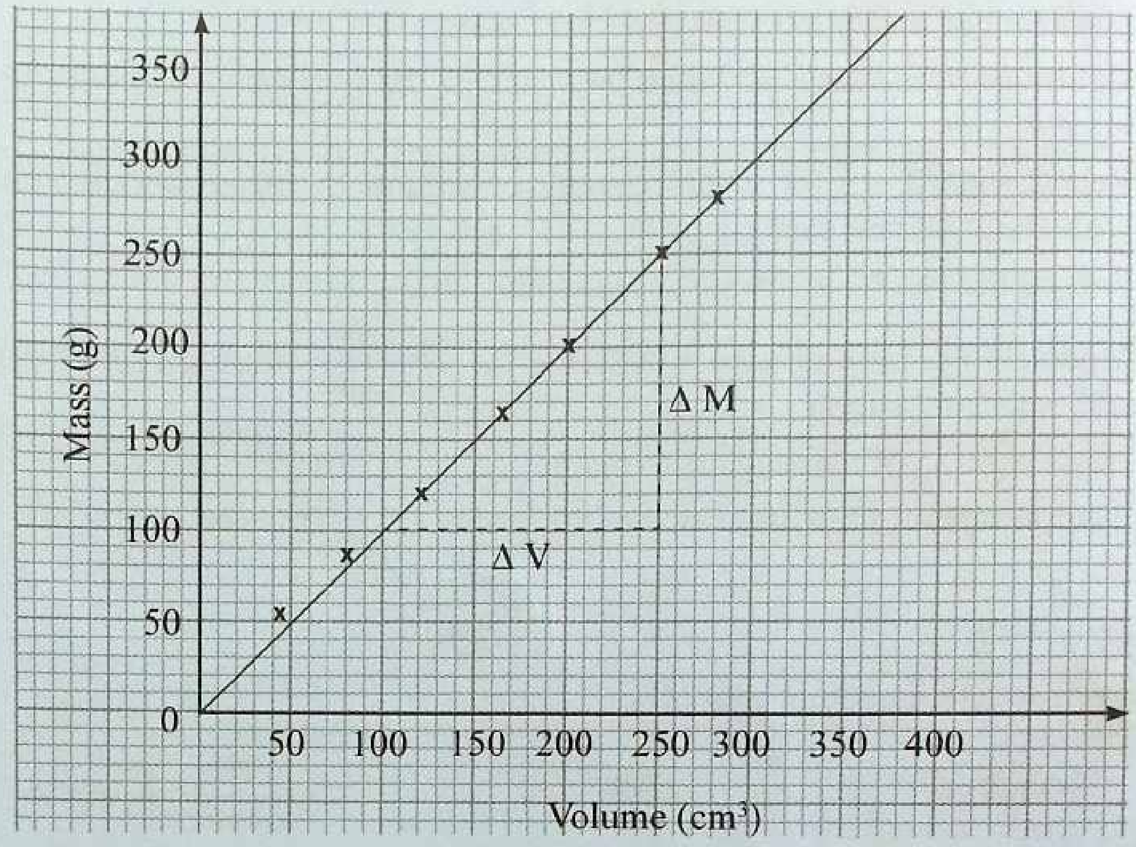


Fig. 1.2

The gradient = $\frac{\text{mass}}{\text{volume}} = \frac{(250 - 100)\text{ g}}{(250 - 100)\text{ cm}^3} = 1.00\text{ g/cm}^3$

This shows that $\frac{\text{mass}}{\text{volume}}$ of the liquid is a constant at 24°C.

Analysis

The results show that indeed the ratio $\frac{\text{mass}}{\text{volume}}$ for water is a constant at a given temperature.

Its average value = 1.0 g/cm^3 at 24°C.

Conclusion:

The ratio $\frac{\text{mass}}{\text{volume}}$ for water at 24°C is 1.02 g/cm^3.

This shows that, allowing for experimental error the hypothesis has been proved to be correct at 24°C.

Comment

The students gave the following comment:

We have only proved the hypothesis to be correct for water. We cannot generalize to include the other three liquids without conducting similar investigations.

However, after researching from books and journals, we found out that many experiments done by other physicists have generally shown the hypothesis to be true; for other liquids, within certain temperature ranges. The value $\frac{\text{mass}}{\text{volume}}$ is unique to the liquid chosen and is called the *density* of the liquid.

Activity 1

(a) Conduct a similar investigation for paraffin.

(b) Use the values you obtain to draw a graph of mass against volume. Your teacher will help if necessary. Draw the line of best fit through the points.

(c) Find the gradient of the line. Use it to determine the density of paraffin.

Note: It is always better to draw a graph than to find the average of a few pairs of values obtained in an experiment. This gives a more accurate value of the quantity being determined.

The line of best fit is an average of all possible pairs of results within a range. It is the preferred method of analyzing graphical data.

The possible sources of errors in the student experiment

Parallax errors - This occurs when the eye is not well positioned when reading the volume of the water in a measuring cylinder.

To minimize this, one should place the eye in the same horizontal level to the lowest point on the meniscus of water in the cylinder, and read the volume mark corresponding to this level on the cylinder scale. One should place the eyes as close as possible to the cylinder scale while reading the volume. See Fig. 1.3.

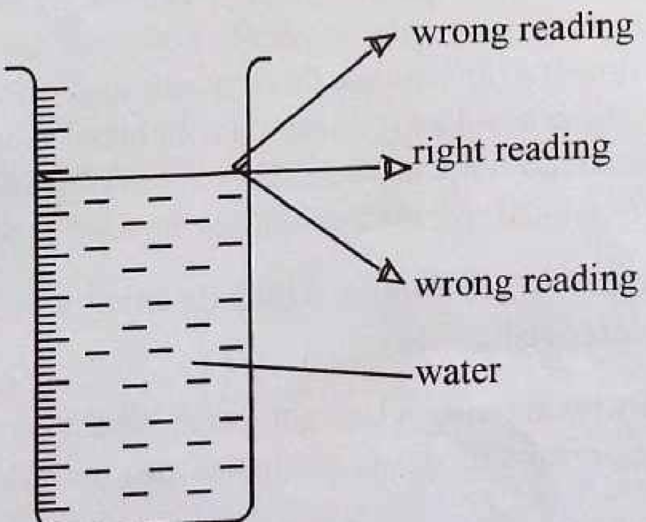


Fig. 1.3: Taking a reading on a measuring cylinder

Unit summary

- Scientific investigation is a systematic study of natural phenomena through observation and experiment.
- A standard science experiment should be structured into the aim, apparatus, procedure, presentation of results, analysis and conclusion.
- Independent variables are the variables you manipulate with suitable ranges of investigation.
- Dependent variables are those that you measure every time you change your independent variables.

Unit Test 1

1. List the six stages of a scientific investigation. [6]
2. Explain the meaning of the following words: [3]
   (a) Hypothesis.
   (b) Prediction.
   (c) Analysis.
3. List the six essential steps of a scientific experiment. [3]
4. You are asked to determine the density of iron. Design (plan) the investigation that you will conduct. In your plan include all the stages of a class experiment discussed in this unit. [6]
5. A student observed that when the room temperature is about 18°C, she felt cold and when she went outside where the temperature was 15°C, she felt even more cold. She formed the hypothesis: *"The rate of heat loss of a body is higher at higher temperatures than at lower temperatures"*. Carefully plan an experiment to investigate this hypothesis. You should be careful to note the quantities you will keep constant throughout in the experiment. It is expected that you will do some heating in your experiment. Indicate how you will plan for safety related to heat and heating in your experiment. [4]
6. Discuss three ways through which the quality of results from an experiment can be improved. [3]
7. Discuss why drawing a straight graph whenever possible is a better way of analyzing results than calculating an average value. [4]
8. Give four precautions on fire during a scientific experiment. [4]

UNIT 2: Thermal Expansion

Success Criteria

By the end of this unit, you must be able to;

- Deduce that different solids and liquids expand by different amounts when heated equally.
- Explain that different gases expand by the same amount when heated equally.
- Describe the various applications of expansion of solids, liquids and gases.
- Explain the effect of sudden expansion and contraction of an object.

2.1 Thermal expansion and contraction

In general, nearly all substances increase in size when heated. The increase in size on heating of a substance is called *expansion*. On cooling, substances decrease in size. The decrease in size on cooling of a substance is called *contraction.* Why is this so?

Expansion and contraction in solids

Experiment 2.1: To demonstrate expansion and contraction using a thin metal rod

Apparatus

- Thin metal rod
- Rollers connected to a pointer
- Source of heat
- G-clamp

Procedure

- Clamp one end of a long thin metal rod tightly to a firm support, with end of the rod resting on a roller fitted with a thin pointer (see Fig. 2.1).

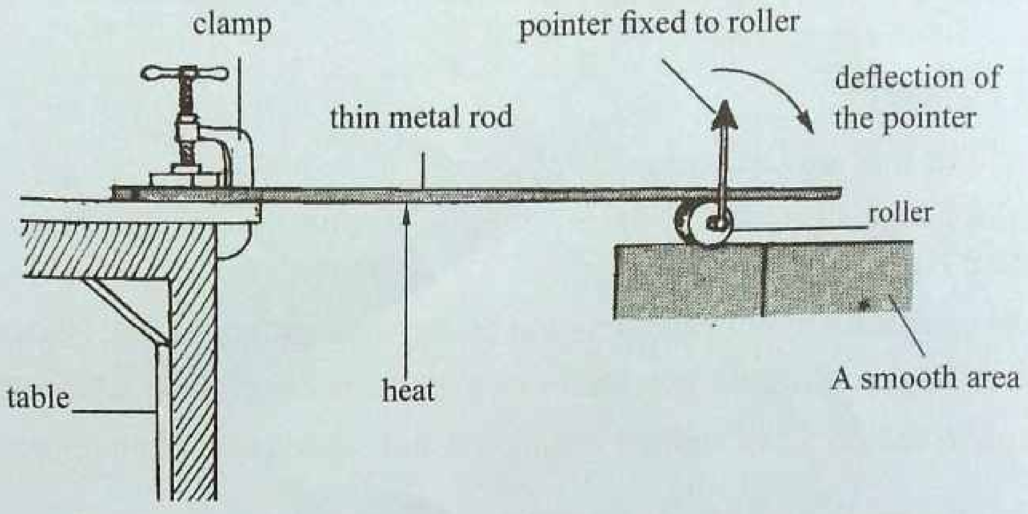


Fig. 2.1: Expansion and contraction of thin metal rods.

- Heat the metal rod for some time and observe what happens.
- Remove the burner and allow the rod to cool. Observe what happens.
- Repeat the experiment with thin metal rods of different materials and observe what happens.

Observation

- The pointer deflects in the clockwise direction on heating and in the anticlockwise direction on cooling.
- The pointer deflects to different extents depending on the material.

Discussion

On heating, there is an increase in length (expansion) in the rods. The expanding rod moves the roller to the right making the pointer attached to the roller to deflect in the clockwise direction. On cooling, the rod contracts and decreases in length. The contracting rod moves the roller to the left hence the pointer deflects in the opposite direction (anticlockwise direction).

Conclusion

- Solids expand on heating and contract on cooling.
- Different metals expand and contract to different extents when heated by the same quantity of heat.

Experiment 2.2: To demonstrate expansion and contraction using the bar and gauge apparatus

Apparatus

- A bar and gauge apparatus
- Bunsen burner

Introduction

A bar and gauge apparatus consists of a metal bar with a suitable wooden handle and a gauge. When both the metal bar and the gauge are at room temperature, the bar just fits into the gauge. (See Fig. 2.2)

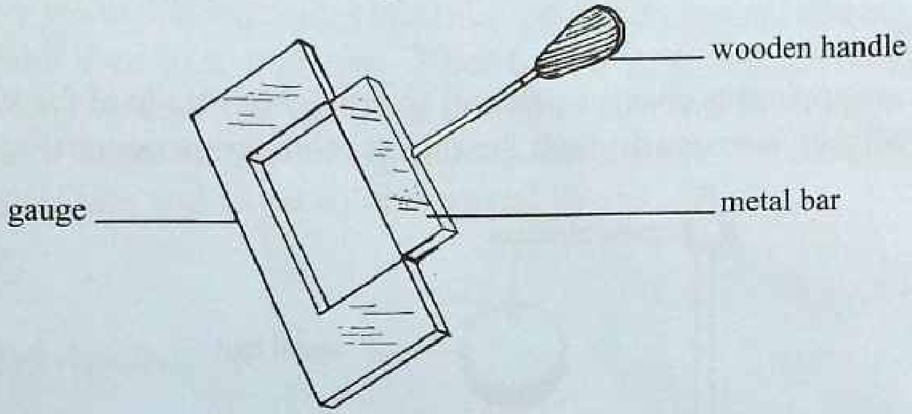


Fig. 2.2: Bar and gauge apparatus

Procedure

- Move the metal bar into and out of the gauge at room temperature (Fig. 2.2). Observe what happens.
- Keep the metal bar away from the gauge and heat the bar for some time.
- Try to fit the bar into the gauge and observe what happens.
- Allow the bar to cool and try to fit it into the gauge. What happens?

Observation

- At room temperature, the bar fits exactly into the gauge.
- On heating, the metal bar does not fit into the gauge; it is larger.
- The metal bar again easily fits into the gauge on cooling.

Discussion

- On heating, the metal bar expands. There is an increase in length and therefore, the bar cannot fit into the gauge.
- On cooling, the bar easily fits into the gauge due to contraction.

Conclusion

Solids expand on heating and contract on cooling.

Experiment 2.3: To demonstrate expansion and contraction using the ball and ring apparatus

Apparatus

- A ball and a ring
- Bunsen burner
- A bowl of cold water

Introduction

A *ball and ring* apparatus consists of a ball and ring, both made of the same metal. The metal ball can *just* pass through the ring at room temperature (Fig. 2.3).

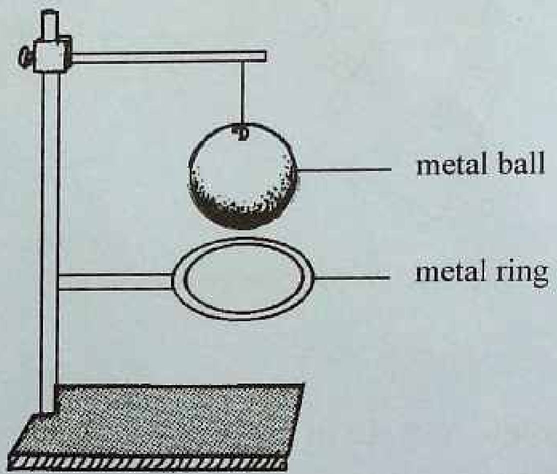


Fig. 2.3: Ball and ring apparatus

Procedure

- Move the ball in and out of the metal ring at room temperature (see Fig. 2.3).
- Keep the metal ball away from the ring and heat it for some time.
- Try to pass the ball through the ring. What do you observe?
- Cool the metal ball in a bowl of cold water and try to pass the ball through the ring again. What do you observe now?

Observation

- At room temperature, the ball passes through the ring.
- On heating, the ball does not go through the ring.
- On cooling, the ball goes through the ring again easily.

Discussion

- On heating, the metal ball expands. There is an increase in volume and the ball cannot pass through the ring.
- On cooling, contraction occurs and the original volume is regained. The ball can now pass through the ring again.

Conclusion

Solids expand on heating and contract on cooling.

Why solids expand on heating

In Form 1, we learnt that molecules of a solid are closely packed and are continuously *vibrating* about their fixed positions. When a solid is heated, the molecules vibrate with larger amplitude about the fixed position. This makes them to *collide* with each other with larger forces which pushes them far apart. The distance between the molecules increases and so the solid expands.

Expansion of liquids

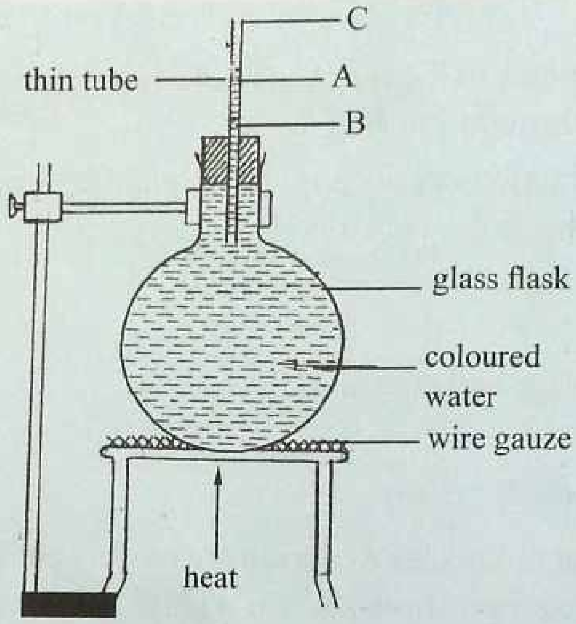
Experiment 2.4: To demonstrate expansion of a liquid

Apparatus

- A glass flask
- Coloured water
- Tripot stand
- A rubber stopper
- Bunsen burner
- Wire guaze

Procedure

- Fill a glass flask with coloured water.
- Fit the flask with a rubber stopper carrying a long narrow glass tubing.
- Note the initial level of water in the glass tube before heating (Fig. 2.4).



- Heat the water in the flask. Observe what happens to the level of water at A immediately the heating starts and after a few minutes.

Observation

At first the level of the coloured water in the tube drops to level B and then rises to level C.

Discussion

On heating, the glass flask expands and its volume increases. The level of water drops from A to B. Water starts to expand when the heat reaches it. Its level rises up the tube from B to C.

If the set up is allowed to cool to below room temperature, the water level drops to a point lower than A and B.

Conclusion

Liquids expand on heating and contract on cooling.

Why liquids expand on heating

Molecules are loosely packed in liquids. The force of attraction between the molecules is weaker than in solids. The molecules move freely in the liquid. On heating, the speed of the molecules increases. The collisions between the molecules increases the distance between them causing the liquid to expand.

Expansion of gases

Experiment 2.5: To demonstrate expansion of air

Apparatus

- A thin glass flask
- A rubber stopper
- A long narrow glass tube

Procedure

- Take a thin glass flask with an open top.
- Close the flask with a rubber stopper carrying a long narrow glass tube.
- Invert the flask so that the glass tube dips into water in a container. What do you observe? (Fig. 2.5).

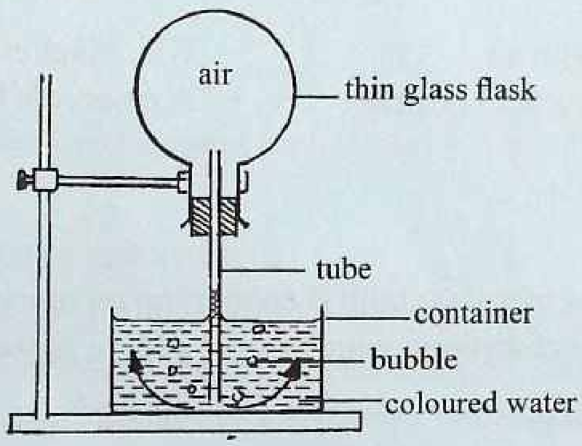


Fig. 2.5: Expansion of air

- Place your hands over the flask to warm it for sometime and observe what happens.
- Remove your hands on the flask and wait for sometime. Observe what happens.

Observation

- The water level rises from the container into the glass tube on inverting the flask to dip the glass tube in water.
- When the flask is warmed, the level of water in the tube drops and some bubbles are seen escaping from the flask through the tube.
- On removing the hands from the flask, water level rises the glass tube again.

Discussion

The water level in the glass tube drops due to expansion of the air in the flask when the flask is warmed. The water level rises in the tube due to contraction of air on cooling.

Conclusion

Gases expand on heating and contract on cooling.

Why a gas expands on heating

The force of attraction between the molecules of a gas is very small (almost negligible) and the distance between the molecules is large compared to solids and liquids. The molecules move freely in all directions. When a gas is warmed, the molecules gain more energy and move far apart hence volume increases. Different gases expand by the same amount when heated equally.

Experiment 2.6: To demonstrate expansion of gases

Apparatus

- A glass bulb B with air
- A metre rule in vertical position
- Steam
- Glass jacket
- A reservoir R with mercury

Introduction

The apparatus consists of a glass bulb B containing mercury. Bulb B is surrounded by the outer glass jacket through which steam can be passed.

Procedure

- Set up the apparatus as shown in Fig. 2.6.

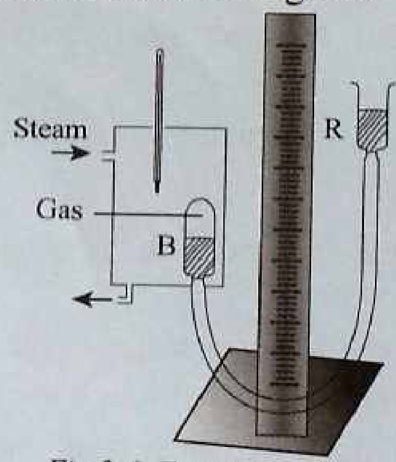


Fig 2.6: Expansion of gases

- Circulate water at 0° C through the jacket and adjust reservoir R so that the level of mercury in B and R is the same.
- Measure the volume of air (gas) in bulb B.
- Pass the steam through the jacket until the temperature is constant.
- Adjust the level of mercury in B and R until they are the same. Measure the

volume of air in B.

- Repeat the experiment with different gases and observe what happens.

Observation

- On passing cold water at 0°C, the volume of the air in bulb B reduces.
- The volume of air increases on passing the steam through the glass jacket.

Discussion

The volume of air reduces on passing cold water at 0°C through the glass jacket due to contraction of air .

The volume increases on passing the steam through the glass jacket due to expansion of air.

Conclusion

Gases contract on cooling and expand on heating.

2.2 Effects of thermal expansion

Solids expand on heating and contract on cooling. During such expansion or contraction, the distance between the molecules changes. This is due to the change in vibration of the molecules. If the free movement of these molecules is *restricted*, a large force is developed.

Experiment 2.7: To demonstrate the force due to expansion using bar breaking instrument

Apparatus

- A bar breaking instrument
- A bunsen burner
- A strong steel bar
- A cast iron pin

Procedure

- Pass a cast iron pin (about 6 mm in diameter) through hole H_1 across the steel bar.
- Clamp the steel bar onto bar breaking instrument tightly with the screw from the inside until there is no room for expansion as shown in Fig. 2.6.

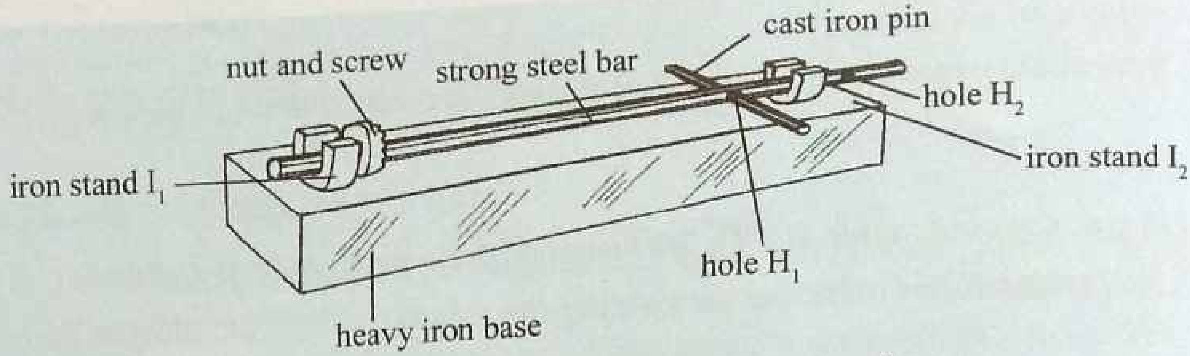


Fig. 2.6: Bar breaking instrument — expansion

- Heat the rod strongly, and observe what happens to the cast iron pin.

Observation

The cast iron pin breaks abruptly.

Discussion

The cast iron pin breaks abruptly due to a very strong force developed when the steel bar expands.

Conclusion

Expansion produces a very strong force.

Experiment 2.8: To demonstrate the force due to contraction using a bar breaking instrument

Apparatus

- A bar breaking instrument
- A bunsen burner
- A strong steel bar
- A cast iron pin

Procedure

- Pass a cast iron pin through hole H_2 across the steel bar.
- Heat the bar then clamp onto the bar the cast iron pin tightly while it is still hot with the screw from the outside as shown in Fig. 2.7.

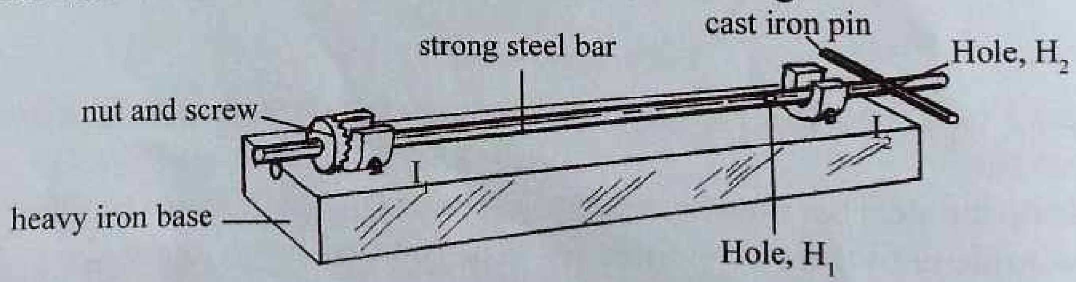


Fig. 2.7: Bar breaking instrument — contraction

- Remove the flame and allow the steel bar to cool down. Observe what happens to the cast iron pin as the bar cools down.

Observations

The cast iron pin breaks abruptly.

Discussion

The cast iron pin breaks abruptly due to a very strong force developed when the steel bar contracts.

Conclusion

Contraction develops a very strong force.

Bimetallic strip

Experiment 2.9: To demonstrate the bending effect of expansion and contraction

Apparatus

- A bimetallic strip
- Bunsen burner

Note: When equal lengths of two different metal strips are riveted together, the resulting compound bar is called a *bimetallic strip*.

Procedure

- Observe a bimetallic strip at a room temperature (Fig. 2.8).

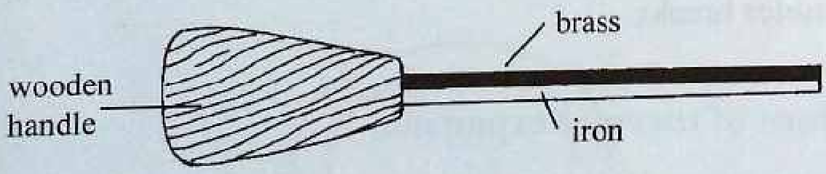


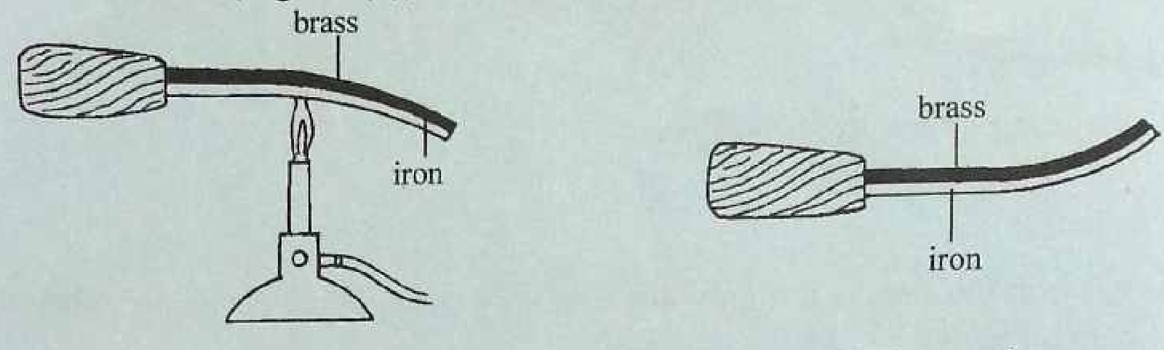
Fig. 2.8: A bimetallic strip

- Take the bimetallic strip with the brass strip at the top and heat it with a bunsen burner flame for some time.
- Remove the flame and allow the bar to cool. Observe what happens.

Observations

- As the temperature increases, the bimetallic strip bends downwards with the brass strip outside. (Fig. 2.9(a)) Why does this happen?

- As the temperature decreases, the bar bends upwards with the iron strip underneath. (Fig. 2.9(b)) What has happened?



(a) On heating (b) On cooling

Fig. 2.9: Bending effect of expansion and contraction

Discussion

As the bimetallic strip is heated, brass expands more than iron. The large force developed between the molecules of brass forces the iron strip to bend downwards. On cooling, the brass contracts more than iron and the iron strip is forced to bend upwards.

Conclusion

The force developed during expansion or contraction causes a *bending effect*.

The force due to expansion in glass

You may have observed that when boiling water is poured into a thick-walled glass tumbler it may break suddenly. Why does this happen? This is because the inside of glass gets heated and expands even before the outside layer becomes warm. There is an unequal expansion between the inside and the outside surfaces. The force produced by the expanding molecules on the inside produces a large strain in the glass and the tumbler breaks.

2.3 Applications of thermal expansion

The effect of expansion and contraction, though on one hand is a nuisance, is quite useful on the other hand. The following are some of the applications.

Electric thermostats

A *thermostat* is a device made of a bimetallic strip that can be used to maintain a steady temperature in electrical appliance such as an electric iron box, refrigerator, electric geyser, an incubator, a fire alarm and an automatic flashing unit for indicator lamps of motor cars. Fig. 2.10 and 2.11 show two such devices.

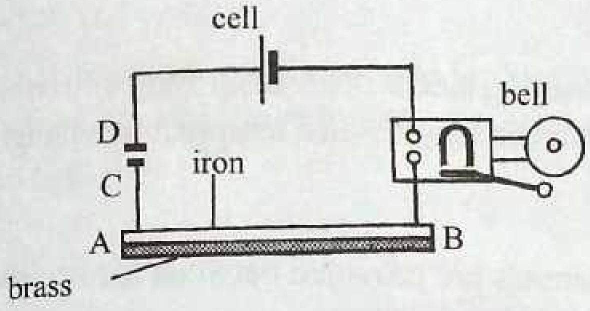


Fig. 2.10: Fire alarm

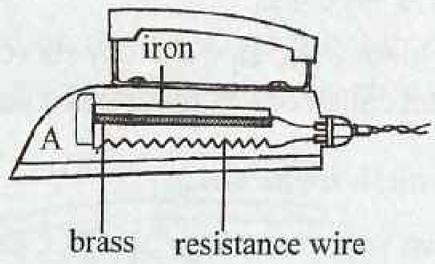


Fig. 2.11: Electric iron box

Caution!: Conserve energy by switching off the socket after using electrical appliances.

Rivets

In industries, steel plates are joined together by means of *rivets*. Hot rivets are placed in the rivet holes and the ends hammered flat. On cooling the force of contraction pulls the plates firmly together (Fig. 2.12).

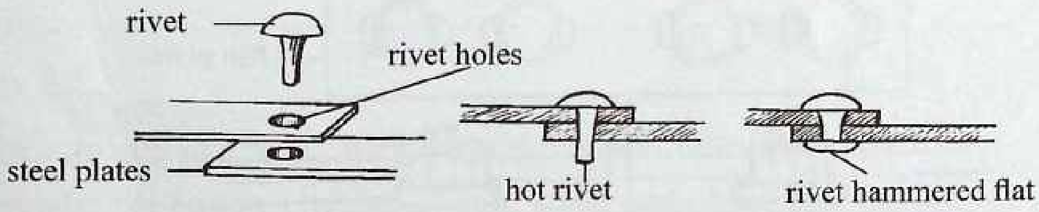


Fig. 2.12: Rivets

Expansion joint

Metal pipes carrying steam and hot water are fitted with *expansion joint* or *loops*. These allow the pipes to expand or contract easily when steam or hot water passes through them or when the pipes cool down. The shape of the loop changes slightly allowing necessary movement of the pipes to take place (Fig. 2.13).

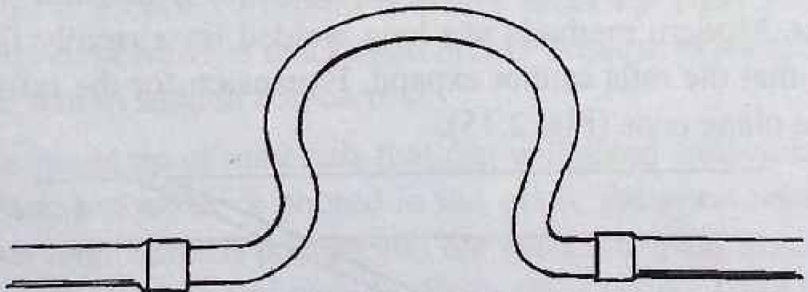


Fig. 2.13: Expansion joint

Loosely fitted cables

Telephone and electricity cables are loosely fitted between the poles to allow room for contraction in cold weather.

Use of alloys

The *measuring tape* used by surveyors for measuring land is made of an alloy of iron and nickel called *invar*. Invar has a very small change in length when temperature changes.

Expansion channels

When *concrete roads are laid*, expansion channels are provided between the sections along the length of the road.

Gaps in railway tracks

Gaps are left between the rails when the railway tracks are laid. The rails are joined together by *fish-plates* bolted to rails. The oval shaped bolt holes allow the expansion and contraction of the rails when the temperature changes (Fig. 2.14).

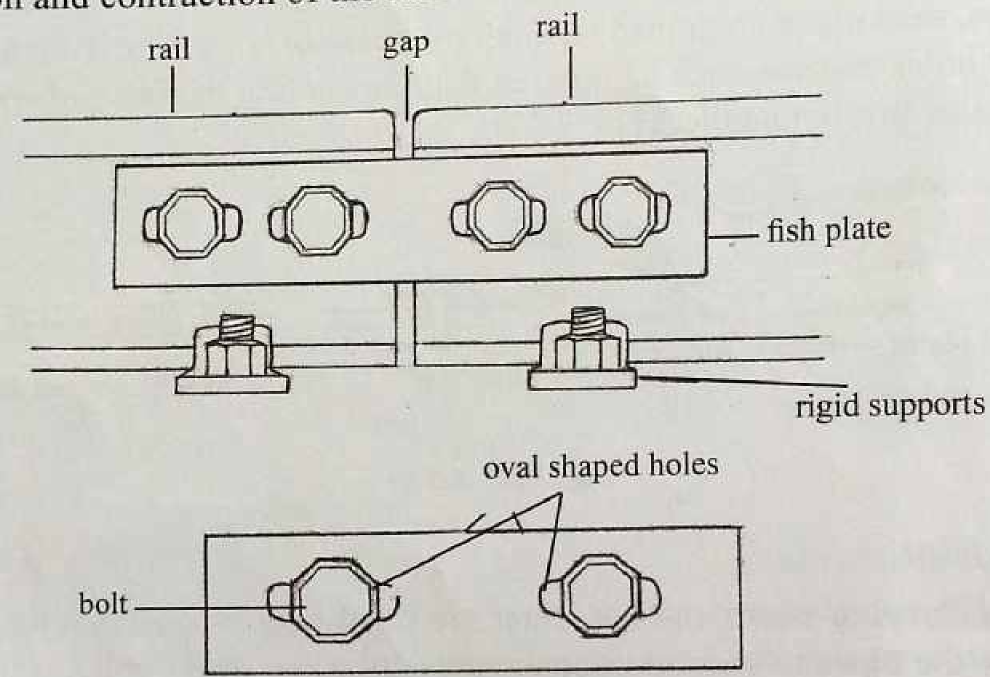


Fig. 2.14: Gaps left between rails

In very hot weather, the gaps may not be enough if the expansion is large. The rails may *buckle* out. Modern methods use long welded lines rigidly fixed to the beds of the track so that the rails cannot expand. Expansion for the rails is provided by overlapping the plane ends (Fig. 2.15).

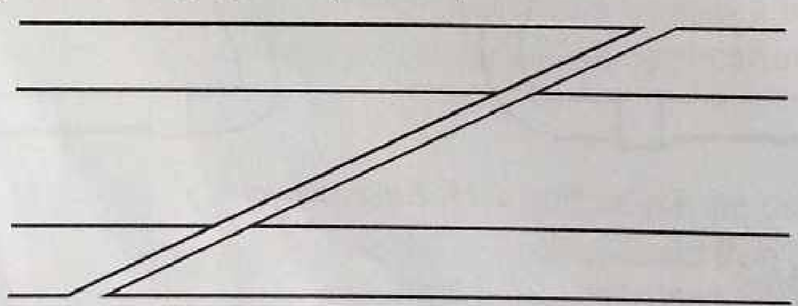


Fig. 2.15: Overlapping joints

Rollers on bridges

The ends of steel and concrete bridges are supported on rollers. During hot or cold weather, the change in length may take place freely without damaging the structure (see Fig. 2.16).

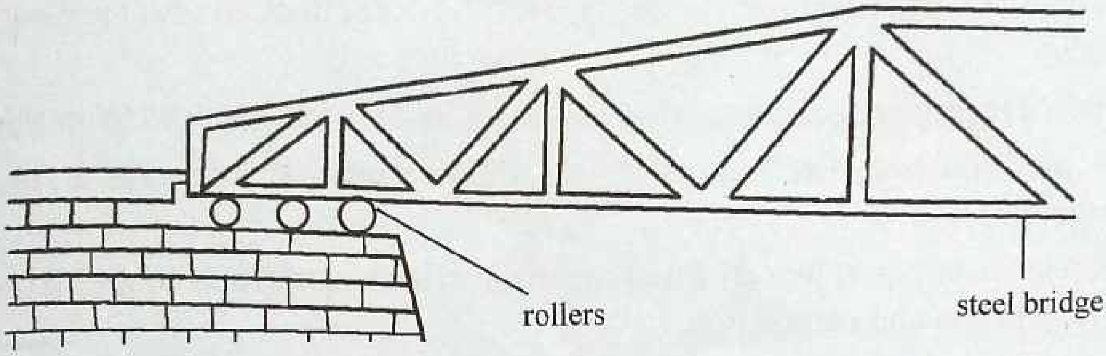


Fig. 2.16: Steel and concrete bridges are supported on rollers

Effects of sudden expansion and contraction

Activity 2.1

(a) Place an egg in a water bath. Heat the bath till the water boil.

(b) Transfer the egg to a beaker of cold water and observe. What happens to the egg?

In Activity 2.1, you must have noticed that, the egg cracks when transferred instantly from hot water to cold water.

Sudden expansion and cooling of an egg causes the shell to crack.

If the same is repeated with a stone, the stone cracks or breaks due to shock and strain resulting from cooling and expanding.

When hot liquid is emptied from an ordinary drinking glass and the glass is immersed in very cold water, it cracks and breaks because of shock and strain on glass molecules due to sudden contraction.

A pyrex glass is made up of materials that can withstand sudden expansion and contraction. When hot water is poured in the glass, the glass material expands uniformly. When cold water is poured into the glass, the glass material contracts uniformly both on the inside and outside. This safeguard the glass from cracking and breaking.

Unit summary

- Thermal expansion is the increase in size and shape of an object when heated.
- Solids expand most followed by liquids and then gases on heating.
- Thermal expansion and contraction causes some force that can result in bending effect.
- Thermal expansion and contraction causes some force that can lead to breaking.
- Electric iron box, fire alarms have a thermostat that maintain a steady temperature.
- Loop in water pipes, loosely fitted cables, overlapping railway line give room for expansion and contraction.
- Sudden contraction and expansion can cause breaking and cracking.

Unit Test 2

1. Gaps are left between the rails to allow [1]
   - A. Contraction of the rails in winter.
   - B. Expansion of the rails in summer.
   - C. Expansion of the rails in winter.
   - D. Contraction of rails in summer.
2. Electric cables are loosely fitted between the poles to allow [1]
   - A. Expansion and contraction of cables easily.
   - B. Conduction of electricity.
   - C. Contraction of electric cables in winter.
   - D. Expansion of cables at night.
3. Steel bridges are fitted with the rollers at one end to allow [1]
   - A. Expansion of bridge in summer.
   - B. The bridge to be stable.
   - C. Contraction of the bridge in winter.
   - D. Expansion and contraction to avoid strain.

Study the diagram in Fig. 2.17 and answer the questions 4 and 5.

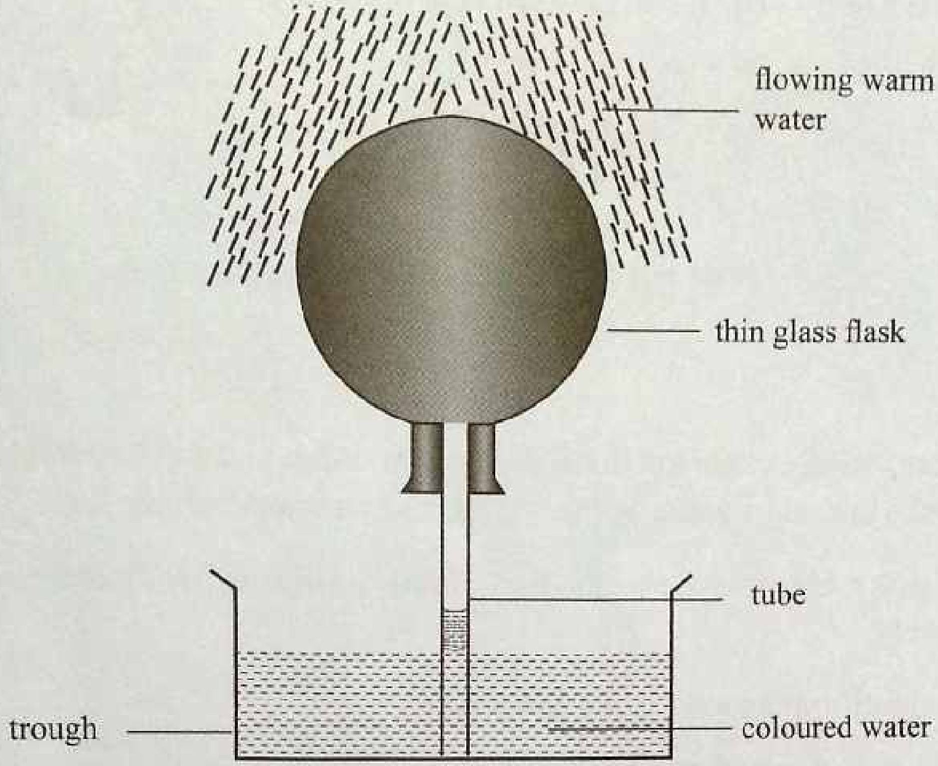


Fig. 2.17

4. What will happen immediately after warm water starts to flow on the flask? [2]

- **A.** Water level in the tube rises.
- B. Water level in the tube falls.
- C. Water level in the tube remain the same.
- D. Coloured water starts to boil.

5. What will happen warm water flows for sometime on the flask? [2]

- **A.** The water level on the trough reduces.
- B. Coloured water evaporates.
- C. Water level in the tube remain the same.
- D. Water level in the tube decrease or drops.

6. Explain, in terms of particles behaviour, why solids expand on heating. [1]

7. **(a)** What is an electric thermostat? [1]

(b) Give three devices in daily life where a thermostat is used. [1]

(c) Explain the action of one of the devices you have chosen. [1]

8. Fig. 2.18 shows a bimetallic strip made of brass and invar.

Describe briefly how it can be used as a thermometer (Fig. 2.18). [3]

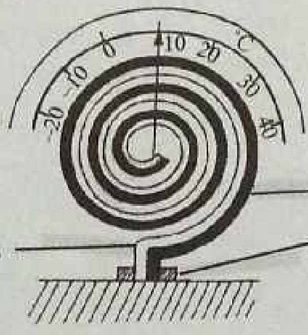


Fig. 2.18

9. Suggest, a single experiment, to demonstrate that alcohol expands more than an equal volume of water for the same rise in temperature. [4]

10. Name four electric devices that need a bimetallic strip to function effectively. [4]

11. Give scientific reasons for the following: [4]

    (a) If a mercury thermometer with a thick glass bulb is dipped into hot water, the mercury level first drops slightly and then rises quickly in the bore.

    (b) If boiling water is poured into a thick walled glass vessel, the vessel may crack.

    (c) The mouth of a glass bottle is gently heated when the glass stopper is rigidly stuck to the mouth.

    (d) Water pipes burst in cold weather when water freezes.

UNIT 3 Density

Success Criteria

By the end of this unit, you must be able to:

- Define density.
- Determine the densities of various objects.
- Relate the densities of substances to their states.
- Explain the effect of temperature changes to the density of a substance.
- Explain why some substances sink and others float on water.
- Describe average density.

3.1 Density

In form 1, we learnt that matter has mass and occupies space. What is the relationship between its mass and volume?

Experiment 3.1: To investigate the relationship between mass and volume of water

Apparatus

- A measuring cylinder
- A beam balance
- Water

Procedure

(a) Measure the mass (m_o) of an empty measuring cylinder on a beam balance.

(b) Pour 20 cm^3 of water into the measuring cylinder. Measure the new mass (m_n) of measuring cylinder and its content.

(c) Determine ($m_n - m_o$), to get the mass of the water.

(d) Repeat procedure (c) and (d) for 40 cm^3, 60 cm^3, 80 cm^3 and 100 cm^3 of water. Record your observations in table 3.1.

Note: The temperature of the set-up must be kept constant.

Volume of water (cm^3)	0	20	40	60	80	100
Mass of water ($m_n - m_o$)(g)						
$\frac{\text{mass}}{\text{volume}}$ (g/cm^3)						

Table 3.1

Observation

The ratio of mass to volume for each quantity of water is constant.

Conclusion

The ratio of mass to the volume of a quantity is known as the density of the substance, is a constant.

The density (symbol) of a substance is defined as mass per unit volume of the substance. Density is therefore, a derived quantity of mass and volume. The SI unit of density is the *kilogram per cubic metre (kg/m^3)*. It is also expressed as g/cm^3.

$$\text{Density} = \frac{\text{mass}}{\text{volume}}$$

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

Experiment 3.2: To determine the density of an irregular solid

Apparatus

- An irregular stone
- A beam balance
- Measuring cylinder with water

Procedure

- Measure the mass (m) of the stone using a beam balance.
- Determine the volume (V) of the stone using displacement method.

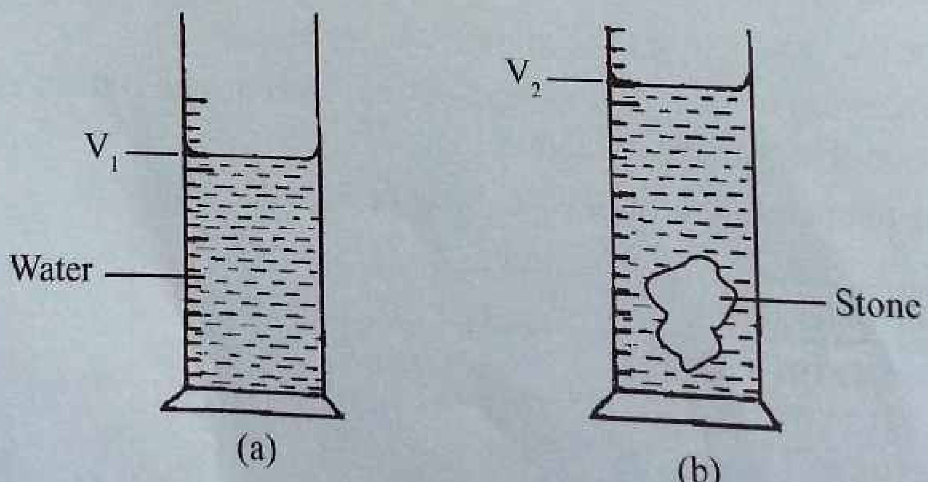


Fig. 3.1: Measuring volume of a stone

$V = V_1 - V_2$ Where V_1 is the initial volume

V_2 is the final volume

$V = V_1 - V_2$

- Determine the density () of the iron stone.

$$\text{Density} = \frac{\text{mass (m)}}{\text{volume (v)}}$$

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

Conclusion

Using this method, the density of a solid is given by:

$$\text{Density} = \frac{\text{mass}}{\text{volume}}$$

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

Experiment 3.3: To determine the density of a regularly shaped solid

Apparatus

- An iron block (a 3 cm by 4 cm by 2 cm cuboid)
- A beam balance
- A metre rule

Procedure

- Measure the mass (m) of the cuboid iron block using a beam balance.
- Measure the length (l), width (w) and thickness (h) of an iron block using the metre rule.
- Calculate the volume of the cuboid.

  $V = l \times w \times h$

Conclusion

The density of a regularly shaped solid is given by:

$$\text{Density} = \frac{\text{mass of the solid}}{\text{volume of the solid}}$$

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

Experiment 3.4: To determine the density of a liquid

Apparatus

- A measuring cylinder
- A liquid (water)
- A beam balance/electronic balance

Procedure

- Measure the mass (m_1) of a clean empty and dry measuring cylinder.
- Carefully pour the liquid (water) into a measuring cylinder and find the total mass (m_2) of the measuring cylinder and the liquid.
- Find the mass of water using, ($m_2 - m_1$).
- Determine the volume, (V) of the liquid using the measuring cylinder.
- Determine the density of the water as

$$\text{Density} = \frac{\text{mass}}{\text{volume}} = \frac{(m_2 - m_1)}{V}$$

- Compare the value of density with the known density of water ($1 g/cm^3$)

Conclusion

Using this method, the density of the liquid is given by:

$$\text{Density} = \frac{\text{mass}}{\text{volume}} = \frac{(m_2 - m_1)}{V}$$

Experiment 3.5: To determine the density of gases (air)

Apparatus

- A beam balance
- A measuring cylinder
- Known masses
- A bicycle pump
- A plastic container

Procedure

- Measure the mass (m_1) of a large plastic container (of capacity approximately 20 *l*) using the beam balance as shown in Fig. 3.2.

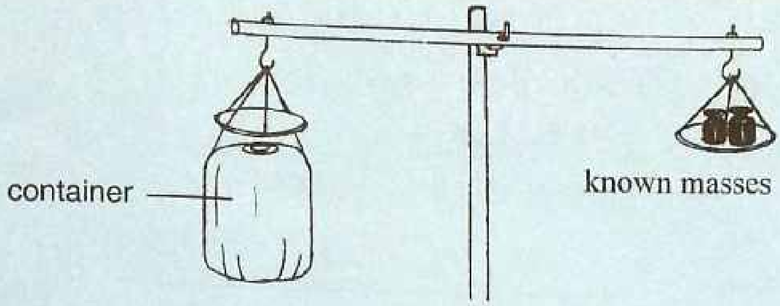


Fig. 3.2: Measuring mass of air

- Pump air into the plastic container, say about 130 strokes of a foot pump or a bicycle pump, in order to get an appreciable mass of air.
- Measure the mass of the container and the extra air pumped in, m_2. Calculate the mass of air pumped $(m_2 - m_1)$.
- Using a 1 000 cm^3 measuring cylinder, collect 800 cm^3 of the air from the container as shown in Fig. 3.3.

