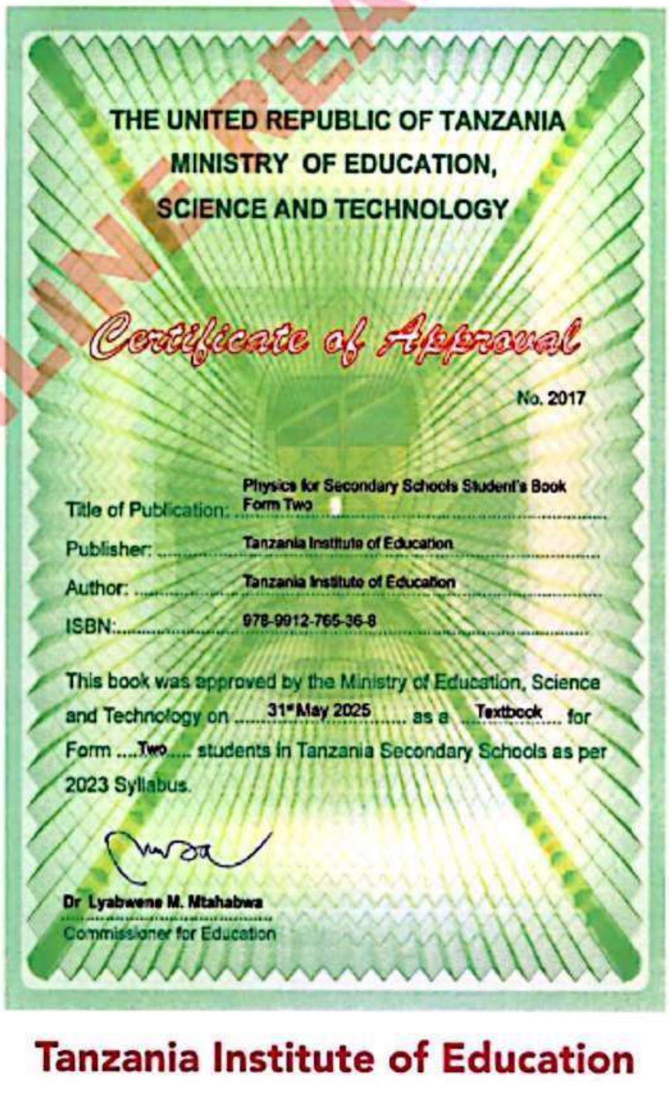
Physics

for Secondary Schools

Student's Book

Form Two



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Preface

This textbook, *Physics for Secondary Schools*, is written specifically for Form Two students in the United Republic of Tanzania. It is prepared in accordance with the Revised 2023 Physics Syllabus for Ordinary Secondary Education, Form I-IV, issued by the Ministry of Education, Science, and Technology (MoEST). It is a revised edition of Physics for Secondary Schools Student's Book for Form Two that was published in 2021 in accordance with the 2007 syllabus issued by the then Ministry of Education and Vocational Training (MoEVT).

The book consists of six chapters: Static electricity, Current electricity, Magnetism, Nature and reflection of light, Refraction and dispersion of light, and Optical instruments. Each chapter contains illustrations, activities, and exercises. You are encouraged to do all the activities and exercises together with other assignments that the teacher will provide. You are also required to prepare a portfolio for keeping records of activities performed in different lessons. Doing so will enhance your understanding and promote the development of the intended competencies for this level.

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Tanzania Institute of Education

Chapter One

Static electricity

Introduction

Clothes containing nylon often crackle when they are taken off the body. Brushing a latex balloon against one's face results in the balloon trying to stick to the face. This is due to static electricity, which results from an imbalance of electric charges within or on the surface of a material. In this chapter, you will learn the concept of static electricity, the origin of charges, the fundamental law of static electricity and the detection of charges. You will also learn about conductors and insulators, capacitors, charge distribution along the surface of a conductor and lightning conductors. The competencies developed will enable you to recognise the effects and applications of static electricity in everyday life.

Think

Application of static electricity in daily life

Concept of static electricity

Have you ever noticed that a nylon garment crackles when taken off the body? Sometimes, tiny sparks are often experienced when undressing in the dark. The crackling sound is caused by small electric sparks caused by charge-discharge. The charge is caused by friction between the nylon and your skin, giving rise to static electricity. Pens and combs made of certain plastic materials attract tiny pieces of paper after being rubbed on the hair or synthetic clothing, as shown in Figure 1.1.

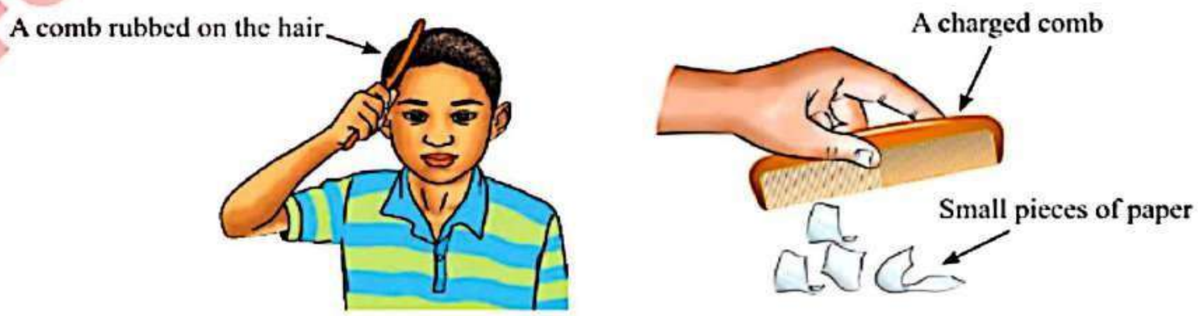
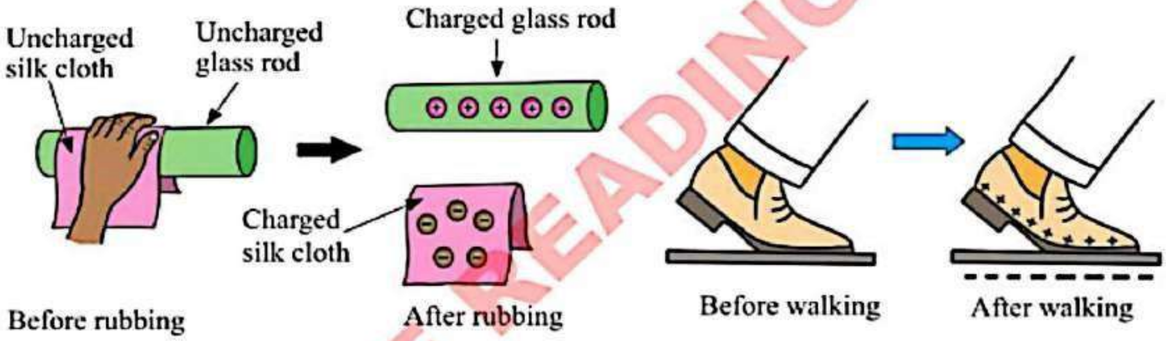


Figure 1.1: *Charged comb attracts pieces of paper*

Static electricity results from the accumulation of static electric charges on a material that does not conduct electricity.

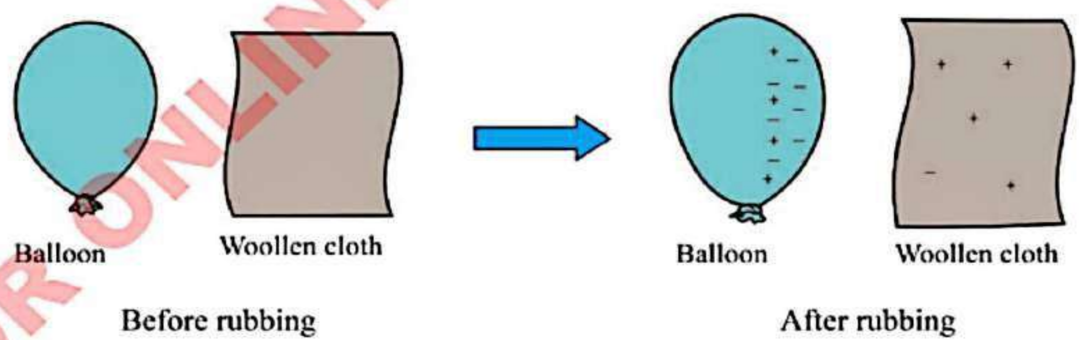
Generating static electricity

Static electricity is generated through the transfer of electrons between materials. This happens when two objects come into contact and are separated, causing one material to gain electrons (becoming negatively charged) and the other to lose electrons (becoming positively charged). Common examples include rubbing a glass rod with cloth (Figure 1.2 (a)), and walking across a carpet (Figure 1.2 (b)) or rubbing a balloon with woollen cloth (Figure 1.2 (c)). The magnitude of the static charge depends on several factors, including the materials involved, the surface properties, and the environmental conditions, such as humidity. This charge build-up can lead to electrostatic discharge, such as a spark.



(a) Rubbing a glass rod with silk

(b) Walking on the carpet



(c) Rubbing a balloon with a woollen cloth

Figure 1.2: *Generating static charges*

Activity 1.1

Aim: To demonstrate the charging of an object

Materials: Wool jumper, dry plastic sheets

Procedure

1. Align two transparent plastic sheets on top of a book.
2. Rub the two plastic sheets with the wool jumper several times.

3. Slowly separate the two plastic sheets and listen to what occurs.
4. Bring the plastic sheets closer and observe the reaction.
5. Separate the plastic sheets, then rub them individually with the wool jumper several times.
6. Bring the sheets close to one another and observe the effect.

Questions

(a) What happened when the two plastic sheets were separated after rubbing them?

(b) Did the plastic sheets attract or repel each other when brought close?

(c) Why do you think the plastic sheets behave differently after being rubbed separately?

When the two plastic sheets are separated, a distinct cracking sound can be heard, and when they are brought together, they attract each other. This phenomenon occurs because the upper sheet acquires a different charge from the lower sheet. Conversely, when the two plastic sheets are rubbed separately and then brought closer, they tend to repel one another due to both sheets acquiring the same charge. The process of charging through rubbing involves the removal or addition of electrons. For instance, when the plastic sheets are rubbed against a sweater, electrons transfer from the sweater to the upper plastic sheet. Meanwhile, the protons in the lower plastic sheet attract the electrons from the upper sheet. This interaction explains why the sheets attract each other after being rubbed together.