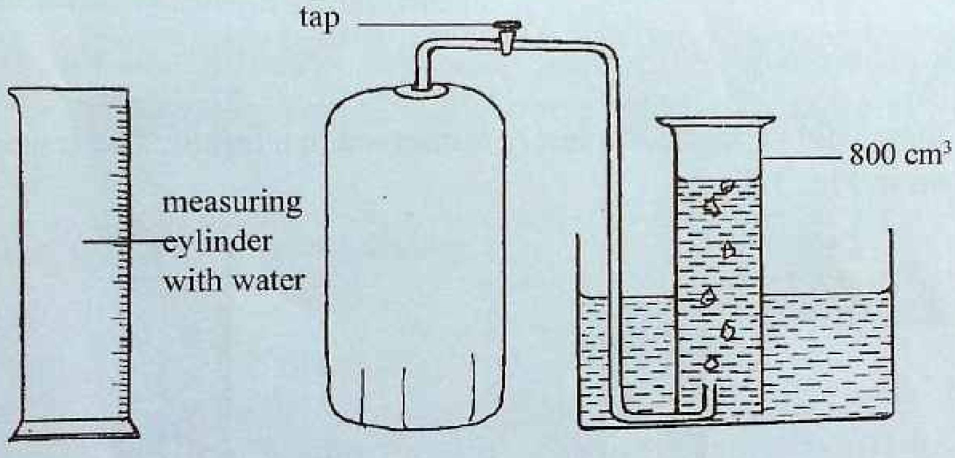


Fig. 3.3: Measuring volume of air

- Once you have collected 800 cm^3 of air, close the tap and repeat the experiment until no more air is released.
- Calculate the total volume (v) of the air by adding the volume of the air collected each time.
- Determine the density of the water as

$$\text{Density} = \frac{\text{mass}}{\text{volume}} = \frac{(m_2 - m_1)}{V}$$

- Compare this with the standard density of air at the same temperature (e.g 0.997 g/cm^3 at 25°C).

Conclusion

Using this method, the density of air is given by:

$$\text{Density} = \frac{\text{Mass of air}}{\text{Volume of air}}$$

$$= \frac{(m_2 - m_1)}{\text{Total volume of air collected}}$$

Density of alloys

An alloy is a metallic substance made by melting two or more pure metals together in a given proportion. If there is no change in volume when the metals combine, the density of the alloy can be found from the densities of the metals used to make it. The density of the alloy lies somewhere between the densities of the metals used to make it.

Example 3.1

A stone of mass 0.04 kg was completely immersed in a liquid. The levels of liquid are as shown in Fig. 3.4.

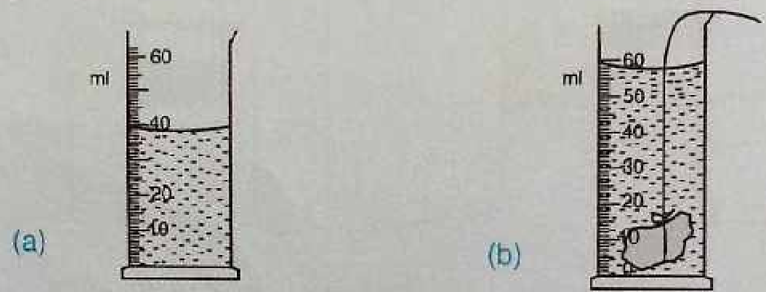


Fig. 3.4

Calculate; **(a)** the volume of the stone in cubic centimetres

(b) the density of the stone in kilograms per cubic metre.

Solution

Volume of liquid displaced = 60 – 40 = 20 ml = 20 cm^3

(a) Volume of the stone = volume of the liquid displaced

= 20 cm^3

(b) $$\text{Density} = \frac{\text{Mass}}{\text{Volume}} = \frac{0.04 \times 1\,000}{20}$$

$$= \frac{40}{20} = 2 \text{ g/cm}^3$$

$$1\text{ g} = \frac{1}{1\,000}\text{ kg},\ 1\text{ cm}^3 = \frac{1}{1\,000\,000}\text{ m}^3$$

$$2\text{ g/cm}^3 = \frac{2}{1\,000}\text{ kg} \div \frac{1}{1\,000\,000}\text{ m}^3$$

$$= \frac{2}{1\,000} \times \frac{1\,000\,000}{1}\text{ kg/m}^3$$

$$= 2\,000\text{ kg/m}^3$$

Density of the stone is 2 000 kg/m^3

Note

To change the density from g/cm^3 to kg/m^3 we simply multiply by 1 000.

Densities of some common substances

Table 3.2 shows that different substance have different densities. What other observations can you make from the table among states of matter and within a state of matter.

State of matter	Substance	Density	
		kg/m^3	g/cm^3
Gas	Hydrogen Air	0.089 9 1.293	0.000 089 9 0.001 293
Liquid	Paraffin Paraffin wax Ice Water Mercury	800 890 900 1 000 13 600	0.8 0.89 0.9 1.0 13.6
Solid	Cork Brick Glass Aluminium Zinc Iron Invar Brass Copper Silver Lead	180 1 300 2 500 2 700 7 100 7 500 8 000 8 500 8 930 10 500 11 300	0.18 1.3 2.5 2.7 7.1 7.5 8.0 8.5 8.93 10.5 11.3

Table 3.2: Densities of states of matter

Example 3.2

A cube of iron of sides 4 cm has a mass of 512 g. Find:

(a) The volume of the cube in m^3

(b) The density of iron in (i) g/cm^3 (ii) kg/m^3

Solution

(a) Volume $= 4\ 4\ 4 = 64\ cm^3$

$$1\ cm^3 = \frac{1}{1\ 000\ 000}\ m^3$$

$$64\ cm^3 = \frac{64}{1\ 000\ 000} = 0.000\ 064\ m^3$$

(b) (i) $$\text{Density} = \frac{\text{Mass}}{\text{Volume}} = \frac{512\ g}{64\ cm^3}$$

$$= 8.0\ g/cm^3$$

(ii) $$\text{Density} = 8\ \ 1\ 000\ kg/m^3$$
$$= 8\ 000\ kg/m^3$$

Exercise 3.1

1. A cube of iron of sides 4 cm has a mass of 1 024 g. The density of iron in g/cm^3 is.
   - A. 4.0
   - B. 8.0
   - C. 12.8
   - D. 16.0
2. The dimensions of a room are 16 m by 4 m by 4 m. The volume of the air contained in this room in m^3 is.
   - A. 64
   - B. 256
   - C. 128
   - D. 16
3. Define density and state its SI unit.
4. Density of copper is 8 900 kg/m^3, express the density in g/cm^3.
5. Describe how you can determine the density of a glass stopper.

6. A block of iron has dimensions 4.2 cm 3.4 cm 5.0 cm. It has a mass of 535.5 g. Calculate
   (a) the volume of the block in cm^3
   (b) the density of block in g/cm^3
7. The density of aluminium is 2.7 g/cm^3. What is the mass of aluminium of volume
   (a) 1 cm^3 (b) 6 cm^3
   (c) 20.5 cm^3 (d) 0.35 cm^3?
8. The density of a substance is 1.3 g/cm^3. What is the volume of a piece of the substance which has a mass of
   (a) 53 g (b) 4.09 g
   (c) 0.93 g (d) 3.1 kg?
9. Ice has a density of 0.9 g/cm^3 and water has a density of 1 g/cm^3. Which has a larger volume; a 15.3 g mass of water or 15.3 g mass of ice?
10. Which has the greater mass, 23 cm^3 of glass or 7 cm^3 of brass? (Take the density of glass as 2.5 g/cm^3 and that of brass as 8.5 g/cm^3).
11. The length of a room is 16.4 m, its width is 4.5 m and its height is 3.3 m. What volume of air does the room contain?
12. Gold has a density of 19.3 g/cm^3. A cube of gold measures 4.3 cm on each edge. Calculate the (a) volume of gold. (b) mass of gold.
13. The density of a brick is 1.3 g/cm^3. Find (a) the mass of a cube of solid brick of side 4.7 cm (b) volume in m^3 of 45 kg solid brick.

3.2 Comparison of densities of solids, liquids and gases

In solids, the molecules are closely packed and hence their densities are very high. In liquids, the molecules are loosely packed compared to solids hence their densities are lower than those solids. In gases, the molecules are far apart hence their densities are the least.

For example,

density of iron = 7 800 kgm^{-3}
density of water = 1 000 kgm^{-3}
density of air = 1.3 kgm^{-3}

3.3 Effects of temperature on density

When a solid is heated, its mass remains constant, while the volume increases. Since the density is the ratio of mass to volume of the substance, the density will decrease.

Since, density = $\dfrac{\text{Mass}}{\text{Volume}}$ i.e. as the volume increases, the density decreases.

3.4 Unusual expansion of water between 0°C and 4°C

We have learnt that solids and liquids expand on heating and contract on cooling. Unlike other substances, water has an unusual behaviour. This behaviour can be demonstrated in the following experiment.

Experiment 3.6: To demonstrate the unusual expansion of water

Apparatus

- A thermometer
- Ice cubes
- Water in the flask
- A source of heat

Procedure

- Set up the apparatus as shown in Fig. 3.5.
- At the beginning of the experiment, control the temperature of water in the flask to be 0°C.

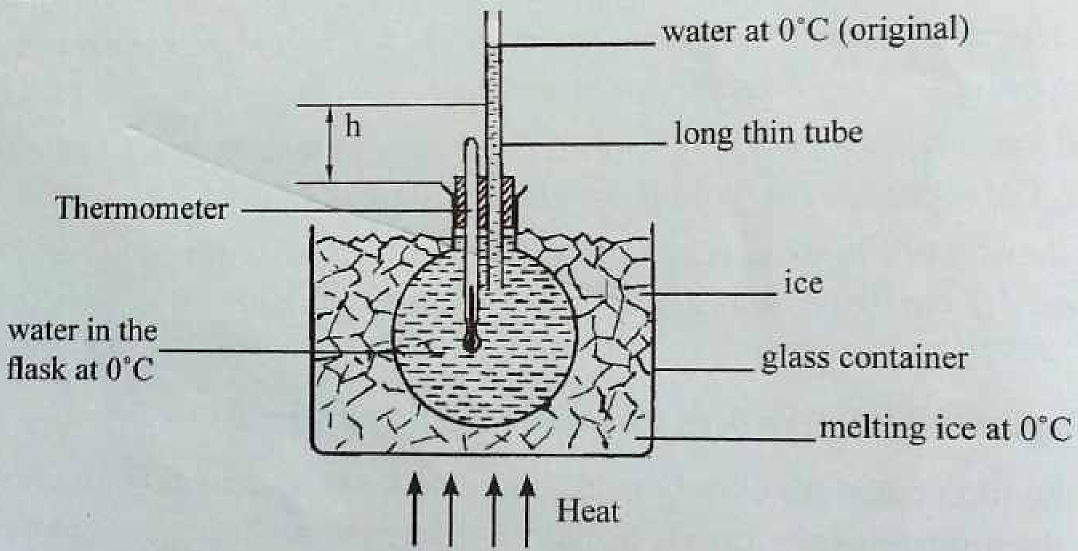


Fig. 3.5: Unusual expansion of water

- Carefully, note the original level of water in the tube at 0°C. (Since water is transparent, place a sheet of white paper behind the tube to mark the level).
- Heat the glass container gently and note the temperature reading on the thermometer.
- When all the ice in the container has melted the temperature of water in the flask increases very slowly to reach the room temperature.
- Continue heating while noting the temperature and the corresponding level

of water in the tube. Record the height, h, of water in a table (see Table 3.3).

Temperature (°C)	0	1	2	3	4	5	6	7	8	9	10	11	12
Height of water in the tube, h(mm)													

Table 3.3

Observation

On heating

- From 0°C to 4°C the water level in the tube drops.
- From 4°C and above, the water level in the tube rises.

Discussion

As the temperature of water increases from 0°C to 4°C, the level of water in the tube falls showing that water contracts on heating from 0°C to 4°C. After 4°C, the level of water in the tube rises showing that the volume of water increases on heating. At 4°C water has the minimum volume.

When a graph of the height of water in the tube against the temperature of water is drawn, it looks like the one shown in Fig. 3.6.

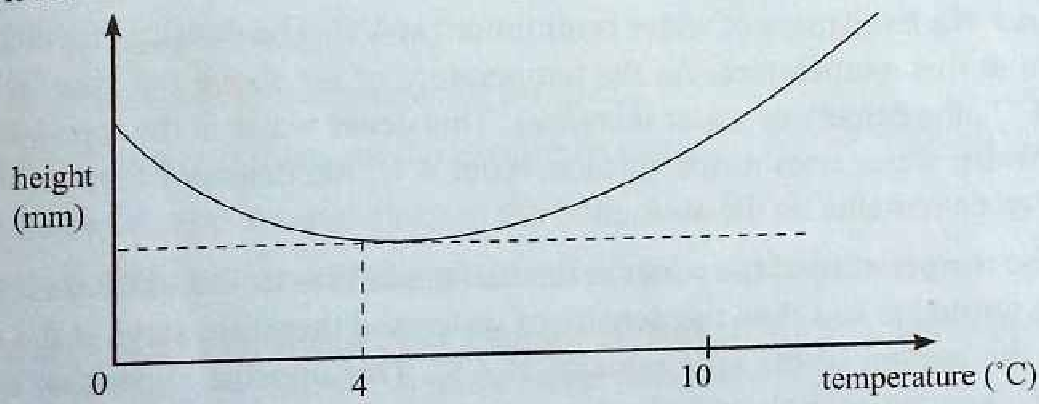


Fig. 3.6: Anomalous behaviour of water

This shows that : water does not expand in the same way as other substances the volume does not increase uniformly with temperature.

Between 0°C to 4°C, water contracts instead of expanding.

Conclusion

This unusual behaviour of water is also referred to as *anomalous expansion*. The molecules of water exist in groups and these groups arrange themselves so as to acquire the least volume at 4°C.

The effect of unusual expansion of water

Freezing of lakes and ponds

In cold weather, when the temperature of the atmosphere falls below 0°C, water in a lake or pond freezes and ice is formed. How do fish then survive in frozen water? The question can be answered by looking at the graph of density of water against temperature in the range 0°C to 10°C (Fig. 3.7).

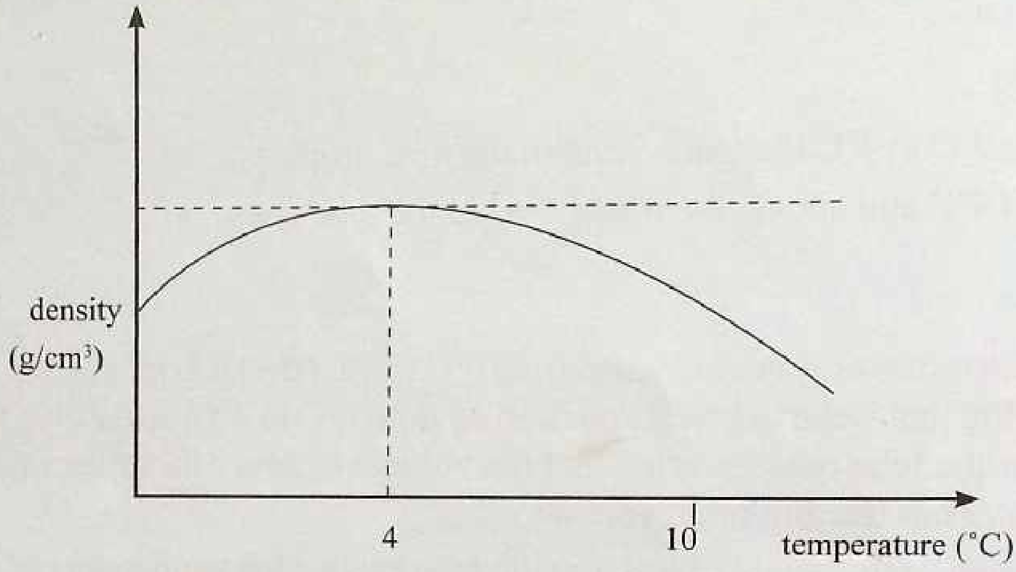


Fig. 3.7: Density of water against temperature

The volume of a fixed mass of water is minimum at 4°C. The density of water is then maximum at this temperature. As the temperature of air above the lake falls from 10°C to 4°C, the density of water increases. This dense water at the top sinks to the bottom. Warm water rises to the surface. After 4°C, the density of water becomes less and hence remains on the surface.

Finally, the temperature of the water at the surface falls to 0 °C and freezes. Density of the ice formed is less than the density of water and therefore stays at the top and water on the bottom of the lake remains at 4°C. This unusual expansion of water enables the aquatic animals and plants to survive in cold weather see Fig. 3.8.

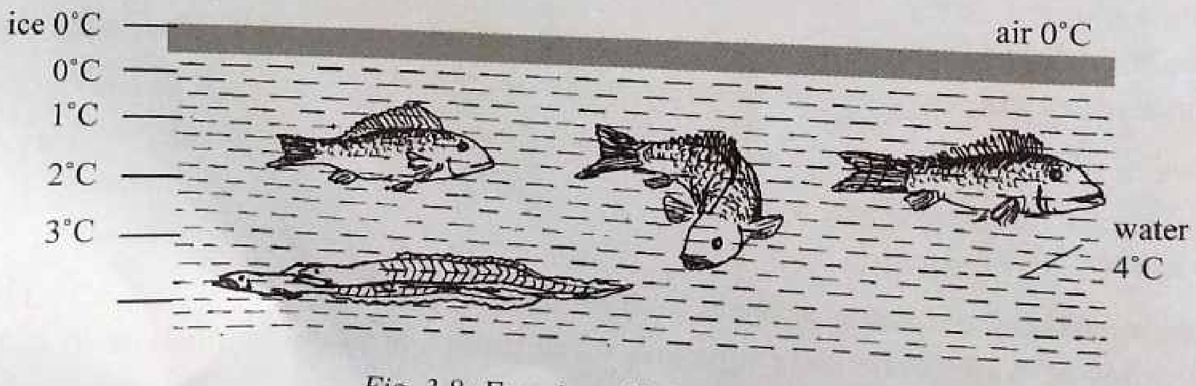


Fig. 3.8: Freezing of lakes and ponds

Bursting of water pipes

Water pipes can burst when the water flowing through the pipes freezes. This is because on freezing, the volume of water increases.

Weathering of rocks

When water freezes in the cracks of a rock, its volume increases. This causes the rock to break into small pieces resulting into weathering of rocks.

3.5 Floating and sinking

Activity 3.1

(a) Pour water into a drinking glass and place a stone on the surface of water. Observe what happens to the stone.

(b) Repeat step (a) with a piece of wood, small piece of copper metal and a cork. Observe what happens in each case.

(c) Compare the known densities of the objects you have used with that of water.

From activity 3.1, we observe that;

(i) The stone sinks to the bottom of the glass.

(ii) A piece of wood floats on the surface of water.

(iii) A piece of copper metal sinks to the bottom water.

(iv) A cork floats on the surface of water, it sinks in water.

If the density of an object is greater than the density of a water, the object sinks in the water. For example, a stone is more dense than water.

If density of an object is less than the density of a liquid, the object floats in the liquid. A piece of cork is less dense than water; the cork floats on water.

Activity 3.2

(a) Pour water in a glass and place a fresh egg on the surface of the water. (See Fig. 3.9(a)) Observe what happens to the egg.

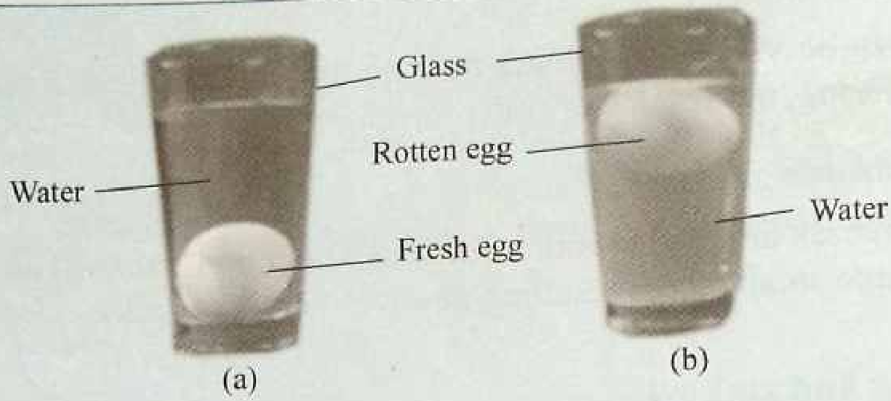


Fig. 3.9

(b) Repeat procedure (a) using a rotten egg. Observe what happens to the egg. (See Fig. 3.9(b))

From Activity 3.2, we note that:

A fresh egg sinks in water, therefore, it is more dense than water.
A rotten egg floats on water; thus it is less denser than water.

3.6 Average density

Average density is the ratio of total mass of all the materials used to compose a body to the total volume occupied by the same body.

Experiment 3.7: To determine the average density of iron.

Apparatus

- An iron pin
- Water
- An iron sheet

Introduction

The average density of a boat is less than the density of water.

Procedure

- Place an iron pin on water and observe what happens.
- Now, place the iron plate on the surface of the water and observe what happens.

Observations

- The iron pin sinks in water.
- The iron plate floats on water.

Discussion

Density of the iron pin is greater than the density of water, hence the pins sinks in water.

The hollow part of the plate contains air. Thus, the total mass of the plate (mass of air in the hollow part the mass of the iron making plate) is quite low in relation to the volume occupied by the plate.

In other words, the average density of the plate is lower than that of water hence it floats. The same phenomena enables ships to float on water yet they are made of heavy metals.

Unit summary

- Density is ratio of mass to volume i.e. Density = $\frac{\text{Mass}}{\text{Volume}}$
- SI unit of density is kilogram per cubic metre (kg/m^3)
- Density of a given mass of solid is greater than that of the liquid or gases of equal mass.
- An increase in temperature of a substance leads to a decrease in its density.
- At 4 °C, water has the minimum volume and maximum density.
- A substances sinks in a liquid if it has a higher density than that of the liquid and vice versa.
- Average density is the ratio of the total mass of all the materials composing a body to the total volume occupied by the body.

Unit Test 3

1. The SI unit in symbols of density is [1]

   A. g/cm^3 B. kg/cm^3

   C. m^3/kg D. kg/m^3

2. If the temperature of a substance increases, its density [1]

   A. Decreases B. Increases

   C. Remain the same D. Increases then decreases

3. A substance has mass, volume and density as its properties. Which properties may change if a lump of sugar is crushed? [1]

A. Volume
B. They remain constant
C. Mass
D. Density

4. Explain why a floating object may sink if the temperature of a liquid is raised. [1]

5. The following is a graph obtained in an experiment of heating water from °C to 10 °C. See Fig. 3.10.

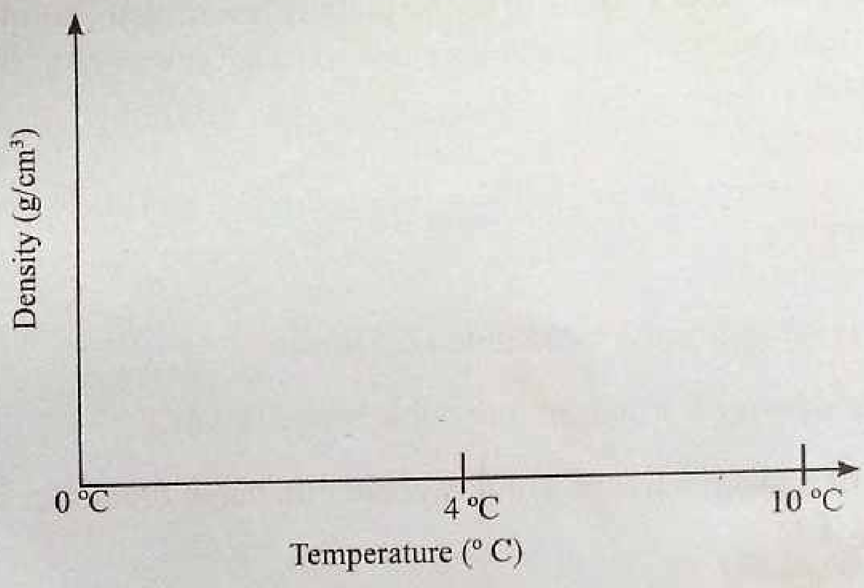


Fig. 3.10: A graph of density against temperature.

(a) Complete the graph by sketching the curve. [2]
(b) At which temperature will the volume be maximum? [2]

6. State four effects of unusual expansion of water. [4]

7. Explain why hydrogen gas is used in parachuts. [2]

8. Describe how you can determine if an egg is fresh. [5]

UNIT 4: Specific Heat Capacity

Success criteria

By the end of this unit, you must be able to:

- Differentiate heat capacity from specific heat capacity
- Demonstrate that different substances have different specific heat capacities
- Explain the importance of specific heat capacity.

Introduction

Heat is a form of energy that flow from a region of high temperature to a region of lower temperature. Cold substances absorb heat energy while hot ones lose heat energy. This unit deals with a measures of the capacities of substances to gain or loose heat energy.

4.1 Heat capacity

Experiment 4.1: To show that the heat energy required to produce a certain change in temperature depends on the mass of the substance

Apparatus

- A beaker
- An immersion heater
- A thermometer
- Water
- A measuring cylinder
- Stop watch

Procedure

(a) Take 200 g of water in a beaker and note its initial temperature θ_1. Heat the water with an immersion heater for 10 minutes (Fig. 4.1 (a)). Note the final temperature θ_2 and calculate the change in temperature, $\Delta\theta = \theta_2 - \theta_1$.

(b) Repeat (a) above by taking 400 g of water in the same beaker and same initial temperature θ_1 (Fig. 4.1 (b)). Note the time taken to produce the same change in temperature as before.

(c) Compare the times taken to produce the same change in temperature in parts (a) and (b). What is your conclusion?

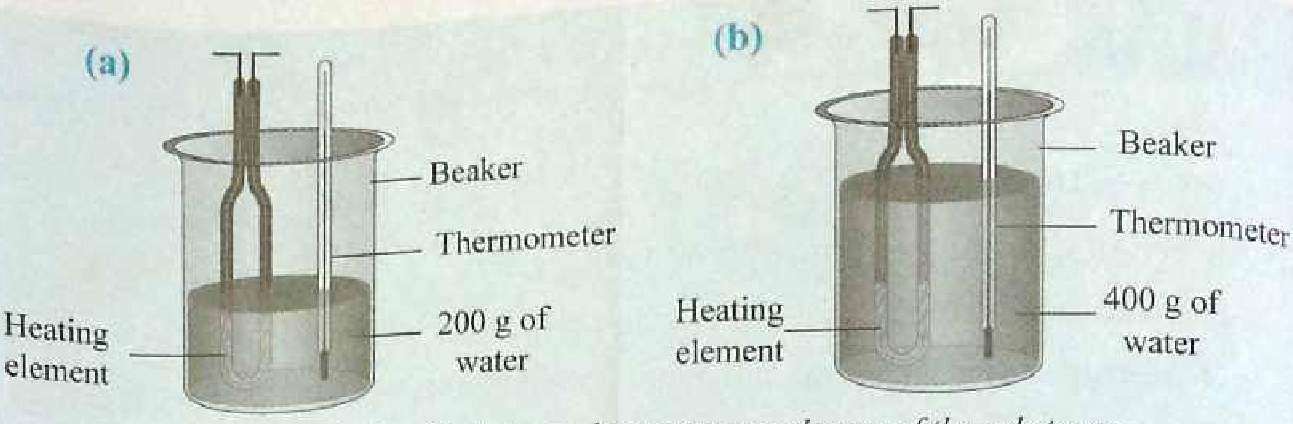


Fig. 4.1: Relationship between heat energy and mass of the substance.

Observation

You will observe that with 400 g of water, takes approximately double the time it takes to produce the same change in temperature in 200 g of water.

Conclusion

The larger the mass, the longer the time needed to change its temperature i.e. by 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 i.e. $Q \alpha m$, when temperature change is constant.

Experiment 4.2: To show that the heat energy required by a substance of a given mass depends on the change in temperature

Procedure

Repeat Experiment 4.1 part (a) with 200 g of water, but this time, heat to produce twice the change in temperature. Note the time taken for this to happen.

Observation

You will observe that it takes double the time to produce twice the change in temperature of 200 g of water.

Conclusion

The longer the time, the greater the temperature change. In other words, the longer the time of heating the mass of the substance, the more heat energy is supplied and the greater the temperature change. The quantity of heat energy Q gained by the substance is therefore directly proportional to the change in temperature $\Delta\theta$. Therefore,

Heat energy, Q is proportional to change of temperature, $\Delta\theta$, when mass of a substance is constant.

From Experiment 4.1 and 4.2, we see that

Quantity of heat, $Q \ \alpha$ mass, m

$Q \ \alpha$ change in temperature, $\Delta\theta$

$Q \ \alpha \ m\Delta\theta$ or

Example 4.1

200 J of heat energy is needed to change the temperature of a given mass of water from 20°C to 34°C. How much heat energy is needed to change the temperature of this mass of water from 20°C to 48°C.

Solution

Initial temperature change = (34 – 20) = 14°C

Final temperature change = (48 – 20)°C = 28°C

(Heat energy needed, Q) = ?

200 J raised 20° to 34°C, $\Delta\theta$ = 14°C

? will raise 20° to 48°C, $\Delta\theta$ = 28°C

Heat energy needed, $Q = \dfrac{200 \times 28}{14}$

$= 400$ J

Heat capacity

Heat capacity of a substance is 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 4.2

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

$$Q = C \times \Delta\theta$$

$$= 520\text{J} \times (39 - 9)\text{ K}$$

$$= 15\,600\text{ J}$$

Example 4.3

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

$$Q = C\Delta\theta \Rightarrow C = \frac{Q}{\Delta\theta}$$

$$= \frac{6\,200\text{ J}}{(65 - 10)\text{K}}$$

$$= 112.73\text{ J/K}$$

The heat capacity of water is 112.73 J/K

Exercise 4.1

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 given out to lower the temperature of a metal block of heat capacity 520 J/K from 60°C to 20°C.

Specific heat capacity

In the equation, $Q = mc\Delta\theta$, specific heat capacity $Q = c$, if $m = 1$ kg and $\Delta\theta = 1$ K. 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 a substance of mass 1 kg by 1 kelvin.

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

Therefore,

Quantity of heat = mass x specific heat capacity x 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/kgK).

Example 4.4

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/kgK.

Solution

Heat energy required = mass × specific heat capacity × temperature change

$$\begin{aligned} Q &= mc\Delta\theta \\ &= 2.5 \times 900 \times (40 - 20) \\ &= 45\,000 \text{ J} \end{aligned}$$

Example 4.5

18 000 J of heat energy is supplied to raise the temperature of a solid of mass 5 kg from 10°C to 50°C. Calculate the specific heat capacity of the solid.

Solution

$$\begin{aligned} c &= \frac{Q}{m\Delta\theta} \\ &= \frac{180\,000 \text{ J}}{(50 - 10)\text{K} \times 5 \text{ kg}} \\ &= 900 \text{ J/kgk} \end{aligned}$$

Example 4.6

Find the final temperature of water, if 12 000 J of heat is supplied by the heater to heat 100 g of water at 10°C.

(Take specific heat capacity of water and 4 200 J/kgk)

Solution

$$Q = mc\Delta\theta = \Delta\theta = \frac{Q}{m \times c}$$

$$= \frac{12\ 000 \text{ J}}{(0.1 \times 4\ 200) \text{ J/K}}$$

$$= \frac{12\ 000 \text{ J}}{420}$$

$$= 28.57°\text{C}$$

$\Delta\theta = \theta_f - \theta_i$, where θ_f – final temperature, θ_i – initial temperature

$\Rightarrow \theta_f = \Delta\theta + \theta_1 = 28.57° + 10°\text{C}$

$\theta_f = 38.57°\text{C}$

The final temperature is 38.57°C.

Exercise 4.2

1. 45 000 J of heat are supplied to 5 Kg of alluminium initially at 25°C. What is its final temperature? (Take the specific heat capacity of aluminium is 900 J/kgk).
2. What is the difference between heat capacity and specific heat capacity?
3. 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.

4.2 Comparison of specific heat capacities of the three states of matter

Substances have different specific heat capacities. Solids require a lot of energy to melt than liquids and gases. This means that solids have higher specific heat capacity than liquids and gases. Gases have the lowest specific heat capacity.

Experiment 4.3: To show different substances have different specific heat capacity

Apparatus

- Two thermometers

- A lid with two holes
- Two boiling tubes (one containing cooking oil and the other water)
- A hot water bath

Procedure

- Pour equal volume of liquids (cooking oil and water) into two identical test tubes. Place identical thermometers in each test tube (Fig. 4.2).

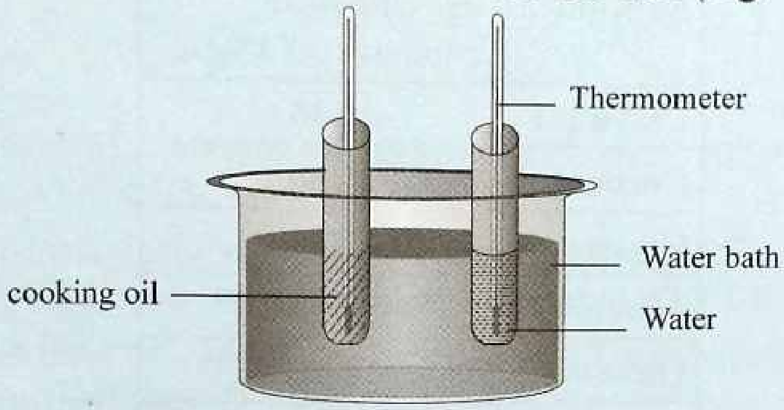


Fig. 4.2

- Heat the test tubes in a hotwater bath for the sametime and observe the temperature change.

Observation

The rise in temperature of liquid (cooking oil) is higher than that of water.

Discussion

The specific heat capacity of water is higher than that of cooking oil.

Conclusion

Different material or substances have different specific heat capacities.

Two different substances of the same mass when subjected to the same quantity of heat, they acquired different changes in temperature. Table 4.1 shows that different substances have different specific heat capacities.

Substance	Specific heat capacity (c) J/kgK
Aluminium	900
Brass	370
Copper	390
Cork	2 000
Glass	670
Ice	2 100
Iron	460

Lead	130
Silver and tin	230

Table 4.1: Specific heat capacities of some solids

Table 4.2 shows the specific heat capacity of some liquids

Substance	Specific heat capacity (c) J/kgK
Castor oil	2 130
Coconut oil	2 400
Glycerol	2 400
Mercury	140
Olive oil	2 000
Paraffin oil	2 130
Sulphuric acid	1 380
Water	4 200
Sea water	3 900

Table 4.2: Specific heat capacities of some liquids

4.3 Applications of specific heat capacity

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 alot 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 big change in temperature after 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 as for making handles of heating devices like kettles, pans and oven covers. This is because they do not get very hot and easily when they absorb high amounts of heat energy.

(f) Water consumed by human beings regulates the temperature of the body since water has a high specific heat capacity.

(h) Sea water is cold during day time when the temperature are high beacuse water has a high specific heat capacity. At night, the temperature of water is high and hot air of low density rises from the sea allowing cold air of high density blow from land to the sea called *land breeze*.

Unit 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, $Q = mc\Delta\theta$.
- To reduce heat loss to the environment, we cover the apparatus by;
    - Wool and a silver foil.
    - Placing a wood around it.
- If heat is not lost;

  Heat energy supplied = Heat energy gained

Unit Test 4

Where necessary, take specific heat capacity of water = 4 200 J/kgK, acceleration due to gravity g = 10 m/s^2.

1. The SI unit in of the symbol specific heat capacity is. [1]

   A. Kg/k B. J/kgk ✓

   C. N/kg/k D. W/kg/k

2. Calculate heat energy required to raise the temperature of 1 kg of gold of specific heat capacity of 130 J/kgk by 20°C is? [3]

   A. 130 J B. 260 J

   C. 2 600 J ✓ D. 65 J

3. What is the specific heat capacity of water is? [1]

   A. 420 J/kgk B. 4 200 J/kgk ✓

   C. 4.2 J/kgk D. 42 000 J/kgk

4. The formular of determining the quantity of heat in symbols is. [1]

A. $Q = m \times c \times \Delta\theta$ ✓ B. $Q = \frac{w}{t}$

C. $Q = c\,\Delta\theta$ D. $Q = m \times F$

5. Define the terms: [2]

(a) heat capacity

(b) specific heat capacity of a substance

6. Calculate the heat capacity if 8 000 J of heat is used to cool a solid from 80°C to 20°C. [3]

7. Calculate;

(a) the heat energy required to raise the temperature of 200 g of gold of specific heat capacity 130 J/kgK by 1 000 °C. [2]

(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/kgK. [3]

8. In experiment requiring storage of heat energy, water is preferred to other liquids. Give two reasons for this. [3]

9. Calculate the heat energy required to raise the temperature of 4 by of water from 25°C to 45°C. Specific heat capacity of water = 4 2000 J/kg°C. [3]

10. 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/kgk. [3]

11. 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. [3]

12. Explain why water is used as a coolant in many factories and car engines. [2]

13. Calculate the heat required to raise the temperature of 2 000 kg sea water through 60°C. [3]

14. Calculate the heat required to heat 0.5 kg of ice at $^-8$°C to staem 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 vapourisation of water = 2.26×10^6 J/kgk. [4]

UNIT 5: Heat Transfer

Success Criteria

By the end of this unit, you must be able to:

- Explain the transfer of heat in substances.
- Compare the rate of conduction of heat by different metal.
- Explain applications of heat transfer in everyday life.

5.1 Heat and temperature

In Form 1, we learnt that temperature is the measure of the kinetic energy of the molecules in a body. We know that molecules in boiling water (at 100°C) move faster than molecules in ice (to 0°C). This means that boiling water posses more energy than ice.

If hot water is poured into a bowl containing ice at 0°C, the temperature of ice and the bowl increases. The fact that the temperature has increased suggests that ice and the bowl have gained heat energy. *Heat is a form of energy which passes from a body of high temperature to a body of low temperature*. The SI unit of heat energy is joule (J).

The following experiment will enable us to understand the difference between heat and temperature.

Experiment 5.1: To investigate the difference between heat and temperature

Apparatus

- A measuring cylinder
- A beaker
- Cooking oil (about 200 g)
- Two test tubes
- A stirrer
- Water

Procedure

- Take equivalent masses of water and of cooking oil in two identical test tubes fitted with two identical thermometers. Place these tubes in a large beaker containing water (Fig. 5.1).

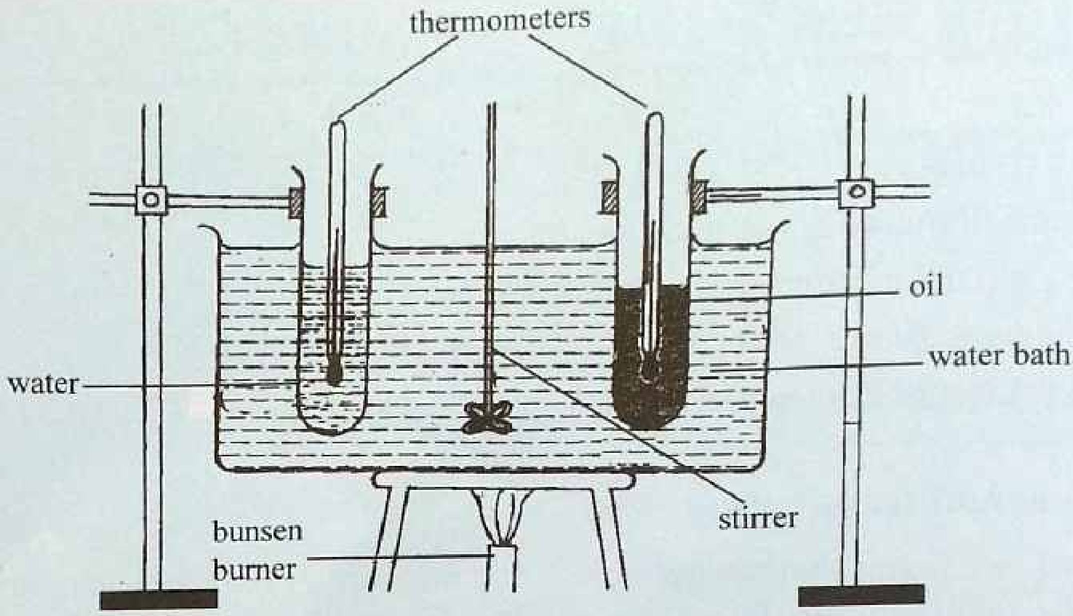


Fig. 5.1: Heat and temperature

- Note the initial temperature of both water and oil in the tubes.
- Heat the water in the beaker and make sure that the heat is distributed uniformly by stirring the water. After sometime, note the temperature of water and oil in the tubes. Are the two temperatures the same?

Observation

The temperature of water is lower than that of oil.

Discussion

You have heated the tubes for the same time i.e. the same heat energy has been passed from the burner to the tubes. Both oil and water have gained equal amount of heat energy but are at different temperatures. Therefore, two substances can have equal heat energy supplied but be at different temperatures.

Conclusion

Heat is the form of energy while temperature is the degree of hotness and coldness of a substance.

5.2 Modes of heat transfer

Activity 5.1

In form 1, we learnt that there are three mechanisms of heat transfer. Identify them. What are the main differences among them?

There are three modes of heat transfer namely: *conduction*, *convection* and *radiation*.

When water in a beaker is heated using a flame (Experiment 5.1), heat energy is transferred from the flame through the base of the beaker to water i.e. a *solid* is transferring heat energy from the flame to the cold water. This mode of heat transfer is called *conduction*. Mostly conduction results from transfer of energy from one particle colliding with the adjacent particle.

In Unit 4, we learnt that in the lake, the warm water containing more energy moves up and pushes cold water to the bottom of the lake, till the temperature falls to 4°C. This mode of heat transfer is called convection. In convection, heat energy is transported by the heated particles.

On a hot day, if you stand in the open air for some time, you feel warm. Heat energy is being transferred from the sun to your body. The heat from the sun can reach us although there is a vacuum between the sun and the earth. This mode of heat transfer is called radiation. Heat energy is transferred through electromagnetic waves.

5.3 Conduction

Conduction is the transfer of heat from one substance to another that is in direct contact with it. The following experiment will illustrate conduction of heat in solids.

Experiment 5.2: To investigate heat transfer in solids

Apparatus

- A metal spoon
- Bunsen burner
- A beaker full of boiling water
- Wax

Procedure

- Take a metal spoon at room temperature. Dip the spoon (with the other end waxed) into a beaker full of boiling water. After a few minutes touch the free end of the metal spoon outside water (Fig. 5.2). What has happened?

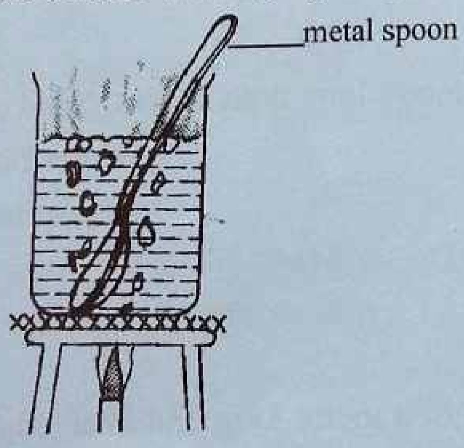


Fig. 5.2: A spoon inside boiling water

Observation

- The wax on the spoon outside the beaker melts.

Discussion

- The free end of the spoon outside the beaker has become hot. Heat energy has been transferred from the inside to the outside through the metal spoon i.e. from a region of *higher temperature* to a region of *lower temperature*.

Conclusion

Solids transfer heat from one point to another.

This process of transfer of heat energy in solids is called *conduction*. In conduction there is no visible movement of the heated particles.

Mechanism of conduction of heat

In Form 1, we saw that when temperature increases, the molecules have larger vibrations. This knowledge can help us understand the mechanism of conduction of heat. The molecules of the metal spoon inside hot water receive heat energy from the hot water and begin to vibrate vigorously. These molecules collide against the neighbouring molecules and agitate them. The agitated molecules, in turn, agitate the molecules in the next layer and so on till the molecules at the other end of the spoon are agitated. Thus the heat is passed from one place to another till the other end becomes hot. Hence, in *conduction,* energy transfer takes place by vibration of the molecules. There is no actual movement of the heated particles.

Factors affecting heat transfer by conduction

Experiment 5.3: To demonstrate that heat energy flows due to a temperature difference

Apparatus

- An iron bar about a metre long with holes drilled at equal intervals
- Oil
- Wooden screen
- A bunsen burner
- A thermometer
- Water bath

Procedure

- Take an iron bar about a metre long and drill small holes at equal intervals all along the length.

- Fill these holes partially with oil and insert the bulb of the thermometers into them. Note the readings of the thermometers.
- Pass one end of the bar through a wooden screen and insert it in a water bath containing water. Heat the water slowly and gradually (Fig. 5.3). After some time note, the temperature readings of the thermometers. What do you observe?

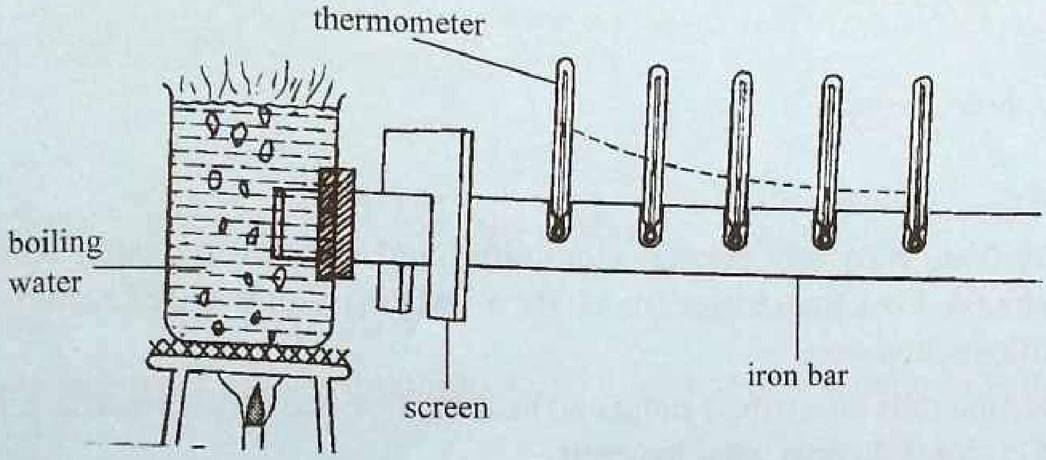


Fig. 5.3: The higher the temperature difference the higher the energy transferred

Observation

The thermometer nearest to the hot water bath registers the highest rise in temperature, and the one farthest away registers the least temperature rise.

Discussion

Initially the readings of all the thermometers were the same. When one end of the rod was inserted into boiling water, a large temperature difference was set up between the two ends and heat energy flowed from the region of higher temperature to that of lower temperature. Hence heat energy flows due to *temperature difference*.

If the experiment is repeated by replacing the hot water bath with a bunsen burner flame (temperature of the bluish part of the flame is about 500°C), the rise in temperature registered by each thermometer is higher. Hence the higher the temperature difference, the higher the energy transfer.

Conclusion

Heat energy in the solids flow due to the temperature difference. The higher the temperature difference, the higher the energy flow.

5.4 Comparing rate of conduction in metals

Experiment 5.4: To show that heat transfer depends on the material

Apparatus

- A copper rod
- Aluminium rod
- Wax
- A bunsen burner
- Iron rod
- 3 match sticks
- Tripod stand

Procedure

- Take three rods, say copper, aluminium and iron, of the same length and thickness. Fix a matchstick (or a light metal pin) to one end of each rod using a little melted wax.
- Place the rods on a tripod stand and heat the free ends with a burner as shown in Fig. 5.4. Observe what happens.

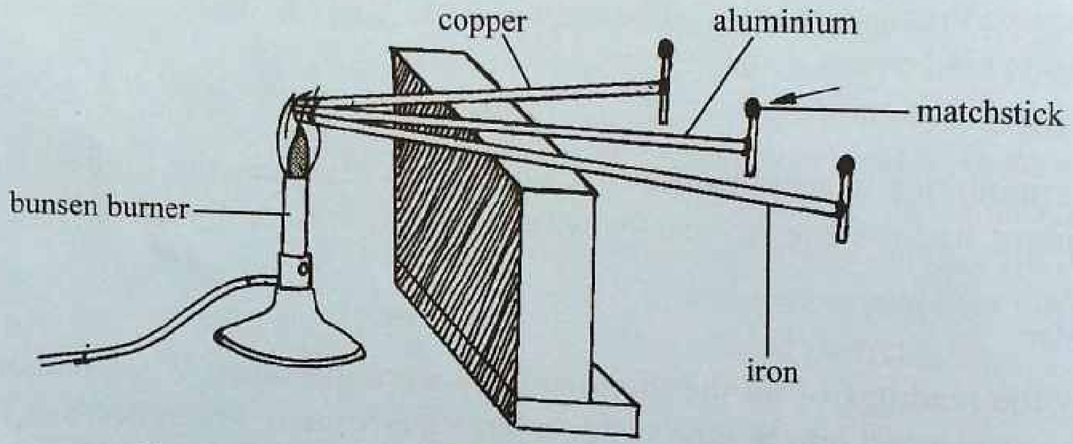


Fig. 5.4: Comparing heat transfer through different conductors

Observation

The matchstick falls off from the copper rod first then aluminium and finally from the iron rod.

Discussion

When the temperatures of the other ends of the rods reach the melting point of wax, the matchstick will fall off. The matchsticks do not fall off at the same time, because the energy transferred is not equal for all the rods. The matchstick from the copper rod is the first one to fall off showing that of the three metals, copper is the best conductor of heat followed by aluminium and then iron.

Conclusion

Different materials conduct heat at different rates.

Experiment 5.5: To show that heat transfer depends on the area of cross-section of the rod

Procedure

Repeat Experiment 5.4 with two rods of the same length and material but of different diameters. Observe what happens.

Observation

The matchstick from the thick rod falls off first.

Discussion

More heat energy is transferred through the thick rod than a thin rod in the same time.

Conclusion

Conduction of heat depends on the cross-section area of a material i.e. the thicker the material the faster the heat is transferred.

Experiment 5.6: To show that heat transfer depends on the length of the rod

Procedure

Repeat Experiment 5.4, with two rods of the same material and same thickness but different lengths. Observe what happens.

Observation

The matchstick from the short rod falls off first.

Discussion

Heat energy is transferred faster through a rod of smaller length than in a longer rod in the same time.

Conclusion

Conduction of heat depends on the length of the material.

Experiment 5.7: To show that heat transfer depends on the duration of heating

Apparatus

- A metal rod
- A bunsen burner
- A stop watch

Procedure

- Take a metal rod and heat one end of the rod with the bunsen burner flame. Note the temperature of the other end of the rod after five minutes.
- Continue heating and note the temperature after ten minutes. Is there any difference in the temperature recorded?

Observation

The rise in temperature after ten minutes is higher than compared to five minutes.

Discussion

More heat energy is transferred in a longer time than in shorter time.

Conclusion

Conduction of heat energy depends on the time taken to heat.

From the above experiments we, can conclude that the quantity of heat transferred in a metal depends on:

1. The temperature difference between the ends.
2. The nature of the materials (usually called the *thermal conductivity* of the material).
3. The cross-sectional area.
4. The length of the conductor.
5. The time taken to transfer heat.

Good conductors and poor conductors

A substance which has the ability to transfer heat through itself easily is called a *good conductor* of heat. Most metals are good conductors of heat. Substances like water, air, glass, wood, plastic, paper, etc. which have a poor ability to transfer heat are called *poor conductors* of heat.

Experiment 5.8: To demonstrate that wood is a poor conductor of heat

Apparatus

- A wooden rod
- A white paper
- A copper rod
- A bunsen burner

Procedure

- Wrap a white paper round the junction of a copper and wooden rod which are joined together.
- Heat the paper at the junction of the rods with a bunsen burner flame. Observe what happens to the paper (Fig. 5.5).

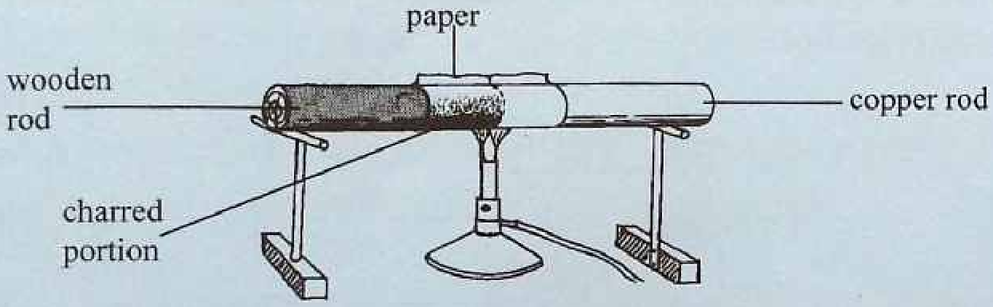


Fig. 5.5: Wood is a poor conductor of heat

Observation

The white paper on the wooden part of the rod is charred but the paper on the copper part of the rod is not charred. What can you say about the conductivities of these two materials?

Discussion

Copper conducts heat energy from the paper so fast that the paper cannot reach the temperature at which it burns. Wood conducts heat so slowly hence, the heat is able to burn the paper.

Conclusion

Wood is a poor conductor of heat.

Experiment 5.9: To show conductivities of paper and water

Apparatus

- A thick paper bag
- A bunsen burner
- A tripod stand
- Water

Procedure

- Get a thick paper bag that does not leak. Place the bag on a tripod stand (do not use a gauze.
- Fill the bag halfway with water. Take care not to puncture the base.
- Heat the water gently with a bunsen burner flame (make sure that the flame does not go to the sides of the bag). Observe what happens to the temperature of water (Fig. 5.6).

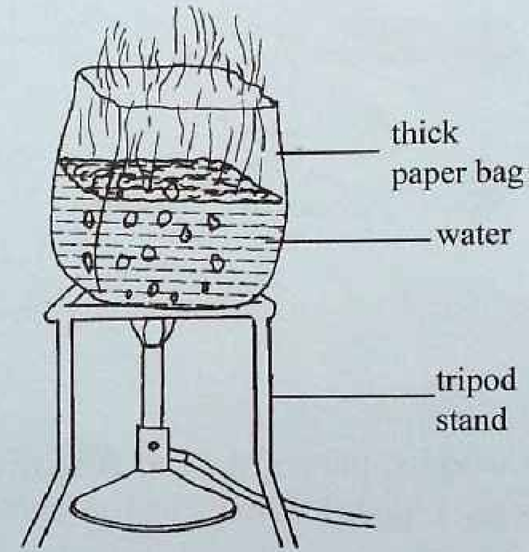


Fig. 5.6 Boiling water in a paper bag

Observation

- Bubbles are seen in the water
- The temperature of water increases and after sometime water starts to boil i.e. there is steam.

Discussion

When heat reaches the paper bag, a lot of energy is transferred from the flame to water rapidly. The paper cannot, therefore, reach the temperature at which it can burn. Although water is a poor conductor of heat, this experiment shows that it is a better conductor of heat compared to paper.

Conductor
Poor good

Conclusion

Paper bag is a poor conductor of heat than water. This is why you can *boil water in a paper bag!*

Experiment 5.10: To demonstrate that paper is a poor conductor of heat

Apparatus

- A white paper
- A candle (source of heat)
- A metal coin
- Procedure

Procedure

(a) Bring a white sheet of paper near to and above the candle flame (Fig. 5.7(a)). See what happens.

(b) Place a metal coin on another white sheet of paper and repeat Experiment 5.7(b). Observe what happens to the paper.

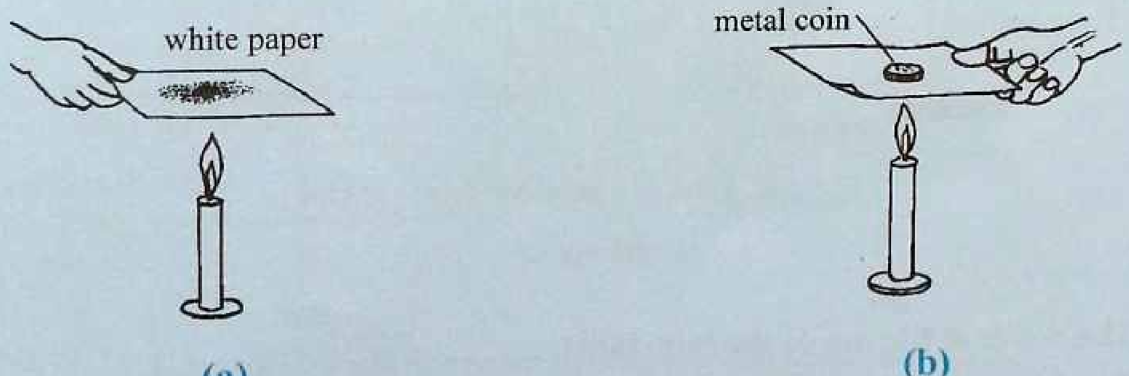


Fig. 5.7: Paper is a poor conductor of heat

Observation

When the metal coin is not on the paper, the paper gets charred. When the metal coin is on the paper, the paper does not get charred.

Discussion

The metal coin conducts heat away so quickly from the paper that the paper is not able to reach a temperature that will char the paper.

Conclusion

The paper is a poor conductor of heat compared to the metal coin.

Experiment 5.11: To demonstrate that water is a poor conductor of heat

Apparatus

- A piece of ice
- A boiling tube
- A bunsen burner
- A wire gauze
- A stand

Procedure

- Wrap a piece of ice in a wire gauze and drop it into a boiling tube containing water. The wire gauze helps the ice to stay at the bottom.
- Heat the water with a bunsen burner flame as shown in Fig. 5.8. Observe what happens.

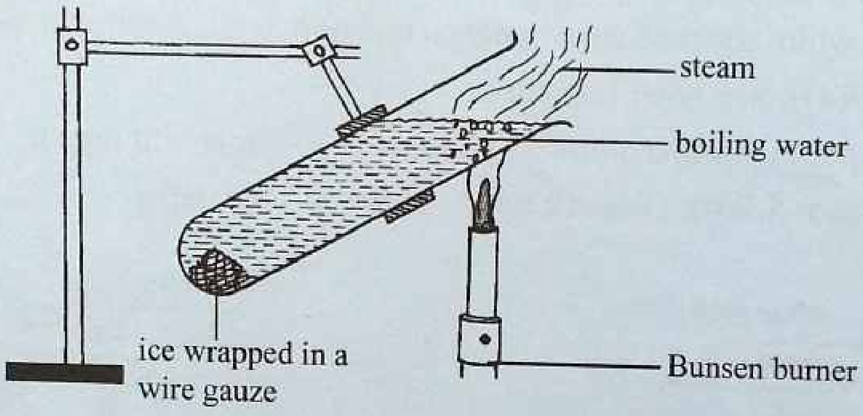


Fig. 5.8: Water is a poor conductor of heat

Observation

- The water at the top of the tube boils.
- The ice at the bottom does not melt easily even after heating for a long time.

> **Caution:** Handle boiling water with care. Do not let the open end of the test tube face you. Bubbles of the boiling water can splash and burn your skin.

Discussion

Though there is a large temperature difference between the top and the bottom, heat is not being conducted easily by water. It takes a long time for heat to be conducted to the bottom through water and glass. This is why the ice at the bottom does not melt.

Conclusion

Water is a poor conductor of heat.

Conduction in liquids

Though liquids are generally poor conductors of heat, different liquids conduct heat at different rates.

Experiment 5.12: To investigate conduction of heat in different liquids

Apparatus

- Two boiling tubes
- Two match sticks
- A thick copper rod
- Water
- 2 clamp stand
- A wooden block
- A bunsen burner
- Oil

Procedure

- Set the experiment as shown in Fig. 5.9.

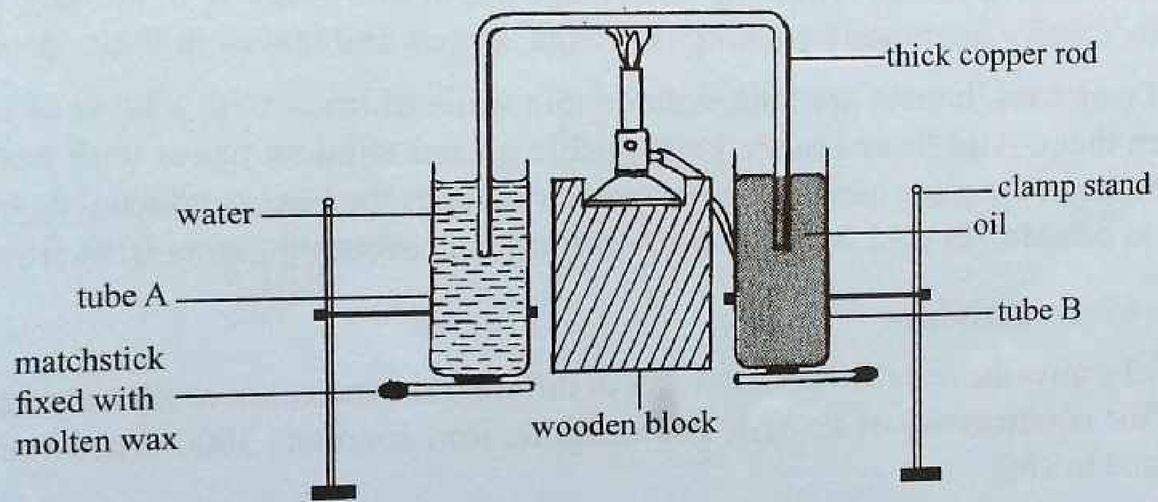


Fig. 5.9: Oil is a better conductor of heat than water.

- Heat the copper rod with the bunsen burner flame. The block of wood (insulator) should be long enough to prevent direct transfer of heat from the flame to the wax. Observe what happens.

Observation

The matchstick stuck to the tube containing oil falls off and the other matchstick stays undisturbed for a longer time.

Discussion

Same heat energy is passed to both water and oil through the copper rod but oil conducts heat faster than water. Hence, the wax underneath the tube B melts first and the matchstick falls off. This shows that *oil is a better conductor of heat than water.*

Conclusion

Different liquids conducts heat at different rates.

Conduction in gases

Compared to solids and liquids, gases are the poorest conductors of heat. A vacuum is the worst conductor of heat.

Air is a poor conductor of heat

It is a common experience that we wear woollen garments in cold weather to keep our bodies warm. The air molecules *trapped* in the knitted wool do not conduct heat from our bodies to the outside. Blankets, fur coats and feathers are good insulators because of the *trapped* air. Even the birds make use of this property in building their nests, by closely but loosely packing the twigs, straws and leaves in their nests.

In cold countries, houses are built with double walls of brick with a layer of air in between them. Also these houses have double glazed window panes with *trapped* air in between the glass panes. The *trapped* air reduces the heat conducted from the inside to outside. In cold weather, straw is used in preventing plants from frost.

Relative conductivities

Table 5.1 shows the *relative conductivities* of different substances at room temperature taking the conductivity of air as 1. For example, iron conducts 3000 times more as compared to air.

Item	Conductivity	Item	Conductivity
Air	1	Iron	3 000
Wood	6	Brass	4 500
Cardboard	8	Aluminium	8 000
Brick	23	Copper	16 000
Water	25	Silver	18 000
Glass (windows)	35		
Mercury	270		

Table 5.1: Relative conductivities of substances

5.5 Convection

Convection is a mode of heat transfer in a fluid by the actual physical movement of the molecules of the fluid due to temperature difference within the fluid.

Experiments to investigate heat transfer through fluids

Experiment 5.13: To observe convection current in water

Apparatus

- A long straw
- A beaker containing water
- A crystal of potassium permanganate
- A bunsen burner

Procedure

- With the help of a long straw, drop a small crystal of potassium permanganate to the centre of the bottom of a flask or a beaker containing water.
- Heat the flask gently at the centre of the flask. Observe what happens (Fig. 5.10).

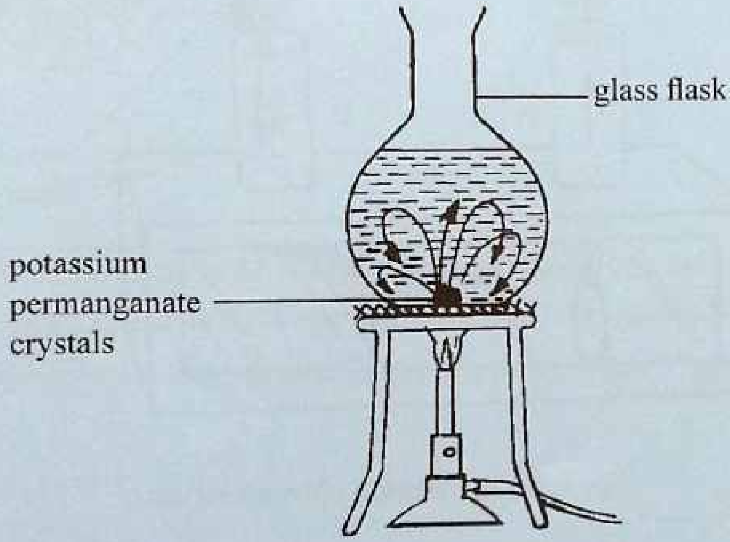


Fig. 5.10: Convection currents in water

Observation

Coloured streaks are observed to rise from the bottom to the top.

Discussion

The crystal dissolves and the hot water of less density starts rising, displacing the cold dense water down. The streams of physically moving warm liquid are called *convection currents*.

Conclusion

Heat energy is transferred by the convection currents in the liquid. The transfer of heat by this current is called *convection*.

Experiment 5.14: To observe convection current in air

Apparatus

- A box with a glass window, and two chimneys
- A candle
- Smouldering pieces of wick

Procedure

- Take a box with a glass window and two chimneys fixed at the top.
- Place a lighted candle under one chimney and hold a smouldering piece of wick above the other chimney as shown in Fig. 5.11. What do you observe?

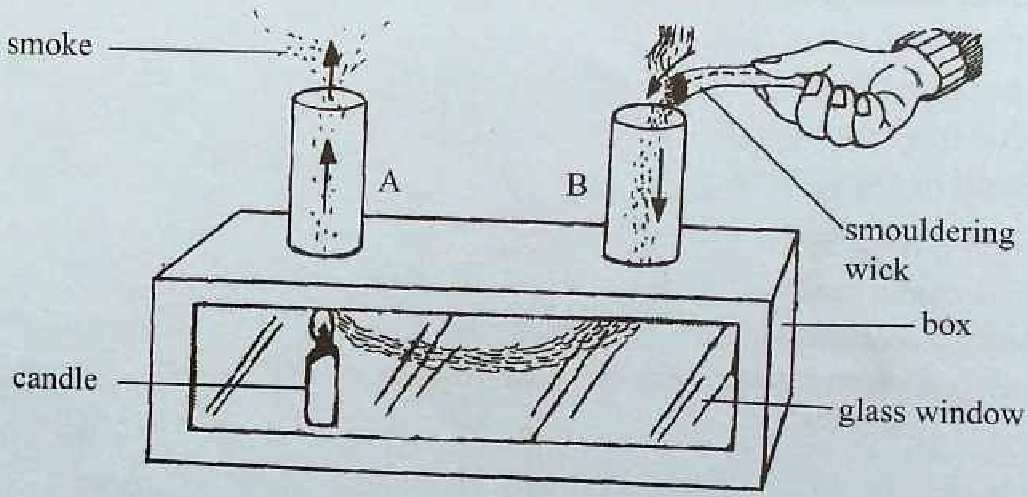


Fig. 5.11: Convection currents in air.

Observation

Smoke from the smoldering wick is seen to move down through chimney B then to the candle flame and finally comes out through chimney A.

Discussion

Air above the candle flame becomes warm and its density decreases. Warm air rises up through chimney A and the cold dense air above chimney B is drawn down this chimney and passes through the box and up the chimney A. The smoke particles from the wick enable us to *see* path of convection current (Fig. 5.11).

Conclusion

Heat is transferred in air through convectional currents.

Experiment 5.15: To illustrate that convection currents are always moving up

In Experiment 5.11 to prove that water is a poor conductor of heat (Fig. 5.8), we heat the water in the tube at the top and not at the bottom of the tube. This arrangement of heating is to ensure that convection current is not set up in the tube.

Conclusion

The convection current can only move upward and not downward.

Experiment 5.16: To illustrate that convection current possesses energy

Apparatus

- A thin circular disk
- A card board
- A candle flame

Procedure

- Take a thin circular disk of tin or cardboard and cut out six blades all round (Fig. 5.12(a)). Pivot the disk on a bent needle (Fig. 5.12(b)).
- Hold the disk above the candle flame for some time. Watch what happens.

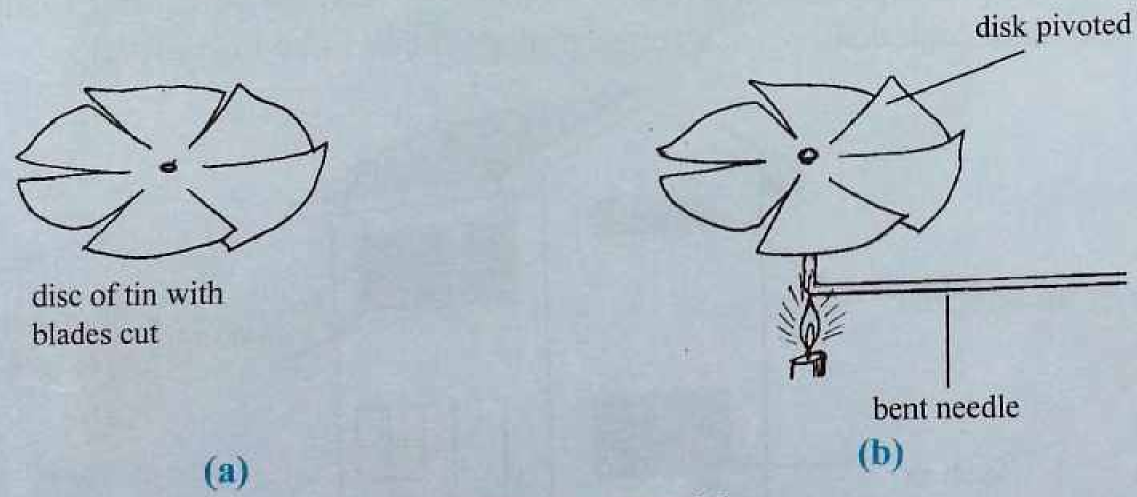


Fig. 5.12: A rotating disk.

Observation

The disk starts to rotate.

Discussion

The rotation is due to the convection current set up. If a powerful electric bulb is available you can make a *rotating lamp shade.*

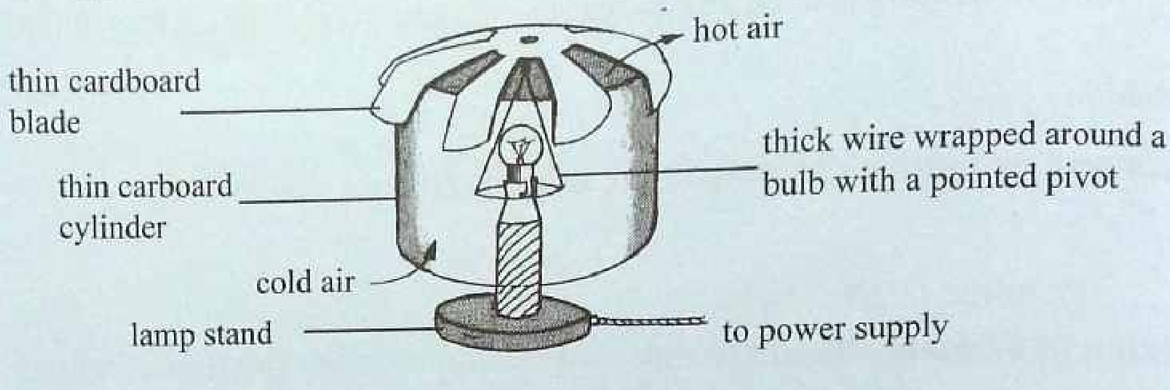


Fig. 5.13 : A rotating lamp shade

Conclusion

Convection current possesses energy. It is for this reason that steam is used to rotate the turbine in geothermal electric plants.

Applications of convection

The principle of convection namely *hot fluid rises and cold fluid sinks* applies in different situations in daily life which include:

Windows and ventilators in buildings

As shown in Fig. 5.14, warm exhaled air of less density goes out through the ventilator and fresh air of high density enters through the windows at a lower level.

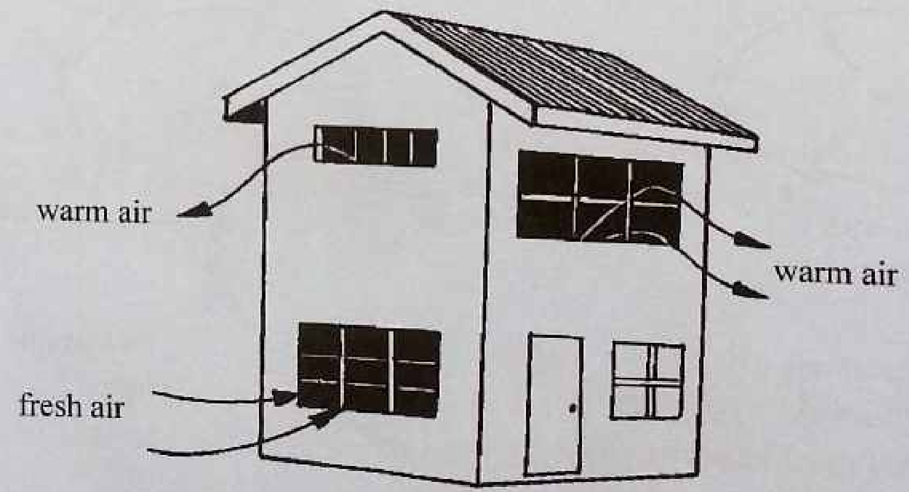


Fig. 5.14: Ventilation in building

Natural convection currents over the earth's surface

Sea breeze

During the day, the temperature of the land rises faster than the temperature of sea water and the air over the land becomes warmer than the air over the sea water. The warm air of less density rises from the land allowing the cold dense air over the sea to blow to the land. This creates a *sea breeze* in the daytime (Fig. 5.15).

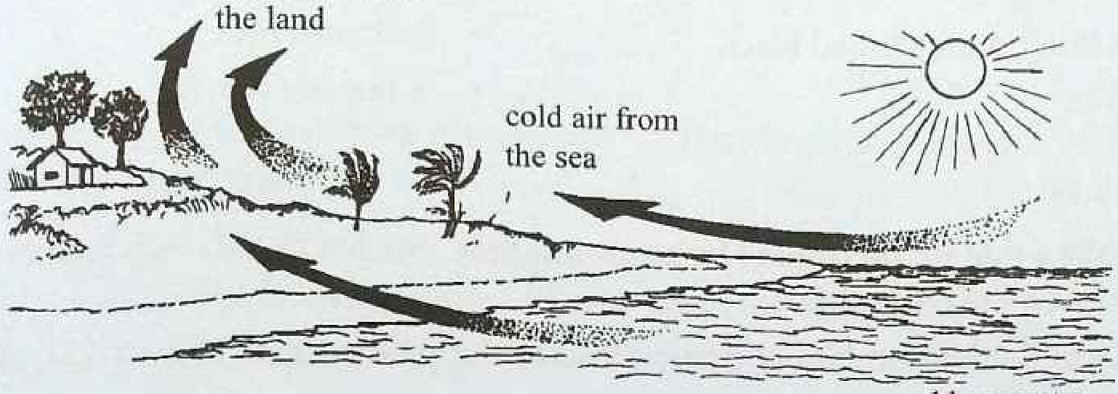


Fig. 5.15 Sea breeze

Land breeze

During the night, the land cools faster than the sea water. Warm air from the sea rises and the dense air from the land moves to the sea. This sets up a land breeze in the sea (Fig. 5.16).

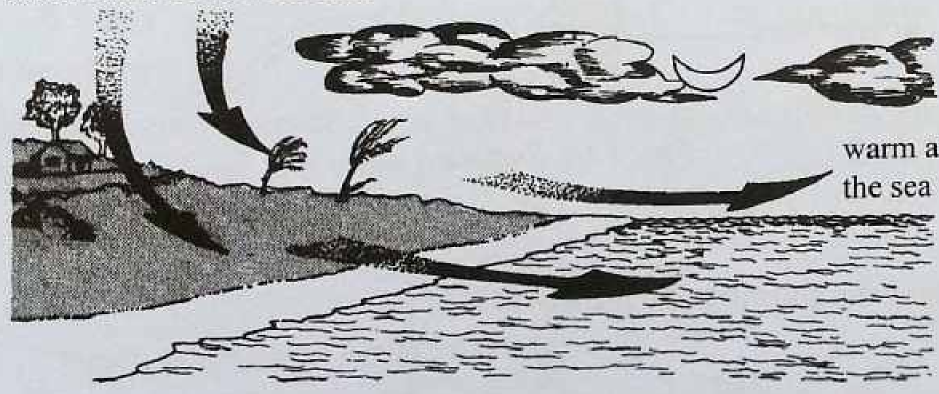


Fig. 5.16: Land breeze

Electrical devices

Electric kettles have their heating coil at the bottom. The refrigerators have the *freezing unit* at the top.

5.6 Radiation

If you stand in front of a fireplace, you feel that your body becomes warm. Heat energy cannot reach you by conduction as air is a poor conductor of heat. How about convection? The hot air molecules in and around the fireplace can only rise and cannot reach you by the movement of the air molecules. How does the energy from the fireplace then reach you? Heat energy must be transferred by a different mode other than conduction and convection.

Experiment 5.17: To show the transfer of heat energy by a different mode other than conduction and convection

Apparatus

- A thin tin lid painted black
- Wax
- A thumb tack
- A bunsen burner

Procedure

- Take a thin tin lid painted black on one side. Stick a thumb tack with melted wax on the other side.
- Keep the bunsen burner flame close to the painted side (Fig. 5.17). What happens?

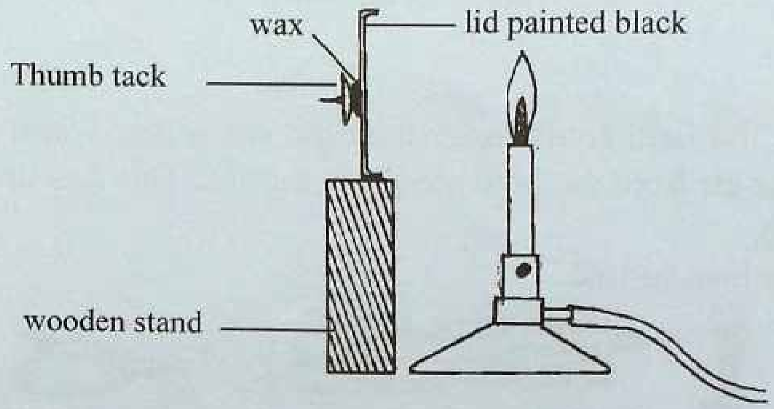


Fig. 5.17: Radiation

Observation

The wax melts and the thumb tack falls off.

Discussion

As discussed in the case of the fireplace, the energy from the flame reaches the tin lid and the wax by a different mode other than conduction and convection. This third mode of heat transfer is called *radiation*. Radiation is a mode of heat transfer from one place to another without affecting the intermediate medium. Heat transfer from the sun travels through empty space (vacuum) and reaches the Earth. This energy is transferred by radiation. The surfaces of all luminous bodies emit radiation. Human face also emits some mild radiations. While conduction and convection need a medium to be present for their transfer, radiation can take place without a medium.

The amount of heat energy radiated depends upon the temperature of the body. In Experiment 5.17, if the bunsen burner is replaced by a candle flame, it will take a longer time for the wax to melt. The temperature of the candle flame is lower than that of a bunsen burner.

Conclusion

Heat transfer can take place without contract or in a vacuum. This method of heat transfer is called *radiation*.

Experiments to investigate the factors affecting the amount of energy absorbed or emitted

Experiments 5.18: To illustrate good and bad absorbers

Apparatus

- Two thin tin lid
- Molten wax
- A metal thumb tacks (match stick)
- A bunsen burner

Procedure

- Take two thin tin lids, one with the inner side shiny and the other with the inner side painted dull black.
- Stick metal thumb tacks (or match sticks) on the outside of each lid using a little molten wax.
- Keep a bunsen burner flame midway between the lids as shown in Fig. 5.18. Watch closely to see what happens.

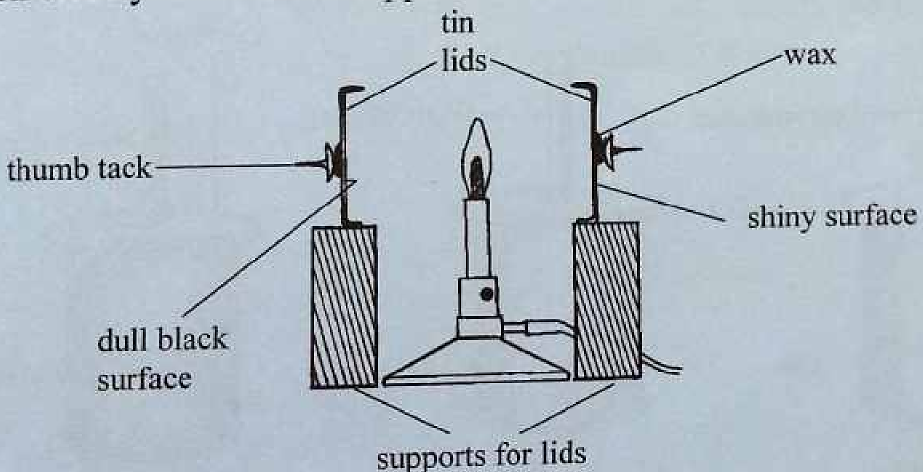


Fig. 5.18: Good and bad absorbers

Observation

The thumb tack stuck to the lid of black surface falls whereas the one on the shiny surface is undisturbed.

Conclusion

Though both lids receive the same amount of heat energy by radiation, the black surface *absorbs* more heat than the shiny surface.

A dull black surface is a better *absorber* of heat radiation than a shiny surface.

Experiment 5.19: To illustrate good and bad emitters.

Apparatus

- Three thermometers
- Three cardboard
- Three identical empty cans

Procedure

- Take three identical empty cans of the same volume with their tops removed. When clean and dry, paint one white and the other black (both inside and out) and leave the third can shiny.
- Prepare three suitable cardboard covers with holes at the centre. Fill the cans to the brim with hot water at 60°C.
- Cover the cans with cardboards and place a thermometer in each can through the hole at the centre of the cardboard (Fig. 5.19).

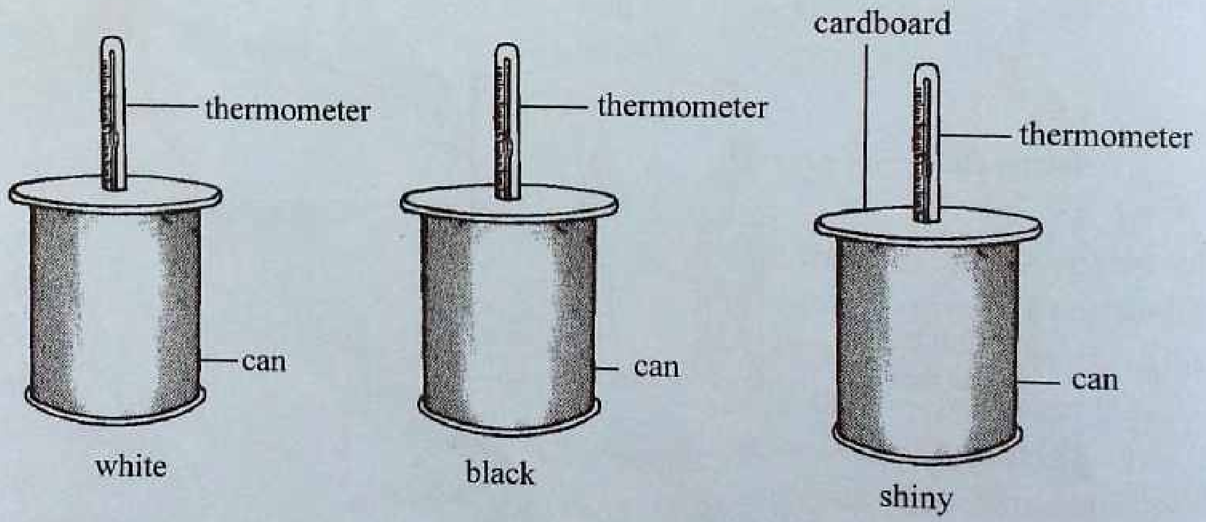


Fig. 5.19: Good and bad emitters

- Record the temperature of water in the cans after a certain time interval. Which can cools the water fastest? Which can takes the longest time to cool the water?

Observation

The water in the can painted black cools the fastest. The water in the shiny can takes the longest time to cool.

Conclusion

Dull black surfaces are good emitter of heat while shiny surfaces are bad emitter of heater.

From Experiments 5.18 and 5.19, we can summarise the following:

Dull black surfaces are good absorbers and also good emitters of heat. Shiny surfaces are poor absorbers and also poor emitters of heat.

5.7 Applications of heat transfer

Vacuum flask

The vacuum flask popularly known as *thermos flask*, was originally designed by *Sir James Dewar.* It is designed such that the heat transfer by conduction, convection and radiation between the contents of the flask and its surroundings is reduced to a minimum.

A vacuum flask, Fig. 5.20 is a double-walled glass container with a vacuum in the space between the walls. The vacuum is to minimise the transfer of heat by conduction and convection. The inside of the glass walls, in the vacuum side, is silvered so as to reduce heat losses by radiation. The felt pads on the sides and at the bottom support the vessel vertically. The cork lid is a poor conductor of heat.

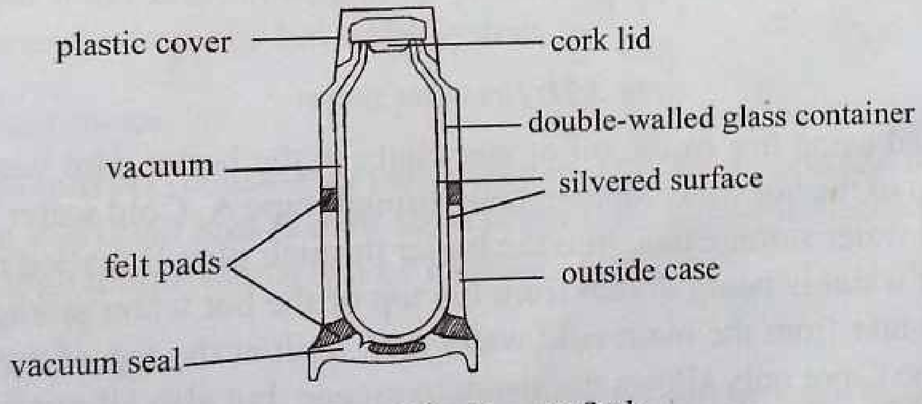


Fig. 5.20: Vacuum flask

When the hot liquid is stored, the inside shiny surface does not radiate much heat. The little that is radiated across the vacuum will be reflected back again, to the hot liquid, by the silvering on the outer surface. There is however, some heat lost by conduction up the walls and through the cork.

> **Caution!:** *Broken vacuum flasks should be well disposed. The broken pieces can be a health hazard in our environment.*

Uses of aluminium foil

- Used in keeping food ward. Hot food is wrapped with an aluminium foil. Heat from the food is reflected back in the food by the shinny surface of the aluminium foil. This makes the food to be warm for sometime.
- Use in designing simple solar heater. Aluminium foil is wrapped on the inner curved surface of a large dish the dish placed with this shinny surface face upwards towards the sun. During daytime, the aluminium surface reflects sunlight to the focal point of the curved surface that causes raise in temperature at this point of focus. The heat at this point can be used to heat water for a shower or even cook. The container with water or food is perfectly placed at the focal point.

Domestic hot water system

A domestic hot water supply system works on the principle of convection current. A schematic diagram is shown in Fig. 5.21.

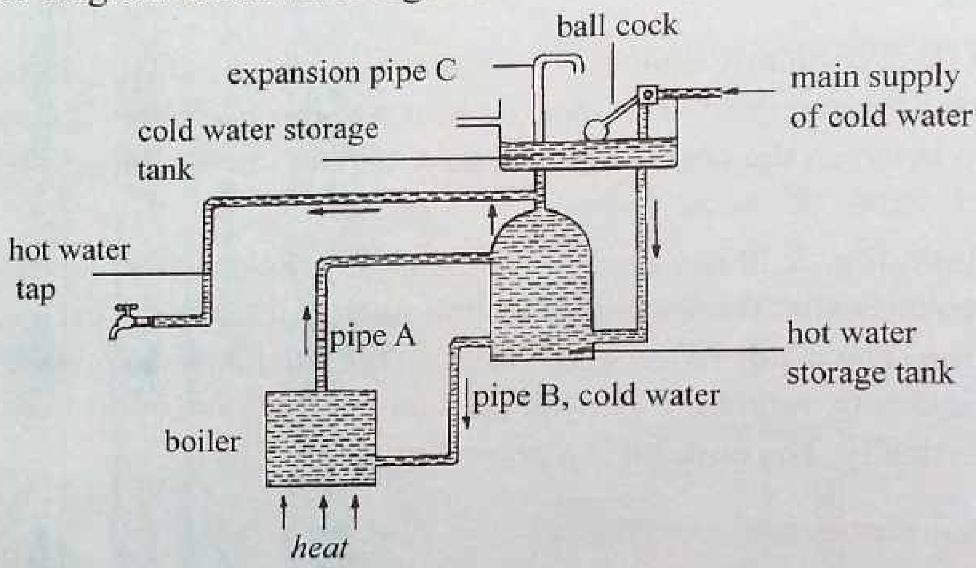


Fig. 5.21: Hot water system

Water is heated using fire wood, oil or electricity in the boiler. Hot water from the boiler goes up to the hot water storage tank through pipe A. Cold water flows down from the cold water storage tank into the boiler through pipe B (called return pipe). When the hot water is being drawn from the top of the hot water storage tank, it is replaced by water from the main cold water tank built at the top of the house. The expansion pipe C not only allows the steam to escape, but also allows dissolved air, to escape. This ensures that the tank does not explode due to the pressure that might be created by the steam produced.

Solar energy

Sun is the main source of energy for us. About 50% of the energy emitted by the sun is absorbed by the earth and sea. Scientists have embarked on projects to harness some of this energy for other uses.

Solar heating

Flat plate collectors, called *solar panels*, are used to heat water. They can heat water up to 70°C. A solar panel consists of thin copper pipes, painted black, which carry the water to be heated. These tubes are fitted in a copper collector plate which in turn is fitted on to a good thermal insulator in a metal frame. A glass plate covers the panel (Fig. 5.22). These panels can be fitted on the roof of houses.

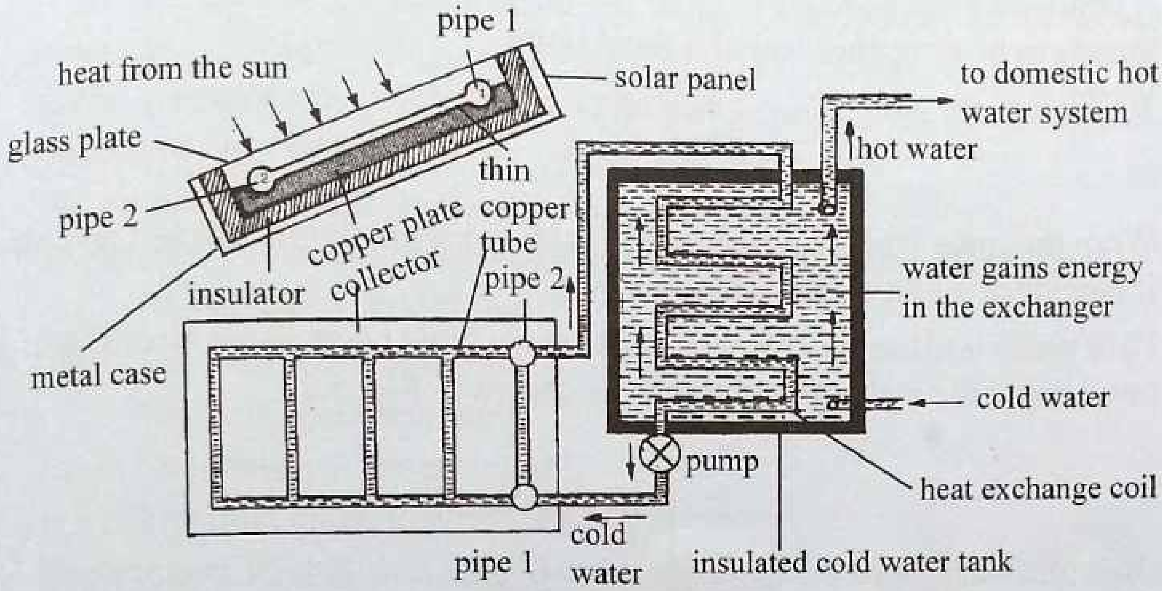


Fig. 5.22: Solar heating

Heat radiation from the sun falls on the tubes and on the collector plate through the glass plate. The heat radiations trapped inside the panel by the glass plate heat the water. The hot water is then pumped to a heat exchange coil in a hot water tank which is connected to the domestic hot water system.

Solar concentrations

Large curved mirrors (concave or parabolic) are used to concentrate heat radiations from the sun to a small area at their focal point. If the boiler is placed at the point of focus, very high temperatures can be reached.

Grass thatched house

Grass thatched roofs of houses have air molecules trapped between the fibres of grass. Since air is a bad conductor of heat, heat loses by conduction is minimised from the house hence maintaining the temperature constant inside the house.

Project

Project work: Making a simple solar cooker

Material

- Aluminium foil (20 cm by 20 cm)
- A paper bag
- A hemispherical bowl
- Stands to hold a paper bag at a focal point
- Water

Procedure

(a) Wrap the inner surface a hemispherical bowl with aluminium foil and place it outside at a place open to the sunshine.

(b) Pour water into the paper bag and hold it at a focal point above hemispherical bowl using the a clamp and stands as shown in Fig. 5.23.

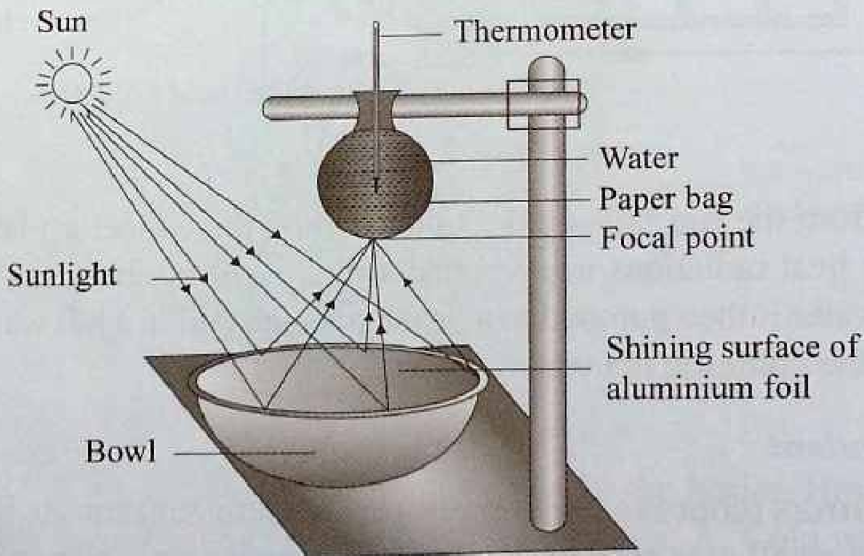


Fig. 5.23: A simple solar cooker

(c) Check the temperature of water with time as the sun continues to shine.

Observation

After sometime, the temperature of water in the paper bag increases. This is one way of tapping solar energy for cooking in (solar stoves) or heating water.

Unit summary

- Heat is a form of energy which is transferred from a region of higher temperature to a region of lower temperature.
- The SI unit of heat energy is joule (J).
- Two substances of equal masses can be at the same temperature but contain different amounts of heat energy and vice-versa.
- Heat energy can be transferred by three different modes: conduction, convection or radiation.

  Solids are heated by conduction and fluids by convection. Radiation can take place through vacuum.
- We get heat energy from the sun by radiation.
- The quantity of heat transferred depends on the following factors:
  - (a) The temperature difference.
  - (b) The nature of the materials.
  - (c) The cross-sectional area.
  - (d) The length of the material.
  - (e) The time taken to transfer heat.
- The vacuum flask is designed to reduce heat losses by convection, radiation and conduction.
- Hot water systems, land and sea breeze are some examples of convection currents.
- Heat from the sun can be harnessed through solar panels.

Unit Test 5

1. Bread can be cooked by placing it below but not touching the heating element. Which process transfer thermal energy from the heating element to the bread? [1]

   A. Conduction B. Convection
   C. Radiation D. Insulation

2. Heat from the sun reaches us through? [1]

   A. Radiation B. Convection
   C. Conduction D. None of the above

3. Heat from the ground at night reach the atmosphere by? [1]

   A. Conduction B. Absorption
   C. Convection D. Radiation

4. Distinguish between *heat* and *temperature*. [2]

5. What are the different modes of heat transfer? Explain clearly their difference with suitable examples. [2]

6. State three factors which affect heat transfer in metals. Explain how one of the factors you have chosen affects heat transfer. [2]

7. Describe an experiment to show that water is a poor conductor of heat. [2]

8. Explain who will be comfortable between a person in a dark suit and the one in a white suit on a hot sunny day. [3]

9. Describe a simple experiment to demonstrate that the heat radiated from a hot body depends upon the temperature of the body. [2]

10. With a suitable diagram, explain the working of a vacuum flask. [4]

11. Explain the following statements: [3]
    - (a) A metallic seat seems to be hotter during the day and colder during the night than a wooden seat under the same conditions.
    - (b) The bottom of cooking vessels are usually blackened.
    - (c) It is safer to hold the other end of a burning match stick.

12. Suggest an experiment to prove that oil is a better conductor of heat than water. [2]

13. A cross-section of a solar panel fitted to the roof of a house is shown below (Fig. 5.23).

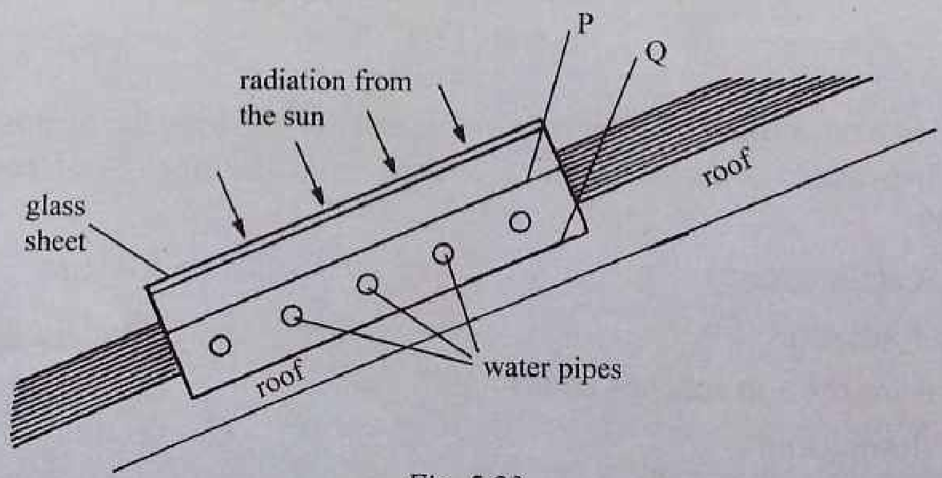


Fig. 5.23

- (i) Surface P is dull black whereas surface Q is covered in shiny aluminium foil. Give a suitable reason for each choice. [3]
- (ii) What is the purpose of the front glass sheet? [2]

UNIT 6 Power and Machines

Success Criteria

By the end of this unit, you must be able to;

- Define power.
- Solve problems involving power.
- Define a machine.
- Explain advantages of using machines.
- State ways in which mechanical advantage of an inclined plane can be increased.
- Explain why the lifting operation in an inclined plane requires greater expenditure of energy.
- Calculate mechanical advantage for inclined planes.
- Explain how pulley systems work.
- Identify uses of levers in everyday life.
- Classify levers depending on the position of load, effort and fulcrum.
- Describe how to reduce effort in levers.
- State the principle of moments in levers.
- Apply the principle of moments in solving problem.

6.1 Power

Consider an object of mass m being pulled along an inclined plane of length l to a platform at a height h by two students one at a time. One student takes t seconds while the other takes 0.5 t seconds (see Fig. 6.1).