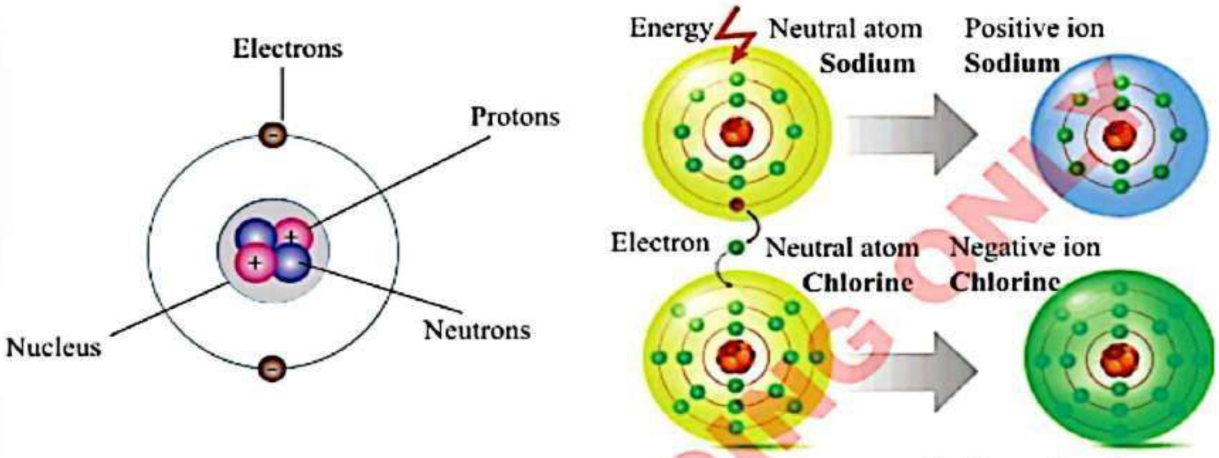
The summary of the acquisition of charges by rubbing for some materials is given in Table 1.1.

Table 1.1: *Acquisition of charges by different materials*

Material	Rubbed with	Charge acquired by the material
Ebonite	Woollen cloth/fur	Negative
Glass	Silk	Positive
polystyrene	Woollen cloth/fur	Negative
Polythene	Woollen cloth/fur	Negative
Perspex	Woollen cloth	Positive
Cellulose	Woollen cloth	Positive

Origin of charges

Electric charge is something that exists inside atoms. In 1890, a scientist named J.J. Thomson found out that all materials have tiny, light particles with a negative charge. He called these particles electrons. Later, between 1909 and 1911, another scientist named Ernest Rutherford discovered that atoms also have a heavy centre called the nucleus, which has a positive charge. Normally, an atom is neutral, which means it is not charged, because the positive charge in the nucleus and the negative charge from the electrons are equal and cancel each other out. But if the atom gets extra energy, it can lose one of its outer electrons. When this happens, the atom has more positive charge than negative charge, so it becomes positively charged. The electron that was removed can stay by itself or join another atom. If it joins another atom, that atom gets a more negative charge and becomes negatively charged. So, gaining or losing electric charge is really about moving electrons from one atom to another. The charge on the electron equals -1.6×10^{-19} C. The proton has a charge of the same magnitude as that of the electron but with an opposite charge. Electrons surround the nucleus in shells. Figure 1.3 illustrates the structure of an atom.



(a) Structure of a two-electron atom

(b) Neutral, negatively charged and positively charged atoms

Figure 1.3: *Origin of charges*

Conductors and insulators

Conductors possess free electrons that facilitate charge movement, enabling an even distribution of charge when a current is added, as shown in Figure 1.4 (a). Examples include copper, iron, and aluminium. In contrast, insulators lack free electrons, resulting in the added charge remaining fixed in place, as depicted in Figure 1.4 (b). This leads to no rearrangement of charge, with examples such as plastic, wood, and rubber

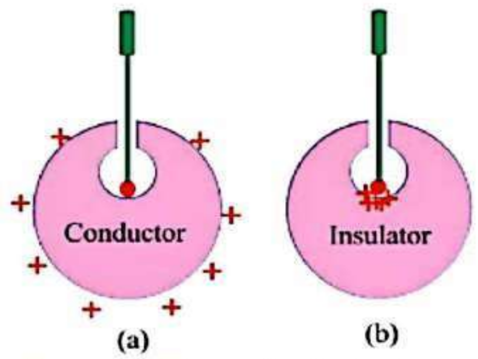


Figure 1.4: *Charge distribution in a conductor and an insulator*

Determine whether an object is an insulator or a conductor based on its charge distribution

Step 1: Identify the initial location where the charges are added to the object and their final locations after a brief period of time.

Step 2: If the charges are spread evenly across the surface of the object, it is a conductor. If the charges remain in the same location where they were added, it is an insulator.

The following examples will help to determine the charge distribution in a conductor and an insulator.

Example 1.1

A charged sphere is brought into contact with an object of unknown material. The sphere transfers electrons to the object, and the charge distribution is measured after a short period of time.

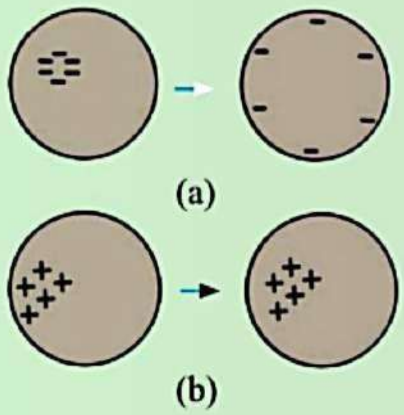


Figure 1.5

Based on the charge distribution:

(i) is the object in Figure 1.5 (a) a conductor or an insulator?

(ii) is the object in Figure 1.5 (b) a conductor or an insulator?

Solution

(i)

Step 1: Identify the initial location where the charges are added to the object and their final locations after a brief period of time. The electrons are initially located in a group where they were added and are then spread out evenly across the surface of the object.

Step 2: If the charges are spread evenly across the surface of the object, it is a conductor. If the charges remain in the same location where they were added, it is an insulator. Therefore, because the charges are distributed evenly, the object is a conductor.

(ii)

Step 1: Identify the initial location where the charges are added to the object and their final locations after a brief period of time. A group of electrons has been removed from a specific location on the object. After short period, this region of net positive charge (due to electron deficity) remains fixed in the same location.

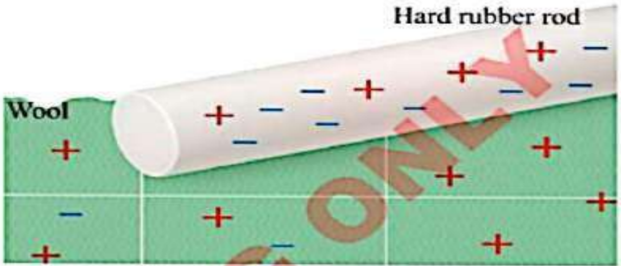
Step 2: If the charges are spread evenly across the surface of the object, it is a conductor. If the charges remain in the same location where they were added, it is an insulator. Based on the charge distribution, the object is an insulator.

Air as a conductor: Air is an insulator. However, under certain conditions, sparks or lightning occur, allowing charge to move through the air as if it were a conductor. The sparks that jump between your fingers and a doorknob after you have rubbed your feet on the carpet discharge you. That is, you have become neutral because the excess charges have left you. Similarly, lightning discharges from a thundercloud. In both cases, for a brief moment, air becomes a conductor.

Separation of charge

If two neutral objects are rubbed together, each can become charged. For instance, when rubber and wool are rubbed together, electrons from the atoms of the wool are transferred to the rubber, as shown in Figure 1.6 (a) and (b). The extra electrons on the rubber result in a net negative charge, while the electrons missing from the wool lead to a net positive charge. The combined total charge of the two objects remains the same. Charging is conserved, which means that individual charges are neither created nor destroyed. All that happened was that the positive and negative charges were separated through the transfer of electrons.

(a)



(b)

Figure 1.6: *Separation of charges*

Law of conservation of charge

A charge is a characteristic of matter that causes it to create and experience electrical and magnetic effects. The underlying idea behind charge conservation is that the system's overall charge is conserved. It can be defined as follows:

> *According to the rule of conservation of charge, the total charge of an isolated system will always remain constant. At any time intervals, any system that is not exchanging mass or energy with its surroundings will have the same total charge.*

When two objects in an isolated system each have a net charge of zero, and one body transfers one million electrons to the other, the object with the surplus electrons will be negatively charged, while the object with fewer electrons will have a positive charge of the same magnitude. The total charge of the system has never changed and will never change.

Electrostatic force

The interaction between static electric charges produces a force known as the electrostatic force. For instance, when plastic rods are charged by rubbing them with fur, they repel each other. Similarly, glass rods rubbed with silk also become charged and repel one another. Additionally, plastic rods attract the fur, while glass rods attract the silk.

French physicist Charles Coulomb measured the force between two charged objects using a torsional balance, establishing a unit of electrical charge named the coulomb in his honour. A coulomb is a much larger quantity of charge than that normally produced by rubbing.

Activity 1.2

Aim: To demonstrate the existence of the electrostatic force

Materials: plastic pen, plastic comb, tissue paper, human hair

Procedure

1. Tear a sheet of tissue paper into several small pieces and lay them on a table.
2. Rub a plastic pen through your hair.
3. Bring the pen closer to the pieces of paper, but do not touch them as shown in Figure 1.7.
4. Hold the pen for 15 seconds.
5. Record your observations.

Questions

(a) What happened when the pen was brought closer to the pieces of paper?

(b) What happened to the pieces of paper on the pen after holding it for 15 seconds?

(c) Discuss your observations.

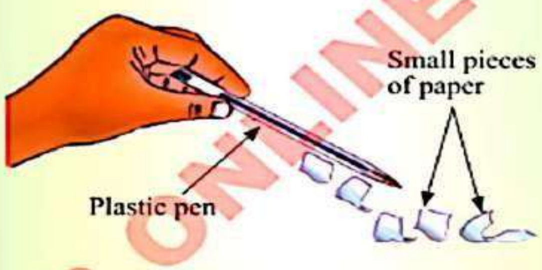


Figure 1.7: *Charged plastic pen attracts pieces of paper*

The pen picked up pieces of paper, which were dropped off after some time. This shows that a plastic pen rubbed with human hair acquires a charge that can attract other substances, such as pieces of paper. After a few seconds, pieces of paper fall off because they acquire similar charges to the pen.

Activity 1.3

Aim: To show the existence of opposite charges

Materials: water, plastic pen, plastic comb, human hair

Procedure

1. Rub a comb with your hair.
2. Bring the comb close to a small, slow stream of water coming from a tap as shown in Figure 1.8 (b).

Questions

(a) What did you observe after rubbing the comb with the hair?

(b) What types of charges were in the water?

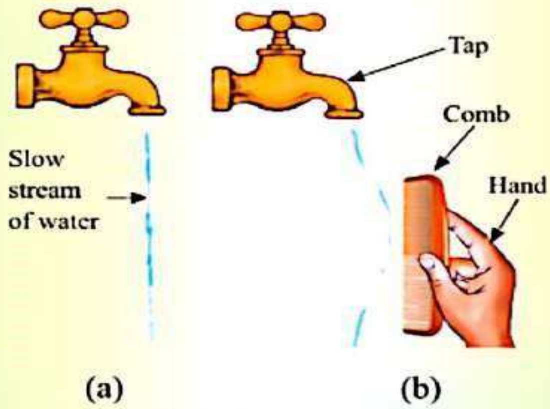


Figure 1.8: *Slow stream of water is attracted to the comb*

Fundamental law of static electricity

The fundamental law of static electricity, also known as the first law of electrostatics, states that, "like charges repel, unlike charges attract".