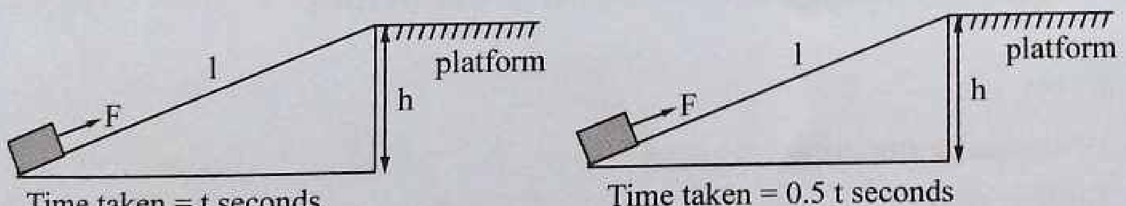


Fig. 6.1: Mass m pulled along an inclined plane

Both students do the same amount of work. However, the second student does the work faster than the first student. Power is about how quickly work can be done. The *rate of doing work is called power*.

$$\text{power} = \frac{\text{work done}}{\text{time taken}}$$

The SI unit of power is J/s or watt (W). 1 watt is equal to 1 J/s.
Watt is the rate of transfer of energy of 1 joule per second.

Relationship between power and velocity

Consider a body being moved at a steady rate by a force, F,

Work done = force × distance moved in the direction of force

$$\text{power} = \frac{\text{work done}}{\text{time taken}}$$

$$\therefore \text{ power} = \frac{\text{force} \times \text{distance moved in the direction of force}}{\text{time taken}}$$

But, $\dfrac{\text{distance moved in the direction of force}}{\text{time taken}} = \text{velocity}$

∴ power = force × velocity at which the point of application of force is moving.

$P = Fv$. The velocity v may be uniform or average.

Example 6.1

A force of 100 N drags a box at a constant velocity of 5 m/s. What is the power of the source of the force?

Solution

$$\begin{aligned} P &= Fv \\ &= 100 \text{ N} \times 5 \text{ m/s} \\ &= 500 \text{ W} \end{aligned}$$

Experiment 6.1: To measure one's own power output

Apparatus

- A weighing machine
- Stair case
- A stop watch

Procedure

- Working in groups of twos, time each other, in turns, as you run up a flight of stairs as fast as you can (Fig. 6.2). Record the time t taken.
- Then measure your weight, w, using a weighing machine.

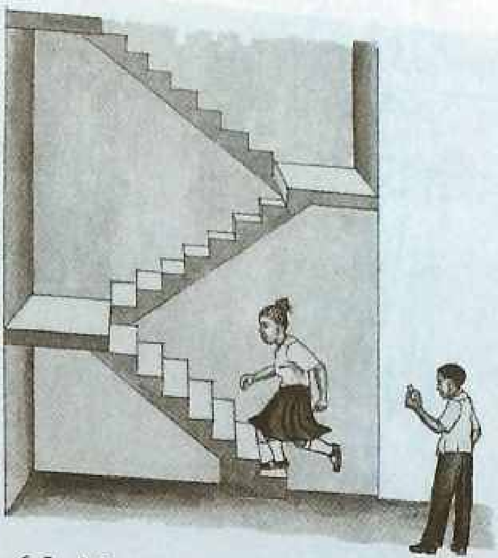


Fig. 6.2: Measuring one's own power output

- Measure the height of one step of the staircase. Count the number of steps.

Discussion

Height moved up h = Number of steps $n \times$ height of one step x

$$h = n \times x$$

Time taken to move height, $h = t$

$$P = \frac{\text{Work done against gravity}}{\text{Time}} = \frac{\text{mgh}}{\text{t}} = \frac{w \times h}{t}$$

$$= \frac{w\ n\ x}{t}$$

$$P = \frac{\text{wnx}}{\text{t}}$$

If x is in metres, w in newtons and t in seconds the power is in watts.

Example 6.2

A student of mass 45 kg runs up a flight of 40 steps in a stair case each 15 cm in 12 seconds. Find the power of the student

Solution

$$\begin{aligned} \text{Work done} &= \text{force} \times \text{distance} \\ &= \text{weight} \times \text{distance} \\ &= 450 \times 40 \times 0.15 \\ \text{power} &= \frac{\text{work done}}{\text{time}} \end{aligned}$$

$$= \frac{450 \times 40 \times 0.15}{12}$$

$$= 225 \text{ W}$$

Example 6.3

A car engine developed 24 kW while travelling along a level road. If there was a resistance of 800 N due to friction calculate the maximum speed attained.

Solution

$$\text{power} = \text{force} \times \text{velocity}$$

$$\text{velocity} = \frac{\text{power}}{\text{force}}$$

$$= \frac{24\ 000}{800}$$

$$= 30 \text{ m/s}$$

Exercise 6.1

1. Power may be calculated using the quantities: [2]
   - **A.** Work, force and area
   - **B.** Work and time
   - **C.** Force and Area
   - **D.** Velocity and time
2. 1 J/S is equal to?
   - **A.** 1 watt
   - **B.** 10 watts
   - **C.** 1 energy
   - **D.** 1 power [1]
3. A car engine produces a forward force of 200 N. This makes the car to move at steady speed of 20 m/s. What will be the car engine's power? [3]
   - **A.** 4 000 N
   - **B.** 400 J/S
   - **C.** 4 000 W
   - **D.** 4 000 J
4. Define the term power and give its SI unit. [2]
5. A motor raised a block of mass 72 kg through a vertical height of 2.5 m in 28 s. Calculate the:
   - **(a)** work done on the block.
   - (b) useful power supplied by the motor.

6. A person of mass 40 kg runs up a flight of 50 stairs each of height 20 cm in 5 s. Calculate

   (a) the work done.

   (b) the average power of the person.

   (c) explain why the energy the person uses to climb up is greater than the calculated work done.

7. A car travels at a steady speed of 17 m/s for 20 s. The total resistive force on the car is 600 N.

   (a) What is the distance travelled by the car?

   (b) What is the work done by the car to overcome the resistive force?

   (c) Calculate the power developed.

8. A runner of mass 65 kg runs up a steep slope rising through a vertical height of 40 m in 65 s. Find the power that his muscles must develop in order to do so.

9. A fork-lift truck raises a 400 kg box through a height of 2.3 m. The case is then transported horizontally by the truck at 3.0 m/s onto the loading platform of a lorry.

   (a) What minimum upward force should the truck exert on the box?

   (b) How much P.E. is gained by the box?

   (c) Calculate the K.E of the box while being transported

10. A stone falls vertically through a distance of 20 m. If the mass of the stone is 3.0 kg,

   (a) Draw a graph of work done by the gravity against distance.

   (b) Find the power of the gravitational pull.

6.2 Machines

Machines are devices that make work easier. For example in loading an oil drum onto a truck, it is easier to roll it up an inclined plane than lifting it up onto the truck (see Fig. 6.3).

(a) Rolling up a drum into a truck **(b)** Lifting up a drum into a truck

Fig. 6.3: Machines make our work easier

A machine may be defined as any device that facilitates a force applied at one point to overcome another force at a different point in the system. In *mechanical machines* the force that is applied is called the *effort (E)* and the force the machine must overcome is called the *load (L)*. A machine is therefore a device which makes work easier.

Terms used in machines

Mechanical advantage of machines, M.A

Machines helps to overcome a large load by applying a small effort i.e. the machines magnify the force applied. The number of times a machine magnifies the effort is called the *mechanical advantage* (MA) of a machine. In other words the mechanical advantage of any machine is the number of times the load is greater than the effort. The mechanical advantage is therefore defined as the *ratio of load to the effort*. Since mechanical advantage is a ratio, it has no units.

$$\therefore \quad \text{Mechanical advantage (M.A)} = \frac{\text{load}}{\text{effort}}$$

Velocity ratio of a machine, V.R

Velocity ratio (V.R.) of a machine is *the ratio of the velocity of the effort to the velocity of the load*

$$\text{velocity ratio (V.R)} = \frac{\text{velocity of the effort}}{\text{velocity of the load}}$$

$$= \frac{\dfrac{\text{displacement of effort}}{\text{time}}}{\dfrac{\text{displacement of load}}{\text{time}}}$$

Since the effort and the load move for the same time,

$$\text{Velocity ratio (V.R)} = \frac{\text{displacement of effort}}{\text{displacement of load}} \text{ or } \frac{\text{effort distance}}{\text{load distance}}$$

Hence velocity ratio may be defined as the *number of times the effort moves further than the load.* Velocity ratio has no units.

Efficiency of machines

For a perfect machine, the work done on the machine by the effort is equal to the work done by the machine on the load. However, there is *no such* a machine because some energy is wasted in overcoming friction and in moving the moveable parts of the machine. Hence more energy is put *into* the machine than what is obtained *out* of it. Thus,

Work input = useful work done + useless work done

To describe the actual performance of a machine we use the term *efficiency*. Efficiency tells us what percentage of the work put into a machine is returned as useful work. Machine is defined as the ratio of its energy ouptut to its energy input.

$$\text{efficiency} = \frac{\text{useful energy output}}{\text{energy input}} \times 100\%$$

or

$$\text{efficiency} = \frac{\text{useful work output}}{\text{work input}} \times 100\% = \frac{\text{load} \times \text{distance moved by load}}{\text{effort} \times \text{distance moved by effort}} \times 100\%$$

$$= \frac{\text{load}}{\text{effort}} \times \frac{\text{distance load is moved}}{\text{distance moved by effort}}$$

$$= \text{M.A} \times \frac{1}{\text{V.R}} \times 100\%$$

$$\therefore \text{efficiency} = \frac{\text{M.A}}{\text{V.R}} \times 100\%$$

The effect of friction on mechanical advantage, velocity ratio and efficiency

The mechanical advantage of a machine is affected by the frictional forces between the parts of the machine present, since a part of the effort has to be used to overcome friction. However, the velocity ratio does not depend on friction but rather on the geometry of the moving parts of the machine. Since the greater friction present the lower the mechanical advantage, the efficiency of a machine is reduced by friction.

Example 6.4

A machine whose velocity ratio is 8 is used to lift a load of 300 N. The effort required is 60 N.

(a) What is the mechanical advantage of the machine

(b) Calculate the efficiency of the machine

Solution

(a) mechanical advantage $= \dfrac{\text{load}}{\text{effort}} = \dfrac{300\text{N}}{60\text{N}} = 5$

(b) efficiency $= \dfrac{\text{M.A}}{\text{V.R}} \times 100\%$

$= \dfrac{5}{8} \times 100\%$

$= 62.5\%$

Example 6.5

An effort of 250 N raises a load of 900 N through 5 m in a machine. If the effort moves through 25 m, find

(a) the useful work done in raising the load

(b) the work done by the effort

(c) the efficiency of the machine

Solution

(a) Useful work done in raising the load

$= \text{load} \times \text{distance moved by load}$

$= (900 \times 5) = 4\,500\text{ J}$

(b) Work done by the effort

$= \text{effort} \times \text{distance moved by effort}$

$= 250 \times 25 = 6\,250\text{ J}$

(c) Efficiency $= \dfrac{\text{work output}}{\text{work input}} \times 100\%$

$= \dfrac{4\,500\text{ J}}{6\,250\text{ J}} \times 100\%$

$= 72\%$

Example 6.6

Calculate the efficiency of a machine if 8 000 J of work is needed to lift a mass of 120 kg through a vertical height of 5 m.

Solution

Work done in lifting the load

$= 1\,200 \times 5 = 6\,000$ J

Work input $= 8\,000$ J

$$\text{Efficiency} = \frac{\text{work output}}{\text{work input}} \times 100\%$$

$$= \frac{6\,000 \text{ J}}{8\,000 \text{ J}} \times 100\%$$

$$= 75\%$$

Exercise 6.2

1. A machine requires 6 000 J of energy to lift a mass of 55 kg through a vertical distance of 8 m. Calculate its efficiency.
2. A machine of efficiency 75% lifts a mass of 90 kg through a vertical distance of 3 m. Find the work required to operate the machine.
3. A machine used to lift a load to the top of a building under construction has a velocity ratio of 6. Calculate its efficiency if an effort of 1 200 N is required to raise a load of 6 000 N. Find the energy wasted when a load of 700 N is lifted through a distance of 3 m.
4. A crane just lifts 9 940 N when an effort of 116 N is applied. The efficiency of the crane is 75%. Find its
   (a) mechanical advantage (b) velocity ratio

Types of simple machines

Simple machines may be classified into two groups i.e. force multipliers and distance or speed multipliers. Force multipliers are those that allow a small effort to move a large load e.g. levers. Distance or speed multipliers are those that allow a small movement of the effort to produce a large movement of the load e.g. fishing rod, bicycle gear etc. Let us consider some simple machines and show how they operate.

Inclined plane

An inclined plane is a ramp or slope that enables a load to be raised more gradually by using a smaller effort than when it is raised vertically upwards. It usually consists of a long plank inclined at an angle θ to the horizontal (Fig. 6.4). It is thus easier to take a heavy load from A to C by dragging along the plank than lifting it upwards from B to C.

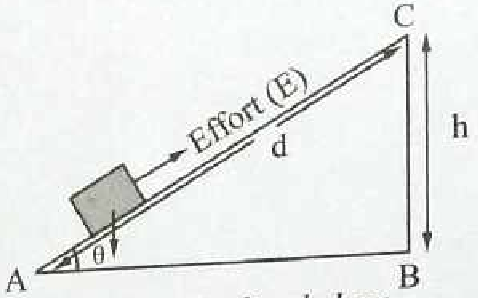


Fig. 6.4: Inclined plane

Velocity ratio of an inclined plane

$$\text{velocity ratio } (V.R) = \frac{\text{distance moved by effort } (d)}{\text{distance moved by load } (h)}$$

$$\text{V.R} = \frac{d}{h}$$

Mechanical advantage (M.A) of an inclined plane

If the inclined plane is *perfectly smooth (no friction)* then the work done by load is equal to the work done by effort

load × h = effort × d

Dividing on RHS by h and m on LHS by effort, we get;

$$\frac{\text{load}}{\text{effort}} = \frac{d}{h}$$

But M.A is given by: $\text{M.A} = \frac{\text{load}}{\text{effort}}$

$$\text{mechanical advantage} = \frac{\text{distance moved by effort } (d)}{\text{distance moved by load } (h)}$$

$$\text{M.A} = \frac{d}{h}$$

Mechanical advantage is greater than one since $\frac{d}{h}$ is more than one. In practice, if the effort needed is more than expected value of energy needed to overcome friction. The mechanical advantage is usually less than the calculated values due to frictional force.

Note: Lifting a load through the vertical height, h, requires more energy. Since the work is being done against the gravity, the effort applied is used overcome the gravitional pull of the load.

Experiment 6.2: To show how the length of the inclined plane affects the mechanical advantage

Apparatus

- An inclined plane
- A trolley load
- Slotted masses
- 1 metre long wire

Procedure

- Measure the mass of a trolley. Place it on an inclined plane of length l, (see Fig. 6.5).

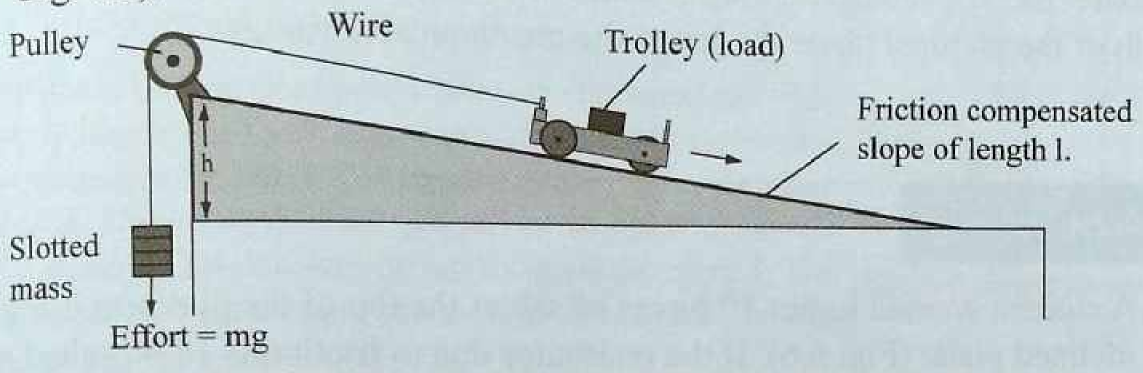


Fig. 6.5: How the length of inclined plane affects the mechanical advantage.

- Add slotted masses until the trolley just begins to move up the plane. Record the values of the load, effort and the length l of the inclined plane.
- Repeat the experiment with inclined planes of different lengths, l. Make sure the height, h, and the load are kept constant. Record the results in Table 6.1. What happens to the applied effort when the length of the incline plane is increased.

Effort (E) (N)	Length (l) (m)	Mechanical advantage = $\frac{L}{E}$

Table 6.1

Observation

When the length l is increased the effort applied is decreased.

Discussion

Work done on the load = load × distance moved by the load

$= L \times h$

Work done on the effort = effort × distance moved by the effort

$= E \times l$

But the work done on the load is equal to the work done by the effort i.e.

$$El = L h.$$

$$\therefore \quad E = \frac{Lh}{l} = \frac{mgh}{l} \text{ since } L = mg$$

But, mgh is a constant

$$\therefore \quad E \,\alpha\, \frac{1}{l}.$$

Conclusion

A small effort applied over a long distance overcomes a great load. The longer the length of the inclined plane the lower the mechanical advantage.

Exercise 6.3

1. A student wanted to put 10 boxes of salt at the top of the platform using an inclined plane (Fig. 6.6). If the resistance due to friction is 10 N, calculate

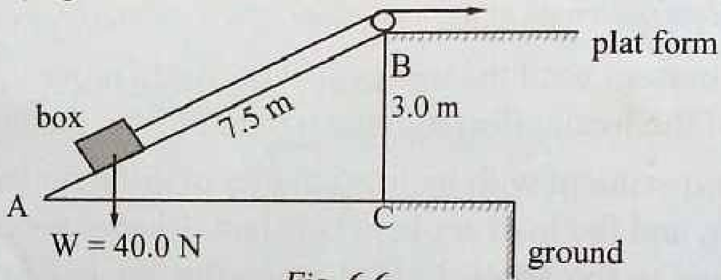


Fig. 6.6

   (a) the work done in moving the 10 boxes.
   (b) the efficiency of this arrangement.
   (c) the effort required to raise one box to the platform.

2. A car of mass 2 000 kg is moving up an inclined plane through a vertical height of 20 m. Calculate the mechanical advantage of the inclined plane if the car covers a distance of 30 m.
3. A body of mass 200 kg is pulled along an inclined plane by a force of 1 500 N as shown in Fig. 6.7 below.

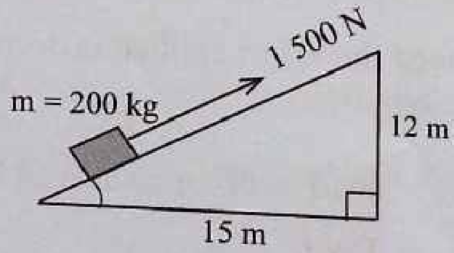


Fig. 6.7

Calculate

(a) mechanical advantage

(b) velocity ratio

(c) efficiency of the inclined plane

Pulleys

A pulley is usually a grooved wheel or rim. Pulleys are used to change the direction of a force. Let us consider three types of pulleys i.e. single fixed, single moving and block and tackle.

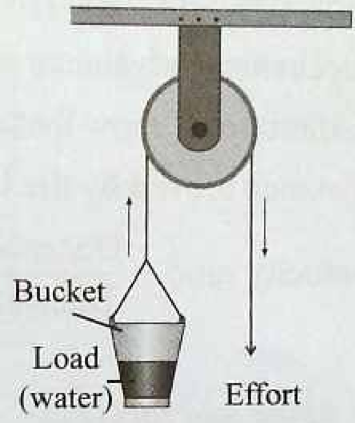
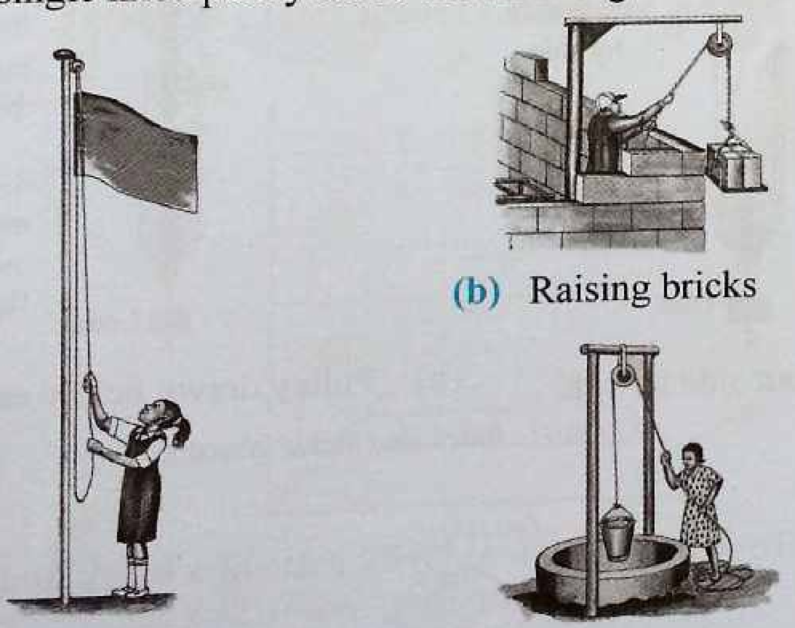


Fig. 6.8: Single fixed pulley

Single fixed pulley

Fig. 6.8 shows a single fixed pulley being used to lift a load. This type of pulley has a fixed support which does not move with either the load or the effort. The tension in the rope is the same throughout. Therefore, the load is equal to the effort if there is no loss of energy. The mechanical advantage is therefore 1. The only advantage we get using such a machine is convenience and ease of raising the load.

Since some energy is wasted in the bearing of the pulley and in lifting the weight of the rope, the mechanical advantage is slightly less than 1. The load moves the same distance as the effort and therefore the velocity ratio of a single fixed pulley is 1. Examples of a single fixed pulley are as shown in Fig. 6.9.



(a) Raising a flag

(b) Raising bricks

(c) Raising water from a well

Fig. 6.9: Examples of a single fixed pulley

The single moving pulley

Fig. 6.10 shows a single movable pulley. The total force supporting the load is given by the tension, T, plus effort, E, but since the pulley is moving up, the tension is equal to the effort. Therefore, the upwards force is equal to twice the effort (2E). Hence the load is equal to twice the effort (2E).

$$\text{Mechanical advantage} = \frac{\text{load}}{\text{effort}} = \frac{2E}{E} = 2$$

However, since you have also to lift the pulley, the mechanical advantage will be slightly less than 2. Experiments show that the effort moves twice the distance moved by the load. Therefore

$$\text{velocity ratio} = \frac{\text{Distance moved by effort}}{\text{Distance moved by load}} = 2$$

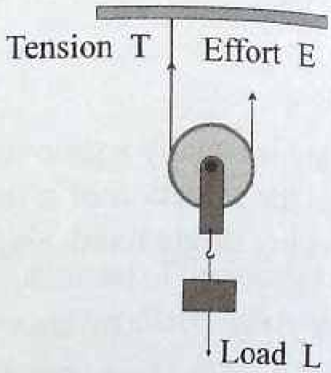
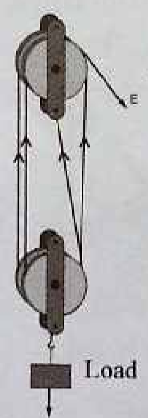


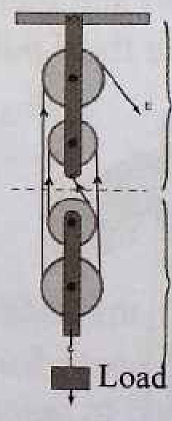
Fig. 6.10: A single movable pulley

A block and tackle

A block and tackle consists of two pulley sets. One set is fixed and the other is allowed to move. The pulleys are usually assembled side by side in *a block* or frame on the same axle as shown in Fig. 6.11 (a). The pulleys and the ropes are called the *tackle*. To be able to see clearly how the ropes are wound, the pulleys are usually drawn below each other as shown in Fig. 6.11 (b).



(a) Pulley put side by side



(b) Pulley drawn below each other

Fig. 6.11: Block and tackle systems.

Experiment 6.3: To determine the velocity ratio of a block and tackle

Apparatus

- Block and tackle pulley
- A metre rule
- A load

Procedure

- Set up a block and tackle system with two pulleys in the lower block and two pulleys in the upper block as shown in Fig. 6.11 (b) above.
- Count the number of sections of string supporting the lower block.
- Raise the load by any given length, l, by pulling the effort downwards. Measure the distance, e, moved by the effort. Record the result in a table. (Table 6.2).

Distance moved by effort (e) cm	Distance moved by load l cm
10	
20	
30	

Table 6.2

- Repeat the experiment by increasing the distance moved by the effort.
- Plot a graph of e, against, l (Fig. 6.12). Determine the gradient of the graph.

Observation

The number of strings supporting the load is 4.

Discussion

When we draw a graph of e (cm) against L (cm), we get, the graph as similar to the one in Fig 6.12.

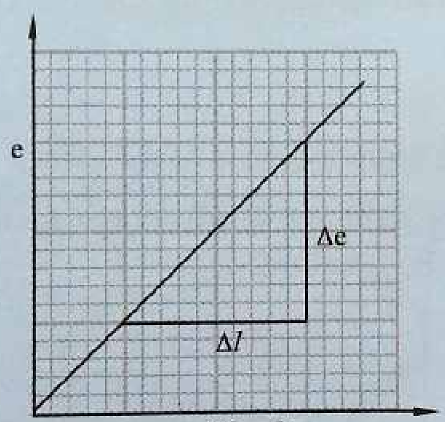


Fig. 6.12: Graphs of the effort against the load.

The gradient $\frac{\Delta e}{\Delta l}$,which is the velocity ratio. Comparing the value of the gradient with the number of sections of string supporting the lower block. —They are the same (4).

Conclusion

Velocity ratio of a block and tackle pulley is equal to the number of strings supporting the lower block.

Precaution: The weight of the block in the lower section of the system has to be considered as this increases the load to be lifted.

Experiment 6.4: To determine the mechanical advantage of a block and tackle

Procedure

- Assemble the apparatus as in Experiment 6.3. For a given load, increase the effort until the load just begins to rise steadily. Record the value of this effort in a table.
- Repeat the experiment with other values of load and record the values of this effort in Table 6.3.

Effort (N)	Load (N)	MA = $\frac{L}{E}$

Table 6.3

- Calculate for each set of load and effort the mechanical advantage. Plot a graph of mechanical advantage against the load (Fig. 6.13). Comment on the shape of the graph.

Observation

Increase in the load leads to an increase of the effort.

When we draw a graph of mechanical advantage against the load, we get a graph similar to the one in Fig. 6.13 below.

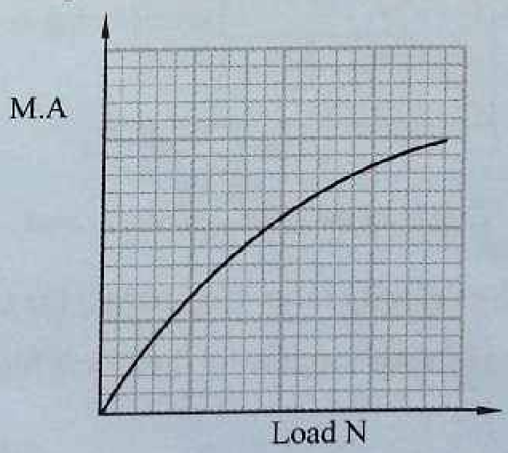


Fig. 6.13: Graph of mechanical advantage against the load

Discussion

As the load increases, the mechanical advantage also increases. When the load is less than the weight of the lower pulley block, most of the effort is used to overcome the frictional forces at the axle and the weight of the lower pulley block. That is, the effort does useless work. However, when the load is larger than the weight of the lower block, the effort is used to lift the load. This shows that the machine is more efficient when lifting a load that is greater than the weight of the lower block. Using the value of the velocity ratio obtained in Experiment 6.3, calculate the efficiency of the pulley system. Plot a graph of efficiency against load.

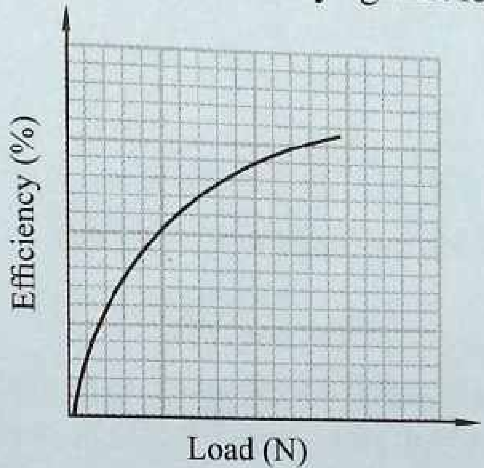


Fig. 6.14: The graph of efficiency against load

Conclusion

The efficiency of the system improves with larger loads.

Example 6.7

For each of the pulley systems shown in Fig. 6.15. Calculate the

(i) velocity ratio.

(ii) mechanical advantage.

(iii) efficiency.

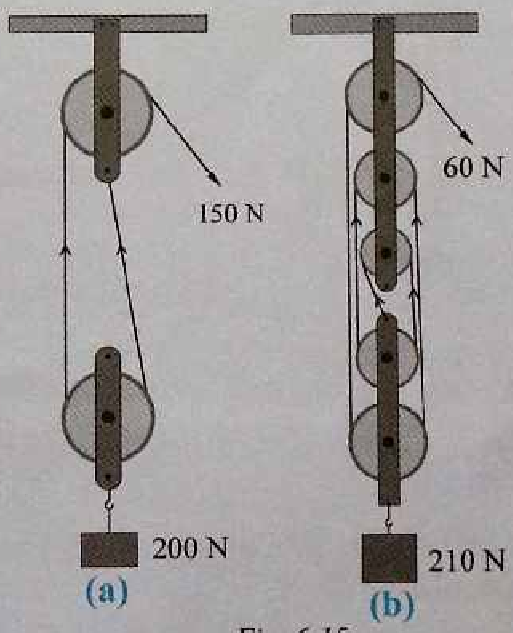


Fig. 6.15

Solution

(a) (i) velocity ratio = 2 (number of sections of string supporting the lower pulley)

(ii) mechanical advantage $= \dfrac{200\text{ N}}{150\text{ N}}$

$$= \frac{4}{3} = 1.33$$

(iii) efficiency $= (\frac{4}{3} \times \frac{1}{2}) \times 100$

$$= 66.6\%$$

(b) In Fig 6.15 (b)

(i) velocity ratio = 5

(ii) mechanical advantage

$$= \frac{\text{load}}{\text{effort}}$$

$$= \frac{210\text{ N}}{60\text{ N}} = 3.5$$

(iii) efficiency

$$= \frac{3.5}{5} \times 100\%$$

$$= 70\%$$

Example 6.8

Draw a diagram of a single string block and tackle system with a velocity ratio of 6. Calculate its efficiency if an effort of 1 500 N is required to raise a load of 5 000 N.

Solution

See Fig. 6.16

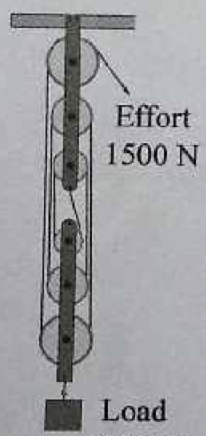


Fig. 6.16

velocity ratio = 6

$$\text{mechanical advantage} = \frac{5\ 000\text{ N}}{1\ 500\text{ N}}$$

$$= \frac{10}{3}$$

$$\text{efficiency} = \frac{\text{M.A}}{\text{V.R}} \times 100 = \frac{10}{3} \times \frac{1}{6} \times 100\%$$

$$= 55.5\%$$

Example 6.9

A block and tackle pulley system has a velocity ratio of 4. If its efficiency is 75%. Find the

(a) mechanical advantage.

(b) load that can be lifted with an effort of 500 N.
(c) work done if the load is lifted through a vertical distance of 4.0 m.
(d) average rate of working if the work is done in 2 minutes.

Solution

(a) efficiency $= \frac{M.A}{V.R} \times 100\%$

$75\% = \frac{M.A}{4} \times 100\%$

Therefore, $M.A = \frac{75 \times 4}{100} = 3$

mechanical advantage is 3.

(b) Mechanical advantage $= \frac{\text{load}}{\text{effort}}$

$3 = \frac{\text{load}}{500}$

Load $= 500 \times 3$

Therefore, Load is 1 500 N.

(c) work = force × distance in the direction of force

$= 1\,500 \times 4$

$= 6\,000$ J

(d) rate of doing work = power

Power $= \frac{\text{work done}}{\text{time}}$

$= \frac{6\,000}{120} = 50$ W

Exercise 6.4

1. A pulley system has a velocity ratio of 4. In this system, an effort of 68 N would just raise a load of 217 N. Find the efficiency of this system.
2. A crane just lifts 9 940 N when an effort of 116 N is applied. The efficiency of the crane is 75%. Find its
   (a) mechanical advantage (b) velocity ratio
3. Fig. 6.17 shows a pulley system. An effort of 113 N is required to lift a load of 180 N.
   (a) What distance does the effort move when the load moves 1 m?
   (b) Find the work done by the effort.
   (c) Find the work done on the load.
   (d) Calculate the efficiency of the system.

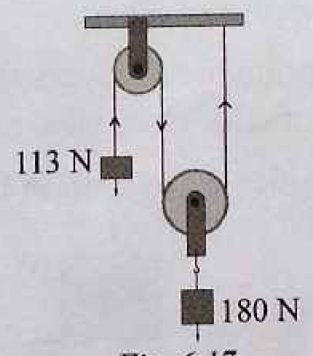


Fig. 6.17

4. The Fig. 6.18 shows a single fixed pulley.

Calculate its (a) V.R (b) Efficiency

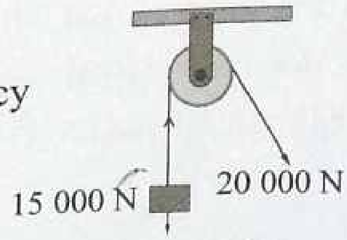


Fig. 6.18

5. In the system shown in Fig. 6.19, the winding machine exerts a force of 2.0×10^4 N in order to lift a load of 3.2×10^4 N.

(a) What is the velocity ratio?

(b) Calculate the M.A.

(c) Find the efficiency.

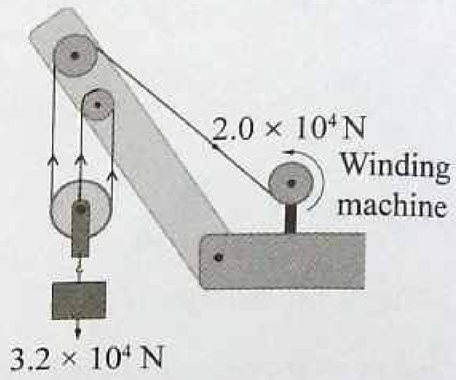


Fig. 6.19: A winding crane

6. (a) Draw a system of pulleys with two pulleys in the lower and upper block.

(b) Describe how you would find experimentally its mechanical advantage.

Levers

Levers are simple machines that apply the principle of moments. A lever is a rigid bar capable of rotating about a fixed point called the *pivot*.

Principles of moment of a force

A moment of a force about a point is the product of the force and perpendicular distance from the point to the line of action of the force.

Moments of a force about a point = Force (N) × perpendicular distance (m)

$= F \times d$

Principles of levers

The principle of levers states that sum clockwise moment at a point is equal to the sum of anti- clockwise moment at the same point at equilibrium.

Consider the system in Fig. 6.20.

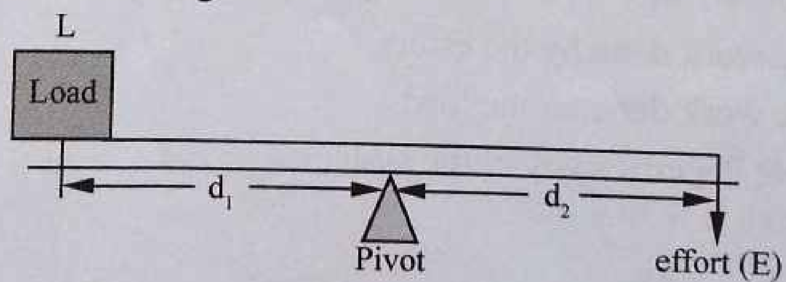


Fig. 6.20

Where d_1 is load distance (load arm)

d_2 is effort distance (effort arm)

From the system in Fig. 6.20.

At balance:

Sum of clockwise moments = sum of anticlockwise moments

$$d_2 \times E = d_1 \times F$$

Example 6.10

Fig.6.21 shows a simple machine in the first class.

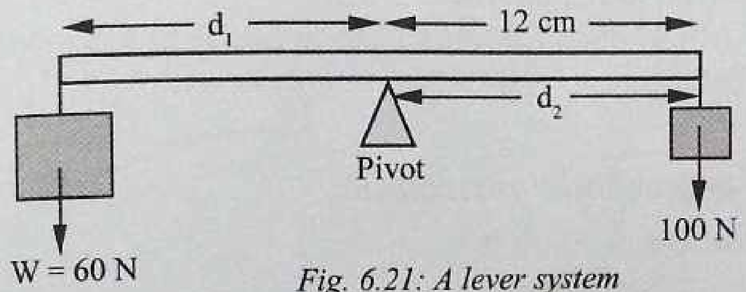


Fig. 6.21: A lever system

Calculate the value of d.

Solution

At equilibrium:

Clockwise moments at a point of action = anticlockwise moments at the same point

$$d_1 \times F_1 = d_2 \times F_2$$

$$60\text{ N} \times d_1 = 12\text{ cm} \times 100\text{ N}$$

$$d_1 = \frac{(\overset{2}{\cancel{12}}\text{ cm} \times 10\cancel{0}\ \cancel{\text{N}})}{(\underset{1}{\cancel{60}}\ \cancel{\text{N}})}$$

$$= 20\text{ cm}$$

Example 6.11

A worker uses a crowbar to lift a rock weighing 800 N as shown in Fig.6.22.

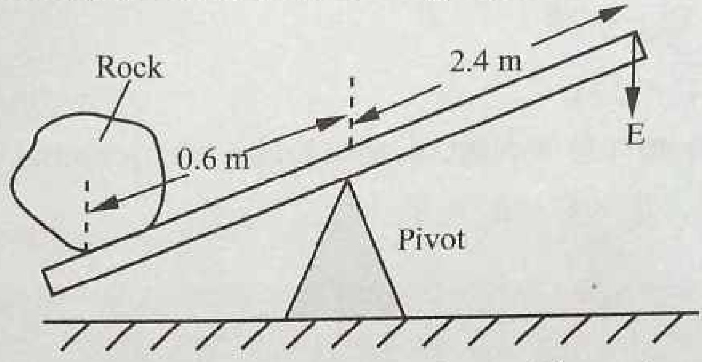


Fig. 6.22: Using a crowbar to lift a rock

Calculate the effort, E used to lift the rock.

Solution

At balance

Clockwise moment = anticlockwise moment

$$2.4\ \text{M} \times E = 0.6\ \text{m} \times 800\ \text{N}$$

$$E = \frac{(\cancel{0.6}^{\,2}\ \cancel{\text{m}} \times \cancel{800}^{\,12}\ \cancel{\text{N}})}{\cancel{2.4}_{\,1}\ \cancel{\text{m}}}$$

$$= 200\ N$$

NOTE: we will deal with principles of moments in Senior 3 in details.

There are three types of levers. The difference between these types depends on the position of the pivot with respect to the load and the effort.

1. The pivot in between the load and the effort. Examples (Fig. 6.23).

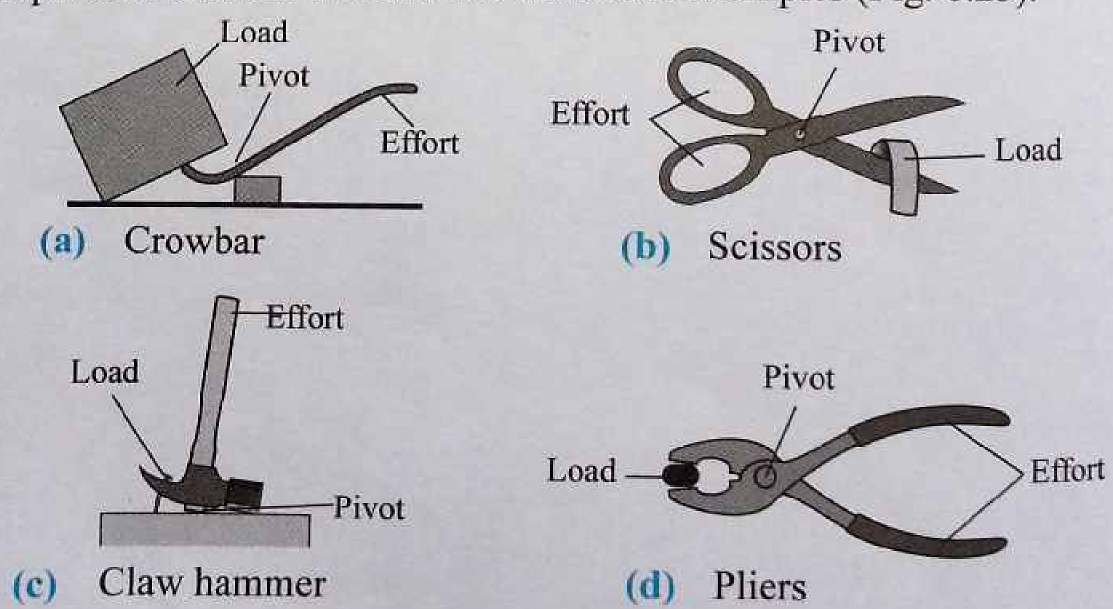
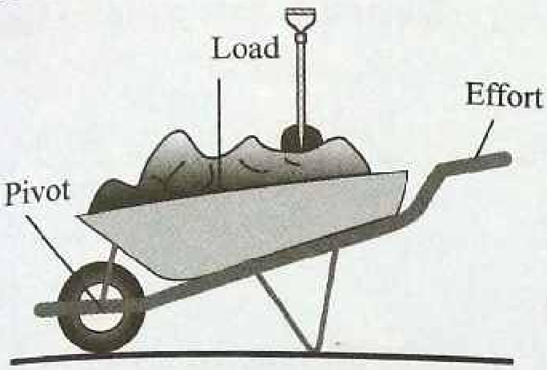
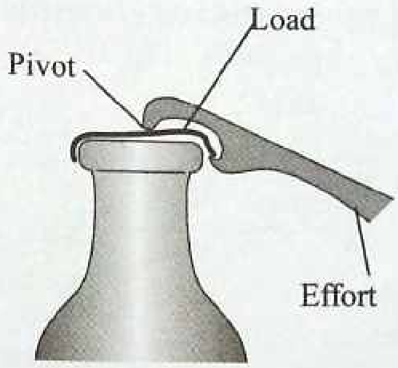


Fig. 6.23: Pivot between the load and the effort

2. Load between effort and pivot. Examples (Fig. 6.24).



(a) Wheelbarrow

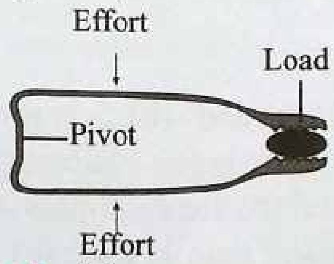


(b) Bottle opener

Fig. 6.24: Load between the effort and the pivot.

3. Effort between load and pivot. Examples (Fig. 6.25).

(b) Fishing rod



(c) Tweezers

Fig. 6.25: Effort between the load and the pivot.

Mechanical advantage of levers

Consider a lever with the pivot between the load and the effort (Fig. 6.26).

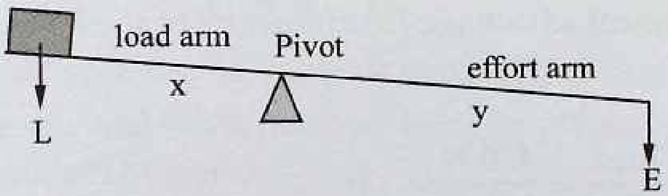


Fig. 6.26: Mechanical advantage for levers.

Taking moment about the pivot

$$\text{load} \times \text{load arm} = \text{effort} \times \text{effort arm}$$

$$\frac{\text{load}}{\text{effort}} = \frac{\text{effort arm}}{\text{load arm}}, \text{ But } \frac{\text{load}}{\text{effort}} = \text{mechanical advantage}$$

$$\text{velocity ratio} = \frac{\text{effort arm}}{\text{load arm}} = \frac{y}{x}$$

This also applies to the other types of levers

Since effort arm is usually greater than load arms, levers have mechanical advantage greater than 1.

Velocity ratio for levers

Consider three types of levers in which the load and the effort have moved a distance d_L and d_E respectively (Fig. 6.27).

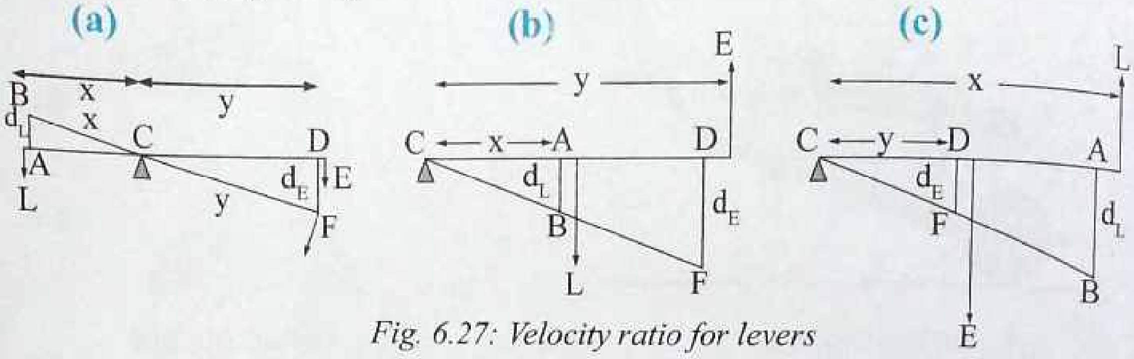


Fig. 6.27: Velocity ratio for levers

Triangles ABC and CDF are similar.

$$V.R = \frac{d_E}{d_L} = \frac{y}{x}$$

In Fig. 6.27(a) and (b), y is greater than x. The velocity ratio is therefore greater than 1. However in (c), y is less than x, and therefore the velocity ratio is less than 1. Cases (a) and (b) are examples of *force multipliers*. All force multipliers have M.A and V.R greater than 1. Case (c) is an example of *distance multiplier* in which both the velocity ratio and mechanical advantage are less than 1.

Example 6.12

A lever has a velocity ratio of 4. When an effort of 150 N is applied, a force of 450 N is lifted. Find (a) mechanical advantage (b) efficiency of the lever.

Solution

(a) mechanical advantage $= \frac{\text{load}}{\text{effort}} = \frac{450\text{ N}}{150\text{ N}} = 3.0$

(b) efficiency $= \frac{\text{M.A}}{\text{V.R}} \times 100\% = \frac{3}{4} \times 100\%$

$= 75\%$

Example 6.13

A worker uses a crow bar 2.0 m long to lift a rock weighing 750 N (Fig. 6.28).

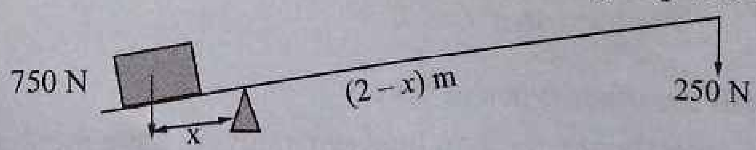


Fig. 6.28

(a) Calculate the position of the pivot in order to apply an effort of 250 N.

(b) Find the (i) velocity ratio (ii) mechanical advantage

(iii) efficiency of the lever.

(c) Comment on your answer.

(Assuming no energy loss)

Solution

(a) applying the principle of moments

$$750x = 250(2 - x)$$

$$750x = 500 - 250x$$

$$1\,000x = 500$$

$$x = 0.5 \text{ m}$$

(b) (i) velocity ratio $= \frac{\text{effort distance}}{\text{load distance}}$

$$= \frac{1.5}{0.5} = 3$$

(ii) mechanical advantage $= \frac{750}{250}$

$$= 3$$

(iii) efficiency $= \frac{\text{M.A}}{\text{V.R}} \times 100 = \frac{3}{3} \times 100\%$

$$= 100\%$$

(c) We have assumed that there is no friction and that the crowbar is weightless.

Levers

Levers are simple machines used in day-to-day life. The following are some of the types of levers and their uses:

- Bottle openers, lid openers; used to open bottle tops and lids respectively.
- See saw and beam balance; used for playing games and comparing weights of different objects.
- Hinges are used in closing and opening of the doors, windows etc.
- Spanners are used in tightening and loosening bolts and nuts.
- A pair of scissors or garden shears used in cutting etc.
- Crowbar used in moving heavy loads.

Exercise 6.5

1. Define the following terms as applied to levers:
   (a) mechanical advantage (b) velocity ratio
2. Find the velocity ratio of the levers shown in Fig. 6.29.

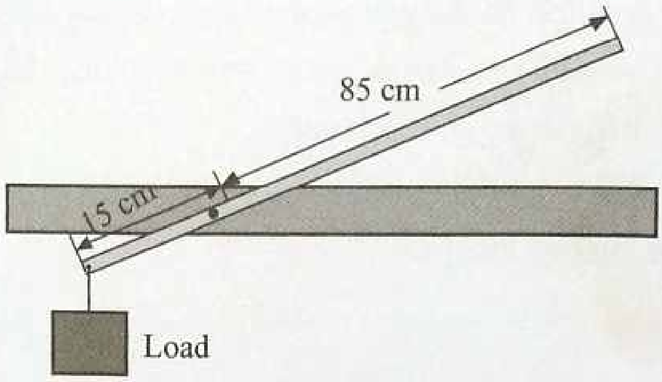


Fig. 6.29

3. Give an example of a lever with a mechanical advantage less than 1. What is the real advantage of using such a machine?
4. Describe an experiment to determine the velocity ratio of a lever whose pivot is between the load and the effort.

Unit summary

- Work is defined as *the product of force and distance moved in the direction of the force.* W = $F \times x$. SI unit of work is the joule (J): 1 J = 1 Nm
- Energy *is the ability to do work*. SI unit of energy is the joule (J).
- Potential energy (P.E) is the energy due to state or position of an object. P.E = mgh
- Kinetic energy (K.E) is the energy due to the motion of the body: K.E = $\frac{1}{2}mv^2$
- Energy can neither be created nor destroyed. It can only be changed from one form to another.
- A device which can change energy from one form to other is called a transducer.
- Power *is the rate of doing work.* SI unit of power is the watts (W). 1 watt = 1 J/s
- A machine is a device that makes work easier.
- Mechanical advantage (M.A) is defined as the *ratio of load to effort*

  $$\text{mechanical advantage} = \frac{\text{load}}{\text{effort}}$$

  The mechanical advantage of a machine depends on loss of energy of the moving parts of a machine. Mechanical advantage is a ratio of similar quantities hence it has no units.
- Velocity ratio (V.R) is defined *as the ratio of distance the effort moves to that moved by the load.*

velocity ratio = $\frac{\text{Distance moved by the effort}}{\text{Distance moved by the load}}$ · Velocity ratio is a ratio of similar quantities hence it has no units.