Activity 1.4

Aim: To verify the fundamental law of static electricity

Materials: 2 dry glass rods, 2 ebonite rods, thread, stand, silk cloth, fur (cotton cloth)

Procedure

1. Rub a dry glass rod with a silk cloth and suspend it using a piece of thread.
2. Bring a second charged glass rod close to the suspended one as shown in Figure 1.9.
3. Record your observations.
4. Repeat steps 1 and 2 using an ebonite rod rubbed with fur.
5. Now, repeat the activity by bringing a charged glass rod close to the suspended charged ebonite rod and the charged ebonite rod close to the suspended charged glass rod. Record your observations.

Questions

(a) What did you observe?

(b) What conclusion can you make from your observations?

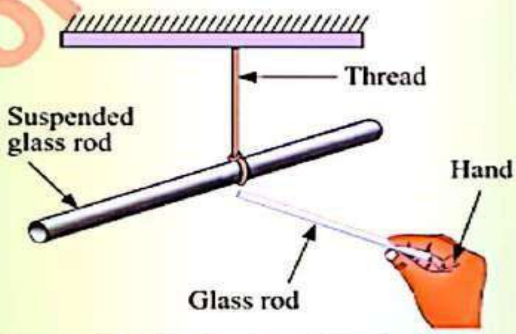


Figure 1.9: *Verification of the fundamental law of electrostatics*

If two negatively charged materials or two positively charged materials are brought near each other, they repel. However, if a positively charged object is placed near a negatively charged object, the objects attract each other. This suggests that unlike charges exert an attractive force on each other, and like charges exert a repulsive force on each other.

Activity 1.5

Aim: To show charge separation in materials

Materials: woollen cloth, glass rod, cotton fabric, plastic pen or comb, string, retort stand

Procedure

1. Hang a comb from a string tied to a retort stand.
2. Rub the comb with a piece of cotton fabric, then hang it.
3. Rub a glass rod with a piece of woollen fabric, then hang it.
4. Bring the charged glass rod near but not touching the hanging charged comb.
5. Bring the piece of woollen cloth that you used to rub the glass rod near but not touching the hanging comb.

Questions

(a) Which material will become positively or negatively charged in steps 2 and 3? (Refer to Table 1.1.)

(b) What did you observe in steps 4 and 5?

(c) Discuss your results.

Charging objects

A neutral object has the same number of positive and negative charges, so they balance each other out. When you bring another neutral object close to it or touch them together, nothing special usually happens because both objects have balanced charges.

However, if something causes one of the objects to have more positive or negative charges than the other, this is called an imbalance of charges. Creating this imbalance is known as charging an object.

There are different ways to charge objects:

(a) Friction: Rubbing two objects together can move electrons from one object to another.

(b) Contact (or conduction): Touching a charged object to a neutral object can transfer electrons.

(c) Induction: Bringing a charged object close to a neutral object can rearrange the charges inside the neutral object, even without touching.

These methods all involve moving electrons to create an imbalance of charges, which makes the object either positively or negatively charged.

Charging by friction

Charging by friction is the oldest method of generating electric charge, and it plays a fundamental role in understanding static electricity. This process occurs when two objects in contact are rubbed against each other, leading to the transfer of electrons from one object to another.

Mechanism of charging by friction

When two insulating materials are rubbed together, friction generates an imbalance of electric charges. Electrons, which are negatively charged particles, are transferred from one object to another. The object that loses electrons becomes positively charged, while the object that gains electrons becomes negatively charged. This transfer of charge is governed by the principle of conservation of charge, meaning that the total charge before and after the rubbing process remains constant. For example, when an ebonite rod is rubbed with fur, electrons move from the fur to the ebonite rod as shown in Figure 1.10. As a result, the fur becomes positively charged (due to the loss of electrons), while the ebonite rod becomes negatively charged (due to the gain of electrons).

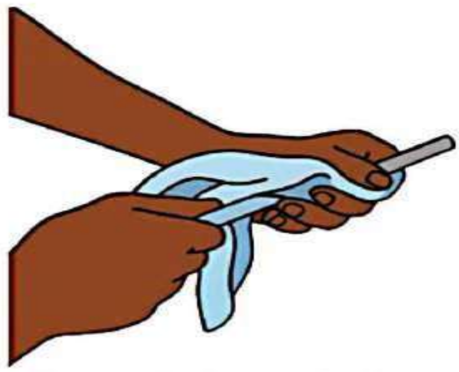


Figure 1.10: *Process of rubbing*

Every day examples of charging by friction

1. Combing hair: When you comb your hair with a plastic comb, electrons are transferred from your hair to the comb. This causes the comb to become negatively charged, allowing

it to attract small bits of paper when brought close.

2. Rubbing a glass rod with silk: When a glass rod is rubbed with silk, the glass rod loses electrons and becomes positively charged, while the silk gains electrons and becomes negatively charged.
3. Wool Sweater and Human Skin: In colder months, when you take off a wool sweater, you may notice sparks or hear crackling sounds. This is due to the static electricity generated as electrons transfer from the wool to your skin.

The Role of insulators and conductors

Not all materials can be charged by friction. Only insulating materials can be effectively charged through this method because their electrons are not free to move. In contrast, conductors allow electrons to move freely, which means they cannot hold a static charge. Common insulating materials include rubber, glass, and plastic, while metals are good conductors.

Triboelectric series

The triboelectric series is a ranking of materials based on their propensity to gain or lose electrons through contact or friction. The position of a material in the series indicates whether it will tend to become positively or negatively charged when rubbed against another material (see Figure 1.11). Materials higher on the list tend to become positive, while those lower become negative. This effect is due to the transfer of electrons between the materials, leading to static electricity. The series is a useful tool for predicting the outcome of charge transfer in various scenarios.

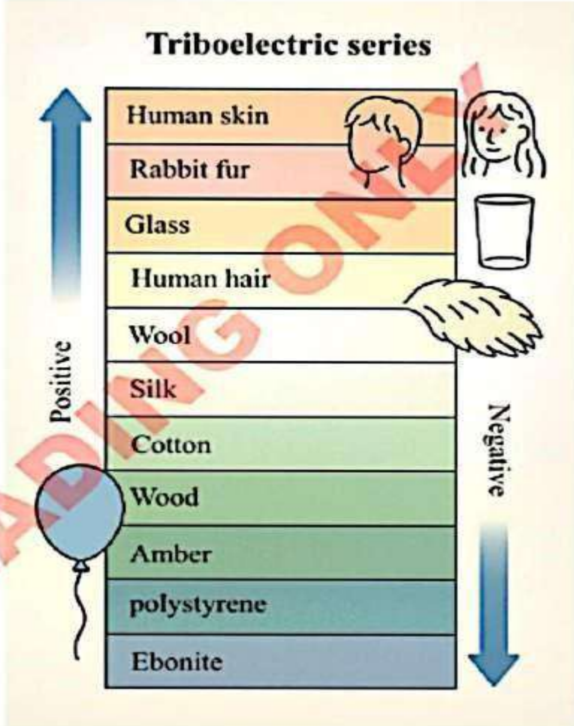


Figure 1.11: *Triboelectric series*

When two materials from this series are rubbed together, the one higher in the series will gain electrons, while the one lower will lose electrons. For example, if you rub a glass rod with silk, the glass rod will lose electrons and become positively charged, while the silk will gain electrons and become negatively charged

Charging an object by contact (conduction)

Charging by contact is achieved by bringing a charged body into contact with an uncharged one. Charges are transferred from the charged body to the uncharged body. Consider two metal plates X and Y, where plate X is positively charged while plate Y is uncharged. Both plates are then placed on insulating blocks brought into contact and then separated as shown in Figure 1.12.

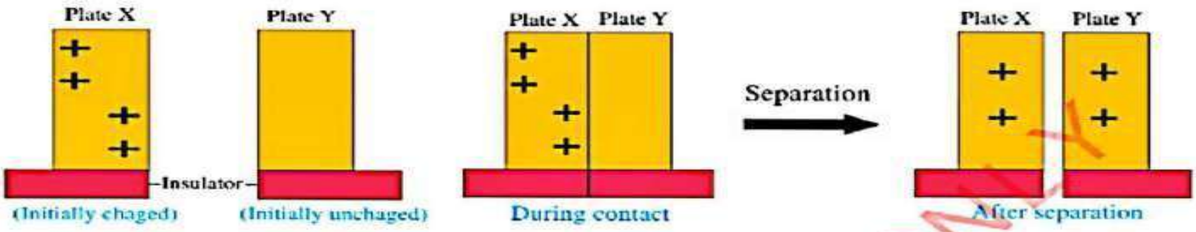


Figure 1.12: *Charging by contact*

Testing the metal plates after separation shows that, when a charged body is brought in contact with an uncharged body, the same electric charges are distributed among the two bodies. As a result, the initially uncharged body acquires charges of the same sign as the charges of the initially charged body.

Charging by induction

Charging by induction is a method of charging an object without actually touching it with any other charged object. Figure 1.13 illustrates the simple steps to induce a charge by induction.

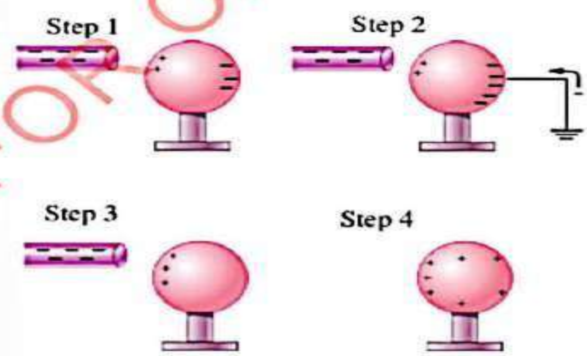


Figure 1.13: *Inducing a charge on a spherical ball*

Step 1: A negatively charged rod is brought near the uncharged spherical ball. The free electrons from the sphere are repelled by the excess electrons on the rod, and they are shifted towards the right. They cannot escape from the sphere because the stand and the surrounding air are insulated.

Step 2: These excess charges, called induced charges, are released to the earth by touching the right part of the sphere with a wire and connecting the other part of the wire to the earth.

Step 3: The wire is disconnected.

Step 4: The negatively charged rod is removed. A net positive charge is left on the spherical ball.

Activity 1.6

Aim: To demonstrate the transfer of conduction electrons in a conductor by the induction method

Materials: iron nail, string, plastic comb, cotton cloth, glass rod, woollen cloth

Procedure

1. Suspend an iron nail from a string, as shown in Figure 1.14.
2. Rub the comb with a piece of cotton cloth.
3. Bring the comb near one end of the iron nail.
4. Rub the glass rod with a piece of woollen cloth.
5. Bring the glass rod near one end of the iron nail.

Figure 1.14

Questions

(a) What do you observe in steps 3 and 5?

(b) What type of charge does the comb acquire?

(c) Explain your results.

(d) Why does a string suspend the iron nail?

When the plastic comb is rubbed with cotton, it becomes negatively charged. When the comb is placed near the iron nail, the conduction electrons at the end of the iron nail near the negative charge on the comb are repelled and move to the opposite end of the iron nail. This leaves an excess positive charge at the end near the comb. The positive charges on the iron nail then attract the negative charges from the comb. Further observation reveals that the iron nail is slightly pulled towards the comb, as shown in Figure 1.15.