- Theoretical value of velocity ratio may be obtained from the dimensions of the machine e.g. in pulleys–number of the sections of string supporting the load.

Machine	VR
Inclined plane	$\frac{d}{h}$
Screw jack	$\frac{2\pi r}{\text{pitch, P,}}$
Wheel and axle	$\frac{\text{Radius of wheel, R}}{\text{Radius of axle, r}} = \frac{R}{r}$

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

$$= \frac{\text{mechanical advantage}}{\text{velocity ratio}} \times 100$$

Unit Test 6

1. The SI units of work is [1]

   A. Mega watts
   B. Joules
   C. Kilojoules
   D. Watts

2. Which of the following lever is not in the first class lever system? [1]

   A. Bottle opener
   B. Claw hammer
   C. A shear
   D. Crowbar

3. What is the formula of efficiency? [2]

   A. Efficiency $= \frac{\text{work}}{\text{power}} \times 100\%$

   B. Efficiency $= \frac{\text{force}}{\text{work input}} \times 100\%$

   C. Efficiency $= \frac{\text{work input}}{\text{work output}} \times 100\%$

   D. Efficiency $= \frac{\text{useful work output}}{\text{work input}} \times 100\%$

4. A farmer draws water from a well using the machine shown in Fig. 6.30. The weight of the bucket and water is 150 N. The force, F exerted by the farmer is 170 N. The bucket and its content is raised through a height of 15 m.

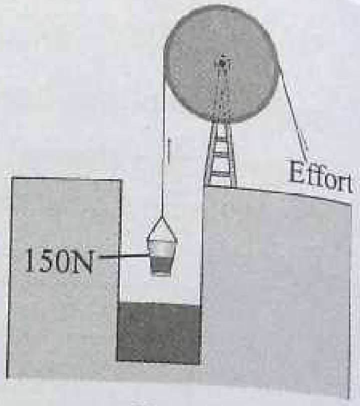


Fig. 6.30

(a) What is the name given to such a machine?
(b) Why is the force, F, larger than the weight of the bucket and water? [2]
(c) What distance does the farmer pull the rope? [2]
(d) How much work is done on the bucket and water? [3]
(e) What kind of energy is gained by the bucket? [2]
(f) How much work is done by the farmer? [2]
(g) Where does the energy used by the farmer come from? [1]
(h) Show with a flow diagram the energy conversion in lifting the water from the well. [2]

5. Fig. 6.31 shows a pulley system. Find

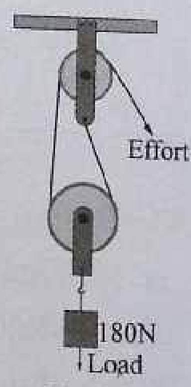


Fig. 6.31

(a) the velocity ratio of the pulley system.
(b) the mechanical advantage, if the system is 80% efficient.
(c) the effort.
(d) the work done by the effort in lifting the load through a distance of 0.7 m.
(e) how much energy is wasted.

6. A factory worker lifts up a bag of cement of mass 50 kg, carries it horizontally then up a ramp of length 6.0 m onto a pick-up and finally drops the bag of cement on the pick-up (Fig. 6.32).

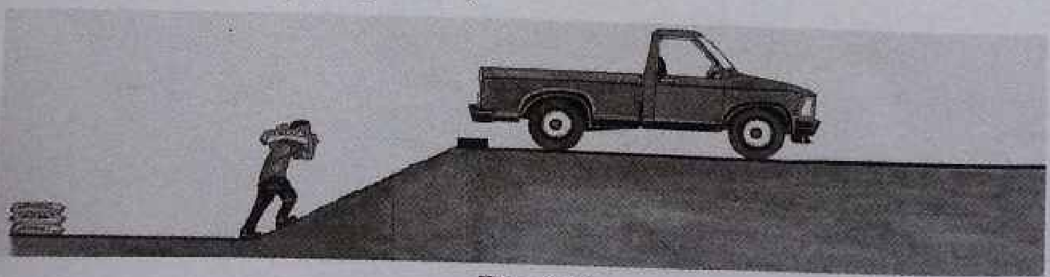


Fig. 6.32

(a) Explain the energy changes in the various stages of the movement of the worker. [2]

(b) During which stages is the worker doing work on the bag of cement.

(c) If the worker has a mass of 60 kg and the ramp is 1.5 m high, find the

(i) velocity ratio.

(ii) efficiency of the inclined plane if the mechanical advantage is 3.

7. Fig. 6.33 shows the cross-section of a wheel and axle of radius 6.5 cm and 1.5 cm respectively used to lift a load. Calculate the efficiency of the machine. [3]

8. Define the following terms. [5]

(a) energy

(b) power

(c) work done

(d) efficiency

(e) mechanical advantage

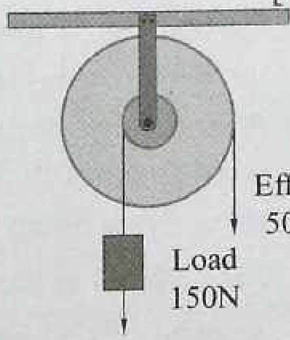


Fig. 6.31

9. A pulley system has a velocity ratio of 3. Calculate the effort required to lift a load of 600 N, if the system is 75% efficient. [3]

10. Fig. 6.34 shows a pulley system.

(a) What is the velocity ratio of the system.

(b) Calculate the efficiency of the system.

(c) Show the direction of the force on the string.

11. A block and tackle pulley system has five pulleys. It is used to raise a load through a height of 20 m with an effort of 100 N. It is 80% efficient.

(a) Is the end of the string attached to the upper or lower block of pulleys if the upper block has three pulleys? Show it in a diagram. [2]

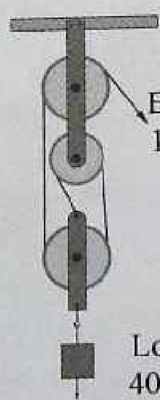


Fig. 6.34

(b) State the velocity ratio of the system. [2]

(c) Calculate the load raised. [1]

(d) Find the work done by the effort. [2]

(e) Find the energy wasted. [1]

12. A man pulls a hand cart with a force of 1 000 N through a distance of 100 m in 100 s. Determine the power developed. [3]

13. An effort of 50 N is applied to a brace of a car's screw jack whose handle moves through a circle of radius 14 cm. The pitch of the screw thread is 2 mm. Calculate the:

(a) velocity ratio of the screw jack. [2]

(b) load raised if the efficiency is 30%. [2]

14. A person of mass 60 kg climbs 16 m up a rope in 20 s. Find the average power developed by the person. [3]

15. A car is doing work at a rate of 8.0×10^4 W. Calculate the thrust of the wheels on the ground if the car moves with a constant velocity of 30 m/s. [3]

16. A student of mass 40 kg climbs a staircase to a height of 14.0 m above the starting point in 55.0 s.

(a) How much force does the student exert in getting to the higher level?

(b) What is the student's power? [4]

17. A lever system has a velocity ratio of 4. When an effort of 250 N is applied, a load of 750 N is lifted. Find:

(a) Mechanical advantage of the lever. [2]

(b) Efficiency of the lever. [2]

UNIT 7: Electrostatics

Success Criteria

By the end of this unit, you must be able to;

- Explain the existence of charges in matter.
- Explain how objects are charged in electrostatics.
- Describe the effect of distance and magnitude on electrostatic force.
- Describe the role of electrostatics in everyday life.

7.1 Introduction

You may have observed the following phenomena.

1. Sometimes one can get a shock when getting out of a car or touching the metal knob of the door.
2. Dust particles stick to a window pane when the pane is wiped with a dry cloth on a dry day.
3. A metal chain is usually attached to the trucks carrying petrol or other inflammable materials.

These experiences are as a result of *electrostatic phenomena*. The physics behind these observations will be clear after going through this unit.

7.2 Electrostatic charging by rubbing

Take a polythene strip and rub it against a material like silk, flannel or fur. Take the strip near a thin stream of flowing water from a tap. Observe what happens to the stream of water.

The stream of water is strongly attracted to the polythene strip as shown in Fig. 7.1.

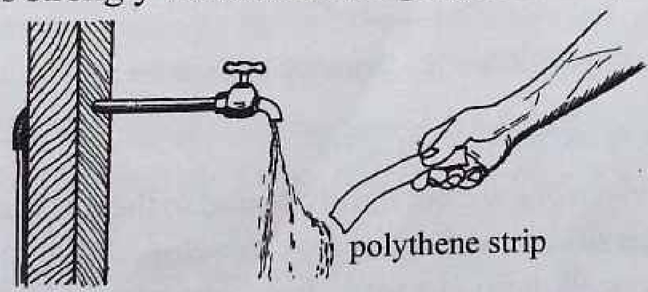


Fig. 7.1: Stream of water attracted to a polythene strip

When the polythene strip is rubbed against silk, it acquires the *attractive* property. We say that the polythene strip has been *charged by friction*. The charged polythene strip *attracts* the thin stream of water.

The charged polythene strip can also attract bits of paper, tiny pieces of cloth, etc. Many substances such as glass, metals, plastic, ebonite, perspex when rubbed with silk, rubber, fur, wool or cat skin acquire the *attractive* property. This implies that we can charge bodies by friction. The charges developed on the materials are at rest and cannot move. We call them *static charges*. There are two types of static charges: *positive charges* and *negative charges*. The study of static charges is called *electrostatics*. Scientists like Benjamin Franklin, and Charles Coulomb contributed a lot to the development of this branch of physics.

When a material of one kind is *rubbed* with some other material, both materials get charged by friction. Where do the charges come from? A simple idea of the *structure of an atom* will enable us to understand the mechanism of charging.

We learnt earlier on that matter is made up of tiny particles called *atoms*. For a long time, scientists thought that the atoms were the smallest building blocks of matter and that they could not be subdivided further. However, in 1897, a new particle smaller than an atom was discovered. It was called *electron*. Later, other particles called *protons* and *neutrons* were discovered. Today we have a better picture of the atom than in 19th century.

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 closely and tightly packed (Fig. 7.2). 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 are equal in an atom and hence an atom is always neutral.

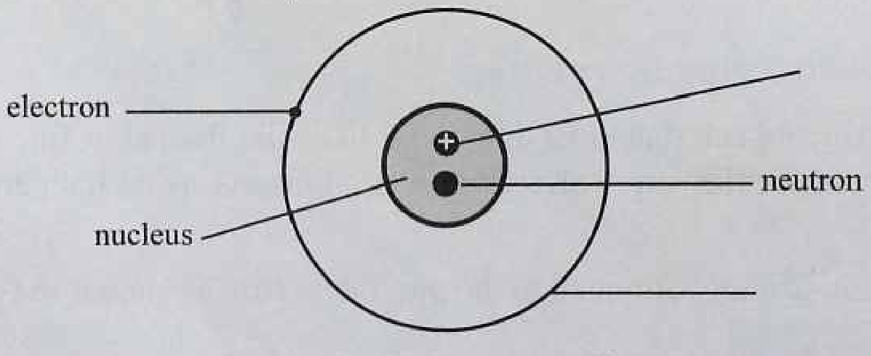


Fig. 7.2: Structure of an atom

7.3 Source of electrostatic charging

In some materials, the electrons are not tightly bound to the nucleus. When two *materials* are rubbed against each other, the heat energy developed due to friction, can possibly 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.

Materials like polythene *gain* electrons from flannel cloth when rubbed and become negatively charged. Flannel cloth loses electrons and becomes positively charged (Fig. 7.3).

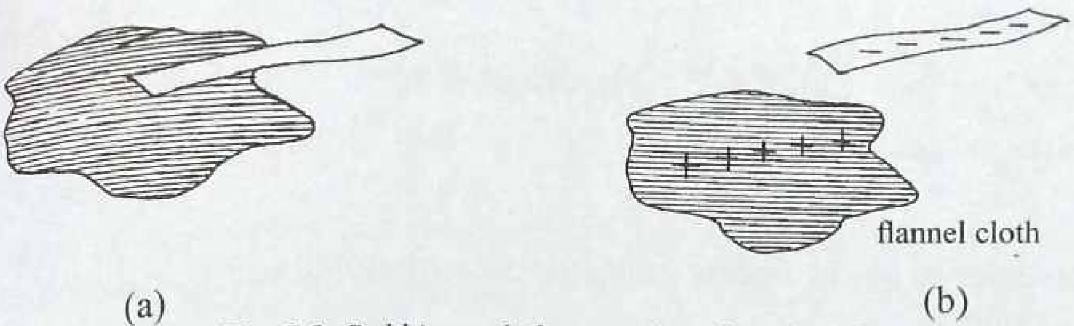


Fig. 7.3: Rubbing polythene against flannel cloth

Materials like glass *lose* electrons to the materials like silk when rubbed and become positively charged. The material of the silk cloth gains electrons and becomes negatively charged (Fig. 7.4).

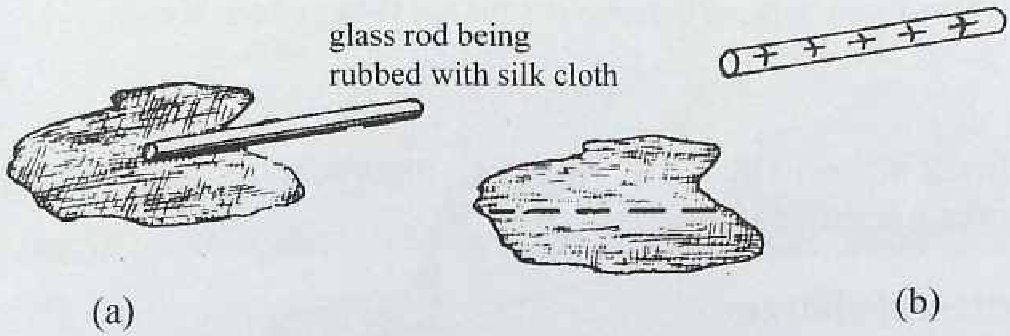


Fig. 7.4: Rubbing glass against silk cloth

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 points when materials are charged by friction:

1. The excess negative charges on one body is equal to the excess positive charges on the other. No new charges have been created.
2. During the rubbing process, some materials always acquire the same kind of charge whereas some materials may acquire either negative or positive charges.
3. 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.

Observation shows that the nature of charge on a rubbed substance depends upon the nature of the rubbing material. From experience physicists have classified the substances in a particular order. The list in Table 7.1 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 7.1

Example 7.1

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 7.2

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.

7.4 The law of charges

Experiments to investigate the effect of charged bodies

Experiment 7.1: To show the force of repulsion between two charged bodies, using different materials

Apparatus

- An ebonite rod
- A thread
- Silk
- Polythene rod

Procedure

- Rub an ebonite rod with silk and suspend the rod with a stirrup and thread. Bring a charged polythene rod near one end of the ebonite rod and observe what happens (Fig. 7.5).

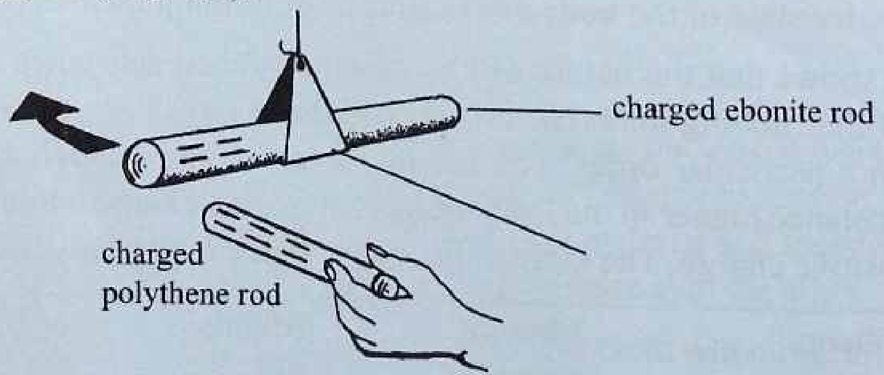


Fig. 7.5: Charged polythene repels charged ebonite rod

Observation

The charged polythene rod *repels* the charged ebonite rod.

Discussion

There is a force of repulsion between the two rods.

Conclusion

The two materials repels each other since they acquired the same charges.

Experiment 7.2: To show the force of attraction between two charged bodies

Procedure

- Repeat Experiment 7.1 by taking a charged glass rod near one end of the suspended charged ebonite rod and observe what happens this time (Fig. 7.6).

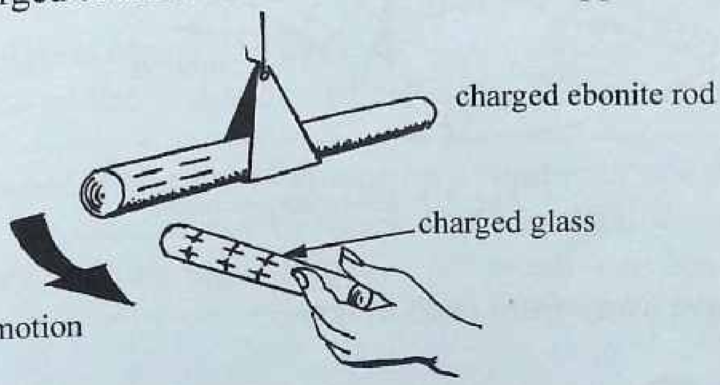


Fig. 7.6: A charged glass rod attracts a charged ebonite rod

Observation

The charged glass rod *attracts* the charged ebonite rod.

Discussion

In Experiment 7.1, the charged ebonite rod is *repelled* by the charged polythene rod whereas in this Experiment, the same ebonite rod is *attracted* by the charged glass rod. These experiments show that the charges on polythene and glass are unlike.

Conclusion

Unlike charges attract each other.

Experiment 7.3: To show the force of repulsion between two similar charges, using rods of the same material

Apparatus

- Two polythene rods
- A silk cloth
- A thread

Procedure

- Rub two polythene rods with a silk cloth vigorously and suspend them with stirrups and thread.
- Bring the two suspended rods close to each other and observe what happens (Fig. 7.7).

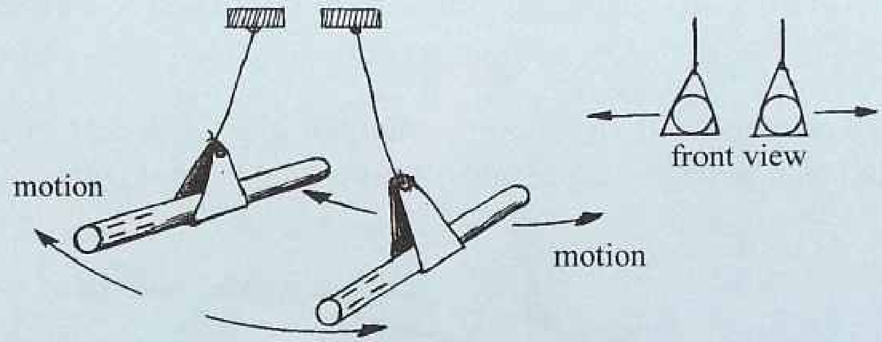


Fig. 7.7: Like charges repel

Observation

The two rods move away from each other.

Discussion

The polythene rods have similar charges and repel each other.

If the above experiment is repeated with two charged glass rods rubbed with silk, the same effect is observed. The two glass rods have similar charges. They repel each other.

Conclusion

Like charges or similar charges repel each other.

From the above experiments we can conclude that:

1. The electric charges are of two types: negative and positive.
2. Unlike charges attract each other.
3. Like charges repel each other.

The law of charges states that like charges repel and unlike charges attract.

To confirm that a body is charged

Though observed that a charged polythene strip attracts a thin stream of water, we should take note that the stream of water is uncharged or neutral. So attraction is not a good test to confirm whether a body is charged or not. A charged polythene rod is repelled when another charged polythene is brought close to it. No uncharged bodies are repelled by charged bodies. *Repulsion* is, therefore, *the best test to confirm that a body is charged.*

SI unit of charge

The SI unit of quantity of charge is the *coulomb (C)*, named after a famous scientist called *Charles Augustin de Coulomb (1736-1806).*

Earthing

Earthing means to neutralise a charged body. If the charges are low, we can earth a charged body by touching it with our hand . If the charges are high, the charged body is connected to a thick metal rod (examples: water pipes or metal grills of a window). The symbol for earthing is ⏚. If a negatively charged plate is connected to the earth, *the excess electrons flow from the plate to the earth* and the plate becomes neutral. If a positively charged plate is connected to the earth, *the electrons from the earth move to the plate* and neutralise the deficiency of electrons. 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".

Electrostatic induction

When a negatively charged polythene rod, called the *inducing charge I,* is brought near a metal plate mounted on a wooden stand, a few electrons are repelled from the end X nearer to the inducing charge (Fig. 7.8). The end Y has gained electrons while there is a deficiency of electrons in the end X.

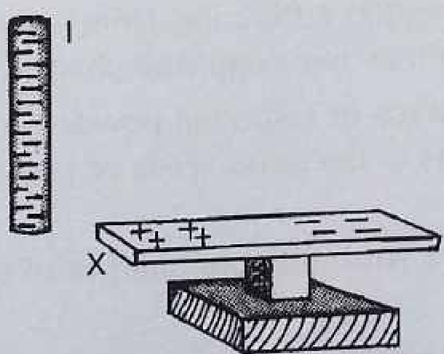


Fig. 7.8: Electrons are repelled from end X

The net or resultant charge of the body XY is still zero (uncharged) since we have only a redistribution of charges. This process where there is re-distribution of charges in a body in the presence of an inducing charge is called *electrostatic induction*. If I is moved away, the electrons return to the end X.

7.5 Electric field and electric field patterns

We are familiar with the observation that a charged body attracts small pieces of paper, dust, hair etc. The basic law of electrostatics states that *like charges repel and unlike charges attract*. So a charged body can affect other nearby objects without touching them. This *action at a distance* can be explained by what is called the *electric field* of a charged body.

Experiment 7.4: To demonstrate the electric fields produced by charged bodies

Apparatus

- A pair of straight wire
- Castor oil
- A glass dish
- Semolina powder

Procedure

- Assemble a pair of straight metal wires, called the *electrodes*, in a shallow glass dish so that their ends are just covered by a layer of an insulating liquid like castor oil or carbon tetrachloride (Fig. 7.9).

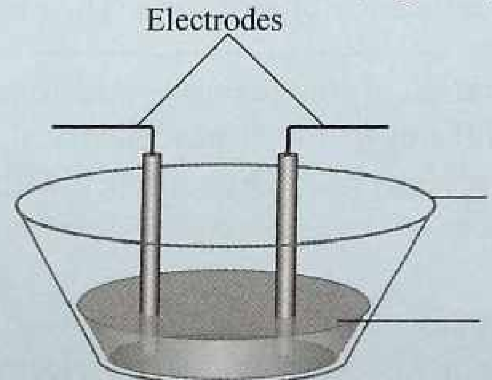
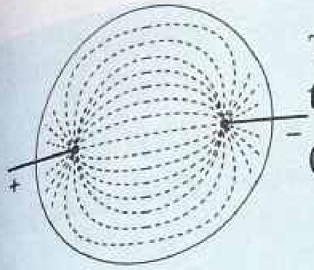


Fig. 7.9: Arrangement to study the electric field

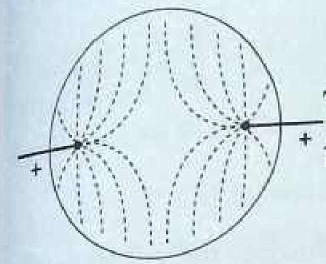
- Apply a very high potential difference, from a suitable power supply, to the two electrodes so that they have opposite charges.
- Then sprinkle grass seeds or semolina powder on the surface of the liquid. Observe what happens to the grass seeds or powder and draw the resulting pattern.
- Repeat the experiment with different charges of electrodes and observe the pattern formed.
- Draw the various patterns and draw the various alignment of the seeds

Observation

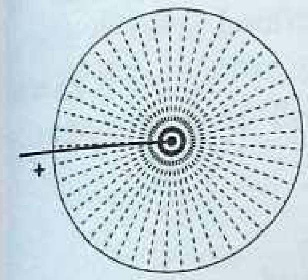
The seeds acquire induced opposite charges at their ends and align themselves in a particular pattern (Fig. 7.10 (a)). This pattern depends upon the charge of the electrodes.



Two straight wires dipped into the liquid and connected to the opposite polarities of a high voltage power supply (Fig. 7.10 (a)).



Two straight wires dipped into the liquid, both connected to the same positive potential terminals (Fig. 7.10 (b)).



A straight vertical wire dipped into the liquid having a high positive charge (Fig. 7.10 (c)).

The above alignment of seeds depict the electric field produced in different arrangements.

Discussion

An electric field may be described as the region or space surrounding a charge. In this region, another charged body may move away from or towards the charged body producing the electric field. In Fig. 7.11, P is a positively charged body and N is a negatively charged body producing an electric field.

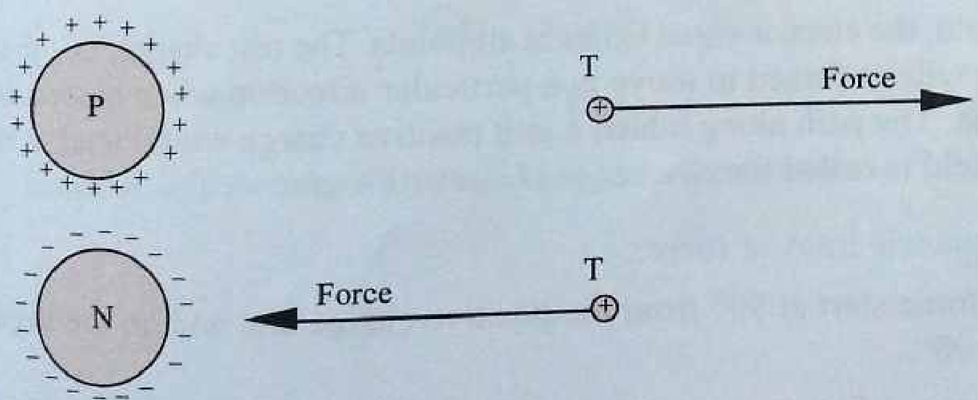


Fig. 7.11: Force between charges in an electric field

If another light charged body T is introduced in this field, the body T may experience a force away from P or towards N.

If a body is positively charged and has a charge of 1 coulomb it is called a *test charge* or *a unit positive charge*. A unit positive charge experiences a force in the electric field.

Conclusion

An electric field is defined as *the region where a charged body experiences a force.*

Direction of an electric field

Fig. 7.12 shows the direction of the force acting on the test charge, indicated by the arrow head. The force is either away from or towards the charge which creates the field. *The direction of the electric field* at a particular point is defined as *the direction in which the unit positive charge is free to move when placed at that point*. It should be noted that the force experienced by a negative charge will be in an opposite direction to that of the electric field.

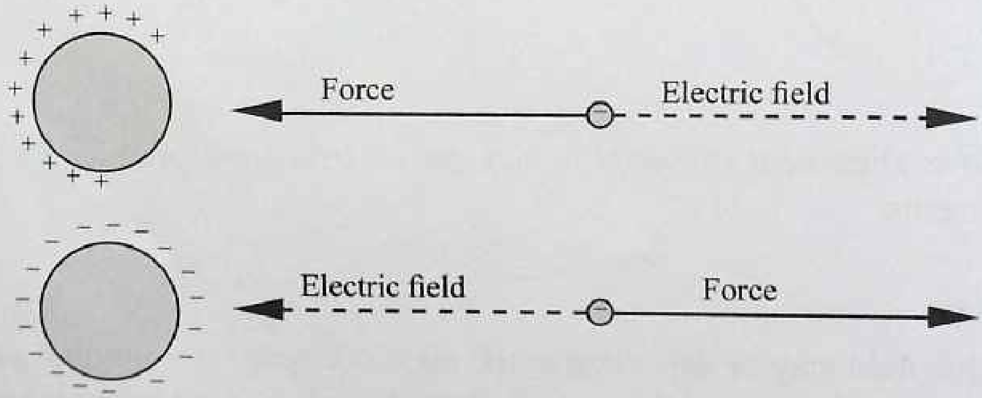


Fig. 7.12: Force acting on a negative charge in an electric field

Electric line of force

In an electric field, the electric force exists at all points. The test charge, i.e., the unit positive charge will be forced to move in a particular direction when placed at any point in the field. The path along which a unit positive charge would tend to move in the electric field is called the *electric field line or the electric line of force.*

Properties of electric lines of force

1. Lines of force start at 90° from the positive charge and end on the negative charge at 90°.
2. No two lines of force can ever cross each other.

3. The field lines are '*elastic*', i.e., the lines tend to contract or expand so that they never intersect each other.

A line of force may be traced by placing a unit positive charge at any point and allowing it to move throughout in the direction of the force acting on it. This is similar to the magnetic line of force in the magnetic field created by a magnet.

Electric field patterns

The electric field pattern around a charged body depends on whether the body is completely isolated or is in the presence of other bodies. The following are some examples of electric field patterns for isolated and non-isolated bodies.

1. Fig. 7.13 shows an isolated positive point charge. The field lines are radially outwards from the positive charge.

2. Fig. 7.14 shows an isolated negative point charge. The field lines are radially inwards towards the negative charge.

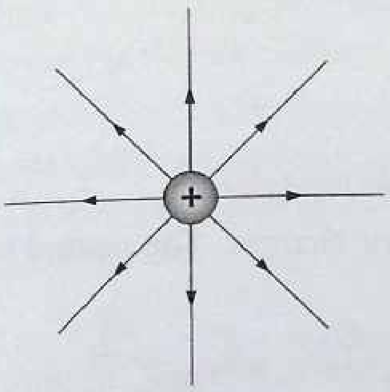


Fig. 7.13: Isolated positive point charge

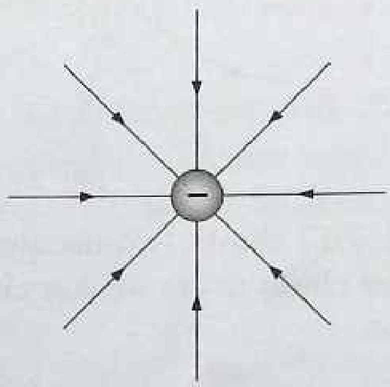


Fig. 7.14: Isolated negative point charge

3. Fig. 7.15 shows two equal positive point charges. The field lines start radially outwards from each charge. The resultant field is due to the electric field produced by each charge.

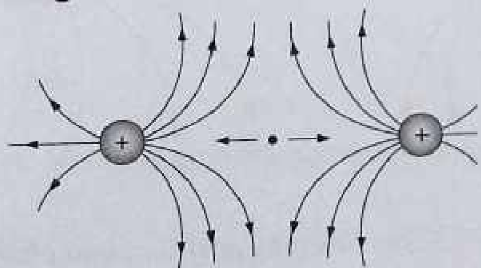


Fig. 7.15: Two equal positive point charges

A point N lies midway between the two charges, on the line joining them. Here the resultant force acting on the unit positive charge is zero and is called a *neutral point*. *A neutral point in an electric field is one where the resultant force acting on the unit positive charge is zero* (Fig. 7.15).

Force due to A = force due to B. i.e. $F_A = F_B$

No field lines exist at the neutral point.

4. Fig. 7.16 shows two equal unlike point charges. The field lines start from the positive charge and end on the negative charge. In this case, there is no neutral points as a unit positive charge placed at any point experiences a force.

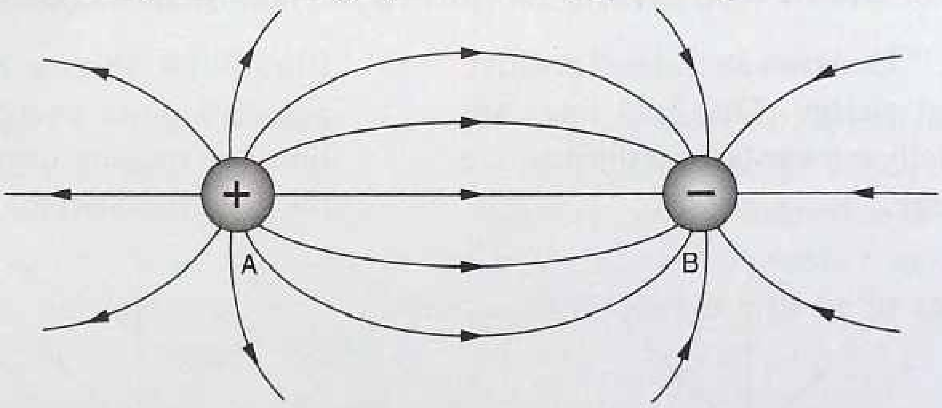


Fig. 7.16: Two equal unlike point charges

5. Fig. 7.17 shows two unequal positive point charges. The neutral point N is more closer to the weaker charge.

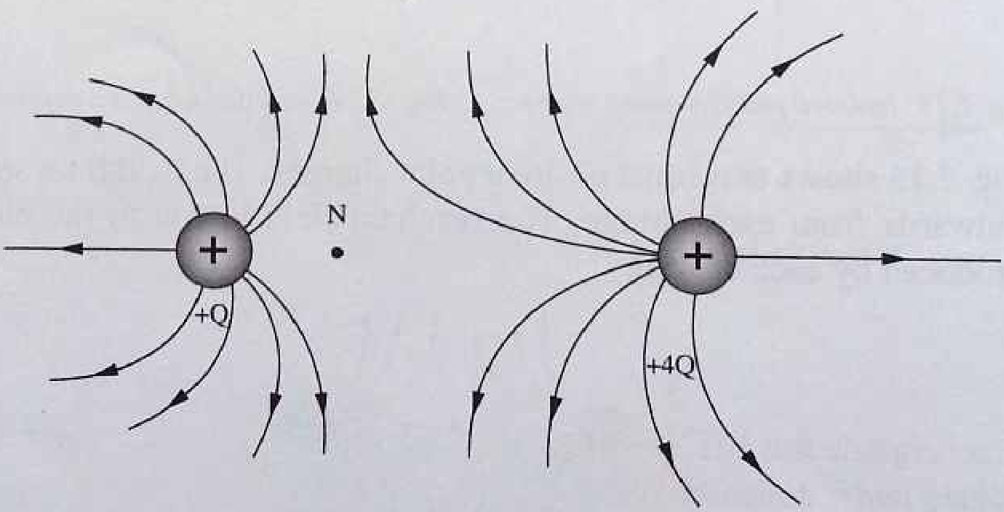


Fig. 7.17: Two unequal positive point charges

Factors affecting the magnitude of the force between two charged objects

Experiment 7.5: To determine the effect of the quantity of charge on the magnitude of the force between two charged particles.

Apparatus

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

Procedure

- Charge polythene rod A *lightly* by rubbing it with a piece of dry cloth and suspend it on a stand Fig. 7.2 (a).
- Charge polythene rod B *strongly* by rubbing it with a piece of dry cloth and suspend it on a stand Fig. 7.2 (b).
- Charge Perspex rod C strongly by rubbing it a piece of dry cloth. Bring the charged Perspex rod in turns near the suspended polythene rods A and B. Compare the magnitudes 0f the force of attraction in both cases. What do you observe?

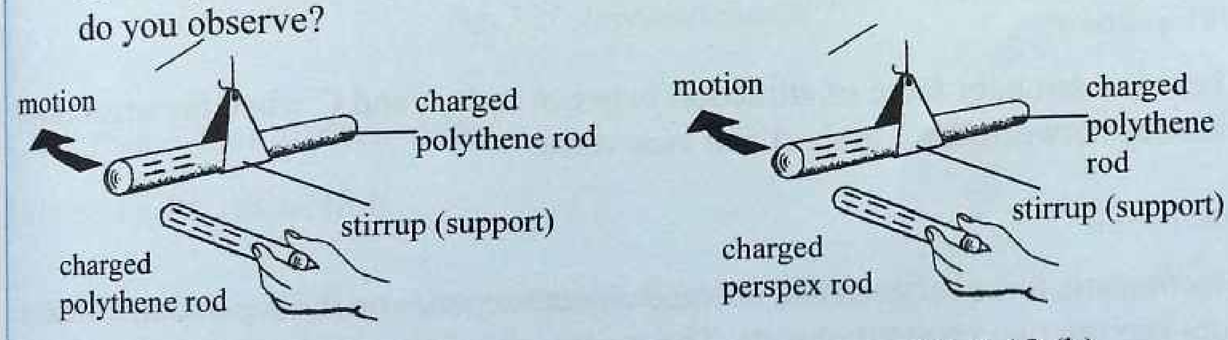


Fig. 7.18 (a)　　Fig. 7.18 (b)

Observation

There is a strong force of attraction between rods A and C than between rods B and C.

Conclusion

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.

Experiment 7.6: To determine dependence of the magnitude of force on the distance of separation.

Procedure

- Using the setup in Fig 7.18 (a) above:
- Bring the charged perspex rod C very close to the suspended charged polythene rod A. Observe the strength of the force of attraction between the two rods (Fig 7.19(a)).
- Bring the charged Perspex C near the suspended charged polythene rod A, a distance far than in step one (Fig 7.19(b)). Observe the strength of the force of attraction between the two rods. What do you notice?

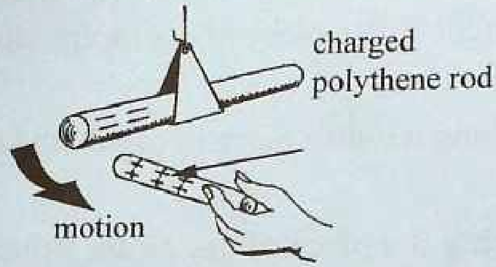


Fig. 7.19 (a)

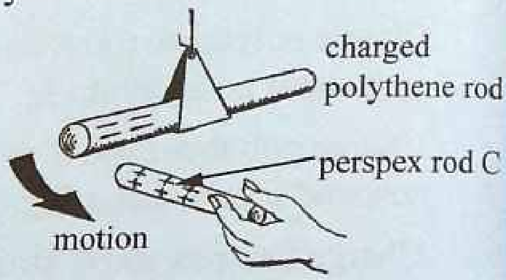


Fig. 7.19 (b)

Observation

There is a stronger force of attraction between rods A and C when the separation distance between them is short and vice versa.

Discussion

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.

Magnitude of the force between two charged objects depends:

- Quantity of charge i.e. the greater the quantity of charge, the greater the force between the body.
- Distance of separation i.e. the greater the distance, the smaller the force.

Exercise 7

1. Define the following terms: electric field, electric field strength, electric line of force, neutral point.
2. Is electric field strength a scalar or a vector quantity? Explain your answer.
3. Explain how a negatively charged pointed edge gets discharged by itself.

Leaf electroscope

A leaf electroscope is a *sensitive instrument that can be used for detecting and testing small electric charges*. This instrument was invented by a clergy man called *Abraham Bennet* at the end of 18th Century.

The leaf electroscope consists of an earthed metal case with 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. 7.21 shows a simplified version of a leaf electroscope. The inside of the electroscope is warmed with a burner or electric heater to achieve dry conditions.

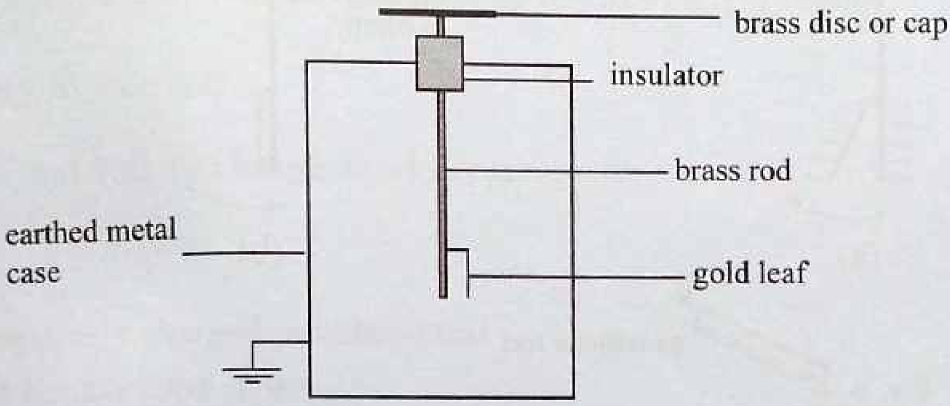


Fig. 7.21: Leaf electroscope

Charging a leaf electroscope

Charging by induction

Experiment 7.7: To charge an electroscope by induction

Apparatus

- An electroscope
- A charged polythene rod

Precaution

To ensure that the electroscope is not charged, touch the cap to earth it. To charge the electroscope, proceed as follows.

Procedure

1. Bring a negatively charged polythene rod close to the cap. Note what happens to the leaf of the electroscope (Fig. 7.22(a)).

2. Without disturbing the rod, touch the cap and note again what happens to the leaf. (Fig. 7.22(b)).
3. Keeping the rod in the same position, withdraw your finger. What happens to the leaf ? (Fig. 7.22(c)).
4. Remove the polythene rod and observe what happens to the leaf (Fig. 7.22(d)).

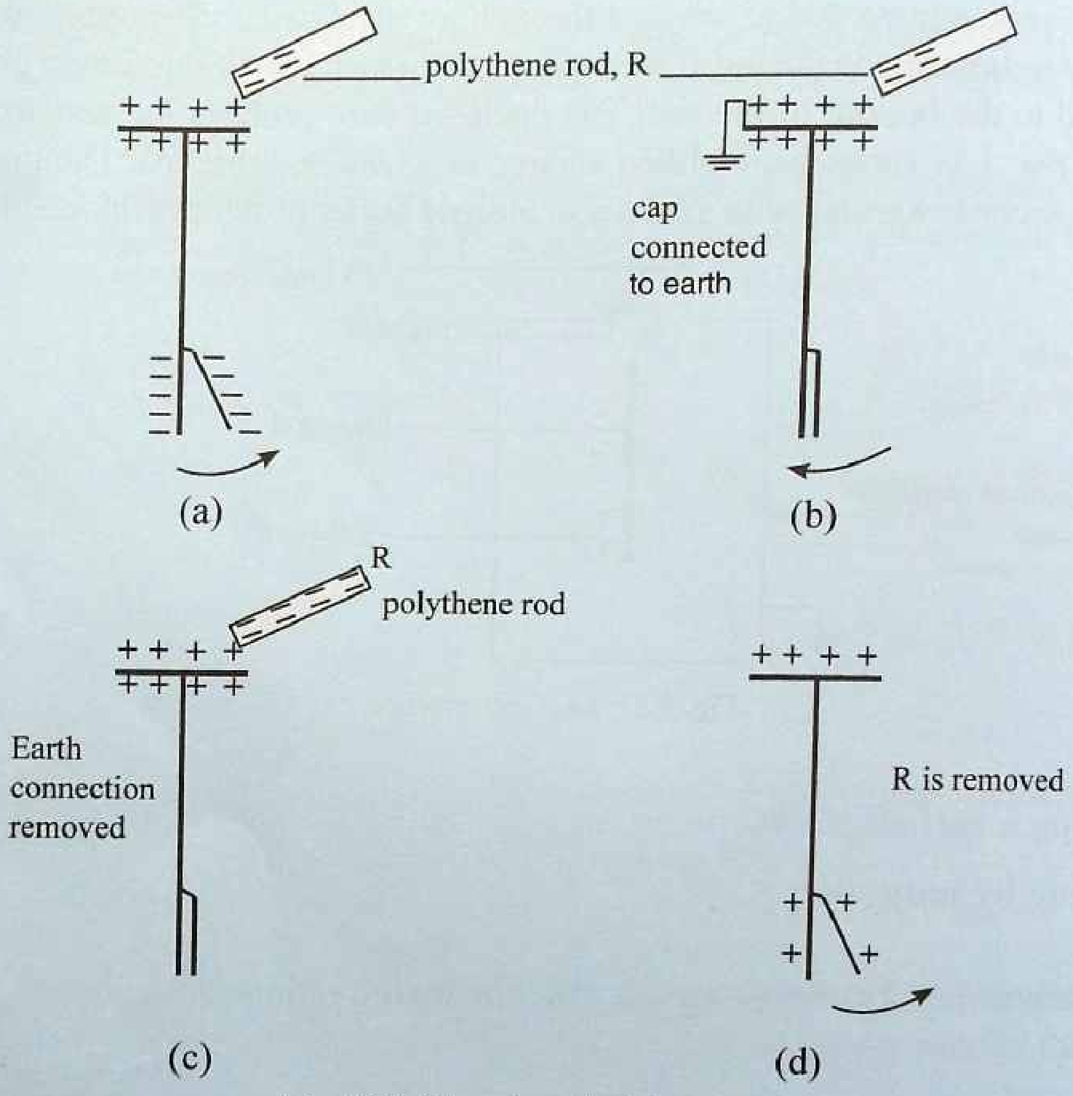


Fig. 7.22: Charging a leaf electroscope

Observations

In Step 1 the leaf diverges.

In Step 2 the leaf collapses.

In Step 3 the leaf stays the same.

In Step 4 the leaf diverges.

Discussion

When a negatively charged polythene rod is brought close to the cap, the electrons from the cap are repelled to the leaf. The bottom end of the rod and the leaf acquires negative charges. The leaf is repelled hence it divergence.

When the cap is touched (earthed), the excess electrons in the leaf and the rod escape to the earth. The leaf collapses. 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 earth connection is removed. The 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 leaf. The leaf diverges again. The leaf electroscope is positively charged.

Conclusion

The leaf electroscope can be negatively charged by using a positively charged glass rod, instead of a negatively charged rod as in Experiment 7.5.

Charging by contact

Experiment 7.8: To charge an electroscope by contact

Apparatus

- Negatively charged polythene rod
- An electroscope

Precaution

- Take a negatively charged polythene rod and rub it a number of times along the cap and withdraw the rod.
- Note what happens to the leaf of the electroscope (see Fig. 7.23).

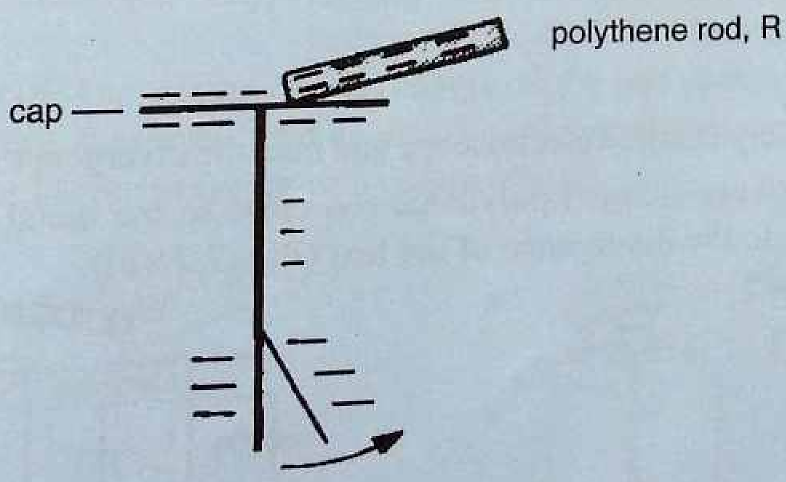


Fig. 7.23: Charging electroscope by contact

Observation

When the cap is being rubbed with the rod R, there is a divergence on the leaf. On withdrawing the rod, there is still some divergence.

Discussion

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

The leaf electroscope can also be charged by contact using a *charged metal rod with a rubber or polythene handle*. Touch the metal cap with the charged metal rod and remove the rod.

Conclusion

The leaf diverges showing that the electroscope has been is charged by contact.

Discharging a charged leaf electroscope

Charge a leaf electroscope. Earth the metal cap by touching with a finger. The leaf immediately collapses showing that the electroscope has been fully discharged.

Experiment 7.9: To identify the type of charge

Apparatus

- A charged electroscope
- A charged polythene rod

Part I

Precaution

- Take a negatively charged electroscope and note the divergence (Fig. 7.24(a)).
- Bring a negatively charged polythene rod close to the metal cap. Observe what happens to the divergence of the leaf (Fig. 7.24(b)).

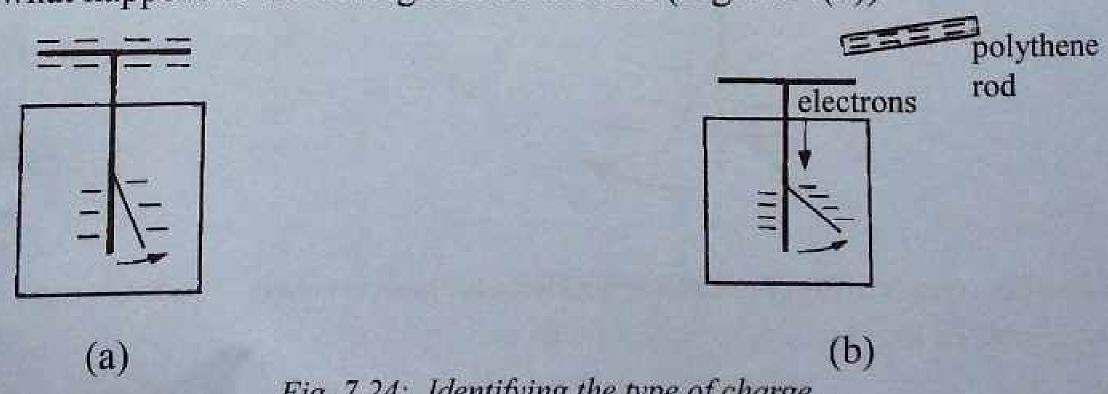


Fig. 7.24: Identifying the type of charge.

Observation

The divergence of the leaf increases.

Discussion

The negatively charged rod repels the electrons from the cap to the leaf. The quantity of the charge on the leaf increases. Hence, divergence increases. Therefore, the divergence of a charged leaf electroscope increases, if the object near the cap has the same charge as the leaf of the electroscope.

Conclusion

The charge on the rod is the same as that of the electroscope i.e. the rod is negatively charged.

Part II

Precaution

- Repeat the experiment by bringing a positively charged glass rod close to the metal cap. Observe what happens to the divergence of the leaf (Fig. 7.25(a)).
- Place your hand close to the metal cap of the electroscope. Note the position of the leaf.

Observation

- The divergence of the leaf decreases.
- The divergence once again decreases on placing the hand close to the metal cap.

Discussion

The positively charged glass rod attracts some of the electrons from the leaf to the cap. The quantity of charge on the leaf decreases. Hence divergence decreases. The hand is an uncharged body. The hand near the cap acquires the *positive charge by induction which attracts the electrons* from the leaf. The electrons move from the leaf to the cap. The quantity of the charge on the leaf decreases (Fig. 7.25(b)). Hence divergence decreases. The decrease in divergence of the leaf is therefore, not an evidence for the presence of a charged body.