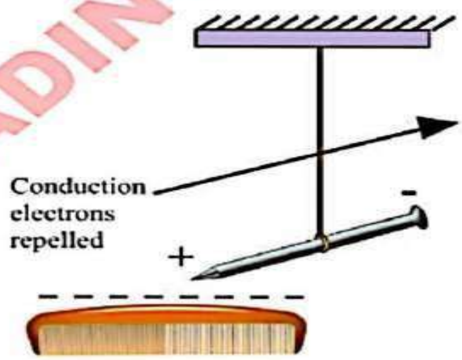


Figure 1.15: *Charging a conductor by induction using a negatively charged comb*

On the other hand, rubbing the glass rod with cotton causes it to acquire a positive charge. When the rod is brought close to an iron nail, the conduction electrons from the iron nail are attracted by the positive charge of the rod and move to the end of the iron nail near the glass rod. This movement results in an excess of positive charge at the opposite end of the iron nail. As a result, the iron nail is pulled slightly towards the glass rod, as shown in Figure 1.16.

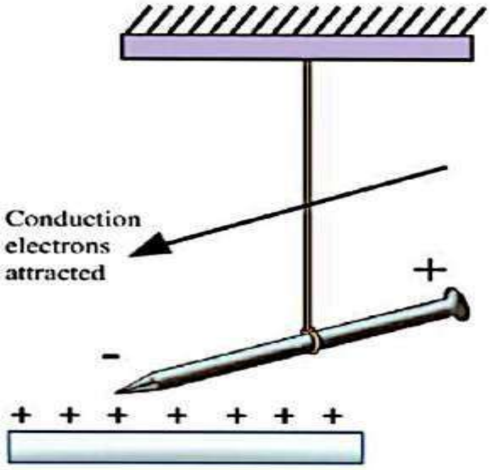


Figure 1.16: *Charging a conductor by induction using a positively charged rod*

If the charging object (comb or glass rod) is removed, the charges in the iron nail return to their normal distribution and the nail is no longer charged.

Detection of charges

Electroscopes detect the presence of electric charges on a body. The most commonly used type of this instrument is the leaf electroscope.

Structure of a leaf electroscope

A leaf electroscope was previously referred to as a gold leaf electroscope. It is an instrument used to detect electric charge on an object. It consists of a metal cap mounted on a metal rod, having at its lower end a small metal plate with a thin metal leaf attached to it. The metal used for the cap, rod and plate is normally brass. The leaf is normally made up of gold, but any other metal, like aluminium, can be used. The metal rod and plate with attached metal leaf are enclosed in a metal or glass case to protect the leaf from air currents. Figure 1.17 (a) shows an example of a leaf electroscope, and Figure 1.17 (b) is its schematic diagram.

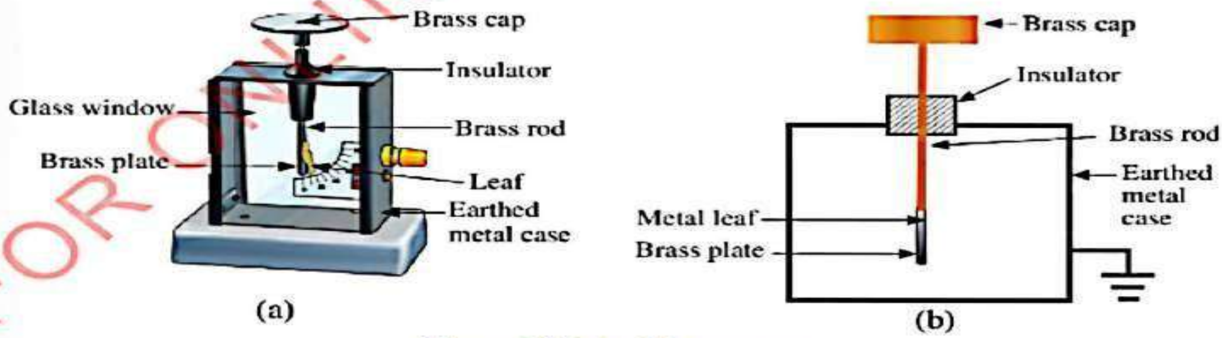


Figure 1.17: *Leaf electroscope*

Construction of a gold-leaf electroscope

The construction includes a metal rod with a conductive ball at the top and two thin gold leaves suspended from the bottom, which visibly respond to changes in charge. Enclosed in a protective casing, the electroscope is an essential tool in electrostatics, enabling clear observation of electrostatic phenomena.

Project 1.1

Construct a simple leaf electroscope using a glass jar, copper wire, straw, strips of aluminium foil, glue, and a jar lid. After construction, test different objects to observe the deflection of the leaves and determine whether they are positively or negatively charged.

The electrophorus

It is a simple device used to produce an unlimited number of electrostatic charges via the process of electrostatic induction.

An electrophorus consists of a circular slab of insulating material (polythene) and a brass disc (conductor) on an insulating handle. Figure 1.18 (a) shows a picture of an electrophorus, and Figure 1.18 (b) is a schematic diagram of it.

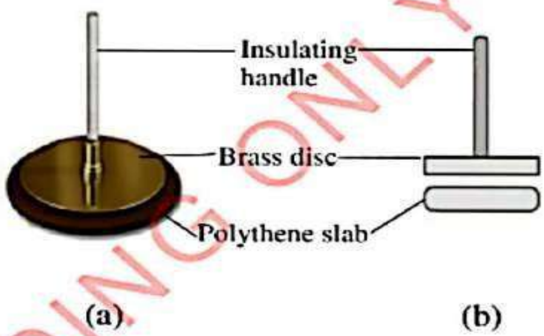


Figure 1.18: *Structure of electrophorus*

Mode of action of an electrophorus

An electrophorus works by electrostatic induction. It can be used to generate positive charges from a single negative charge. The polythene slab is first negatively charged by rubbing it vigorously with fur. The brass disc is then placed on it, as shown in Figure 1.19 (a). Since the surfaces are only in contact at relatively few points, a positive charge is induced on the lower surface of the brass disc, and a corresponding negative charge is produced on its top surface. The top of the brass disc is then touched briefly using a wire that touches the ground, thereby carrying away the negative charges to the earth, as shown in Figure 1.19 (b). This is known as earthing.

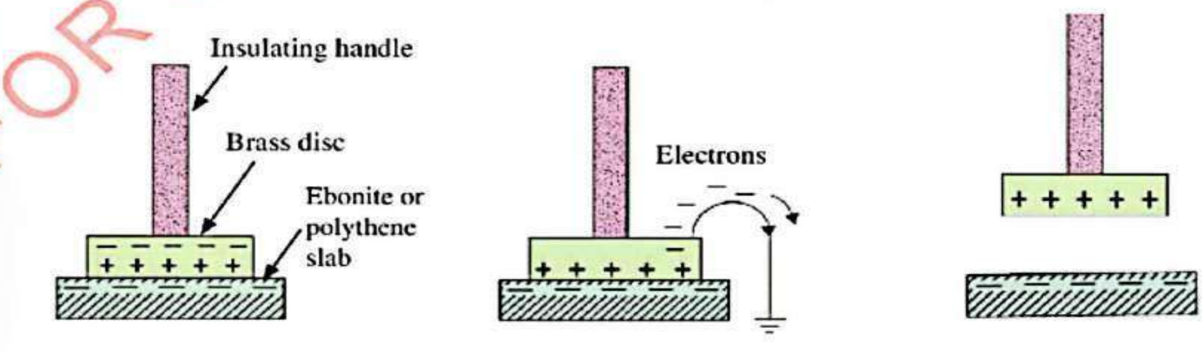


Figure 1.19: *Action of the electrophorus*

This process leaves a net positive charge on the brass disc after separation, as seen in Figure 1.19 (c). The electric force between the brass disc and the polythene base is fairly strong, so some mechanical work has to be done to overcome it. The top of the disc can be repeatedly charged in the same way. In principle, an unlimited amount of induced charge can be obtained from a single charge, but the insulated disc slowly discharges to the surroundings. An electrophorus can be used to charge an electroscope through contact and induction.

Task 1.1

Construct an electrophorus using materials such as a metal tray, a foam or rubber disk, and an insulating handle. After assembling the electrophorus, use it to demonstrate the charging process by induction.

Charging and discharging a leaf electroscope

A leaf electroscope can be charged or discharged either by contact or by induction. If a charged object touches the metal cap, the metal leaf diverges from the plate. This is because the same charge has been conducted through the metal cap and the metal rod to the metal plate and the leaf. This makes them repel each other, and thus, the leaf diverges from the plate. This is charging by contact.

If you touch the brass cap with a conducting wire that touches the ground, the charge is transferred through the wire to the earth, and the leaf of the electroscope then collapses back. If the electroscope is brought near a charged object without touching it, the leaf also diverges from the plate. This is because charges on the metal cap with the same charge as the object are repelled to the leaf. This is charging by induction.

Charging the electroscope by contact

Charging by contact takes place when contact is made between a neutral electroscope and a charged object. If a positive or negatively charged object is brought into contact with the brass cap of the neutral electroscope, the leaf diverges. The neutral electroscope becomes charged when contacted by the charged object. An electroscope that becomes charged by contact always gets the same type of charge as the object used to charge it.

Activity 1.7

Aim: To charge a leaf electroscope by contact

Materials: charged ebonite rod, electroscope, silk cloth, glass rod

Procedure

1. Place the electroscope on a table and discharge it by earthing.
2. Bring the charged ebonite rod in contact with the brass cap of the electroscope as shown in Figure 1.20.

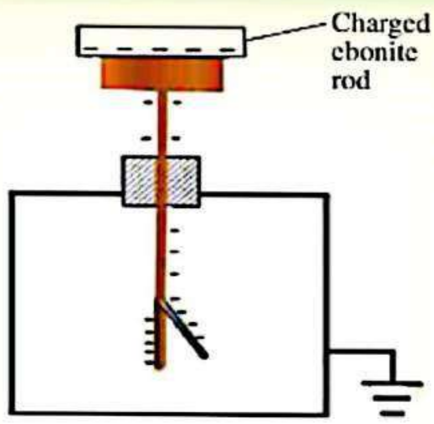


Figure 1.20

3. Observe the leaf of the electroscope.

   Note: If the leaf does not stay diverged, bring the charged ebonite rod in contact with a brass cap of the electroscope until the leaf stays diverged.
4. Remove the charged ebonite rod from the brass cap of the electroscope and observe what happens to the leaf of the electroscope.
5. Charge the glass rod by rubbing it with a silk cloth.
6. Bring the charged glass rod close (not touching) to the brass cap of the electroscope. Note your observations.

Questions

(a) Explain your observation.

(b) Why does the leaf collapse when a glass rod is brought near the cap?

When the negatively charged rod is brought into contact with the electroscope, the latter gets charged and the leaf diverges. It acquires a negative charge. The charge on the electroscope can be determined by testing using the charged glass rod. When a positively charged glass rod is brought near the brass cap, positive charges on the cap are repelled towards the brass plate. Therefore, the plate becomes positively charged. This causes the leaf to collapse, as shown in Figure 1.21.

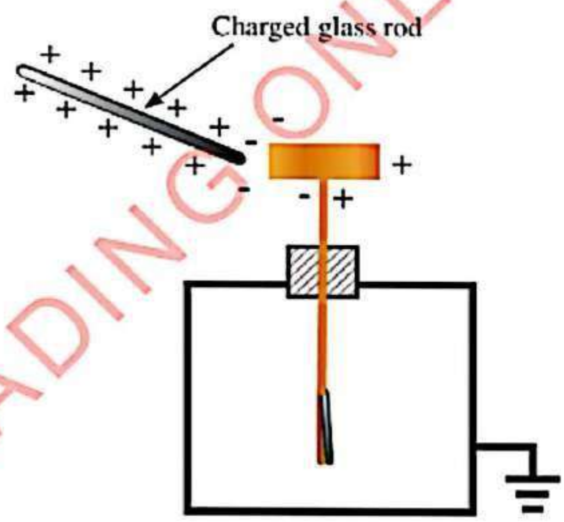


Figure 1.21: *Testing a charged electroscope by using a charged glass rod*

Charging an electroscope by induction

Having learnt how to charge an object by induction, the same method can be applied to charge a leaf electroscope. In this process, a positively charged electrophorus is advised.

Activity 1.8

Aim: To charge an electroscope by induction using a positively charged electrophorus

Materials: electrophorus, glass rod, ebonite rod, silk cloth or fur, leaf electroscope

Procedure

1. Place the electroscope on a table and discharge it by touching it with an earthed wire.
2. Charge the electrophorus by induction.
3. Hold the charged electrophorus close to the cap of the electroscope.
4. Earth the electroscope momentarily, as shown in Figure 1.22

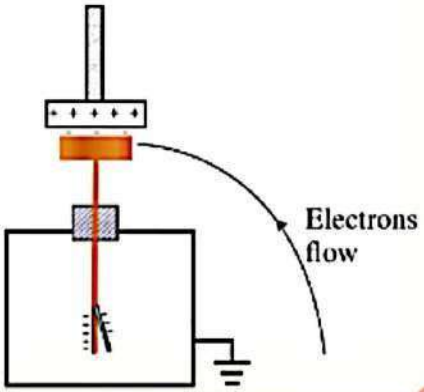


Figure 1.22

5. Remove the electrophorus and observe the leaf of the electroscope.
6. Test for charges on the electroscope using charged rods of glass and ebonite.

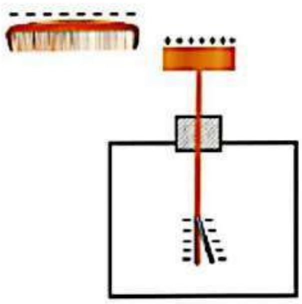
Questions

What charge does the electroscope acquire?

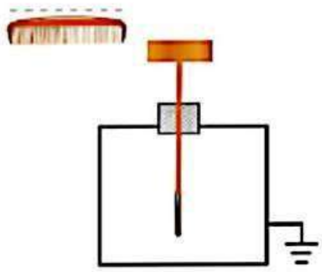
When the electroscope is charged this way, it acquires a negative charge. The charged glass rod, therefore, causes a collapse of the leaf, while a charged ebonite rod causes further leaf divergence. Recall, the glass is positively charged while ebonite is negatively charged after being rubbed with silk and cloth, respectively.

Discharging a leaf electroscope

Having charged a leaf electroscope by either contact or induction, the same can be effectively discharged through induction. If a negatively charged object is brought near the brass cap of a positively charged electroscope, electrons in the brass cap are repelled and move down to the leaf, as shown in Figure 1.23 (a). When a positively charged electroscope is earthed by a wire, the excess electrons flow from the electroscope to the earth, causing the electroscope leaf to collapse, causing it to discharge. This cancels the positive charges. With no net charge, the leaf collapses back to the plate, and the electroscope becomes discharged, as shown in Figure 1.23(b).



(a) Discharging by induction



(b) Discharged by induction

Figure 1.23: *Electroscope discharged by induction*

Similarly, when a negatively charged electroscope is earthed by a wire, the excess electrons flow from the electroscope to the earth, causing the electroscope leaf to collapse, causing it to discharge.

Activity 1.9

Aim: To investigate the charging and discharging of a leaf electroscope by induction

Materials: leaf electroscope, a piece of cotton cloth, a glass rod

Procedure

1. Rub a glass rod with a piece of cotton cloth.
2. Bring the rod near but not touching the brass cap of the electroscope.
3. Record your observations.
4. With the rod still near the cap, touch the cap with an earthed wire.
5. Note what happens.
6. Remove the rod.
7. Now rub the glass rod with a piece of wool, causing the rod to become positively charged.
8. Bring the positively charged glass rod near but not touching the brass cap of the electroscope.
9. Remove the glass rod.

Questions

(a) What happened to the electroscope? Why?

(b) Which type of charge is on the leaf of the electroscope?

Task 1.2

Use rubbing and direct contact techniques to charge and discharge an electroscope, then analyse and share your findings with peers.

Application of the electroscope

Applications of an electroscope include:

1. **Testing for the sign of charge on a body**

   The leaf divergence increases when a negatively charged ebonite rod is brought near a negatively charged leaf electroscope. Introducing a material of unknown charge near the cap will cause the leaves to collapse if it is positively charged. To test for a negative charge, the electroscope must first be positively charged; if the leaves collapse, the material is negatively charged. However, a decrease in divergence can also occur with uncharged objects, so an increase in divergence is the sure test for charge presence.

Table 1.2: *Charges and their effects on the leaf electroscope*

Charge on the electroscope	A charge is brought near the cap	Effects on leaf divergence
+	+	increase
-	-	increase
+	-	decrease
+ or -	uncharged body	decrease

2. **Identifying the insulating properties of materials**

   An electroscope that is positively charged can be used to test for the insulating properties of materials. If the material that is placed near the cap of an electroscope is a conductor, then the metal leaf collapses. If the material being tested is an insulator, the leaf electroscope retains its charge, and the leaf remains raised.

3. **Detecting the presence of charge on a body**

   When a charge is induced on the leaf electroscope by a charged body, the leaf diverges. When the charged body is removed, the leaf collapses, indicating that the induced charge on the electroscope is temporary and due to the charged body.

Electrostatic potential

You have learnt that like charges repel each other, and unlike charges attract each other. Therefore, work must be done to overcome the repulsive force in moving a positive charge towards another positive charge. Likewise, work is done to overcome the attractive force to move a negative charge away from a positive charge. The above processes apply to all points in the region surrounding any charges. This means an electrostatic force field around a charge exists. The work required to move a unit charge from a reference point to a specific point against the electrostatic force field of another charge is called *the electrostatic potential* at the specific point. Therefore, there is a difference in electrostatic potential between any two points in the electrostatic force field.

Potential of a charged body

A charged body is considered to be at a positive potential if, upon grounding, electrons flow from the earth to the body. Similarly, if electrons move from the body to the earth upon contact, the body is at a negative potential. This electron flow continues until the body's potential matches that of the Earth, which is defined as zero potential as indicated in Figure 1.24. Therefore, any grounded conductor is considered to be at zero potential by definition.

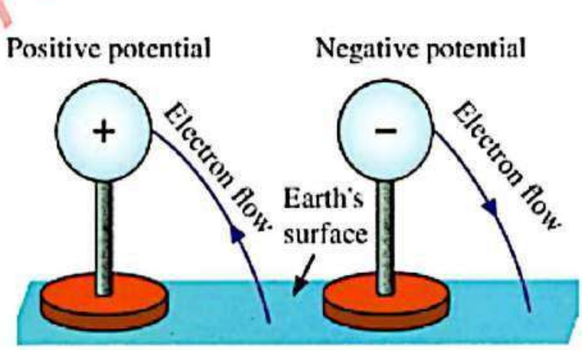


Figure 1.24: *Flow of electrons to and from the body and the Earth*

Potential difference (p.d.) refers to the work required to move a charge between two points with different electric potentials, measured in volts (V). The volt is named after the Italian physicist Alessandro Volta, where one volt equals one joule of work per coulomb of charge. In a leaf electroscope, leaf divergence occurs due to this potential difference between the leaf and the cap. When a negatively charged conductor is grounded, negative charges flow from it to the earth. Equally, a positively charged conductor can gain electrons from the ground, driven by the potential difference. If a wire connects two conductors at different potentials, electrons will flow between them until they reach the same potential, resulting in equal average potential energy for the free electrons in both conductors. Typically, electrons move from areas of low potential to high potential as shown in Figure 1.25.

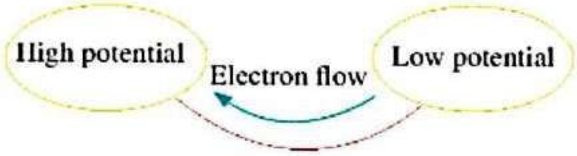


Figure 1.25: *Flow of electrons*

Exercise 1.1

1. Explain why:
   (a) Nylon clothes crackle as you undress.
   (b) Petrol road tankers usually have a long metal chain that hangs down and touches the ground.
   (c) Some clothes tend to cling to the body of a person.
   (d) It is possible for an air passenger to get an electrical shock when the passenger touches the knob of the toilet door in a high-altitude flying aeroplane.
2. Children playing with a plastic comb and some pieces of paper notice that the paper pieces are attracted to the comb after it has been rubbed through their hair.
   (a) Explain the concept of charge transfer in this scenario.
   (b) How does the interaction between the comb, hair, and paper illustrate the principles of static electricity?
3. (a) Why do TV screens become dusty after a while? Discuss.
   (b) Explain any two applications of electrostatics and hazards of electrostatics
4. If you are given two metal spheres standing on insulator stands and a positively charged rod, explain how you can charge the two metal spheres with equal and opposite charges by induction.
5. (a) How can a charged leaf electroscope be neutralised?
   (b) An object with an unknown charge is brought close to the electroscope. The leaves of the electroscope come closer together. Does the object have a positive or a negative charge? Explain.