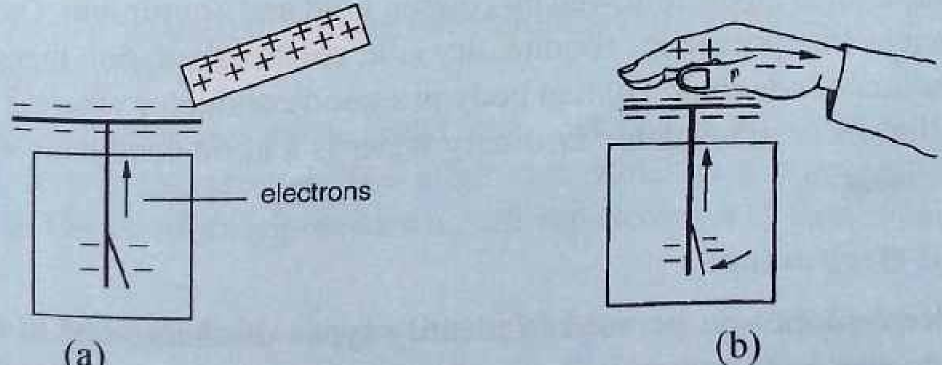


Fig. 7.25: Decrease in divergence is not an evidence for presence of a charged body

Experiment 7.10: To identify conductors and insulators

Apparatus

- A negatively charged electroscope
- A metal rod

Precaution

1. Take a negatively charged electroscope. Hold a metal rod, (say copper) and touch the cap of the electroscope. Observe what happens to the divergence of the leaf.
2. Repeat the above experiment by holding a wooden rod, say half metre rule and observe what happens to the divergence of the leaf.

Observation

- In step 1, the leaf collapses.
- In step 2, there is no change in divergence.

Discussion

In step 1, the electroscope has been earthed and the electroscope discharges fully. The charges on the electroscope pass easily through the metal rod and get into the body.

In step 2, the leaf remains in the same position. The charges on the electroscope are unable to pass through wood and the electroscope is not discharged.

Conclusion

From the above observations, we can classify matter into two groups namely, materials which allow charges (electrons) to pass through them called *conductors* and materials which do not allow the charges (electrons) to pass through them easily called *insulators*.

Most metals are good conductors while most non-metals are insulators. The best metallic conductor is silver followed by copper, gold and aluminium. On the other hand substances like porcelain, ebonite, dry silk, plastic glass, polythene, etc. are insulators or *bad conductors*. Human body is a good conductor whereas air under normal conditions is an insulator. Ordinary water is a good conductor while *pure* water is an insulator.

Uses of a leaf electroscope

A charged electroscope can be used to identify types of charge and to distinguish between conductors and insulators.

7.6 Effects and application of electrostatics

When large quantities of charges build up on bodies, they may become a nuisance. On the other hand electrostatic charging is quite useful to mankind. The following are some 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 *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.

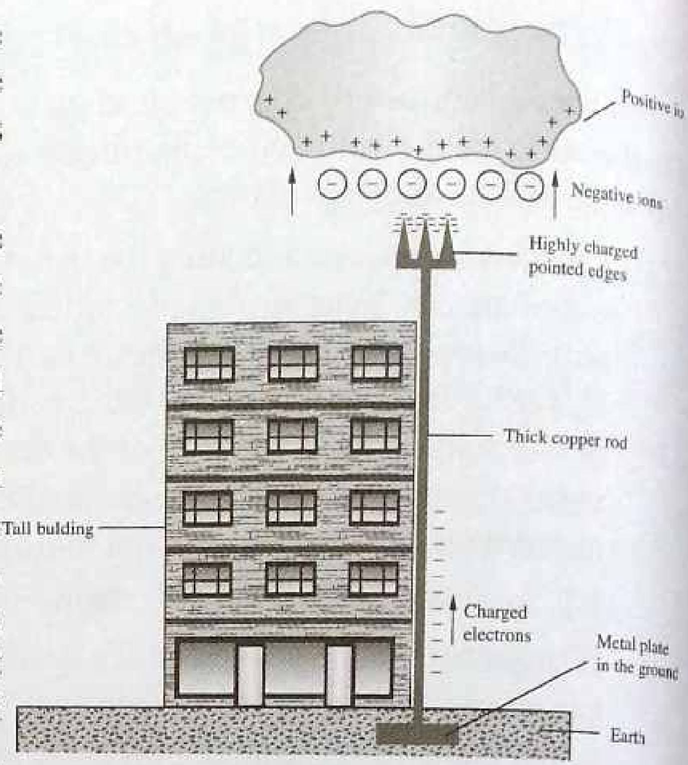
6. Though rubber is an insulator, special materials called *conductive rubber* is used to make aeroplane tyres. The conductive rubber tyres reduce the risk of an explosion during refuelling the aircraft. When the metal sprout of the fuel pipe touches the petrol tank *sparks* can be produced leading to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

Lightning arrestor

The discharge action of points is utilised in an important device called *lightning arrestor or conductor* used to prevent tall buildings and towers against the destructive effect of lightning.

A lightning conductor is a thick metal rod. One end is attached to a metal plate and buried deep in the ground. The other end, which is pointed, sticks up above the building. The conductor provides a path for electrons to flow easily through it (Fig. 7.26).

If a positively charged cloud is above the building, a negative charge will be induced on the pointed edges of the lightning conductor. Electrons concentrate on these points and by the discharge action of the pointed edges, *negative ions are sprayed into the* *air* and are attracted by the positive charges on the cloud. Thus the charge on the base of the cloud is reduced. This prevents a large build-up of charges which otherwise would result in discharges to the earth in the form of lightning. If the neutralising effect is insufficient and even if the lightning strikes, the huge electrical charge is conducted through the metal rod, to the earth. Thus the building is saved from any damage. In the absence of a lightning arrestor, lightning would strike the highest point of a building and a large current would pass to the earth through the building. The heat generated by the passage of this large current can set fire to the building.



Warning! Do not shelter under a tree during rains. Trees are good conductor of charges! Touching a tree that is being struck by lightning creates a channel for charges to flow through your body hence you are electrocuted.

Unit summary

- Materials can be charged by rubbing. The charge acquired can be positive or negative.
- A body acquires a negative charge, if it gains electrons from the substance with which it is rubbed. The negative charge means excess of electrons and the positive charge means deficiency of electrons.
- Like charges repel and unlike charges attract.
- SI unit of charge is coulomb (C).
- A leaf electroscope is used to detect and distinguish charges.
- Charges can neither be created nor destroyed but can only be redistributed in a body in the presence of another charged body.
- All substances can be classified as either conductors or insulators of electricity. Conductors allow electrons to flow through them freely, but insulators do not.

Unit Test 7

1. A body is said to be negatively charged if? [1]
   A. have excess protons
   B. have excess electrons
   C. have excess atoms
   D. have a deficiency of electrons

2. The SI unit of a charge is [1]
   A. an ampere B. An atom
   C. An ohm D. A coulomb

3. A plastic rod is rubbed with a dry cloth and became positively charged. Why has the rod become positively charged? [2]
   A. It gained electrons B. It gained neutrons
   C. It lost electrons D. It lost neutrons

4. A glass rod is rubbed with silk. Explain how both the silk and the rod acquire charges. [2]

5. What does the study of electrostatics deal with? [2]

6. What is an electroscope? [1]

7. State the law of charges. Explain the law with a suitable example. [3]

8. Two balloons inflated with air are tied with strings and held 1 metre apart. Both the balloons are rubbed with fur. Why do the balloons move apart when brought close together? [3]

9. Metal foil bobs X and Y may be charged either positively or negatively. Fig. 7.27 shows the bobs X and Y when placed near each other. For each situation, state whether the force between them is repulsive or attractive. [3]

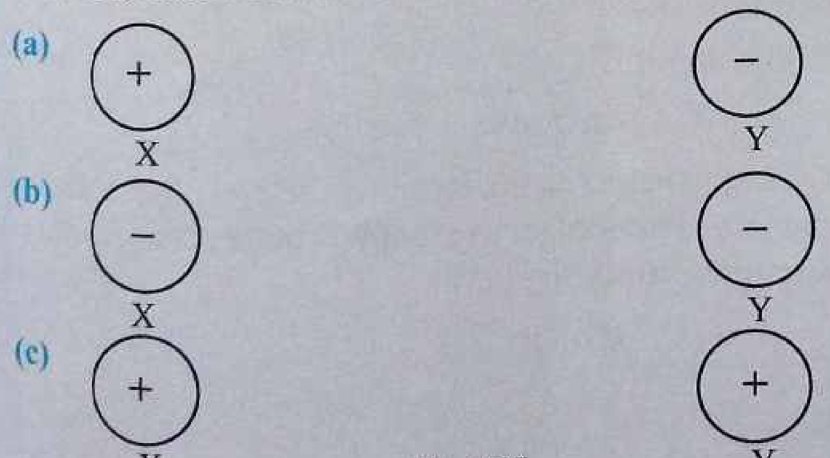


Fig. 7.27

10. When a charged rod is held close to a metal sphere placed on an insulated stand, the charge distribution on the sphere is as shown in Fig. 7.28.

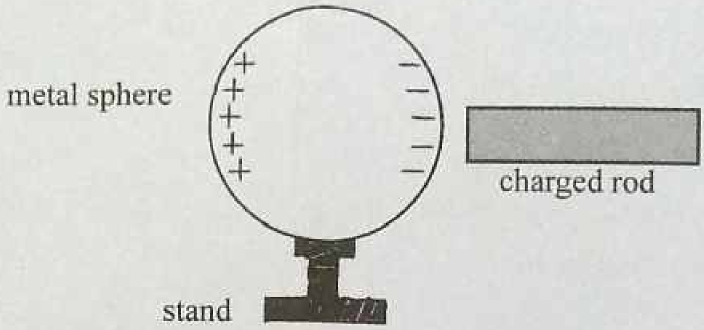


Fig. 7.28

(a) What is the sign of charge on the rod? [1]

(b) Describe a simple method to charge the rod. [2]

(c) Explain why the far side of the metal sphere has a positive charge. [2]

(d) What happens to the charges on the metal sphere, if the charged rod is moved away from the sphere? [2]

11. 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. 7.29).

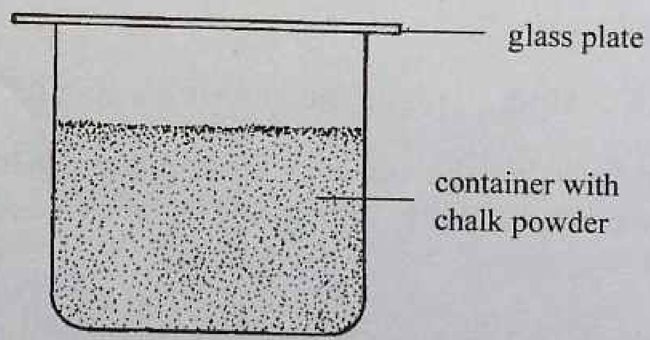


Fig. 7.29

State and explain the effects of:

(a) Rubbing the lid with fur. [2]

(b) Touching the lid with a finger after sometime. [2]

12. 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. 7.30). [3]

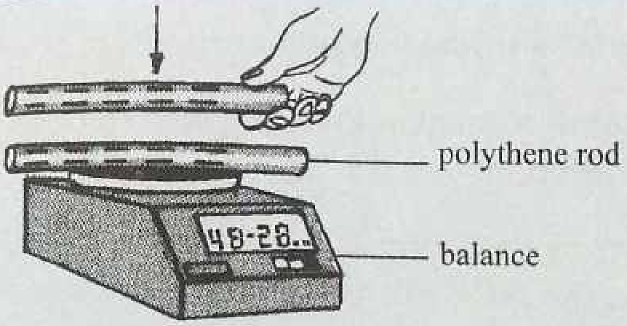


Fig. 7.30

13. 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. 7.31). [3]

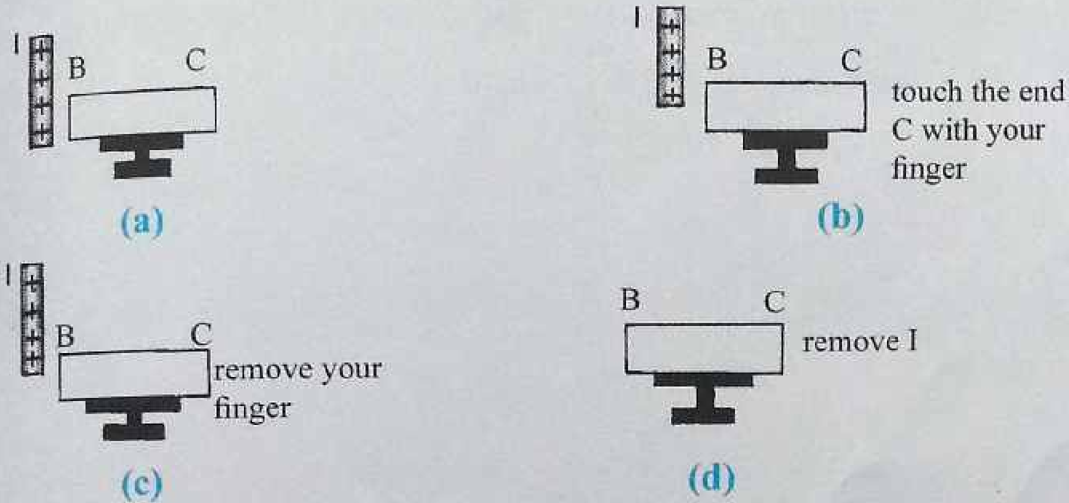
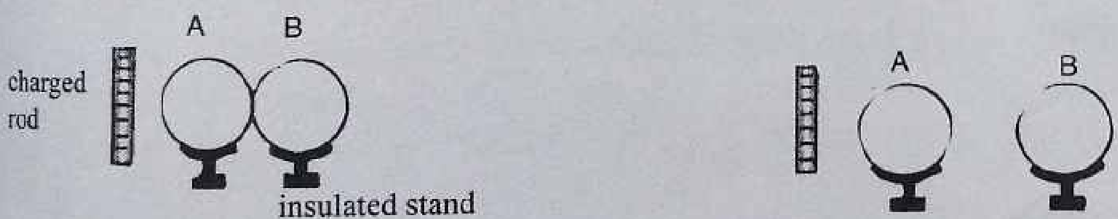


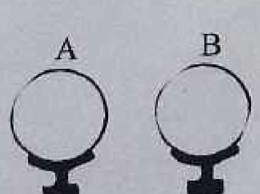
Fig. 7.31

14. Copy the following diagrams and show the charge on each metal sphere placed on insulated stands (Fig. 7.32). [2]



(a) two spheres touching each other

(b) sphere B is moved away from A



(c) the charged rod is removed

Fig. 7.32

15. Draw a diagram to show the important features of a leaf electroscope. [2]

16. Explain, with aid of a suitable diagram, how to charge a leaf electroscope negatively, by induction. [3]

17. A leaf electroscope is positively charged. Explain how to use this electroscope to test charge on two rods, where one is negative and the other positive. [2]

18. What are conductors and insulators? Give three examples of each. [2]

19. Why are metal chains attached to the trucks carrying petrol or other inflammable materials? [2]

20. Describe the construction of a lightning arrestor and explain how it helps to neutralise the positive charges on a cloud during thunderstorm. [3]

UNIT 8: Light

Success Criteria

By the end of this unit, you must be able to:

- Describe the propagation of light.
- Explain how shadows are formed.
- Explain how eclipses are formed.
- Explain how a pin hole camera functions.
- Describe reflection of light on plane surfaces.
- State the laws of reflection.
- Describe the characteristics of images formed by plane mirrors.
- Explain the applications of reflection of light.
- Describe refraction.
- Explain the formation of a spectrum.
- Explain apparent depth.
- Explain why an object appears bent when partially submerged in water.

8.1 Rectilinear propagation of light

Light is a form of energy. It enables us *to see* the surrounding objects. Light itself is not visible but its effect is felt by the eye. For example, the track of light entering a room cannot be seen; but the track becomes visible, if some dust particles are present in the room. In a cinema theatre, light from the projector to the screen is visible due to the dust or smoke moving through the path of light.

Stand at a distance in front of a huge tree. Hold your finger close to and in front of one of your eyes. Close the other eye and try to look at the tree. The tree cannot be seen. This property of light will become clear, after you go through the experiment given below.

Experiment 8.1: To show that light travels in a straight line.

Apparatus

- Soft board
- A plane mirror
- Plasticine
- White sheet of paper

Procedure

- Take three cardboards P, Q and R of equal sizes mounted on wooden stands.
- Make a small hole at the same height and also at equal distances from the edges on each cardboard. Place the cardboards on a flat surface (bench). When a thread is passed through these holes, it should be straight and taut. This is to ensure that the three pinholes are along a straight line.
- Remove the string without disturbing the setup of the three cardboards.
- Place a lighted candle in front of the hole in the cardboard P and view from the side of R as shown in Fig. 8.1. What conclusion can you make about the alignment of the three holes and the manner in which the light travels?

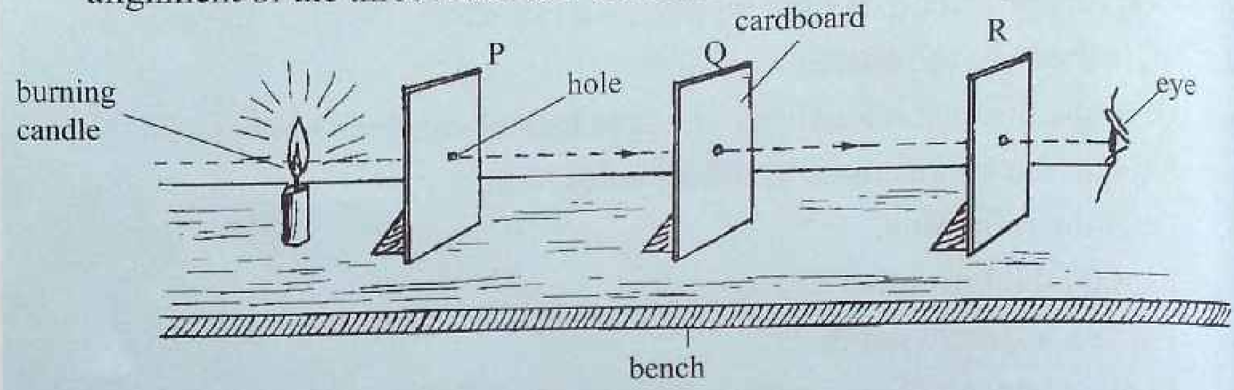


Fig. 8.1: Investigating how light travels

- Disorganise the arrangement by moving cardboard Q slightly to one side. Observe what happens.

Observation

- When the holes are aligned, light from the candle is seen through the straight line through the three holes.
- When the holes are not aligned, the light is not seen.

Discussion

The observation shows that light can pass in turn through the pinholes, only if they lie along the same straight line, suggests that light travels in a *straight line*.

Conclusion

Scientists use the word *rectilinear* instead of the phrase *in straight lines* and *propagated* in place of *travel*. Instead of stating that light travels in a straight line, we can say that *light has the property of rectilinear propagation.*

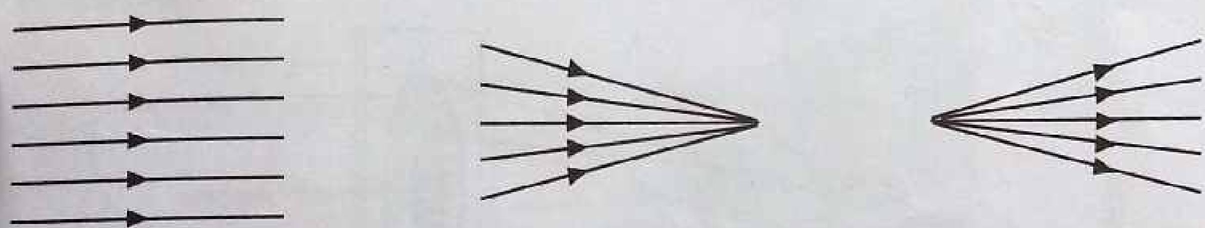
Some useful terms in the study of light

Luminous bodies: These are bodies which emit light on their own. The sun, a candle flame, etc., are known as *self-luminous bodies.*

Non-luminous bodies: These are bodies which have no light of their own, but become visible in the presence of some luminous bodies e.g. moon, door, tree, etc.

Optical medium: This refers to a substance through which light can pass. A medium can be *transparent*, *opaque* or *translucent*. A medium like water, air, glass through which light can pass freely is said to be *transparent*. A substance like wood, rock or metal which does not allow the light to pass through is said to be *opaque*. *Translucent* bodies are those through which light passes partially. The objects viewed through translucent bodies are not very clearly seen. Examples of translucent bodies include oiled paper and ground glass.

A ray of light: The path along which light travels in a medium is called a *ray*. A collection or groups of rays is called a *beam*. A beam can be parallel, convergent or divergent (Fig. 8.2).



(a) parallel beam **(b)** convergent beam **(c)** divergent beam

Fig. 8.2: Beams of light

8.2 Formation of shadows and eclipses

Shadows

A shadow is a shade cast by an object blocking the direct rays of light.

Formation of shadows with a point source of light

A narrow opening through a cardboard forms *a point source of light*, when illuminated with light. An opaque object PQ, placed between opening L and a white screen, obstructs rays of light (Fig. 8.3).

The area between the lines PR and QS receives no light at all. A shadow of PQ is cast on the screen. The area between R and S is in complete darkness. The region of complete darkness is called *umbra* (latin term meaning shadow).

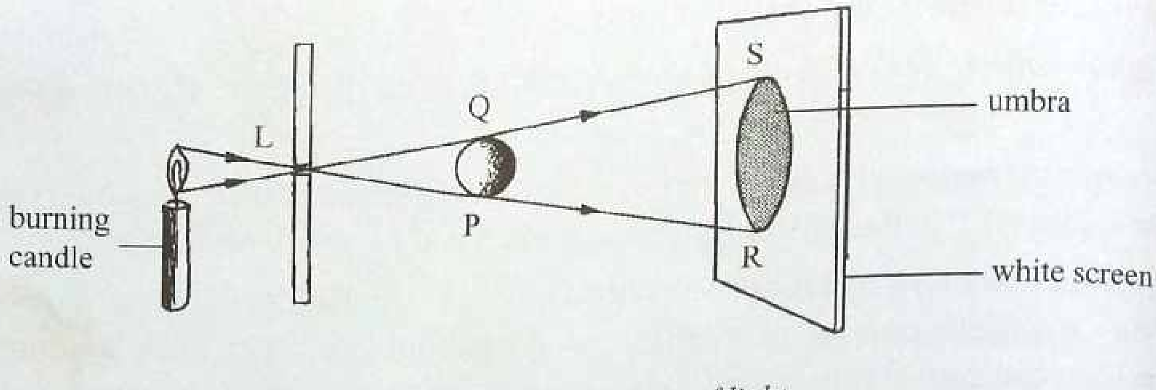


Fig. 8.3: A point source of light

Formation of shadows with an extended source of light

A large opening through cardboard forms *an extended source of light* when illuminated with light. An opaque object PQ placed between EL and a white screen obstructs light rays (Fig. 8.4).

The region RS on the screen is in complete darkness. The region RT and SV are in partial darkness because light comes from only one part of the extended source. This region of partial darkness is called *penumbra* (latin term meaning almost shadow).

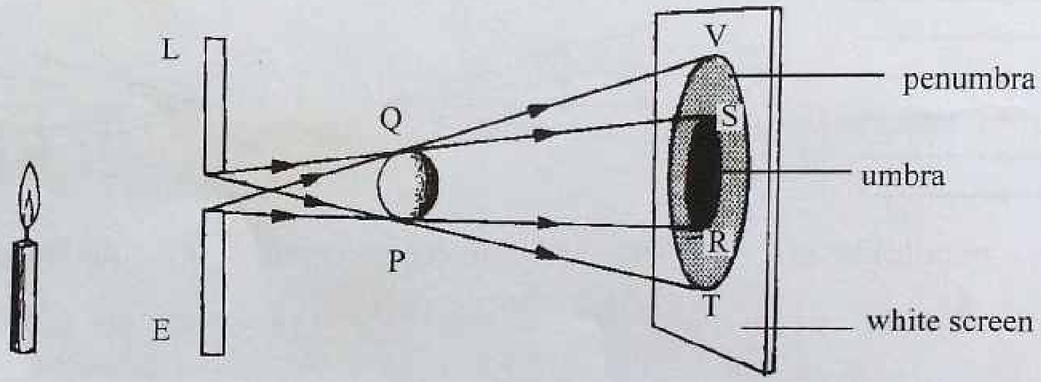


Fig. 8.4: Extended source of light

Eclipses

An important example of the formation of shadows is the occurrence of *eclipses*. The term eclipse means that light is *blocked* or *cut off* from region of observation. Two eclipses will be discussed here namely solar eclipse and lunar eclipse.

Solar eclipse

When the moon, revolving around the earth, comes in between the sun and the earth, the shadow of the moon is formed on the earth. This is called the *solar eclipse* or the *eclipse of the sun*. Depending on the position of the moon, some parts of the earth lie in the region of umbra and some in the region of penumbra. Total eclipse occurs in the regions of umbra and partial eclipse in the regions of penumbra (Fig. 8.5).

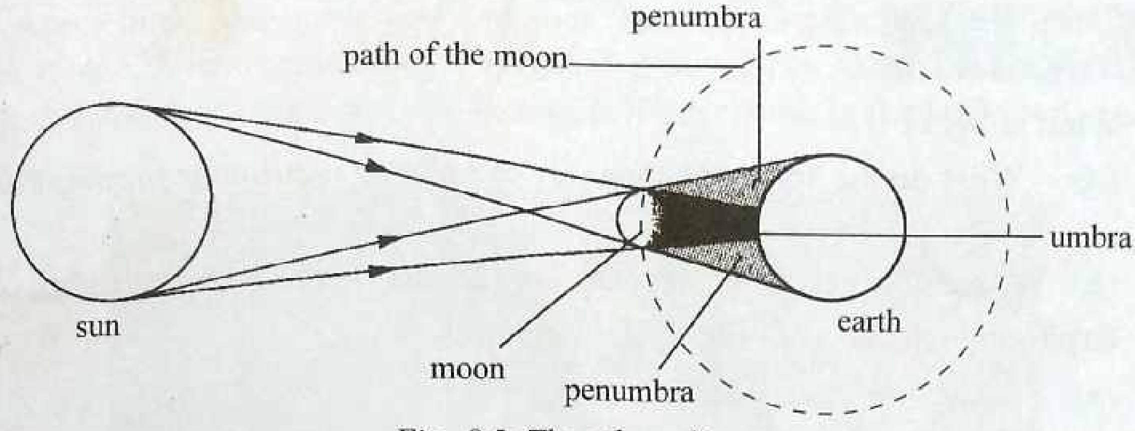


Fig. 8.5: The solar eclipse

Lunar eclipse

The moon is a non-luminous object. It can only be seen when light from the sun is incident on it. When we look at the moon, we see only the shape of the lighted portion. When the earth comes in between the sun and the moon, *lunar eclipse* or the *eclipse of the moon* occurs. Depending on the position of the moon, a total eclipse or partial eclipse of the moon will occur. Total eclipse will occur if the moon is in the region of umbra. Partial eclipse will occur if any part of the moon is in the region of penumbra (Fig. 8.6).

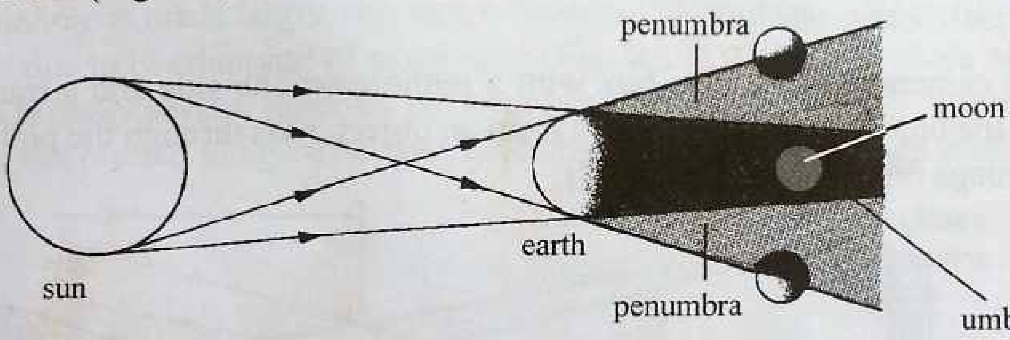
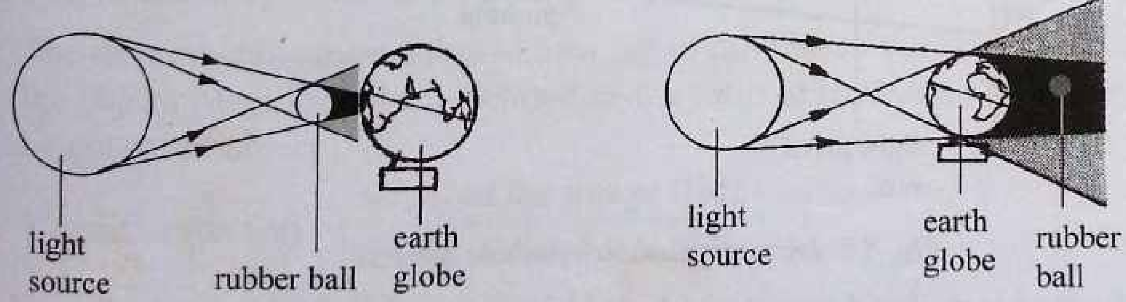


Fig. 8.6: The lunar eclipse

Demonstration to show solar and lunar eclipses

In Fig. 8.7(a) and (b) imagine the source of light as the sun and the rubber ball as the moon revolving around the earth (globe). Fig. 8.7(a) demonstrates the solar eclipse while Fig. 8.7(b) demonstrates the lunar eclipse.



(a) Solar eclipse **(b)** Lunar eclipse

Fig. 8.7: Eclipses.

Exercise 8.1

1. What is light?
2. (a) What do the scientists mean by the phrase *rectilinear propagation of light*?
   (b) Suggest a simple experiment to illustrate this property of light.
3. Explain the meaning of the following terms:
   (a) A non-luminous object.
   (b) An opaque object.
   (c) A ray and a beam of light.
   (d) A shadow.
4. With a simple labelled diagram distinguish between the terms *umbra* and *penumbra*..
5. Describe, with a suitable labelled diagram, the formation of (a) the total solar eclipse and (b) lunar eclipse.

8.3 Pinhole camera

A pinhole camera consists of a box with a pinhole on one side and a translucent screen on the opposite side. Light rays from an object, pass through the pinhole and form an image on the screen (Fig. 8.8).

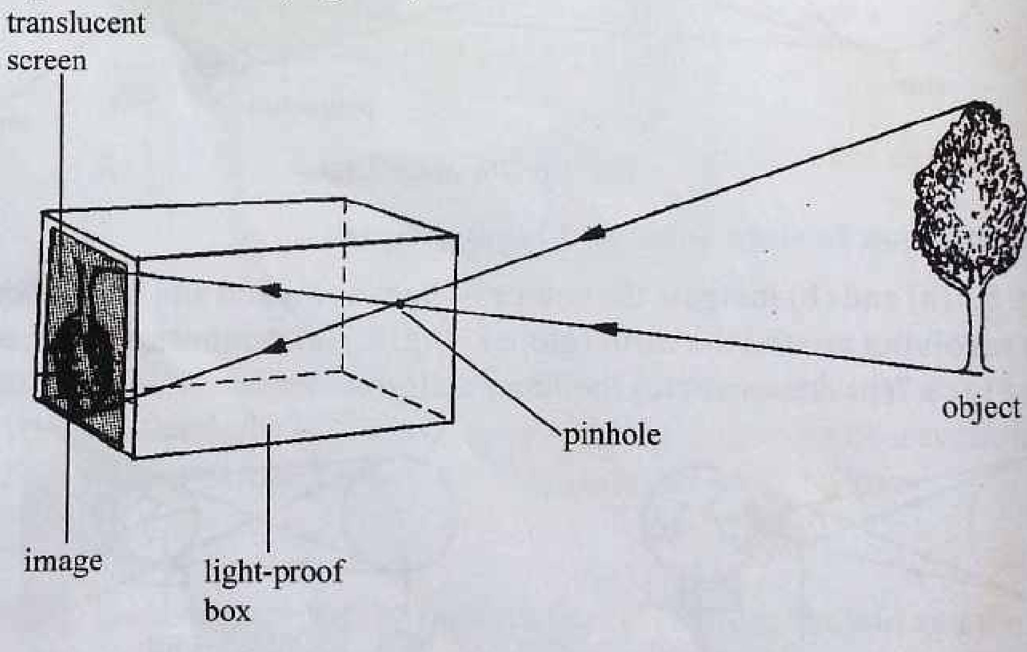


Fig. 8.8: Image formed on a pinhole camera

The image formed is *real* and *inverted.* (A real image is an image that can be formed on a screen. An image that cannot be formed on a screen is called a *virtual image).*

A pinhole camera has a *large depth of field* or *a large depth of focus*.

This means that objects, both far and near from the camera form focussed images on the screen. A lens camera has a limited depth of focus as seen in the photograph in Fig. 8.9. Whereas the frog is in focus, the other details in the background are out of focus.

Fig. 8.9: Limited field of focus

If the pinhole is made larger, the image becomes blurred (out of focus), bigger and brighter due to overlapping of many rays (Fig. 8.10). A large pinhole of a pinhole camera is really several pinholes put together. Therefore overlapping images make a bigger but blurred image. The large hole allows more light hence a brighter image.

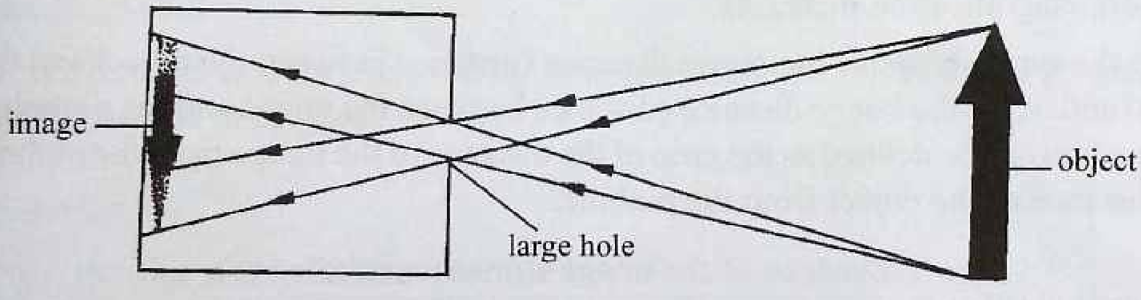


Fig. 8.10: Formation of blurred image due to a large pinhole.

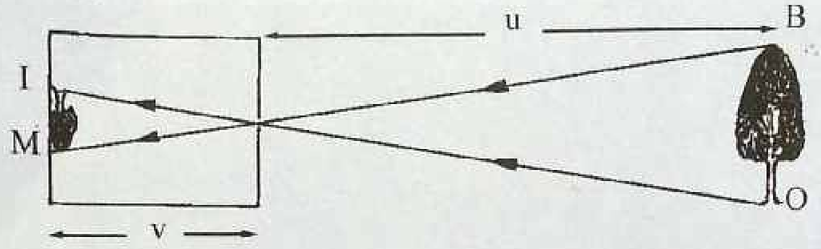
Magnification produced by a pinhole camera

The term magnification refers to how *big* or how *small* the image is as compared to the object. Magnification is defined as the ratio of the height of the image and the height of the object.

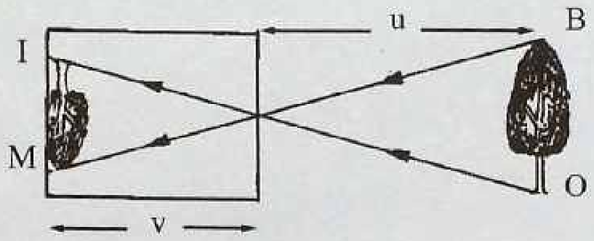
$$\text{Magnification (m)} = \frac{\text{height of the image (IM)}}{\text{height of the object (OB)}}$$

$$m = \frac{IM}{OB}$$

Sometimes it becomes difficult to measure the height of the image or the height of the object accurately. In such cases, magnification can be calculated in terms of distances. For example, consider a pinhole camera far from a tree and another one near a tree (Fig. 8.11).



(a) far from a tree



(b) near a tree

Fig. 8.11: Image formed on a pinhole camera

The height of the image in Fig. 8.11(a) is smaller compared to the height of the image in Fig. 8.11(b). This is because the distance of the tree from the camera in (a) is more than the distance from the camera in (b). When the object distance is decreased, magnification increases.

Using the symbols, u, for the object distance (distance between the object and the pinhole) and, v, for the image distance (distance between the image and the pinhole), magnification can be defined as the ratio of the distance of the image from the pinhole to the distance of the object from the pinhole.

$$\text{Magnification (m)} = \frac{\text{distance of the image from the pinhole (v)}}{\text{distance of the object from the pinhole (u)}}$$

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

Combining the two equations, we can write the formula for magnification as

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

Example 8.1

A pinhole camera of length 20 cm is used to view the image of a tree of height 12 m which is 40 m away from the pinhole. Calculate the height of the image of the tree obtained on the screen.

Solution

$$\text{Magnification, m} = \frac{\text{height of the image}}{\text{height of the object}} = \frac{\text{image distance}}{\text{object distance}}$$

$$\therefore \quad m = \frac{IM}{OB} = \frac{0.20}{40}$$

$$\therefore \quad \frac{IM}{12} = \frac{0.20}{40}$$

$$IM = 12 \times \frac{0.20}{40} = 0.06 \text{ m} = 6 \text{ cm}$$

$\therefore$ The height of the image of the tree is 6 cm.

Example 8.2

If the pinhole camera is moved by 10 m towards the tree, what will be the height of the tree on the screen?

Solution

Now the object distance has decreased by 10 m. Therefore the new object distance, u = 30 m

$$\text{Magnification m} = \frac{IM}{OB} = \frac{v}{u}$$

$$\therefore \quad \frac{IM}{12} = \frac{0.20}{40}$$

$$IM = 12 \times \frac{0.20}{40}$$

$$IM = 0.08 \text{ m} = 8 \text{ cm}$$

$\therefore$ The height of the image is 8 cm.

Exercise 8.2

1. Explain, with a labelled diagram, how a simple pinhole camera works. Describe the size and the nature of the image formed.
2. The distance of the object from the pinhole is increased. Discuss how this change affects the brightness, sharpness and the size of the image formed.
3. State and explain the effect on the image formed in a pinhole camera, if,
   (a) the hole is made larger (b) the length of the box is increased.
4. A pinhole camera is used to take the photograph of a person who is 4 m away from the pinhole. If the length of the box used is 18 cm and the height of the image of the person is 9 cm, calculate:
   (a) The magnification produced by the pinhole camera.
   (b) The height of the person.

8.4 Reflection on a plane surface

All objects, except self-luminous objects, become visible because they *bounce* light back to our eyes. This *bouncing off* of light is called *reflection*. There are two types of reflections namely *regular* and *diffuse* reflections.

When light is reflected by a plane of a smooth surface, the reflection is regular; when reflection occurs at a rough surface, it is called a diffuse reflection. (Fig. 8.12(a) and (b)).

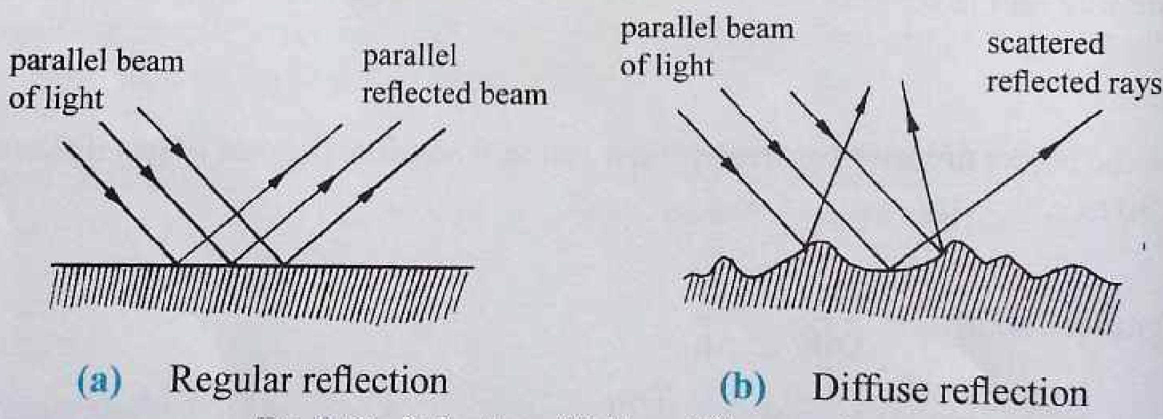


Fig. 8.12 : Reflection of light on different surfaces.

Plane mirror

A thin glass plate coated with silver on one side and a protective layer on the other side is called a *plane mirror* (Fig. 8.13).

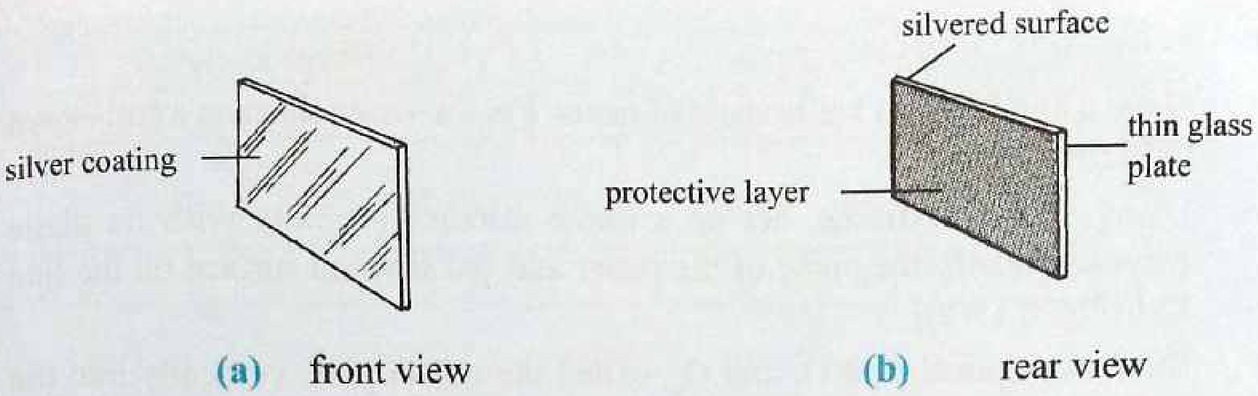


Fig. 8.13: A plane mirror

Fig. 8.14 shows a ray of light AB striking the plane mirror at B and bouncing off to C. The ray AB is called *incident ray* and the ray BC is called *reflected ray*. A line drawn perpendicular to the surface of the mirror at the point where the incident ray and the reflected ray meet is called the *normal* (BN). The angle between the incident ray and the normal (∠ABN) is called the *angle of incidence* (∠i). The angle between the reflected ray and the normal (∠CBN) is called the *angle of reflection* (∠r).

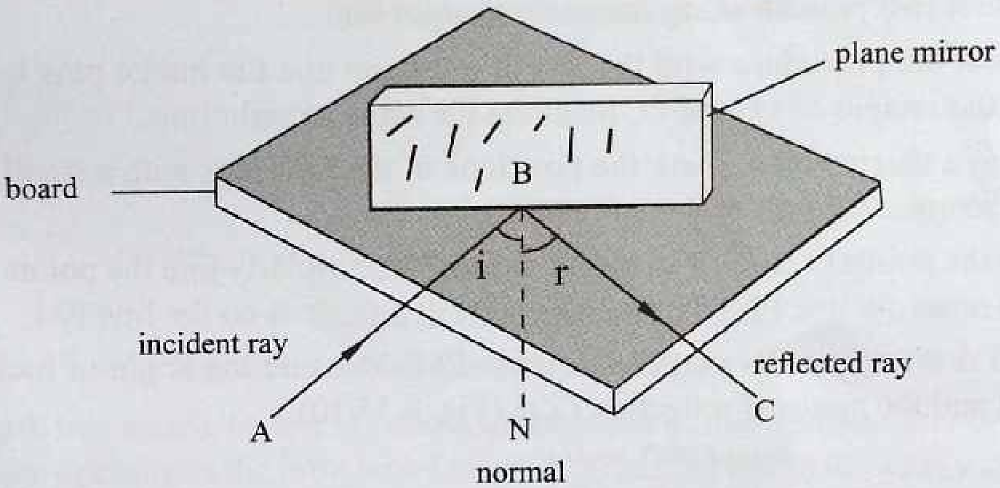


Fig. 8.14: Reflection at a mirror

Experiment 8.2: To verify the laws of reflection

Part I: Using optical pins

Apparatus

- A soft board
- A plane mirror
- Plasticine
- Protractor
- White sheet of paper
- Drawing pin
- 4 optical pins
- A ray box

Procedure

- Draw a line PM on a white sheet of paper. Fix the white sheet on a soft-board with drawing pins.
- Using some plasticine, set up a plane mirror vertically with its plane perpendicular to the plane of the paper and the silvered surface on the line PM (Fig. 8.15(a)).
- Stick two optical pins O_1 and O_2, called the object pins, vertically into the softboard, about 6 or 7 cm apart.
- Keeping the eye along the plane of the paper and in a convenient position, look into the mirror. The images of the two pins are seen. These images appear to be at the rear of the mirror. (Fig. 8.15(a)).
- Move your head to and fro slowly until in one particular position, the images of the two pins lie in a straight line.
- Fix a third pin, I_1, called the image pin, such that this pin and the images of the first two pins lie along the same straight line.
- Repeat the procedure with the fourth pin I_2, so that the image pins I_1 and I_2 and the images of O_1 and O_2 lie along the same straight line.
- Using a sharp pencil, mark the positions of the four pins with a small circle and remove the pins and the mirror.
- Join the points O_2 and O_1 to meet the line PM. Similarly join the points I_2 and I_1 to meet the line PM. These lines meet at a point B on the line PM.
- At B draw a line BN perpendicular to PM. Measure the angle of incidence ($\angle i$) and the angle of reflection ($\angle r$) (Fig. 8.15(b)).

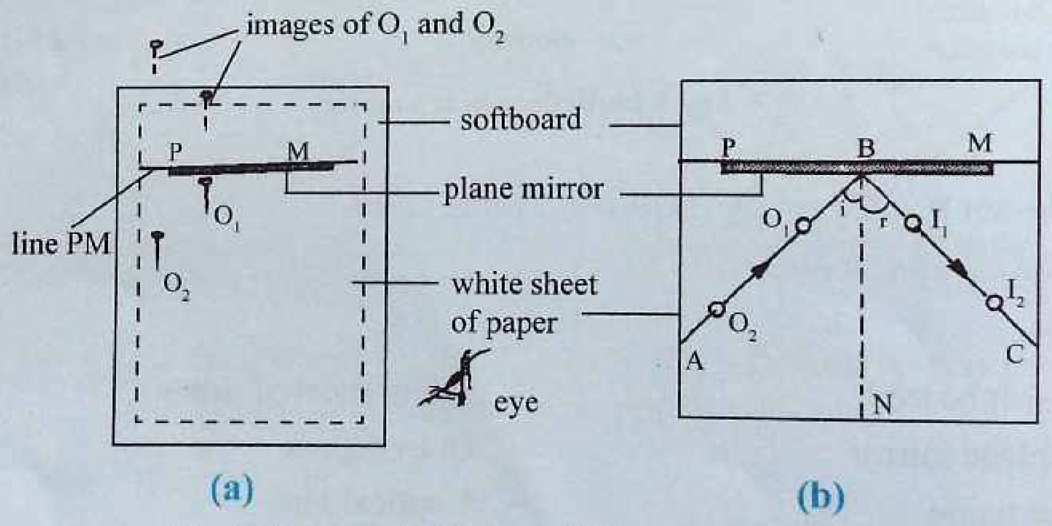


Fig. 8.15: Laws of reflection of light using optical pins

- Repeat the experiment for three different angles of incidence and record the four readings in a table as shown in Table 8.1. What is the relationship between these two angles?

Angle of incidence, i (°)	Angle of reflection, r(°)

Table 8.1

Part II : Using a ray box

Procedure

- Direct light from a narrow opening of a ray box on a plane mirror placed over a white sheet of paper in a semi-dark room. What do you see? The light is reflected as a thin beam as shown in Fig. 8.16.

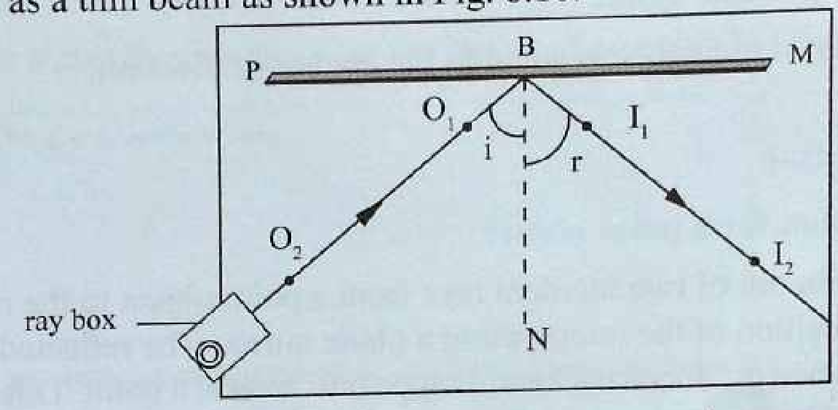


Fig. 8.16: Laws of reflection of light using a ray box

- Mark two points, O_1 and O_2, one near the plane mirror and the other very close to the opening in the light box. Observe the path of the reflected ray and mark the points I_1 and I_2, as shown.
- Remove the ray box and join the points O_2 and O_1 to the line PM. Similarly join points I_2 and I_1, to meet line PM. These lines meet at point B on line PM. At B draw a line BN perpendicular to line PM.
- Measure the angle of incidence ($\angle$ i) and the angle of reflection($\angle$ r).
- Repeat the experiment for three different angles of incidence and record your readings in a table similar to Table 8.1. What is the relationship between these two angles?

Observation

In parts I and II, you will observe that the angle i is equal to angle r , Q_2 Q_1 joint to the mirror is at the same point (B) with I_1, I_2 and NB.

Discussion

The above observations also show that the incident ray, the reflected ray and the normal, all lie in the plane of the paper.

Conclusion

These observations form the laws of reflection of light.

(a) the angle of incidence, *i*, is equal to angle of reflection, *r*.

(b) the incident, the reflected ray and the normal all lie in the plane of the paper.