Capacitors

A capacitor is a device used to store electric charge. It consists of two electrically conductive plates separated by an insulator material. The shape of a capacitor can be square, circular, rectangular, or cylindrical. Insulators can be ceramic, plastic film, air, paper, mica, or liquid gel. The insulating material between the conductive plates is called a *dielectric* material. When a power source is connected across plates, one plate is *charged negatively, and the other plate positively. The charge continues to accumulate on the plates with time until the capacitor is fully charged. Figure 1.26 (a) shows a capacitor, (b) its structure and (c) its circuit symbol.*

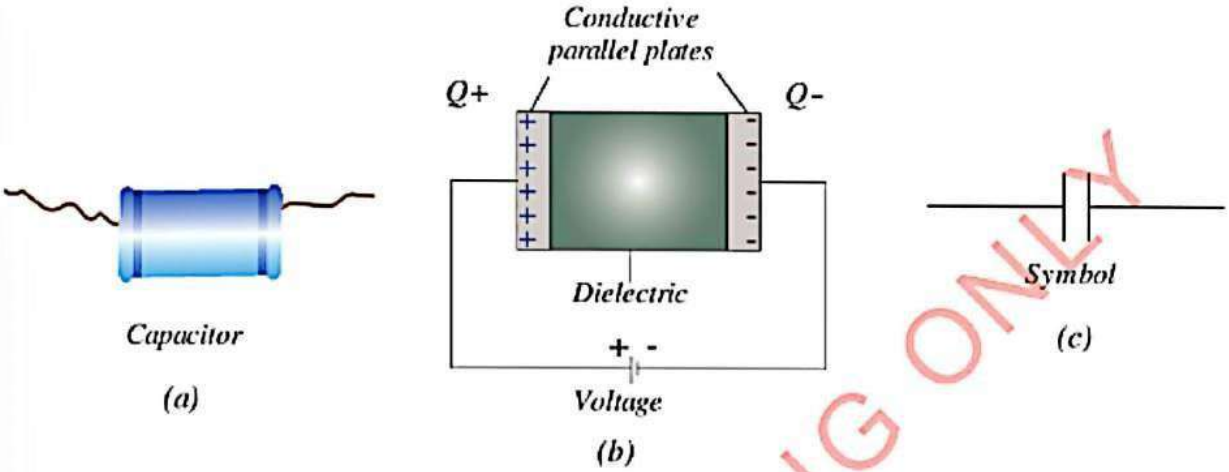


Figure 1.26: ***Capacitor and its symbol***

Capacitors are used as parts of electrical circuits in many common electrical devices. They store energy in the electrostatic field created by the electric *charges on their plates. Consider electric devices* like the radio or stereo system; the power lamp fades out slowly when power is switched off. On the other *hand, the stereo system has its sound playing for* some seconds after the power is switched off. This is *because capacitors store electrical energy, and, as a result, the electronic appliances then continue being supplied with it. Capacitors are used in computers, televisions and other electronic circuits. Figure 1.27 shows mounted capacitors in a radio circuit board.*

Figure 1.27: ***Capacitors in a radio circuit board***

A fully charged capacitor has a positive charge on one plate and an equal amount of negative charge on the other. The potential difference *between the capacitor plates is measured by connecting a voltmeter across them.*

Capacitance

When more charges are added to the capacitor, the value of its positive and negative potential rises. Why does this happen? The reason *is that the increased charge repels any incoming charge more strongly than before. Thus, more work has to be done to increase the charge on the capacitor. A measure of the amount of charge the capacitor (or any conductor)* can hold for a given potential difference is called **capacitance, C**. If Q is the charge stored by a capacitor, then:

$$\text{Capacitance, } C = \frac{\text{Amount of charge stored by a capacitor, Q}}{\text{Potential difference between plates, V}}$$

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

Since $Q \propto V$, the ratio of $\frac{Q}{V}$ is constant for a given capacitor. Also, $Q = CV$.

The SI unit of capacitance, **C**, is the farad, F. Normally, the value of C is a very small number; therefore, the millifarad (mF), microfarad (μF), nano farad (nF), and picofarad (pF) are also used, where:

$$1\text{ mF} = 10^{-3}\text{ F};\ 1\text{ μF} = 10^{-6}\text{ F};\ 1\text{ nF} = 10^{-9}\text{ F and } 1\text{ pF} = 10^{-12}\text{ F}$$

A farad is defined as the capacitance of a capacitor when a charge of one coulomb changes its potential difference by one volt.

One farad is the capacitance of a very large capacitor. In real-world applications, radio receivers usually measure capacitance in microfarads, while modern electronic circuits, such those found in hi-fi systems, often measure capacitance in picofarads.

Example 1.2

A capacitor with a capacitance of 200 μF is being charged, and the potential difference across its plates is 10 V. What is the amount of charge accumulated on its plates?

Solution

Given, p.d = 10 V,
capacitance = 200 μF

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

$$Q = CV$$

but, $C = 200\text{ μF} = 200 \times 10^{-6}\text{ F}$
$= 2 \times 10^{-4}\text{ F}$

Therefore, $Q = 2 \times 10^{-4}\text{ F} \times 10\text{ V}$
$= 2 \times 10^{-3}\text{ C}$
$= 2\text{ mC}$

Therefore, one plate has a charge of -2 mC, and the other has $+2$ mC.

Exercise 1.2

1. A capacitor with a capacitance of 50 pF is charged to 30 V. What is the charge on its plates?
2. A parallel-plate capacitor is connected to a battery and fully charged. While still connected to

the battery, a dielectric material is carefully inserted between the plates. How would the capacitance be affected? Justify your answer.

3. A capacitor of capacitance 3 μF stores a total charge of 3.6×10^{-5}C. Calculate the potential difference (voltage) across the capacitor.
4. If a cell with a voltage of 1.5 V is used to charge a capacitor, calculate the capacitor's capacitance when the charge is 90 C.

Types of capacitors

Different types of capacitors depend on the dielectric materials used to make them. These include the following:

1. Paper or plastic capacitors

A paper or plastic capacitor has metal foil strips as its conductor plates. Waxed paper or plastic forms the insulating material. Polyester film can also be used as a separating or insulating material. See Figure 1.28. Insulating materials are rolled up and sealed inside a metal box to prevent moisture from entering, which could reduce the insulation.

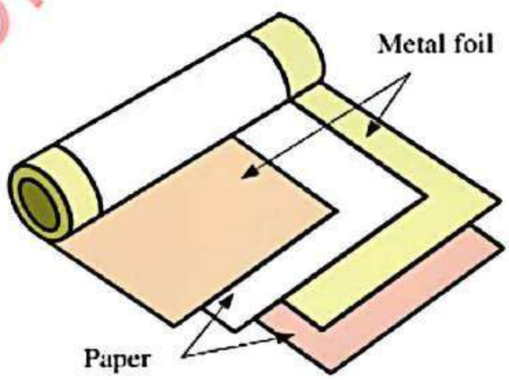


Figure 1.28: *Paper capacitor*

2. Mica capacitor

Note that any arrangement of two conductors separated from one another by an insulator forms a capacitor. In an ordinary laboratory, this could be two sheets of metal foil isolated by small pieces of plastic in between, with air as the insulating material. In a mica capacitor, the sheets of metal foil are separated by strips of mica, as shown in Figure 1.29. Mica is preferred because it is a natural mineral and splits easily into very thin sheets.

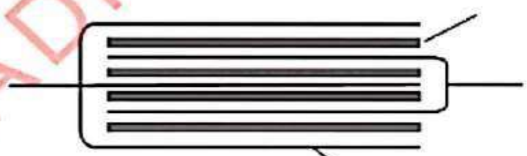


Figure 1.29: *Mica capacitor*

3. Electrolytic capacitor

Metal sheets are separated by paper previously soaked in a chemical compound (Figure 1.30). The soaked paper is not an insulating material. As the capacitor charges, a thin layer of aluminium oxide is formed on the positive plate, thereby providing a thin insulating layer between the plates. The thinner the layer, the higher the capacitance. Electrolytic capacitors are connected with great care. Their ends are labelled positive or negative as a safety precaution because a wrong connection can lead to an explosion.

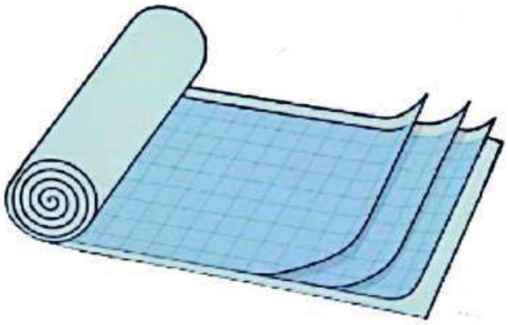


Figure 1.30: *Electrolytic capacitor*

4. **Air-filled capacitors**

In an air-filled capacitor, air forms the insulating material (Figure 1.31). The capacitance of such devices is altered by changing the overlapping area between the plates.

Figure 1.31: *Air-filled capacitor*

An air-filled capacitor is a good example of a variable capacitor. The semicircular plates are separated by air. Variable capacitors are mainly used for tuning radio sets. One set of plates is fixed, while the other one can be rotated using a knob. Rotation changes the area of the plates. Generally, the capacitor whose capacitance can be varied is termed a variable capacitor. On the other hand, the capacitor whose capacitance cannot be changed is a fixed capacitor.

Charging a capacitor

Consider the circuit in Figure 1.32 for charging a capacitor.

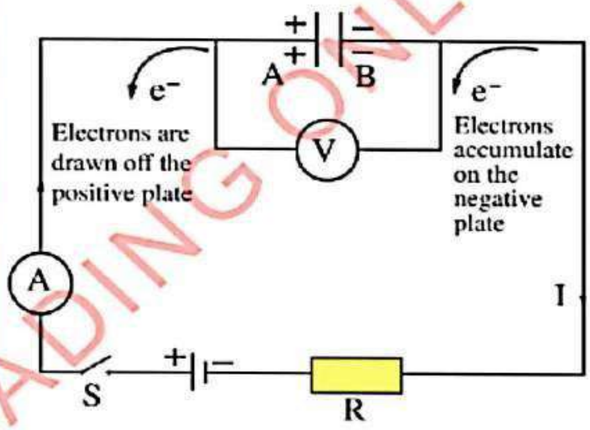


Figure 1.32: *Charging a capacitor*

An uncharged capacitor has no potential difference between its plates. It does not prevent the current from arriving at one plate or leaving the other. This is because the initial current in the circuit is determined only by the resistance of the connecting wires. Due to the presence of insulation between the capacitor plates, electrons tend to accumulate on the plate connected to the negative terminal of the charging cell. This is partly due to the attraction of the positive side of the cell or repulsion from the nearby negative charge. Current flows until the p.d across the capacitor is equal to the voltage of the charging cells. Charging of the capacitor then stops. Figure 1.33 shows a graph of charge against time for a charging capacitor.

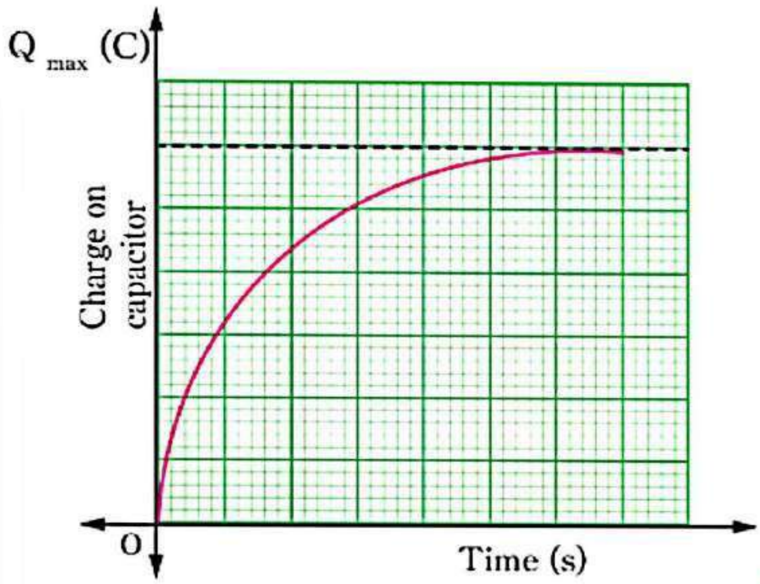


Figure 1.33: *Graph of the charge against time for a charging capacitor*

The resistance, *R*, controls the current in the circuit.

$$\textit{Initial charging current} = \frac{\textit{Potential difference across the cell}}{\textit{Resistance in the cell}}$$

The gradient of the charging curve gives the current. Therefore, the initial current is the gradient of the graph at the origin (time = 0).

Activity 1.10

Aim: To demonstrate the charging of a capacitor

Materials: a cell, an uncharged capacitor, a high-resistance voltmeter, a resistor, a switch, connecting wires and an ammeter

Procedure

1. Connect the circuit as in Figure 1.32, keeping the switch open.
2. Close the switch and then record the values of current at different time intervals.
3. Tabulate your results as follows:

Time (s)	0	20	30	40	50	60	70	80	90
Current (mA)									

Questions

(a) Plot a graph of current against time.

(b) What does the area under the graph represent?

The area under the current (I) versus time (t) graph represents the charge (Q). When a cell is connected to a circuit, electrons flow accumulating on the plate connected to the negative terminal, while the opposite plate experiences less accumulation due to attraction from the positive terminal. Charging continues until the potential difference (p.d.) between the plates equals the total potential difference across the cell, at which point the current drops to zero. The capacitor stores equal but opposite charges, $+Q$ and $-Q$, on its plates.

Discharging a capacitor

Theoretically, an isolated but charged capacitor should hold its charge indefinitely. However, due to leakage between the plates, the capacitor is eventually discharged. A capacitor can also be discharged by connecting its plates to a resistor. Figure 1.34 shows a circuit used for discharging a capacitor.

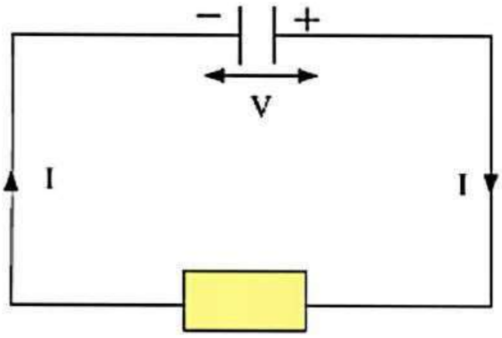


Figure 1.34: *Discharging a capacitor*

Figure 1.35 shows a graph of charge against time for a discharging capacitor.

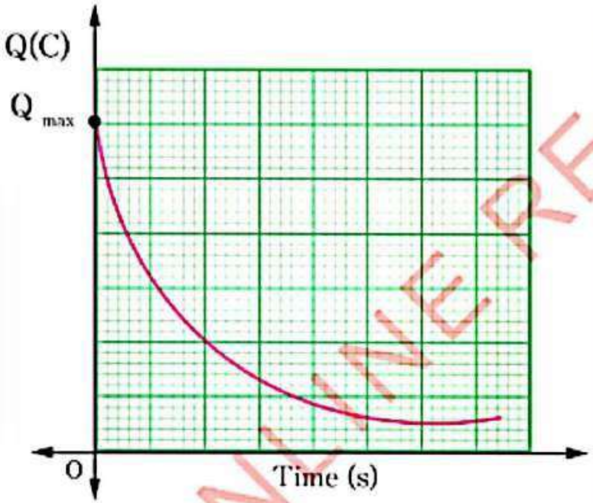


Figure1.35: *Graph of discharging a capacitor*

At $t = 0$, $Q = Q_{max}$

A graph of the charge against time gives an exponential decay curve. The gradient of the curve gives the discharging current.

$$Discharging\ current = \frac{Charge}{Time}$$

$$I = \frac{Q}{t}$$

But, $Q = CV$

Therefore,

$$I = \frac{CV}{t}$$

Construction of an air-filled capacitor

Project 1.2

In groups, construct an air-filled capacitor. Note that any arrangement of two parallel conductors, such as metal plates placed close together but at a suitable fixed distance, makes up a capacitor. When air forms the insulating medium between the plates, the dielectric here is air.

Combination of capacitors

Capacitors have voltage ratings that should not be exceeded. Continuous charging using a large voltage can result in an explosion, as the potential difference between the plates can break the insulation. To adjust the voltage rating and capacitance, capacitors are connected either in series or in parallel in a circuit.

Capacitors in series

Figure 1.36 shows a series connection of capacitors, where C_1, C_2, and C_3 are respective capacitances.

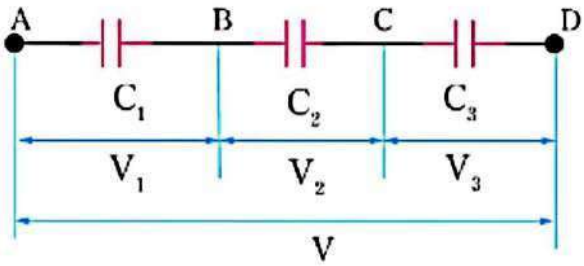


Figure 1.36: *Capacitors in series*

If V_1, V_2, and V_3 are potential differences are developed between the various plates, then the total potential difference, V, across AD is:

$$V = V_1 + V_2 + V_3 \qquad (1)$$

When capacitors are in series, there is an equal distribution of charge on the plates. Charge Q on C_1 is transferred to C_2 and C_3 by induction. Then,

$$V_1 = \frac{Q}{C_1},\ V_2 = \frac{Q}{C_2},\ \text{and}\ V_3 = \frac{Q}{C_3}$$

Substituting V_1, V_2, and V_3 into equation (1), you get;

$$V = \frac{Q}{C_1} + \frac{Q}{C_2} + \frac{Q}{C_3} \qquad (2)$$

$$V = Q\left(\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}\right) \text{ but, } V = \frac{Q}{C}$$

Where C is the combined or equivalent capacitance.

Then, $\frac{Q}{C} = Q\left(\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}\right)$,

Simplifies to:

$$\frac{1}{C} = \left(\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}\right) \qquad (3)$$

Therefore, Equation (3) is used to calculate the total capacitance of the three capacitors connected in series.

Thus, if two capacitors are in series, then their total capacitance, C, can be obtained using equation (3) as follows:

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2}$$

$$C = \frac{C_1 C_2}{C_1 + C_2}$$

Example 1.3

Three capacitors, labeled A, B, and C, have capacitances of 10 μF, 20 μF, and 30 μF, respectively, and are connected in series. Find the value of a single capacitor that could replace them.

Solution

Use the formula for capacitors in series.

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

$$\frac{1}{C} = \frac{1}{10\ \mu\text{F}} + \frac{1}{20\ \mu\text{F}} + \frac{1}{30\ \mu\text{F}}$$

$$= \frac{6+3+2}{60\ \mu\text{F}} = \frac{11}{60\ \mu\text{F}}$$

$$C = \frac{60\ \mu\text{F}}{11} = 5.45\ \mu\text{F}$$

Therefore, the value of an equivalent single capacitor is 5.45 μF.

Capacitors in parallel

In a parallel arrangement, all capacitors have the same potential difference across them, as shown in Figure 1.37. However, the charges for all capacitors are different.

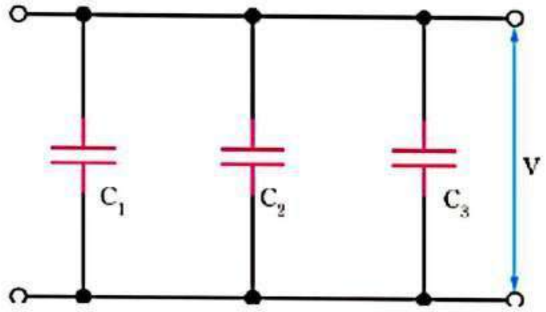


Figure 1.37: Capacitors in parallel

The total charge is given by,

$$Q = Q_1 + Q_2 + Q_3 \quad (4)$$

$$Q_1 = C_1V, \quad Q_2 = C_2V, \quad Q_3 = C_3V$$

Substituting Q_1, Q_2, and Q_3 into equation (4), you get;

$$Q = C_1V + C_2V + C_3V$$

But, $Q = CV$, where C is the total capacitance. Then,

$CV = C_1V + C_2V + C_3V$ which simplifies to:

$$C = C_1 + C_2 + C_3 \quad (5)$$

Therefore, equation (5) is used to calculate the total capacitance of the three capacitors connected in parallel.

Example 1.4

An electric circuit has two capacitors each with the capacitance of 20 μF. If they are connected in parallel to a cell. Calculate their total capacitance.

Solution

$$C_1 = C_2 = 20\ \mu F$$

Using Equation (5);

$$C_T = C_1 + C_2$$
$$= 20\ \mu F + 20\ \mu F$$
$$= 40\ \mu F$$

$$Q = C_1V + C_2V$$

$$C_T = C_1 + C_2$$

Therefore, their total capacitance is 40 μF.

Exercise 1.3

1. A 1 000 μF capacitor has been charged to a p.d of 25 V. What is the charge on the plate of the capacitor?
2. A capacitor of capacitance 250 μF is allowed to charge until the potential difference between its plates is 10 V. How much charge accumulates on the plates during the charging process?
3. What value of capacitor could be used to replace a set of 5 μF, 10 μF and 15 μF capacitors connected in series?
4. Three capacitors of values 2 μF, 3 μF and 6 μF respectively, are:
   (a) connected in series, and
   (b) connected in parallel.

   What is the equivalent capacitance in each case?

Factors affecting capacitance

The capacitance of a parallel plate capacitor is affected by three major factors, namely:

(a) area of the plates;
(b) insulating property of the medium; and
(c) distance between the plates.

(a) Area of the plates

An increase in the area of the plates causes a decrease in the potential difference between the plates, hence an increase in capacitance.

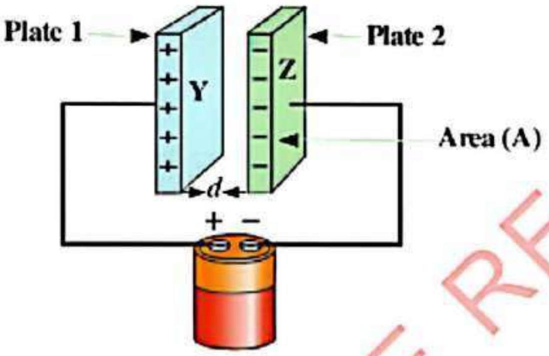


Figure 1.38: *Area of plates of a capacitor*

From experiments, $C \propto A$, where C is the capacitance, and A is the effective area between the plates Y and Z, as shown in Figure 1.38. A distance, d, separates the plates. If d is kept constant, and Z is moved parallel to Y, the overlapping area is varied.

(b) Insulating property of the medium

If the air between the plates of a capacitor is replaced with another insulating medium, such as glass, paper, or polythene, while the area A and the distance d remain constant, the capacitance increases. From experiments, capacitance C is directly proportional to the insulating property of the medium between plates Y and Z (Figure 1.39).

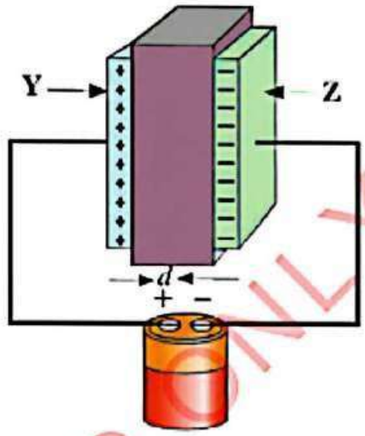


Figure 1.39: *Insulating property of materials*

(c) Distance between plates

A charged capacitor is connected such that one plate is earthed while the other is connected to an electroscope, as shown in Figure 1.40. The distance between the plates varies, and its effect on the leaf divergence is noted. It is observed that the closer the plates are to each other, the smaller the divergence and the lower the potential. In conclusion, capacitance increases with the closeness of the plates.