Laws of reflection

The laws of reflection of light state that:

1. The incident ray, the reflected ray and the normal, at the point of incidence all lie in the same plane.
2. The angle of incidence is equal to the angle of reflection.

Image formation

Image formation for a point object

We need a minimum of two incident rays from a point object to the mirror in order to locate the position of the image using a plane mirror. The reflected rays from the plane mirror, when produced backwards appear to meet at a point. This is the position of the image. The image is *virtual* as it *only appears to be there* and it *cannot be projected on a screen* (Fig. 8.17).

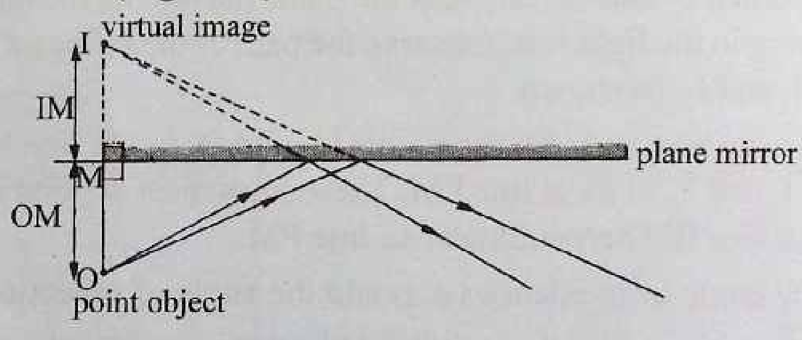


Fig. 8.17: Image of a point object

Measure the perpendicular distance (OM) from the point object O to the mirror and the perpendicular distance (IM) from the position of the virtual image I to the mirror. The image distance from the mirror is equal to the object distance from the mirror, OM = IM

Image formation for an extended object

Place an extended object in front of a vertical plane mirror and observe the image formed (Fig. 8.18). Is the image upright or inverted? What is the size of the image? The image is erect and the size of the image is the same as the size of the object.

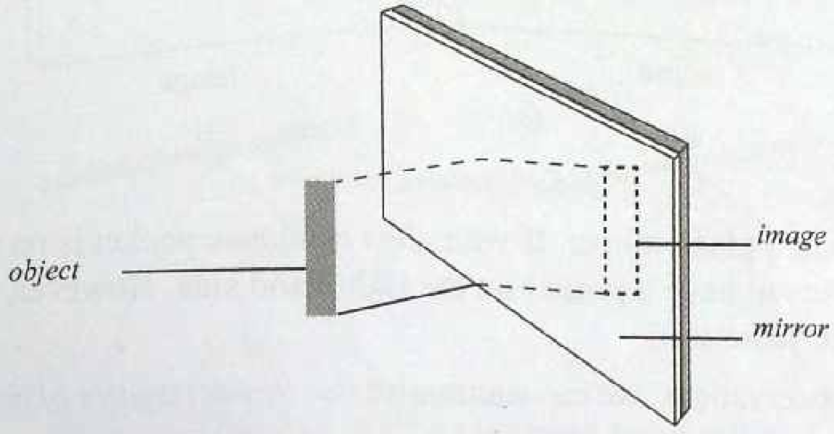


Fig. 8.18: Image of an extended object

Fig. 8.19 shows a ray diagram showing the image of an extended object.

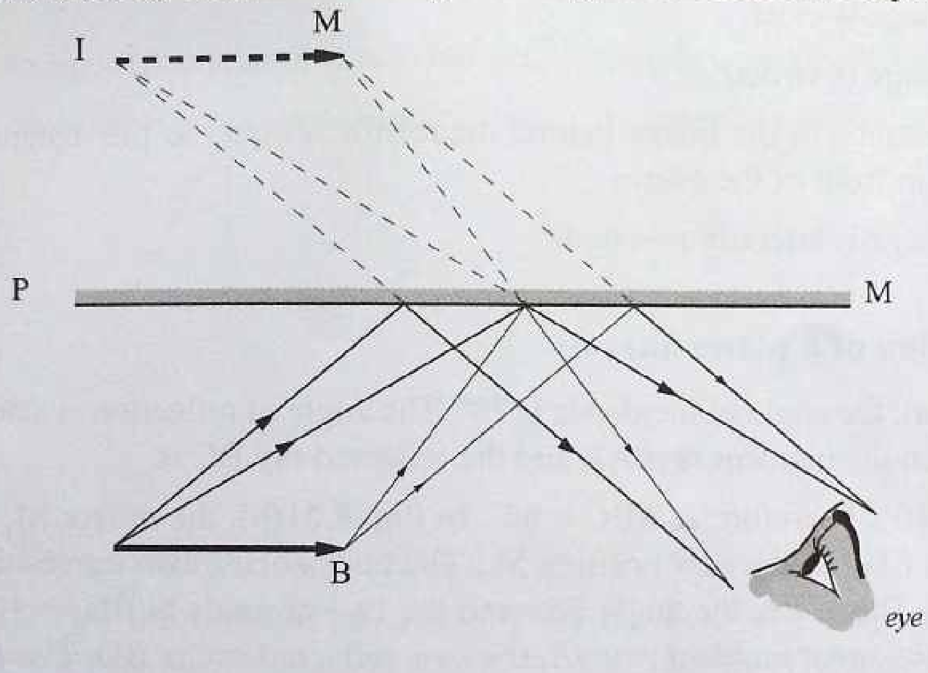


Fig. 8.19: Image formed on a plane mirror

Lateral inversion

Fig. 8.20 shows the image of a sign board in a mirror as seen by a person keeping the eye at E. The eye sees the letter P in the signboard on the left hand side, but the image of the letter P in the mirror is on the right hand side.

The left hand side of the object becomes the right hand side of the image. We say the image is *laterally inverted*.

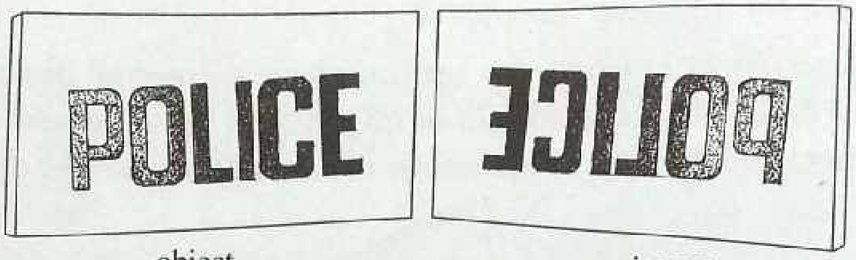


Fig. 8.20: Lateral inversion

Look at yourself in a plane mirror. If your shirt or blouse pocket is on the left side, your *image* appears to have a pocket on the right hand side. However, the image is upright and of the same size.

From the above observations, we can summarise *the characteristics of images formed by plane mirrors* as follows:

1. The size of the image is equal to the size of the object.
2. The image is erect.
3. The image is virtual.
4. The distance of the image behind the mirror is equal to the distance of the object in front of the mirror.
5. The image is laterally inverted.

8.5 Rotation of a plane mirror

In Fig. 8.21(a), the angle of incidence is 30°. The angle of reflection is also 30°. The angle between the incident rays AB and the reflected ray BC is

$30^\circ + 30^\circ = 60^\circ$. Therefore $\angle ABC = 60^\circ$. In Fig. 8.21(b), the mirror M_1 is rotated by an angle of 10° to the new position M_2. The normal BN_1 also moves through an angle of 10°. Therefore, the angle between the two normals $N_1BN_2 = 10^\circ$. In Fig. 8.21(c), for *the same incident ray AB*, the new reflected ray is BD. The new angle of incidence = $30^\circ + 10^\circ = 40^\circ$. The new angle of reflection = 40°

Hence $\angle ABD = 40^\circ + 40^\circ = 80^\circ$. In Fig. 8.21(d), the angle between the two reflected rays BC and BD = 20°. Observe that when the mirror is rotated through an angle of 10°, the ray is turned through an angle of 20° i.e.

For the same incident ray, the angle of rotation of the reflected ray is twice the angle of rotation of the mirror.

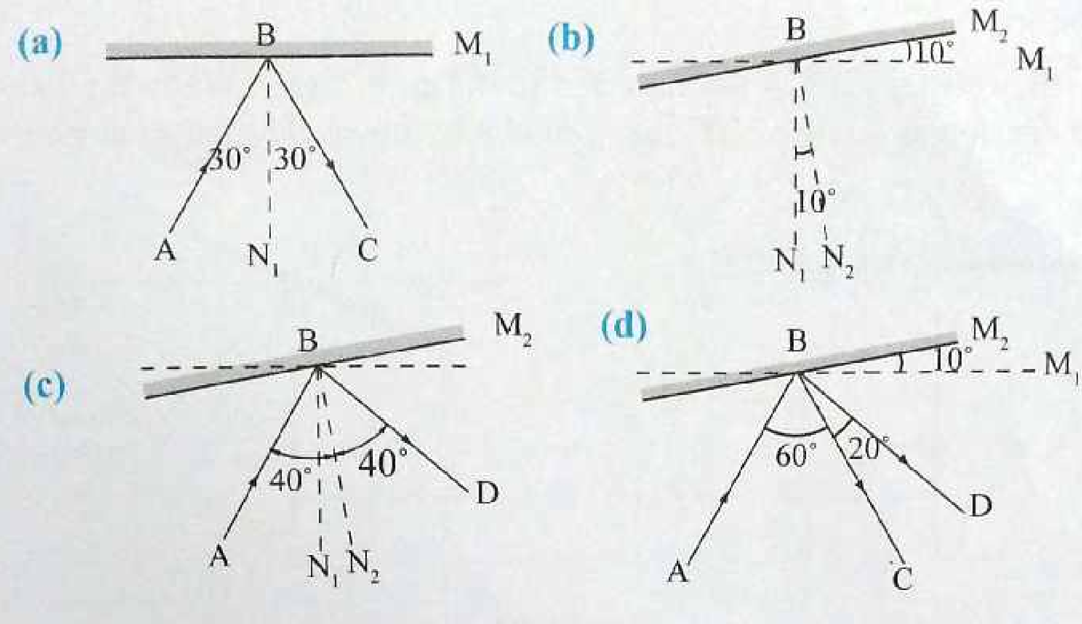


Fig. 8.21: Rotation of a plane mirror

Example 8.3

What is the angle of reflection in each of the following figures (Fig. 8.22(a) and (b))?

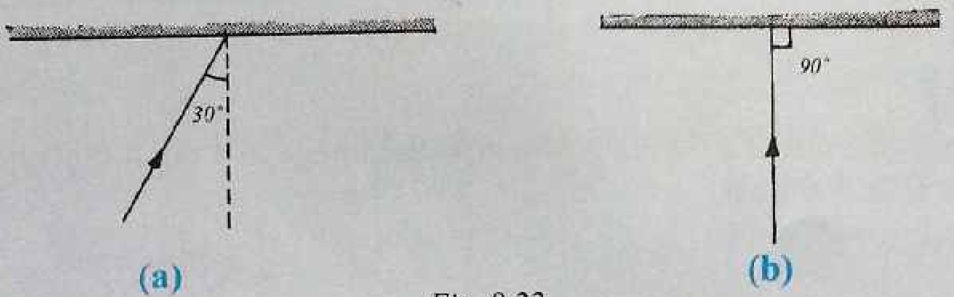


Fig. 8.22

Solution

In Fig. 8.22(a), the angle of reflection = 30°

In Fig. 8.22(b), the incident ray is along the normal. Therefore the angle of incidence = 0°. Hence the angle of reflection = 0°. The ray is bounced back along the normal.

Example 8.4

A ray of light is incident along the normal in a plane mirror. The mirror is then rotated through an angle of 20°. Calculate the angle between the first reflected ray and the second reflected ray.

Solution

Before the rotation, BA is the reflected ray (Fig. 8.23(a)). When the mirror is rotated through an angle of 20°, the normal also moves through an angle of 20°.

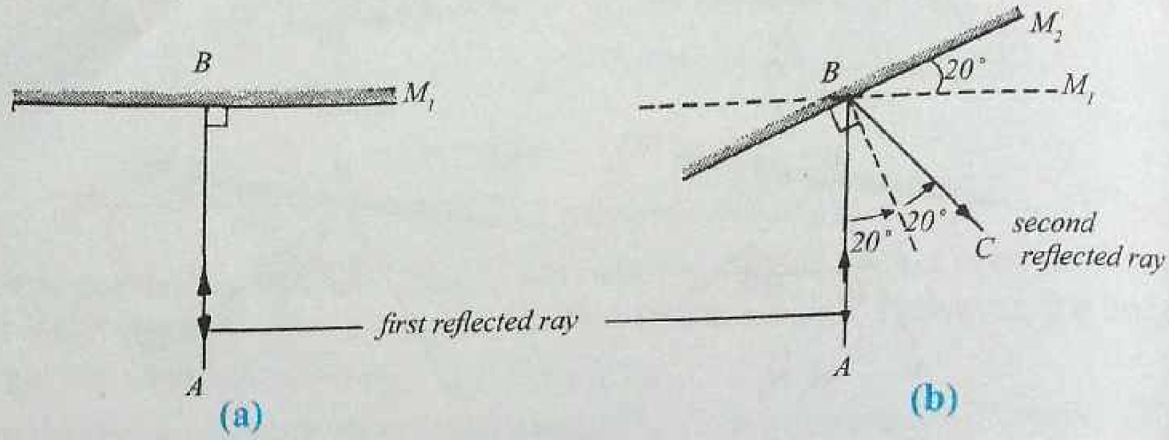


Fig. 8.23

Therefore $\angle$ i = 20° and $\angle$ r = 20°.

Hence $\angle$ ABC = 40°.

∴ The angle between the two reflected rays = 40° (Fig. 8.23(b))

Example 8.5

Explain with the aid of a ray diagram, how the image of a point object O is seen by the eye (Fig. 8.24(a)).

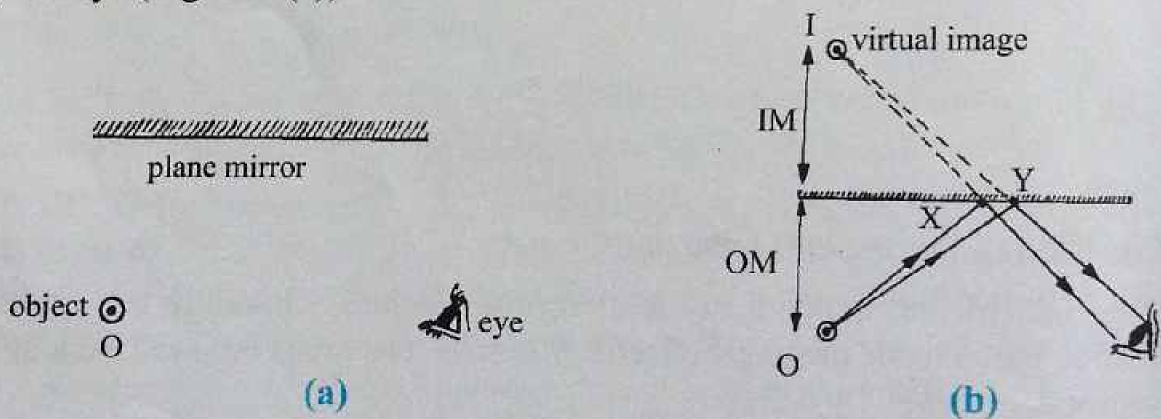


Fig 8.24

Solution

In order to see the image, the reflected rays must reach the eye. The image distance behind the mirror is equal to the object distance from the mirror (IM = OM). Hence fix the position of the image first and then draw the two reflected rays from I to reach the eye of the observer. Finally draw the two incident rays OX and OY (Fig. 8.24(b)). Produce the reflected rays back to meet at I.

Example 8.6

Complete Fig. 8.25 with suitable rays to show how a person may see his full image in the mirror.

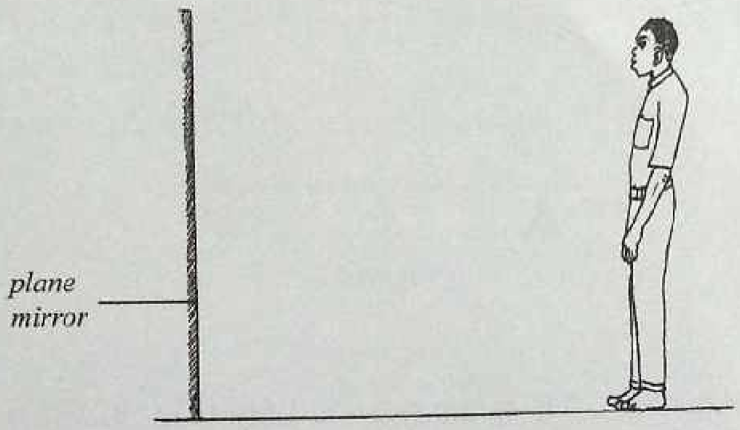


Fig. 8.25

Solution

First fix the images of the head and the toe, say M and I, at equal distances from the mirror. The reflected rays from M and I must reach the eyes of the person. Therefore first draw the reflected rays from M and I to reach the eyes. Draw the incident rays HX and TY. The person can see his full image IM in the portion of the mirror XY.

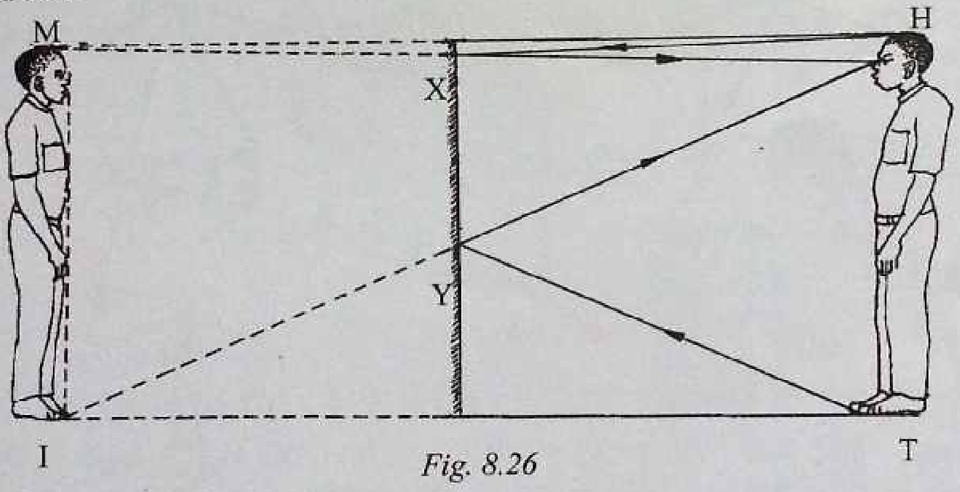


Fig. 8.26

Note

Measure XY and the length of the person TH in Fig. 8.26.

The height of the mirror needed XY is always *half* the height of a person.

Example 8.7

The ray OA is incident on mirror M_1 as shown in Fig. 8.27. Draw a second plane mirror M_2 positioned such that the ray OA reflected by mirror M_1 is again reflected by the second mirror M_2 so as to reach the eye of the observer.

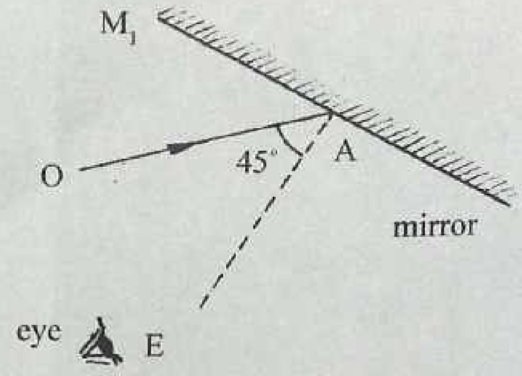


Fig. 8.27

Solution

$\angle i = 45^\circ$, hence $\angle r = 45^\circ$. AB is the reflected ray (Fig. 8.28(a)) and it has to be reflected by the second mirror in order to reach the eye. From the eye draw a line to meet the reflected ray AB at C (Fig. 8.28 (b)). At C draw a line CN such that it divides $\angle ACE$ into 2 equal parts (Fig. 8.28(c)). Draw a line CM_2 at C such that it is perpendicular to the line CN (Fig. 8. 28(d). This line M_2C represents the position of the second mirror M_2 so that the reflected ray can reach the eye.

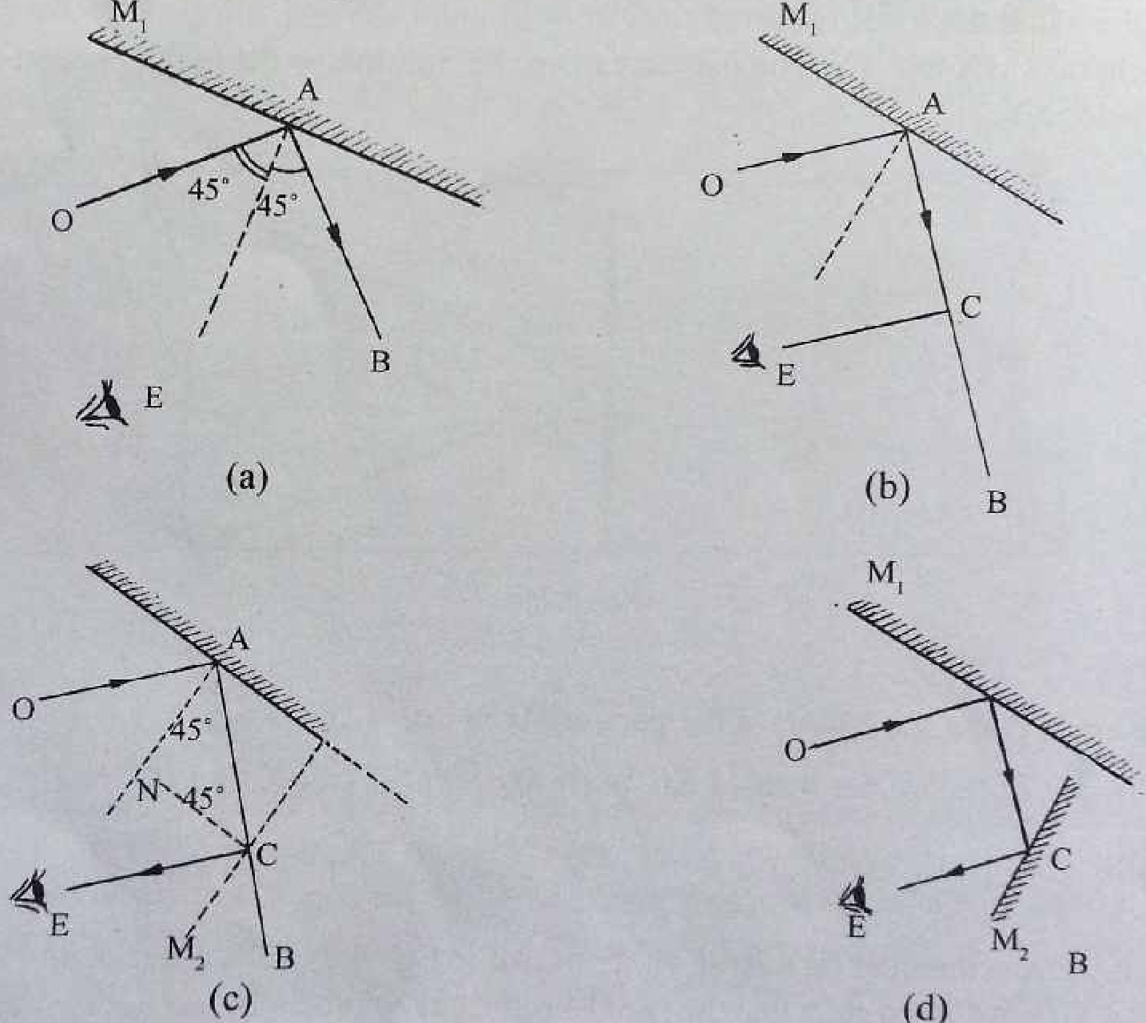


Fig. 8.28

Exercise 8.3

1. (a) Define the terms: angle of incidence, angle of reflection, and the normal.
   (b) What is the relationship between the angle of incidence and the angle of reflection.

2. Fig. 8.29 shows a plane mirror where the angle of incidence is 30°.

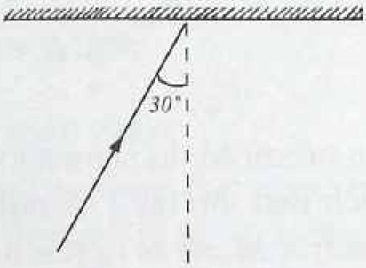


Fig. 8.29

   (a) What is the angle of reflection?
   (b) If the angle of incidence is increased to 40°, with the aid of a sketch diagram, show that the angle between the two reflected rays is 10°.

3. State the laws of reflection. Suggest a simple experiment to prove that the angle of incidence is equal to the angle of reflection.

4. Show the appearance of a print FG as seen in a plane mirror (Fig. 8.30).

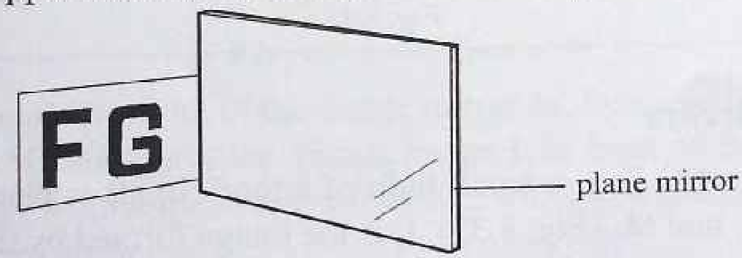


Fig. 8.30

5. Draw a diagram to show how the eye of a person sees the image of

6. A ray of light AB is incident on a mirror M_1 at an angle of 30° as shown in Fig. 8.31. Copy and complete the diagram to show the path of the ray AB after reflection from mirror M_2 and hence calculate the angle of reflection from the mirror M_2.

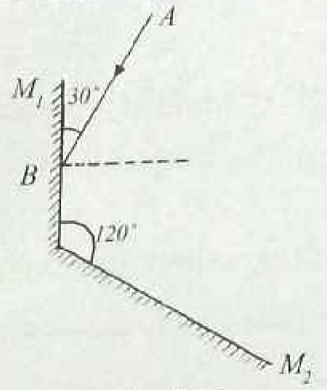


Fig. 8.31

7. The ray OA is incident on mirror M_1 as shown in the diagram. Draw a second mirror M_2 positioned such that the ray OA reflected by mirror M_1 is again reflected by the second mirror M_2 so as to reach the eye of the observer (Fig. 8.32).

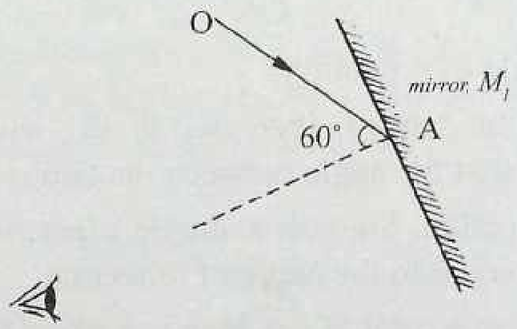


Fig. 8.32

8.6 Parallel mirrors

A bright point object O (e.g. a small bulb of a torch light) is placed between two parallel mirrors M_1 and M_2 (Fig. 8.33). I_1 is the image formed by the mirror M_1 and I_2 is the image formed by the mirror M_2. I_1 (a virtual image) acts as an object in front of the mirror M_2 and an image $I_{1.2}$ is formed behind M_2. $I_{1.2}$ acts as an object in front of the mirror M_1 and an image $I_{1.2.1}$ is formed behind M_1.

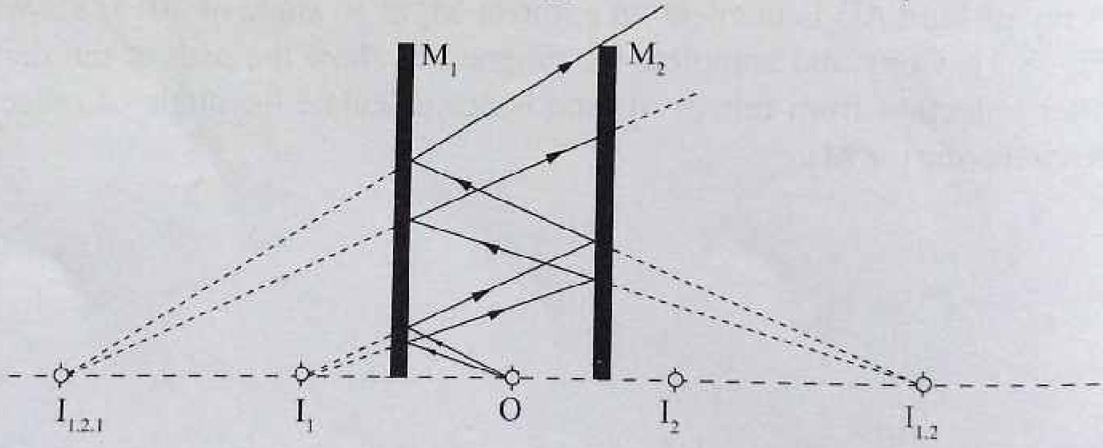


Fig. 8.33: Parallel mirrors

The image $I_{1.2.1}$ acts as an object in front of the mirror M_2 and forms another image and so on. In this way the number of images formed is infinite (countless). But the images become dimmer as the distance travelled keep increasing with each reflection. It should be noted that the images of I_2 are not considered in the construction above.

This principle of multiple reflections is used in beauty parlours, tailor and barber shops, etc.

8.7 Mirrors inclined at an angle

Two plane mirrors at 90° to each other

O is a bright point object placed between two plane mirrors M_1 and M_2 as shown in Fig. 8.34. I_1 is the first image formed by M_1. I_2 is the second image formed by M_2.

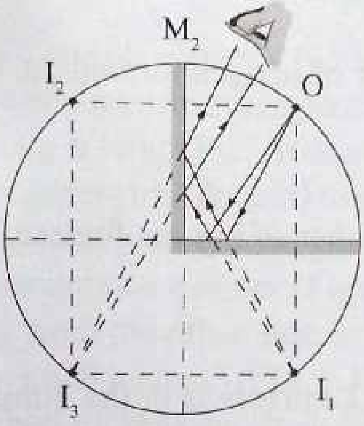


Fig. 8.34: Mirrors inclined at 90°

The virtual image of I_1 in front of the image mirror M_2 forms an image I_3 behind the image of mirror M_2. Similarly the virtual image I_2 in front of the image of mirror M_1 forms an image behind the image mirror M_1, which coincides with the image I_3. Hence three images are formed.

Two plane mirrors inclined at an angle of 60°

O is a bright point object placed between the two plane mirrors M_1 and M_2 inclined at an angle of 60° as shown in Fig. 8.35. Image I_1 is formed by M_1. Image I_2 is the second image formed by M_2.

The virtual image I_1 (in front of M_2) forms an image I_3 behind M_2. Similarly I_2 (in front of M_1) forms an image I_4 behind M_1. I_3 forms an image I_5 due to reflection at M_1 and I_4 forms an image due to reflection at M_2, which coincides with I_5. Hence five images are formed.

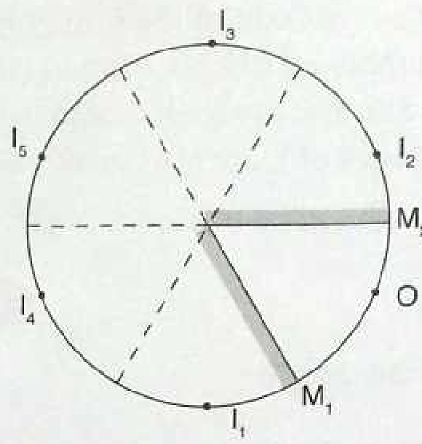


Fig. 8.35: Mirrors inclined at 60°

Formula to calculate the number of images formed, n, when two mirrors are inclined at an angle θ

When angle θ is 90°, the number of images formed , n, is 3. i.e.

$$n = \frac{360^\circ}{90^\circ} - 1 = 3$$

When the angle θ is 60°, the number of images formed, n, is 5 i.e.

$$n = \frac{360^\circ}{60^\circ} - 1 = 5$$

In general if the angle between 2 mirrors is θ, the number of images formed is, n, is given by.

$$n = \frac{360^\circ}{\theta} - 1$$

8.8 Applications of reflection at plane surfaces

Periscope

A periscope is a device which enables us to see over the top of an obstruction (e.g. a wall). As shown in Fig. 8.36, a periscope uses two plane mirrors kept parallel to each other and the polished surfaces facing each other. Each plane mirror makes an angle of 45° with the horizontal. Light from the object OB is turned through 90° at each mirror and reaches the eye.

The final image produced IM is virtual, erect and the same size as the object. The lateral inversion produced by the two plane mirrors cancel out each other.

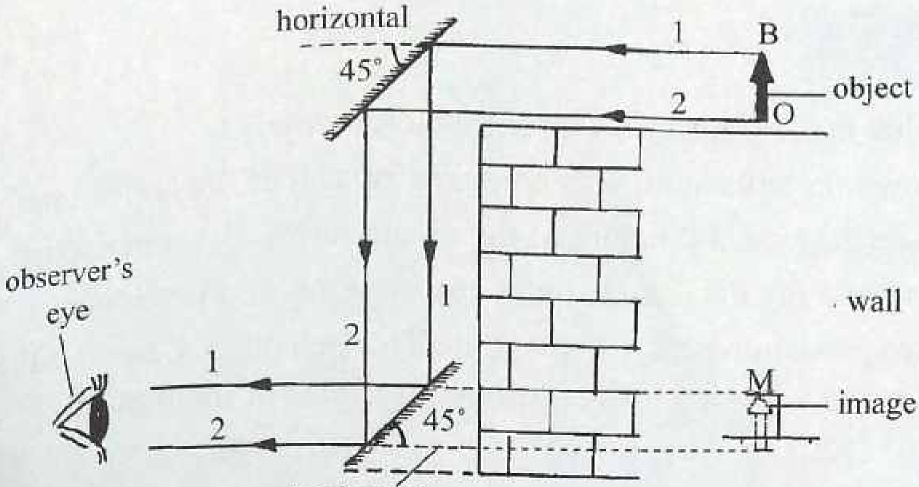
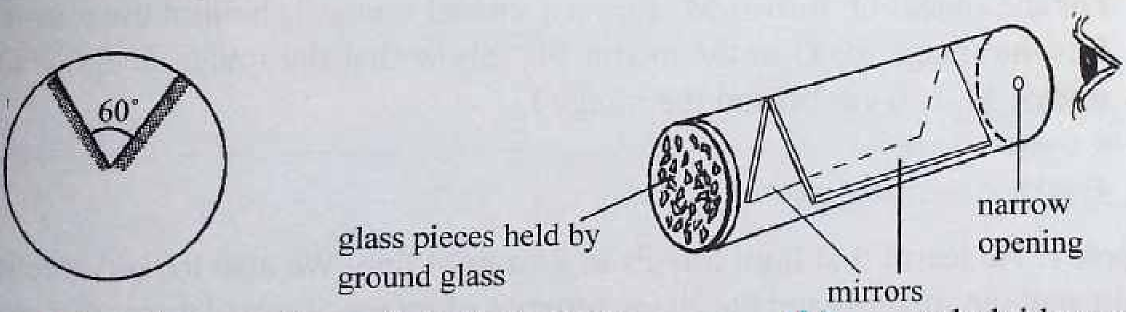


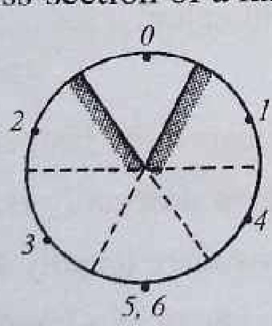
Fig. 8.36: A periscope

Kaleidoscope

A kaleidoscope (or a mirrorscope) is a device (which was originally developed as a toy) used to produce a series of beautiful symmetrical images. Two plane mirrors are placed at an angle of 60° inside a long tube. At one end of the tube there is a ground glass plate or a grease-proof paper (translucent) to allow light to fall on the coloured glass pieces scattered on the glass plate (or the grease proof paper). These coloured glass pieces act as objects for the two mirrors (Figs. 8.37(a) and (b)). When viewed through the narrow opening from the other side, six identical views of the object is seen (the object and its five virtual images) (Fig. 8.37(c)). If the original arrangement of the glass pieces is disturbed by shaking the tube, an entirely different pattern is formed. Though a kaleidoscope was originally developed as a toy, fashion designers and artists use it to get different colour configurations and unimaginative perspectives.



(a) Cross-section of a kaleidoscope. **(b)** a kaleidoscope



(c) 5 segments of images

Fig. 8.37:

Exercise 8.4

1. (a) What is a (i) periscope? (ii) kaleidoscope?
   (b) How many plane mirrors are there in each of the above instruments?
   (c) State the size and nature of the image formed by a periscope.
2. Draw a simple ray diagram to show the working of a periscope.
3. (a) Two plane mirrors are kept inclined to each other. Calculate the number of images formed for the following angles of inclination
   (i) 120° (ii) 90° (iii) 60° (iv) 30°
   (b) Which of the above set up is used in the construction of a kaleidoscope?
4. A bright point object O is placed between two parallel plane mirrors M_1 and M_2 as shown in Fig. 8.38. (not to scale).

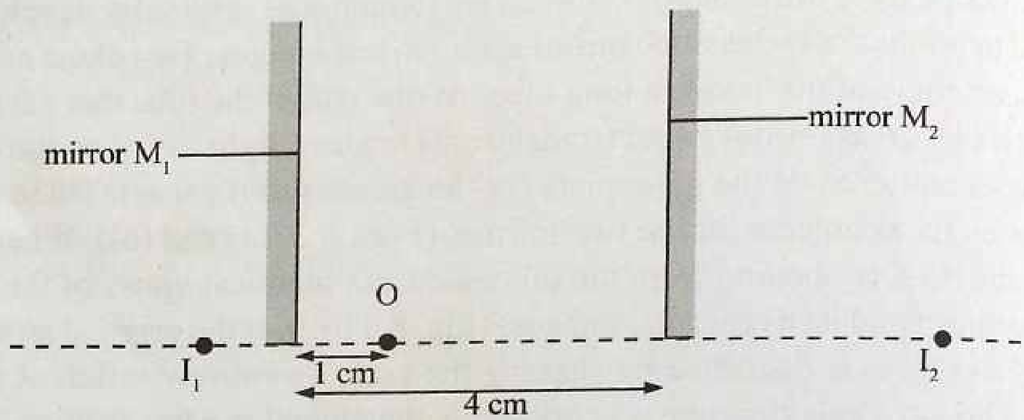


Fig. 8.38

For the object O, mirror M_1 forms a virtual image I_1 behind the mirror M_1. I_2 is the image of O in the mirror M_2. Show that the image of I_2 due to the mirror M_1 is 6 cm behind the image I_1.

8.9 Refraction of light

In Book 1, we learnt that light travels in a straight line. We also looked at reflection of light at plane surfaces and the characteristics of images formed under this property. Now we shall introduce another property of light called *refraction of light.*

You may have observed that:

1. A thin rod dipped obliquely into water appears to be bent at the water surface.
2. A pool of water appears to be shallower than it actually is.
3. A colourful rainbow is formed in the atmosphere usually after some rainfall.
4. A 'shimmering' pool of water seems to be ahead of a traveller on tarmac road or desert sand on a hot day.

These and many other similar effects are caused by refraction of light.

8.10 Simple experiments to illustrate refraction of light

Experiment 8.3: To show the appearance of a plastic ruler dipped obliquely into water

Apparatus

- A plastic ruler
- A transparent container
- Clean water

Procedure

- Dip a plastic ruler into a transparent container of clean water and view the ruler from the top and the side of the container (Fig. 8.39).

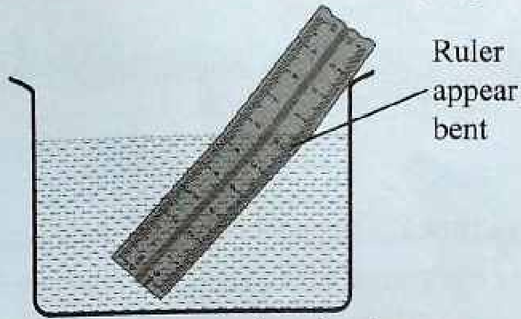


Fig. 8.39: Appearance of a ruler in water.

Observation

The ruler appears to be bent at the point where it enters into water.

Experiment 8.4: To determine the direction of a ray of light incident at the surface of water

Apparatus

- A ray box.
- Water in a transparent container.

Procedure

- Pass a narrow beam of light into water contained in a transparent vessel in a semi-dark room and observe the effect (Fig. 8.40).

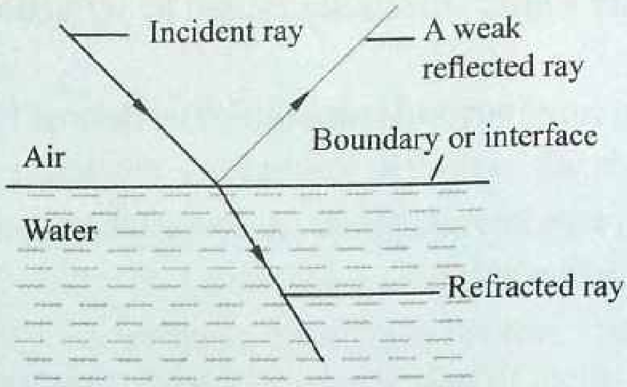


Fig. 8.40: A ray passing from air into water

Observation

The direction of light passing from air into water changes at the air-water boundary. A weak reflected ray is also observed from the surface of water, back into the air.

Experiment 8.5: To determine the direction of light ray passing through a rectangular glass block

Apparatus

- A rectangular glass block.
- A ray box.

Procedure

- Pass a narrow beam of light through a rectangular glass block in a semi- dark room and observe the path of light (Fig. 8.41).

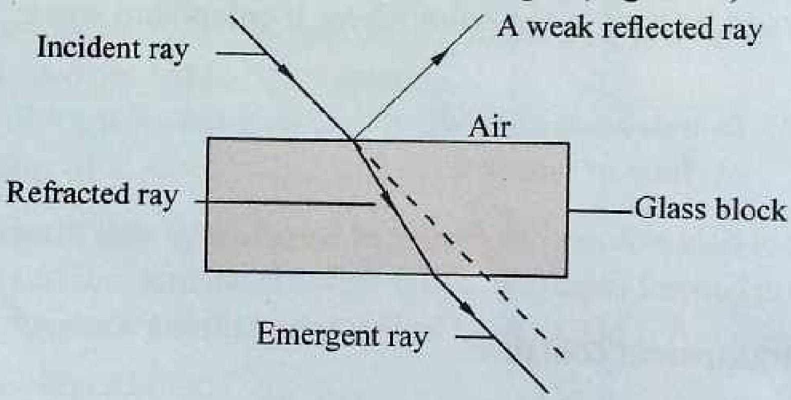


Fig. 8.41: A ray of light passing through a rectangular glass block.

Observation

The direction of the ray of light inside the glass changes. Some of the light is also reflected from the surface of glass. The emergent ray is parallel to the incident ray.

Experiment 8.6: To investigate how a ray of light passes through a triangular glass prism

Apparatus

- A triangular glass block.
- A ray box.

Procedure

- Pass a ray of light through a triangular prism in a semi-dark room and observe the effect (Fig. 8.42).

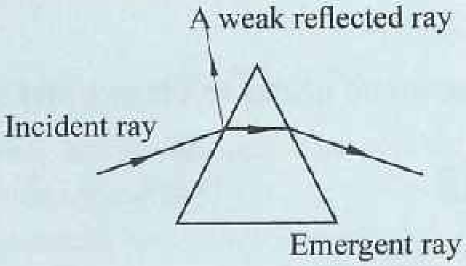


Fig. 8.42: A ray of light through a triangular prism.

Observation

There is a change of direction of the ray of light inside the glass. Some of the light is also reflected from the surface of glass. The emergent ray is not parallel to the incident ray. This means that it emerges in a new direction.

Experiment 8.7: To show the appearance of a coin inside water

Apparatus

- Two glass containers.
- Two identical coins.
- Water.

Procedure

- Take two glass containers and place identical coins at the bottom of each container.
- Fill one container with water and observe from the top of the containers in turn to see the position of the coins in each container (Fig. 8.43).

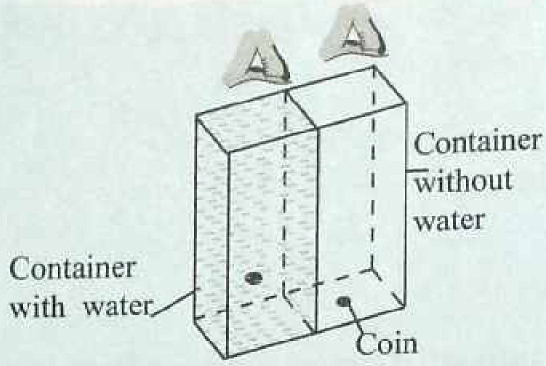


Fig. 8.43: Appearance of a coin inside water.

Observation

The coin inside water appears to be nearer to the eye and slightly bigger than the other coin.

Discussion

In all the above experiments, when light travels from air to another medium like water or glass and vice versa, there is a change in the direction of the path of light at the boundary of the two media. This property of light is called *refraction*.

Conclusion

When light travels from one medium to another of different optical density, it bends. The bending of light is called *refraction*.

Refraction is caused by: change in velocity of light and light travelling across a boundary of two media of different densities.

Refraction is the change of direction or bending of light when it travels from one medium to another.

Refraction is caused by the change of velocity of light as it travels from one medium to another. Experiments show that the velocity of light in air (vacuum) is 3×10^8 m/s. The velocity of light is less in all the other media. Hence air is considered as an optically *rarer medium*. All the other media, are considered as optically *denser media than air*.

Terms associated with refraction

Consider a rectangular glass block ABCD (Fig. 8.44). AB is a boundary that separates the two media i.e. air and glass. Ray PQ travelling in air is incident at the point Q at the boundary. On entering into glass, the ray travels along a path QR (Experiment 8.5). NQM is the normal drawn at Q to the line AB.

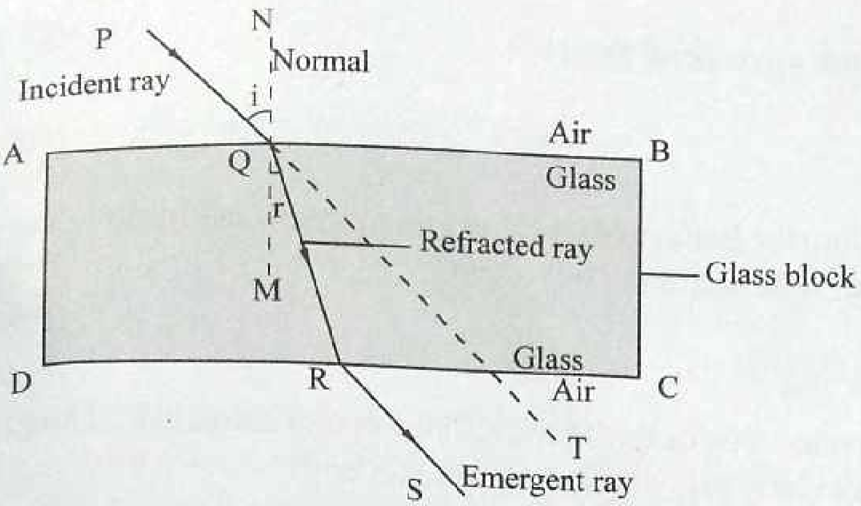
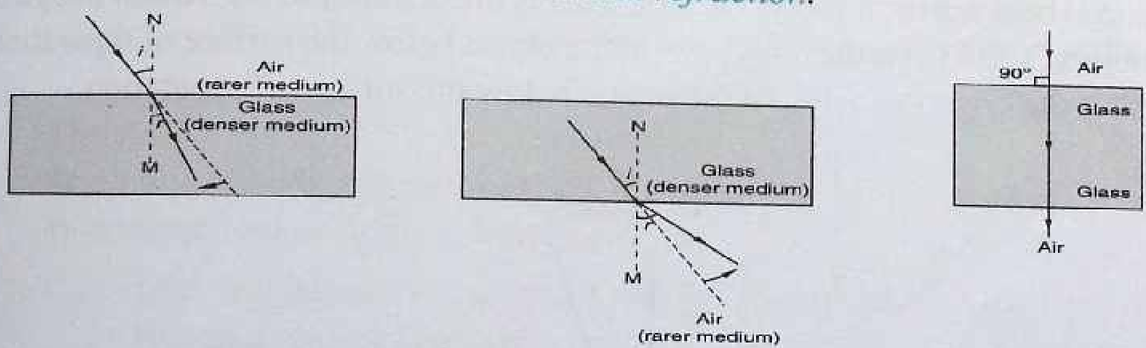


Fig. 8.44: Terminologies used in refraction of light.

The ray PQ is the *incident ray* and the ray QR is the *refracted ray*. The angle PQN, between the incident ray and the normal, is the *angle of incidence*, i. The angle RQM, between the refracted ray and the normal, is the *angle of refraction*, r. The ray RS is the *emergent ray*. As seen in Experiment 8.5 the emergent ray RS is parallel to the incident ray PQ, shown by the dotted line QT.

A ray passing from a rarer medium to a denser medium bends *towards the normal*. On the other hand, a ray passing from a denser medium to a rarer medium bends *away from the normal* (Fig. 8.45).

At the boundary or the surface that separates the two media, there is a change in velocity of light that causes the change of direction. However, if light travels at right angles to the boundary as shown in Fig. 8.45 (c) there is no change in direction. Light continues to travel in a straight line but the speed of light is reduced in the glass. This is, sometimes, referred to as the *normal refraction*.



(a) *Refracted ray moves towards the normal* **(b)** *Refracted ray moves away from the normal* **(c)** *Normal refraction*

Fig. 8.45: Refraction of light in different media

8.11 Real and apparent depth

Activity 8.1

Drop a coin into the bottom of a beaker containing water observe the depth of coin and state your observations.

Observations

The coin appears to be nearer to the surface than it actually is. The beaker or basin also appears to be shallower than its actual depth.

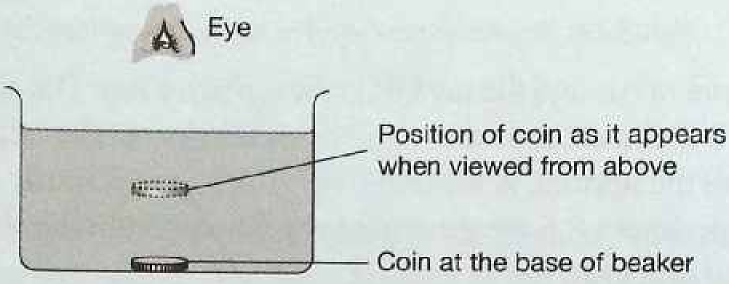


Fig. 8.46: Coin in water

Discussion

The coin appears to be at a shallower position than its actual depth due to refraction of light rays.

Consider Fig. 8.47 ray OA is incident along the normal. The ray goes undefeated as AC at the surface of the two media. Another ray OB, incident obliquely at B and close to A bends away from the normal and proceeds along BD. When DB is produced backwards, it meets OC at I. This is the position of the virtual image of the object O. OA (x) is the *real depth* of the object below the surface of separation. IA (y) is the *apparent depth* of the image below the surface of separation.

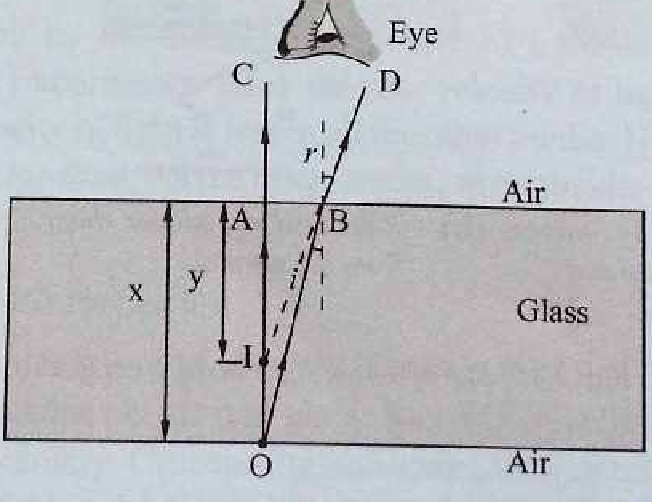


Fig. 8.47: Image formation in a glass block

Exercise 8.5

1. In Fig. 8.48, the eye can see point P inside an empty cup, but not the coin inside. Suggest a simple method by which the observer can see the coin without moving the position of the eye, the coin or the cup.

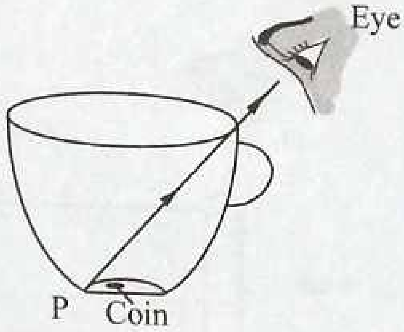


Fig. 8.48

2. The length of a glass block is 6 cm (Fig. 8.49). Using a ray diagram, show how the eye can see the virtual image of object O, if the refractive index of glass is 1.50.

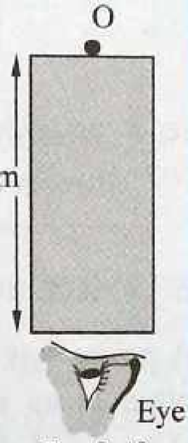


Fig. 8.49

3. Describe an experiment to determine the refractive index of a glass block using two pins.

4. In a transparent liquid container, an air bubble appears to be 12 cm when viewed from one side and 18 cm when viewed from the other side (Fig. 8.50). Where exactly is the air bubble, if the length of the tank is 40 cm?

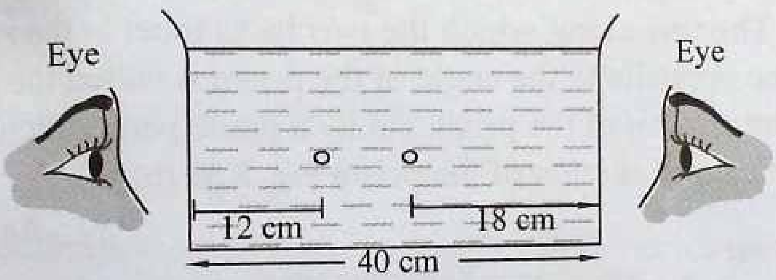


Fig. 8.50

5. The graph in Fig. 8.51 shows the real depth against the apparent depth of a swimming pool as water is being filled.
   (a) Use the graph to calculate the refractive index of water.
   (b) Which physical property of light changes as light leaves the pool of water?

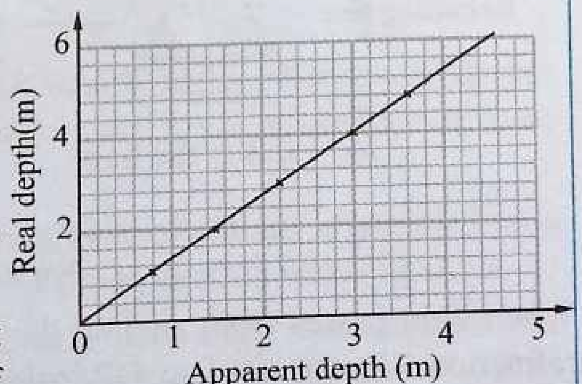


Fig. 8.51

6. Describe an experiment to determine the refractive index of water.

7. Copy and complete a ray diagram to show how the eye sees the image of the dipped part of the pencil (Fig. 8.52). (Refractive index of water is 1.33).

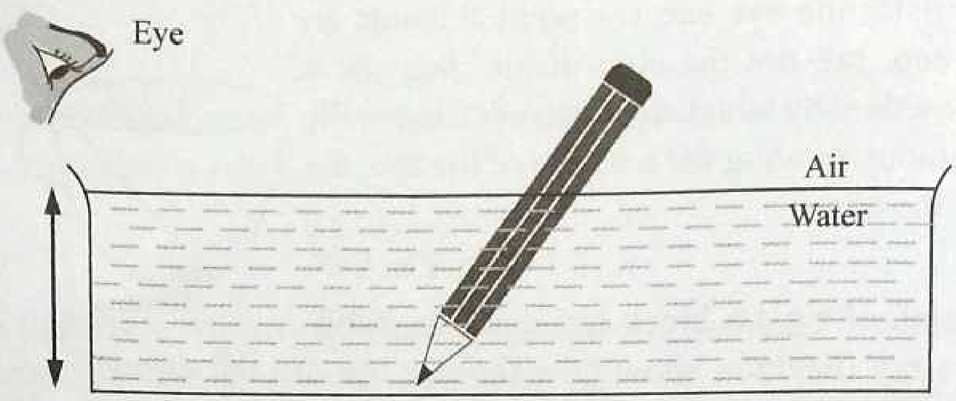
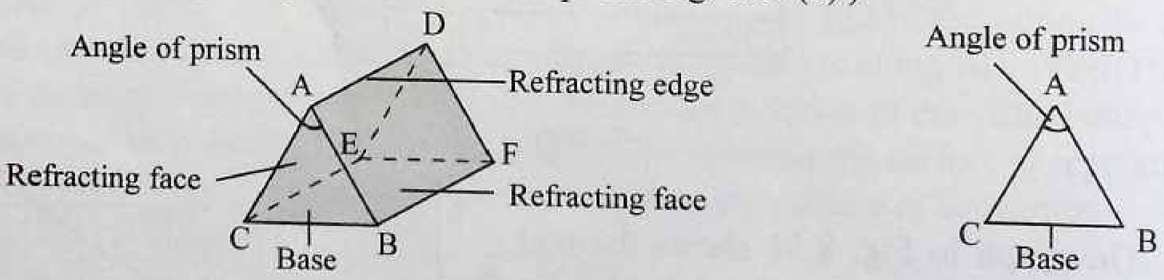


Fig. 8.52

8. A pool of water seems to be shallower than the real depth whereas the apparent height of a star in the sky is more than the real height. Explain this observation.

8.12 Refraction of light through a prism

A prism has a refracting medium bound by two plane surfaces inclined to each other at an angle. The two planes are the *refracting faces(ADEC and ADFB in (Fig. 8.53 (a))* and the angle between the faces is called the *angle of the prism (∠CAB in Fig. 8.53 (a))*. The line along which the two faces meet is the *refracting edge* of the prism. The face opposite to the angle of the prism is called the *base of the prism* (Fig. 8.53 (a)). The section of the prism cut by a plane perpendicular to the edge of the prism is the *principal section* of the prism Fig. 8.53 (b))



(a) CB is the base

(b) Principal section of a prism

Fig. 8.53: Glass prism

When light passes from air into the triangular glass prism (ray PQ), it undergoes refraction. The refracted ray QR inside the glass bends towards the normal N_1N_2. The emergent ray RS bends away from the normal N_3N_4 (Fig. 8.54). Ray PQ produced meets ray RS produced backwards at T. Notice that, the incident ray has *deviated* from its original direction. Angle VTR is called the *angle of deviation*. Hence the action of a prism is to *deviate light rays*.

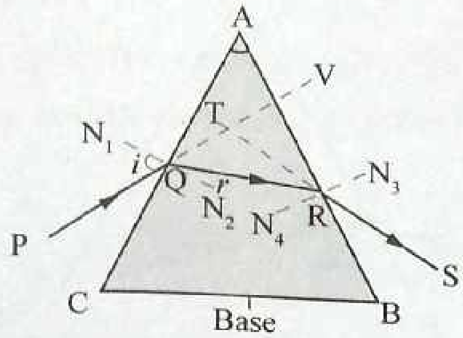


Fig. 8.54: Refraction of light through a prism

Monochromatic light and white light

A *monochromatic light* is one that has a *single colour* and a *single frequency* or *single wavelength*. White light is not monochromatic because it is made up of seven different colours. Non-monochromatic light is also called *composite light*.

8.13 Dispersion of white light

Dispersion of light is the splitting of white light into its constituent colours after passing through a refractive material. The following experiment will illustrate dispersion of white light.

Experiment 8.9: To illustrate dispersion of white light

Apparatus

- A carbon arc lamb
- A cardboard with a hole at the centre
- A prism

Procedure

- Direct a narrow beam of white light (such as sunlight, light from carbon arc lamp or a mercury vapour lamp) from a narrow slit, in a semi-dark room, to an equilateral glass prism.
- Adjust the angle of incidence until a distinct band of colours is obtained on a white screen placed on the other side of the prism as shown in Fig. 8.55.

  What colours are obtained on the white screen? How many of the colours can you identify? Is the angle of deviation the same for each colour?

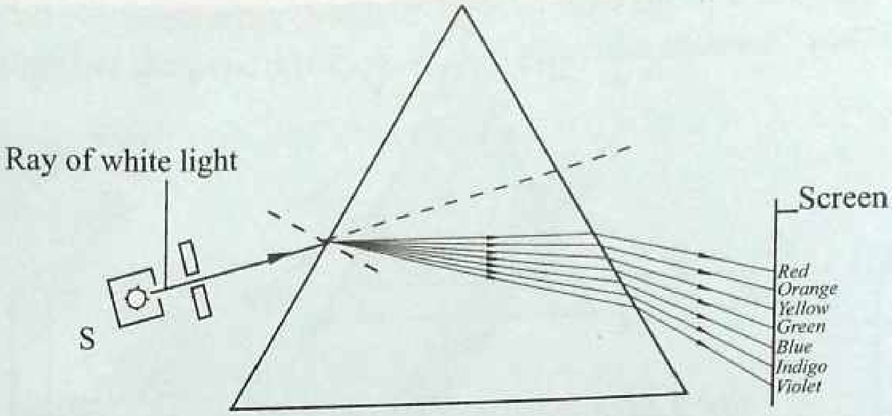


Fig. 8.55: Dispersion of white light forming a spectrum of colours

Discussion

This experiment was first carried out by Sir Isaac Newton. He noticed that *violet light is the most deviated colour* while *red light is the least deviated colour*.

It is observed that white light is split up into a series of colours as it enters the glass prism. Different colours are deviated to different angles. The colours are *red, orange, yellow, green, blue, indigo and violet*. These colours gradually blend into one another.

The splitting of white light into its constituent colours is called *dispersion*. The coloured band produced is called *visible spectrum* (Fig. 8.56).

For the same angle of incidence, each colour has its own angle of refraction inside the glass prism and angle of deviation.

Therefore each colour travels with its own speed inside glass. For example, violet light having the least angle of refraction has the greatest refractive index for glass. This means that the speed of violet light is the least in glass.

If two identical prisms are placed as shown in the Fig. 8.56, the final spectrum produced is more spread out. This means that the angle of deviation of each colour is increased.

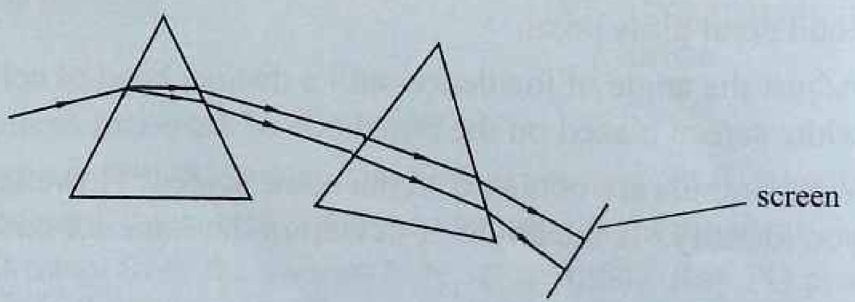


Fig. 8.56: More spread out spectrum.

Conclusion

A white light ray disperse into several colours after passing through a prism.

Combination of spectrum colours

The dispersion created by one prism can be *reversed* by a second prism (Fig. 8.57). When reversed, a white light parallel to the incident white light emerges from the second prism.

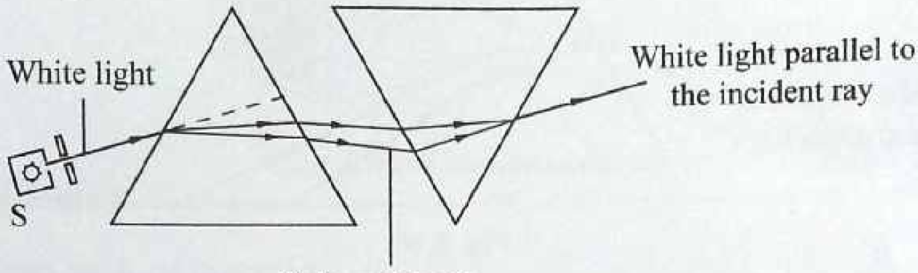


Fig. 8.57: Separation and combination of colours by prisms

Exercise 8.6

1. Copy and complete Fig. 8.58 to show the path of a ray of light through the glass prism. Mark the angle of incidence and the angle of deviation in your diagram

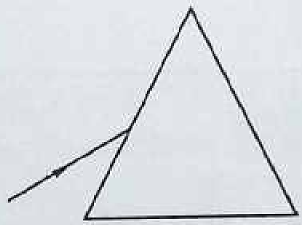


Fig. 8.58

2. Distinguish between monochromatic and composite light. Give an example of each.
3. What do you understand by the terms deviation and dispersion.
4. Write down the colours in a visible spectrum in the decreasing order of angle of deviation.
5. Fig. 8.59 shows the path of a ray of white light incident on a glass prism.

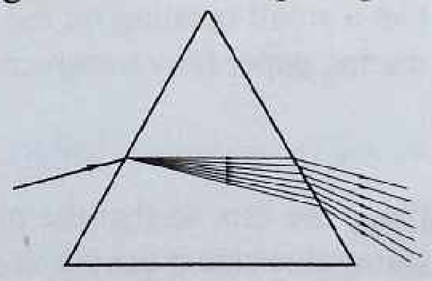


Fig. 8.59

   (a) What name is given to the spreading out of white light inside the prism?
   (b) What name is given to the band of colours seen on the screen?
   (c) Name two physical properties which change for all the colours when they enter the prism.
   (d) Mark the position of violet, blue and red light as seen on the screen.

6. Describe an experiment to illustrate the dispersion of white light.

7. A beam of light made of a mixture of red and green light is shone through a prism (Fig. 8.60).

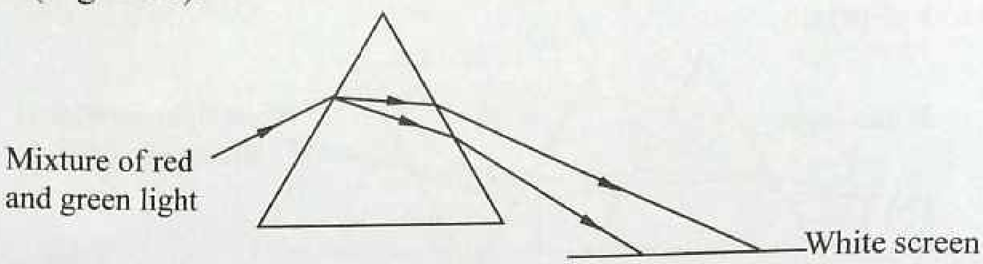


Fig. 8.60

(a) What name is given to the 'bending' of light as it enters the glass prism?

(b) Why does light 'bend' as it enters glass prism?

(c) Why do the two colours of light bend by different amount inside the prism?

(d) Which colour 'bends' the least?

8.14 Project work

Construction of pinhole camera

Suggested materials

An old cardboard shoe-box or a carton of size 40 cm × 15 cm × 12 cm, a sewing needle or a paper pin, grease proof paper, tracing paper or frosted glass, black paint and brush or black paper (optional), a black cloth big enough to cover the box and the head of the viewer (optional).

Assembly

- If black paint is available, paint the inside of the box black or stick black paper inside. Pierce a small hole with the tip of a needle or pin on one side. Cut a small opening on the opposite side and paste a grease proof paper or a tracing paper (any translucent material will be sufficient).

How to use the assembled model

- Place the box so that the pin hole faces a bright object, say a building on a sunny day (or a candle in a semi dark room) . View the translucent screen (Fig. 8.61).
- Cover the box and the head of the viewer with a black cloth to cut off any stray light entering the box or falling on the translucent screen.

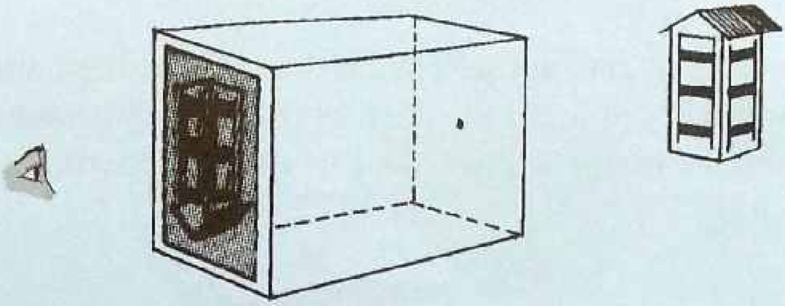


Fig. 8.61: A pinhole camera

Construction of a periscope

Working model

Materials needed

Retort stands, boss and clamp, small pieces of wood or old erasers to hold the mirrors firmly without breaking, candle.

Assembly

Set up the two mirrors at an angle of 45°, with the horizontal and the silvered surfaces facing each other as shown and look for the image (Fig. 8.62).

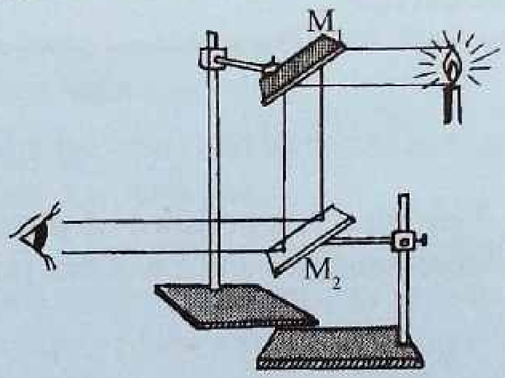


Fig. 8.62: A model periscope

Project: Construction of a periscope

Suggested materials

A narrow long cardboard box (e.g. tennis ball/ shuttle cock containers) or a carton of cardboard of size 40 cm × 5 cm × 5 cm, two plane mirrors (5 cm × 5 cm), adhesive tapes, a razor blade or a pair of scissors.

Assembly

- Insert the two mirrors, one at the top and the other at the bottom at an angle of 45° to the line joining the mirrors (mirror adjustments can be made later when the image is viewed). Cut suitable openings near each mirror (Fig. 8.63).

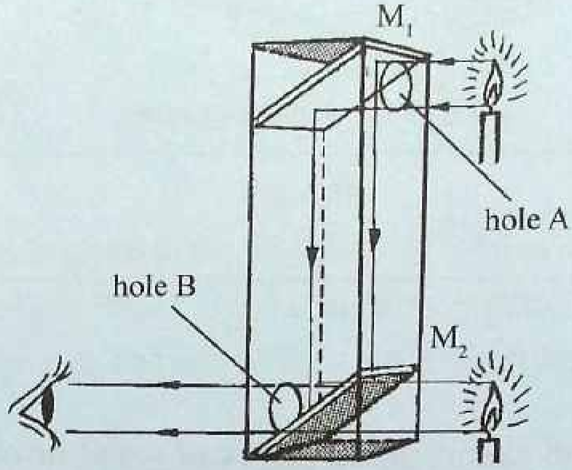


Fig. 8.63: A periscope

How to use

A candle is held near the opening A and the image is seen through the opening B.

Construction of a kaleidoscope

Working model

Materials needed

2 plane mirrors (10 cm × 3 cm) or a thin polished tin plate (10 cm × 3 cm) bent at an angle of 60°, some coloured marbles and a wooden protractor.

Assembly

Draw a circle of radius 10 cm (or the length of the mirrors chosen) on the top of a table and divide the circle into six equal segments. Join the ends of the mirrors with a sticky paper so that the angle between them is 60°. Place the mirrors (or the bent tin sheet) vertically with the junction at the centre of the circle.

Arrange the marbles in the space between the mirrors. Keeping the eye between the mirrors, look for the five images (Fig. 8.65).

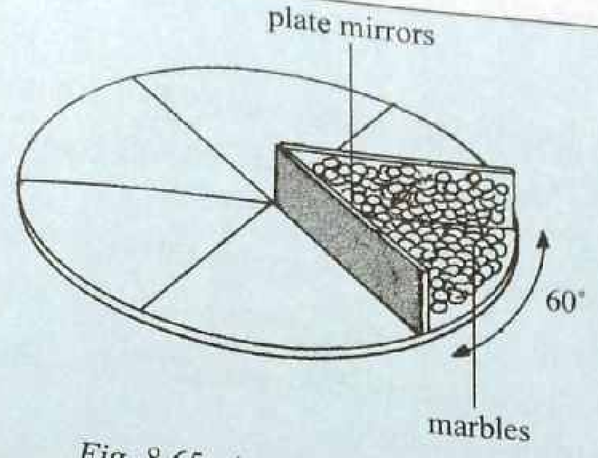


Fig. 8.65: A model kaleidoscope

Project: Constructing a kaleidoscope

Suggested materials

A long cardboard box (e.g tennis ball/ shuttle cock containers) open at one end, brightly coloured glass pieces, two circular ground glasses or a grease proof paper, adhesive tapes and two plane mirrors (10 cm × 3 cm) or a tin plate as suggested in the model above.

Assembly

- Insert the two plane mirrors joined together so that the angle between them is 60° into the box from the open end.

Keep the box vertical with the open end upwards and cover the open end with a grease proof paper or stick a ground glass.

Scatter the glass pieces over the grease proof paper and place the ground glass over these glass pieces and fix the glass gently to the box, taking care for the free movement of the glass pieces. Make a small opening on the other closed side of the box to enable you to see the inside of the tube (Fig. 8.66(a) and (b)).

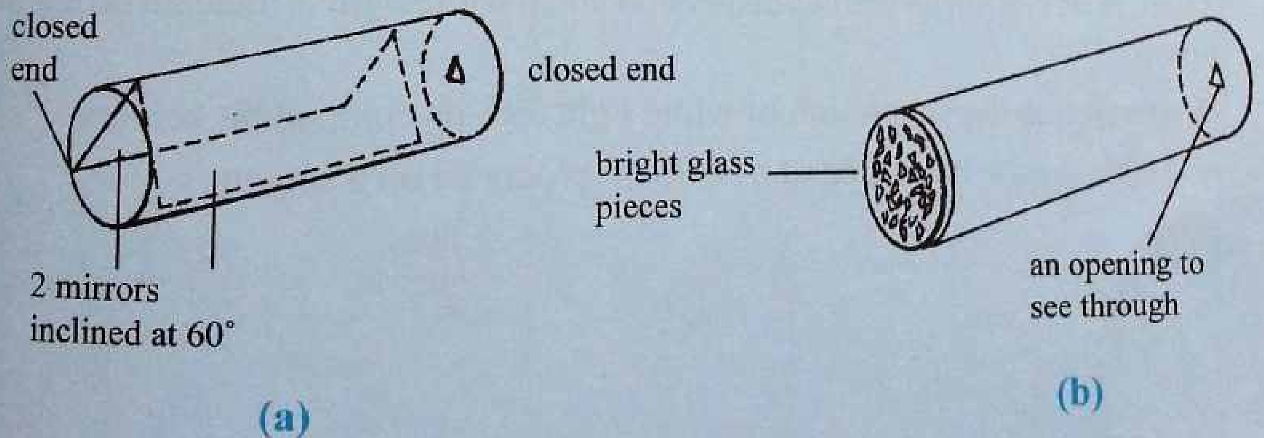


Fig. 8.66: A kaleidoscope

Unit summary

- Light helps us to see objects. Light is a form of energy just like heat.
- Light travels in a straight line. This property of light is called the rectilinear propagation of light.
- A substance through which light can pass through is a medium.
- A shadow is a region where light cannot reach.
- Formation of shadows and pinhole cameras are direct evidences for the rectilinear propagation of light.
- A plane mirror bounces light back into the same medium. The angle of incidence is equal to the angle of reflection.
- A plane mirror forms an image of the same size as the object. The image is erect and laterally inverted. The distance of the image from the mirror is the same as the distance of the object from the mirror.
- Periscopes and kaleidoscopes use the properties of light reflected in plane mirrors.
- Magnification (m) $= \dfrac{\text{height of the image}}{\text{height of the object}} = \dfrac{\text{image distance}}{\text{object distance}}$
- Refraction of light is the bending of light as it passes from one medium to another.
- Refraction of light takes place as the velocity of light is different in different media.
- Monochromatic light is of single colour and single frequency whereas white light is a composite light made of seven different colours.
- Different colours of light have different refractive indices and velocities in different media.
- A glass prism deviates a monochromatic light from its original path and the light bends towards the base of the prism.
- There is deviation as well as dispersion when white light is incident on a glass prism.
- Dispersion is the separation of white light into its component colours.
- A visible spectrum is a band of colours produced on a screen.

Unit Test 8

1. The image formed by a plane mirror is upright. Which row is correct according to the characteristics of the image? [1]

	Laterally inverted	Magnified	Virtual
A.	No	Yes	Yes
B.	Yes	Yes	Yes
C.	Yes	No	Yes
D.	Yes	No	No

2. The diagram in Fig. 8.68 shows a ray of light reflected from a plane mirror.

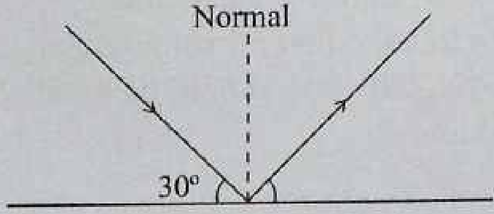


Fig. 8.68

What is the angle of reflection? [3]

A. 20° B. 90°

C. 60° D. 30°

3. Which diagram in Fig. 8.69 correctly shows a ray of light passing through a rectangular glass block? [2]

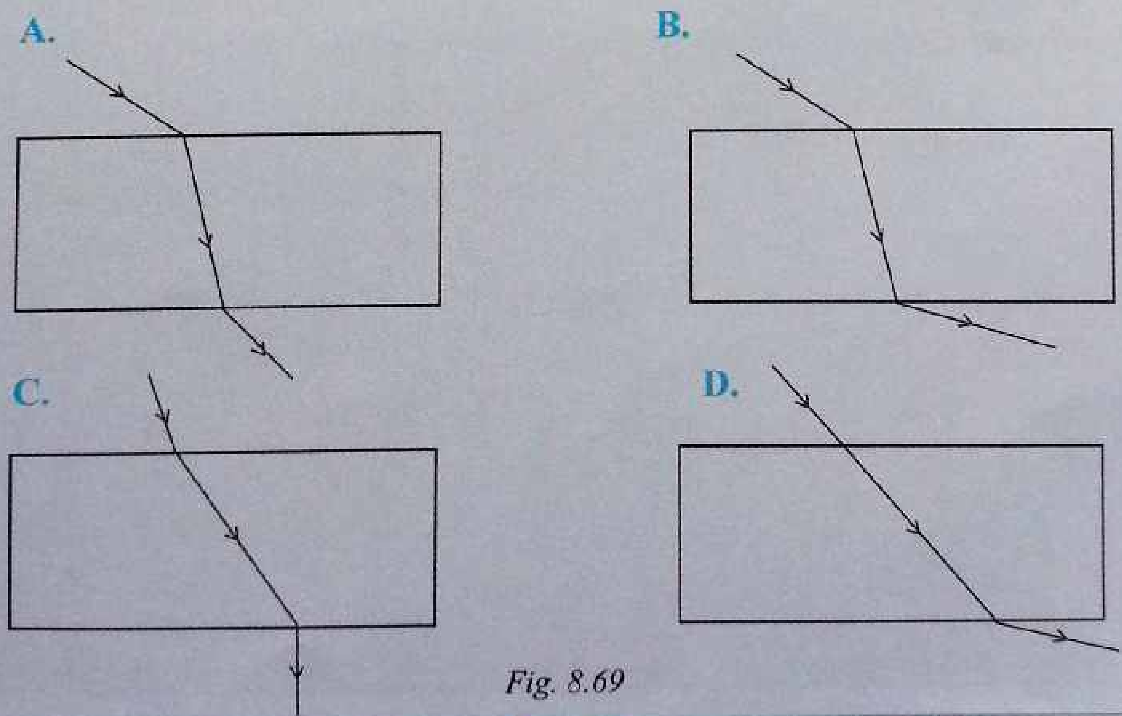


Fig. 8.69

4. Bouncing back of light rays is known as? [1]

A. Dispersion B. Diffusion

C. Refraction D. Reflection

5. A ray of light strikes a plane mirror as shown in Fig. 8.70. Copy the diagram and draw the path of the reflected ray. Mark clearly any two angles which are equal. [2]

Fig. 8.70

6. Draw the reflected ray of light for the incident ray shown in Fig. 8.71. Now draw a second mirror like the first mirror arranged so that the reflected ray is again reflected. The reflected ray should be parallel to the original path but in the opposite direction. [3]

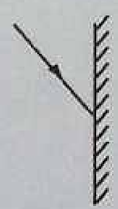


Fig. 8.71

7. A triangular object ABC is on one side of a vertical mirror (Fig. 8.72). Draw the image formed by the mirror. [3]

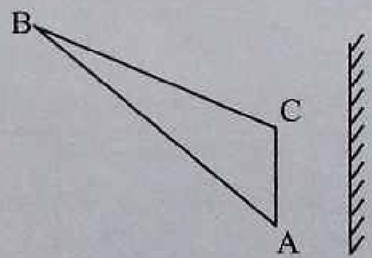


Fig. 8.72

8. Fig. 8.73 shows the path of light PQRS in a simple optical fibre which undergoes reflection. Calculate the angle between the rays PQ and RS. [2]

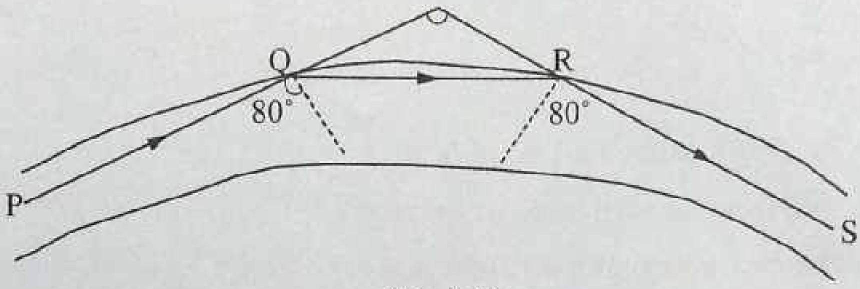


Fig. 8.73

9. Distinguish between solar and lunar eclipses. [2]

10. Describe a project on how to make a periscope. [5]

11. Draw rays from the object OB to show the image formed by a pinhole camera on a screen (Fig. 8.74). Is the image upright or inverted? Is the image real or virtual? [3]

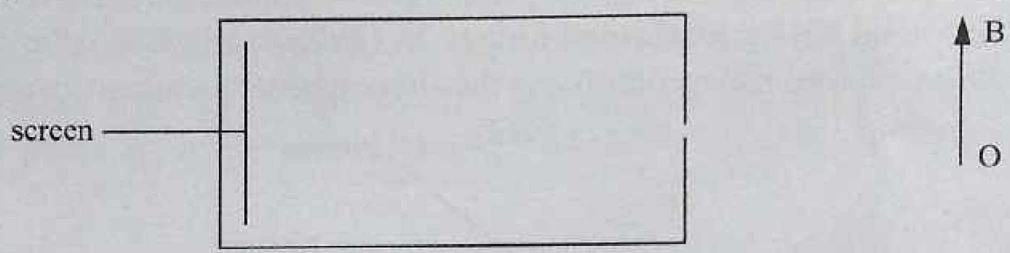


Fig. 8.74

12. State and explain the effect on the image formed in a pinhole camera if
   (a) the object distance is decreased
   (b) the length of the box used is decreased. [2]

13. A pinhole camera forms an image of size 10 cm. The object is 5 m tall and 10 m away from the pinhole. Calculate the length of the pinhole camera. [3]

14. Describe how a kaleidoscope works. [5]

UNIT 9: Introduction to Nuclear Physics

Success criteria

By the end of this unit, you must be able to:

- Describe the nuclear structure of an atom.
- Describe the characteristics of isotopes.
- Describe the types of radioactive emission.
- State the dangers and safety measurer of radio active emissions.
- Mention the applications of radioactive emissions.

9.1 Structure of an atom

In Junior 1, learnt that matter is made up of tiny particles called atoms. For a long time, scientific activities thought that atoms are the smallest building blocks of matter and they could not be subdivided further. In 1897, a particle smaller than an atom called *electron* was discovered. Today they have a better picture of an atom.(Fig. 9.1)

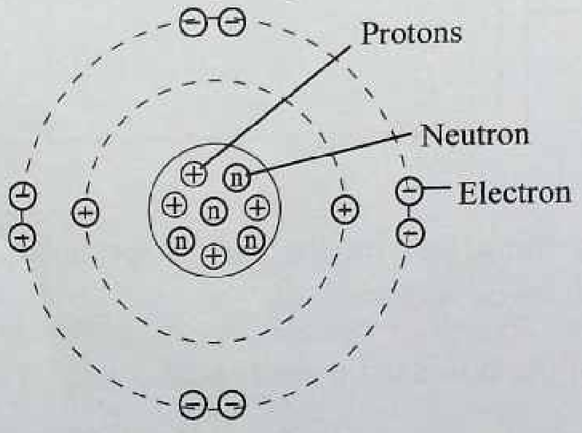


Fig. 9.1

An atom is made up of two parts. The central core called the nucleus where protons ⊕ and neutrons ⓝ are closely packed and an outer orbit where electrons go round its nucleus. They carry a *negative* charge. Protons carry a *positive* charge. Neutrons carry no charge. The number of protons and neutrons are issued in as an atom and hence an atom is always neutral or uncharged.

Charge number or atomic number (Z) is the number of protons inside its nucleus

Mass number or atomic weight (A) is the number of protons and neutrons inside the nucleus. Protons and neutrons are called the nucleus.

The composition of the atoms of an element is represented as:

$^{A}_{Z}X$ where X – as symbol for the element
A – atomic mass
Z – atomic number

Example 9.1

Given that Lithium atom, ${}^{7}_{3}Li$ .Identify the charge number, mass number and the number of neutrons.

Solution

The charge number is 3, i.e the number of protons inside the nucleus

The mass number is 7, i.e the number of protons and neutrons inside the nucleus.

The number of neutrons is equal to $7 - 3 = 4$

Example 9.2

Given a Uranium atom, ${}^{238}_{92}U$, determine the charge number, mass number and the number of neutrons.

Solution

The charge number is 92 i.e the number of protons inside the nucleus

The mass number is 238 i.e the number of protons and neutrons inside the nucleus.

The number of neutrons is equal to $238 - 92 = 146$

9.2 Isotopes

Isotopes of an element are atoms which have the same number of protons but different number of neutrons i.e. isotopes are atoms with the same atomic number but different mass number.

Example 9.3

Explain why ${}^{1}_{1}H$, ${}^{2}_{1}H$ and ${}^{3}_{1}H$ are isotopes hydrogen atom.

Solution

${}^{1}_{1}H$, ${}^{2}_{1}H$ and ${}^{3}_{1}H$ have the same number of protons ($z = 1$) but different mass number i.e different number of neutrons.

In ${}^{1}_{1}H$ there are no neutrons. In ${}^{2}_{1}H$ hence 1 neutron and in ${}^{3}_{1}H$ there are 2 neutrons

Example 9.4

Explain why

$^{12}_{6}C$ and $^{14}_{6}C$ are isotopes of carbon atom.

Solution

$^{12}_{6}C$ and $^{14}_{6}C$ have the same number of protons ($Z=6$) but different mass number of neutrons i.e. different number of neutrons.

In $^{12}_{6}C$, there are 6 neutrons and in $^{14}_{6}C$ there are 8 neutrons.

9.3 Radioactivity

In 1896, Henri Becquerel, a scientist in Paris, placed a few crystals of double sulphate of potassium and uranium near a photographic plate well wrapped in a black paper in a light proof drawer. On developing the photographic plate, he found that the plate had been affected. This observation prompted Becquerel to conclude that the uranium salt had the power of emitting some invisible penetrating radiation spontaneously on its own. On further examination, it was found that the intensity of this radiation was not affected by any variation of temperature, pressure or application of any electric or magnetic field or any other external influence. It was further found that the radiations were emitted by all chemical forms of uranium and the emission of the radiation were attributed to the nucleus. These radiations were named *Becquerel rays*. Becquerel's discovery led to an intense search by many scientists for other materials that emit Becquerel rays. Madam Curie, a scientist from Poland discovered a substance which was 400 times more active than uranium. She called it *polonium*, in honour of her native country. Six months later, she and her husband Pierre Curie discovered another new element millions times more active than uranium. This element was named *radium*. Madam Curie described these elements which are capable of emitting Becquerel rays as being 'radioactive'. *Radioactivity* is therefore the spontaneous disintergration of the nucleus of certain substances which emit Becquerel rays.

9.4 Radioactive decay and half-life

Radioactive decay

Atoms of some elements are known to disintegrate, by emitting either *particles* or *radiations*. It has been shown that these particles or radiations are from the nucleus of the atom. Such elements are called *radioactive elements*.

A radioactive element may change itself into another element by disintegration. The process by which an element changes into another element by emitting a particle (s) or radiations from the nucleus is called *radioactive decay*.

It is not yet understood what causes a particular atom to disintergrate at a particular moment. The disintergration is random and haphazard and it is not possible to predict which atoms are going to decay and when they are likely to decay. Hence *radioactivity is a spontaneous and random process*.

9.5 Types of radiations emitted and their properties

A number of experiments were carried out by a physicist called Ernest Rutherford, to determine the exact nature of radiations emitted by a radioactive substance during the process of disintegration. On the basis of such experiments, it has been established that the radiation emitted by a radioactive substance are of three different types. The radiations are called the *alpha* (α), *beta* (β) and *gamma* (γ) rays. Every radioactive element does not necessarily emit all the three types of radiations.

Properties of alpha (α) particles

1. An alpha particle is a *helium nucleus*, i.e, a helium atom without the two orbital electrons. An alpha particle is about 8 000 times heavier than an electron. The charge of an alpha particle is + 2e, where e is the charge of a proton which is equal to the charge of an electron in magnitude. It thus has a mass number 4 and atomic number 2.
2. Alpha particles, travel in a straight line in free space
3. Alpha particles travel almost with the same speed, which is about 1×10^6 m/s.
4. Due to their heavy mass, alpha particles possess a lot of kinetic energy and also are mono-energetic, since they all have approximately the same energy.
5. They affect photographic papers, — the 'fogging' effect is prominent.
6. They ionise the gas through which they travel.
7. They cause fluorescence on certain substances like zinc sulphide, barium, platinocyanide, etc.
8. Their range in air is about 5-7 cm. During this distance, they ionise the air molecules and lose their energy almost completely.
9. Since they lose their energy in the ionisation process, their penetration power is limited.
10. Alpha particles are deflected in both magnetic and electric fields.
11. Alpha particles get scattered while passing through thin metal foils.

Properties of beta (β) particles

1. A beta particle is a negatively charged fast moving electron emitted from the nucleus. During a beta emission, a neutron which is slightly heavier than a proton, emits an electron and becomes a proton.

neutron → proton + electron.

2. Beta particles do not have a well defined path like alpha particles.
3. Speed of beta particles is about 10-15 times the speed of alpha particles. The most energetic beta particles are emitted with almost the speed of light.
4. Beta particles are emitted with different energies.
5. Beta particles affect photographic paper but the effect is slightly less than that of alpha particles.
6. Beta particles ionise the gas through which they travel, but their ionising power is less than that of alpha particles.
7. Beta particles cause fluorescence on certain substances like zinc sulphide and other fluorescent materials.
8. The 'range' in air of beta particles is a few metres, the maximum range being about 5 m.
9. The penetrating power of beta particles is more than that of the alpha particles.
10. Beta particles are deflected by both magnetic and electric fields.

Properties of gamma (γ) rays

Gamma rays:

1. Are uncharged electromagnetic radiation having no mass and no charge. They are like visible light or X-rays, but of very short wavelength (10–11 – 10–13 m) and high frequencies. They originate from the energy changes in the nucleus of an atom. There is no change in the composition of the nucleus during gamma ray emission.
2. Travel in a straight line, but have no well defined path.
3. Travel with a speed of light (3×10^8 m/s) in air.
4. Possess energy called *photon energy*. Each gamma ray photon has an energy = hf, where h is the Planck's constant and f is the frequency of the gamma rays emitted.
5. Affect photographic papers, but the effect is the least as compared to alpha and beta particles.
6. Ionise the gas through which they travel.
7. Cause fluorescence on certain materials.
8. Have an almost infinite range in air.
9. Have the highest penetrating power when compared to alpha and beta particles.
10. Are not deflected in either electric or magnetic field.
11. Show diffraction effect in crystals and they are transverse in nature.

9.6 Dangers of radioactivity

All radioactive substances are dangerous because the radiations they emitted can ionise the medium through which they travel. The radiation can cause different chemical changes in living cells. Since the body absorbs the radiation energy, ions produced can change or destroy living cells. Widespread damage of cells may cause death.

Apart from the immediate effect like skin burns, vomiting, diarrhoea, there are also possible delayed effect of radiation like loss of hair, cancer, leukaemia and genetic damage. The leakage of radioactive materials to the ground or atmosphere can lead to disasters and the *damage done to the environment is extensive*.

Radioactive waste, produced in the nuclear reactors, are dangerous to health and continue to be dangerous for a long time. Many people died when a nuclear reactor exploded in Chernobyl (Russia) in 1986. The atomic bombs dropped in Hiroshima and Nagasaki (Japan) in 1945 not only killed many thousand of people, but the survivors of the explosion suffered from serious mental depression and genetic damage.

Fig. 9.2: Warning symbol

Precautions

When outside the human body, alpha particles do not penetrate far into the body and therefore the risk is small; but when they come from inside the body the risk is high. They ionise living cells leading to dehydration. Necessary care must be taken to avoid radioactive materials being eaten or radiation inhaled from air. No eating, drinking or smoking is allowed where any radioactive materials are handled. Disposable gloves, protective clothing (lead lined aprons) and masks are to be worn. The warning symbol alongside should be displayed clearly at the prominent places where radioactive material are kept (Fig. 9.2).

Gamma rays can penetrate deep into the body. People exposed to external source of gamma rays must be protected by limiting the dosage of radiation using shielding metal (aluminium, lead), keeping the exposure time as short as possible and keeping large distance between the source and the person.

People should use remote controlled tools like tongs to handle the radioactive materials and sit behind a shielding wall made of concrete and lead. People should use radiation "badges".

In medicine, the radioactive materials used should have a short half-life so that the materials reaching the body quickly decays away.

Though the radioactive materials used in the school laboratories have low activity, they should be kept in lead boxes and handled with tongs, forceps, tweezers, etc. for safety. The source should not be pointed at people.

Radioactive waste must be buried in deep trenches inside the earth far away from place of human habitation and their activity monitored till they become harmless.

Caution!

Cancer is a killer disease. You should have regular medical check up.

9.7 Applications of radioactivity

Uses in medicine

Radioactive materials can be used as tracers in medicine. For example, a radioactive nuclide like iodine-131, which has a short half-life, is used as a tracer to monitor the function of thyroid gland which controls the metabolism rate (rate at which the body 'burns' its food). Also blood clots can be traced by injecting radioactive sodium to the body and using detectors to find where the blood flows stops.

Strong sources of radiation, such as gamma rays emitted by cobalt-60, are being used to kill the harmful tissues such as cancerous cells inside the human body.

The plastic disposable syringes used for inoculations are sealed inside airtight plastic bags and irradiated with the gamma rays from cobalt-60. This kills all the bacteria in the plastic bag and remains sterile until ready for use.

Uses in biology and agriculture

Tracer techniques are used to monitor how plants take up the fertilisers. Radiation can be used to sterilise insects and to eliminate pests which destroy crops. Wheat, maize etc. when irradiated with mild gamma rays can be stored for a long time without damage.

Uses in industries

Leakages in underground water pipes can be located using a gamma ray source of short half-life (Fig. 9.3).

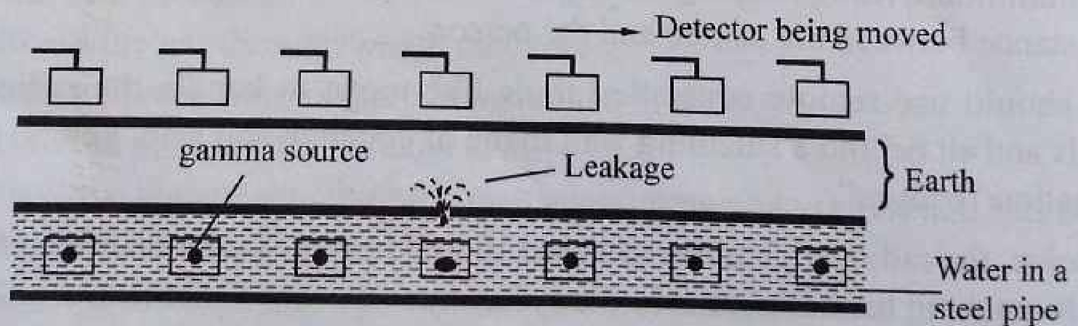


Fig. 9.3: Leakage in underground pipe

The radiations from the gamma rays source emerge out through the leak in the steel pipe and give a much higher count rate than the rest of the pipes. Leakages can be detected without having to dig long distances of the earth.

Also thickness of paper manufactured can be monitored with a beta particle source having a long half-life. Similarly a gamma ray source could be used to gauge the thickness of manufactured metal sheets.

Tea leaves packing industries use beta particles sources to monitor the volume of tea leaves in the packing processes.

Source of electrical energy

The energy released in the fission or fusion process is used to drive a turbine of a generator to generate electrical energy. Since the fuel required for fusion process (heavy water, ${}^{2}_{1}H$) is available in plenty in the sea, electrical energy from the fusion process may be the solution to man's electrical energy crisis.

Unit summary

- Radioactivity is the spontaneous disintegration of the nucleus of certain substances.
- Radioactive decay is a process by which an element changes into another element by emitting a particle(s) or radiations from the nucleus.
- Radiations from a radioactive source are random in nature.
- There are 3 possible types of radiations that are emitted from a radioactive source— alpha particles, beta particles and gamma rays.
- Alpha particles and beta particles are charged particles and are deflected in electric and magnetic fields; gamma rays are uncharged electromagnetic radiations.
- An alpha particle is a positively charged helium nucleus, made of 2 protons and 2 neutrons.
- A beta particle is a negatively charged electron emitted from the nucleus. A heavier neutron emits an electron and becomes a proton.
- Table 9.1 compares the charge, mass, range in air, ionising power, penetrating power and source of alpha, beta particles or gamma rays.

	Charge	mass	range in air	ionising power	penetrating power	source
α	+2e	about 8 000 m_e	about 5–7cm	most	least	Am–214
β	−e	m_e negligible	about 3–5 m	slightly less	slightly more	Sr–90
γ	0	0	infinite	least	most	Co–60

Table 9.1

- Atomic number (Z) of an atom is the number of protons in the nucleus of the atom.
- Mass number (A) of an atom is the sum of protons and neutrons in the nucleus of the atom.
- Nucleon number is the common name given to protons and neutrons inside the nucleus.
- Isotopes of an element are atoms which have the same number of protons but different number of neutrons.
- All radioactive substances are dangerous as they emit radiations which can ionise living cells.
- Necessary precautions should be taken in handling all the radioactive materials.
- Radioactivity is widely used in medicine, agriculture, archaeology, industry, etc.

Unit Test 9

1. Which statement about a carbon nucleus represented by ${}^{14}_{6}C$ is correct? [3]

   A. It contains 6 neutrons.
   B. It contain 14 electrons.
   C. It contains 6 protrons.
   D. It contains 8 protons.

2. A radioactive nucleus emits a β particle. What happens to the proton number (atomic number) of the nucleus? [2]

   A. It stays the same.
   B. It decreases by 4.
   C. It decreases by 2.
   D. It increases by 1.

3. A nuclide of substance X has the symbol ${}^{26}_{12}X$. How many electrons are here in a neutral atom of substance X? [3]

A. 14

B. 26

C. 38

D. 12

4. How many neutrons and how many protons are contained in a nuclear of $^{238}_{92}U$? [2]

	neutron	proton
A.	238	92
B.	146	238
C.	146	92
D.	92	146

5. The neutral atoms of all isotopes of the same element contain the same number of: [1]

A. neutrons and protons

B. neutrons only

C. electrons and neutron

D. electrons and protons

6. What is meant by the following terms in relation to radioactivity: [8]

(a) Randomness.

(b) Activity.

(c) Radioactive decay.

(d) Half-life.

7. (a) Define the terms: (i) radioactivity (ii) background radiation. [2]

(b) State 2 possible sources of background radiation.. [2]

8. What are gamma rays? State three properties of gamma rays which differ from that of alpha and beta rays. [2]

9. Which property of the radiation from a radioactive source makes it harmful? Explain. [2]

10. Alpha particles are more dangerous when inside a human body than outside. Explain. [2]

11. State two hazards which can be inflicted immediately by the strong radiation from a radioactive source and two of long term effects. [3]

12. As a school student, explain the fundamental precautions that should be taken in handling a radioactive source. [4]

13. State how radioactivity is used in: [6]

(a) industries.

(b) archaeology.

(c) medicine.

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