Thus, $C \propto \frac{1}{d}$, where C is the capacitance, and d is the distance between plates.

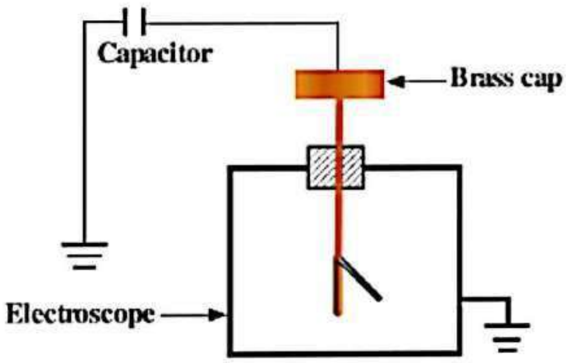


Figure 1.40: *Capacitor connected to an electroscope*

Charge distribution on a conductor

Induced charge resides on the surface of a conductor. Conductors appear in many different shapes, such as spherical, pear-shaped and cylindrical surfaces. Charge distribution on conductors depends on the shape of the conductor.

Charge distribution on the surface of a conductor

The distribution of charges on a conductor depends on the shape of the conductor. A proof plane and a gold-leaf electroscope can be employed to investigate this phenomenon. This is accomplished by successively pressing the proof plane against various regions of the surface of a conductor and then transferring the collected charge to the electroscope. The extent to which the leaves of the electroscope diverge provides a rough estimate of the amount of charge that has been transferred within a certain region, which, in turn, offers insight into the surface charge density of the conductor, as shown in Figure 1.41.

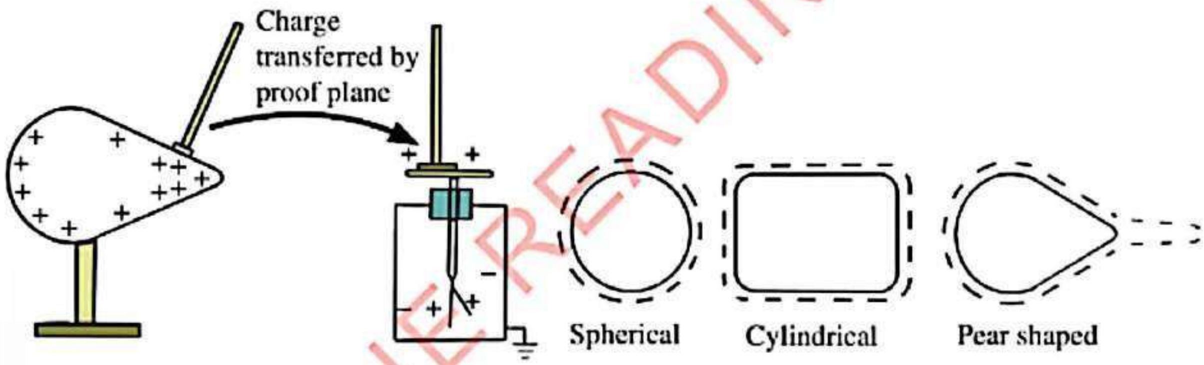


Figure 1.41: *Testing charge distribution according to the shape of the conductor*

The charge density of charged conductors of various shapes, such as spherical, cylindrical, and pear-shaped, can be tested. To examine the charge distribution on a conductor, carry out Activity 1.11.

Activity 1.11

Aim: To examine the distribution of charge through various conductors (pear, spherical, cylindrical and conical conductors

Materials: proof plane, leaf electroscope, aluminium foil, various conductors

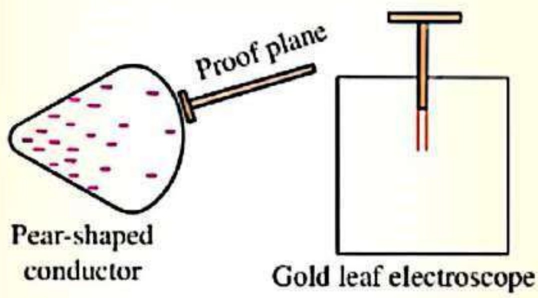


Figure 1.42

Procedure

1. Charge a pear-shaped conductor.
2. Using a proof plane, touch the flat side of the conductor

3. Hold up the proof plane to an electroscope and note minor deflections.
4. Touch the pointed side of the conductor with the proof plane
5. Hold up the proof plane to an electroscope and note the deflection

Questions

(a) What can you say about the deflection of the leaf in steps 3 and 5?

(b) Write a summary of your observation.

In a solid conductor, the electrons move apart when charges are gathered from various points on the conductor. The extent of this divergence is influenced by the quantity of charges collected at each location. As demonstrated in Activity 1.11, the leaf shows greater divergence when charges are drawn from a sharp point compared to the flat end of the object. Conversely, in a hollow conductor, charges collected from the exterior cause the leaf to diverge, while those collected from the interior show no divergence. This suggests that in any conductor, charges primarily exist on the outside rather than within the material.

Activity 1.12

Aim: Demonstrate where the charge resides

Materials: Proof plane, leaf electroscope, aluminium foil, hollow charged conductor

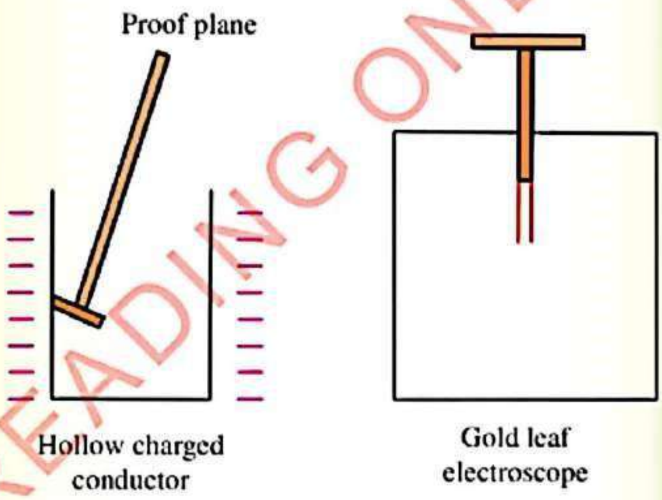


Figure 1.43

Procedure

1. Charge a hollow shaped conductor as shown in Figure 1.43.
2. Using proof plane, touch of the inside the conductor.
3. Hold up the proof plane to an electroscope and note the deflection.
4. Touch the outside of the conductor with the proof plane.
5. Hold up the proof plane to an electroscope and note the deflection.

Questions

(a) What can you say about the deflection of the leaf in step 3 and 5?

(b) Write a summary of your observations.

Task 1.3

Construct a proof plane using materials such as aluminium foil, a small piece of cardboard, and a wooden stick. Once constructed, use the proof plane in conjunction with a leaf electroscope to determine the sign of the charge on a charged object.

Lightning and thunderstorms

Lightning, a dramatic electrostatic phenomenon, results from charge separation within storm clouds. Ice crystals and water droplets collide, creating positive and negative charges that segregate. A stepped leader, an ionised air channel, descends from the cloud, meeting a positive charge rising from the ground. This interaction forms the return stroke, the visible lightning flash. The rapid heating of air by lightning causes its expansion, resulting in the sound waves we recognise as thunder. The process occurs in milliseconds.

Lightning is a large spark due to electrostatic discharge within a cloud, between two clouds or between a cloud and the ground. Interaction between updrafts and downdrafts in the cloud produces static charge by friction. The lower portion of the cloud becomes negatively charged, and the upper part is positively charged. The ground beneath the cloud can become positively charged by induction. Figure 1.44 shows positively and negatively charged clouds.

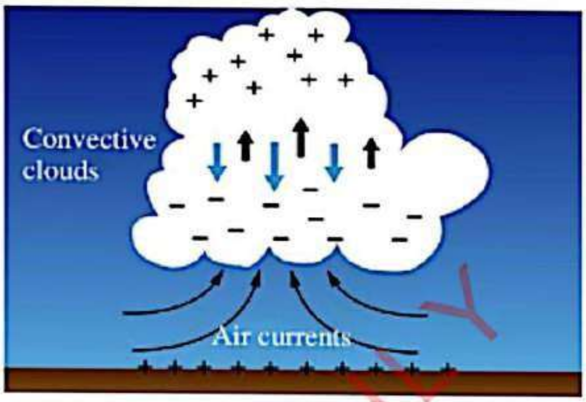


Figure 1.44: *Positively and negatively charged clouds*

As charge builds up beyond a certain limit, the insulating property of the medium between positive and negative charge centre breaks down. Hence, a large current suddenly passes, ionising the air molecules on its way, accompanied by the sudden expansion of the air. The ionisation of air results in the observed flash of light (lightning), as shown in Figure 1.45. Sudden expansion results in the booming sound (thunder) that is heard a few seconds after the flash is seen.

Figure1.45: *Lightning*

Thunderstorms are intense weather conditions characterised by lightning, heavy rain, and powerful winds.

The electrical current and heat generated by lightning can lead to significant damage to both property and lives. Lightning can reach temperatures of approximately 27,000 degrees Celsius. When lightning strikes, it creates a tunnel-like gap in the air known as a channel. Once the lightning disappears, this channel collapses, and the resulting sound from this collapse is what we hear as thunder.

Lightning protection

Lightning cannot be prevented, but protection against destruction is possible by using lightning conductors. A lightning conductor works because the charge concentrates more on sharp points, such as mountains, trees, and tall houses. These sharp points have a high density of earth charges, so they are liable to be struck by lightning.

Structure of the lightning conductor

The lightning conductor in Figure 1.46 is made of: a copper plate, a copper rod and copper spikes.

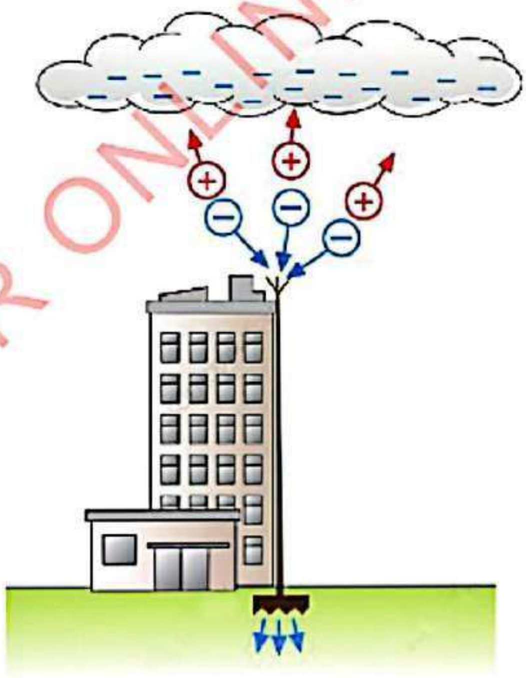


Figure 1.46: *Lightning conductor*

A lightning conductor, also known as a lightning rod, is a metal rod, typically made of copper, installed atop a structure to protect it from lightning strikes.

It offers a low-resistance path for the electrical current of a lightning strike to travel safely to the ground, thereby preventing damage to the building. This system usually comprises a copper wire connecting the rod to a grounding system, such as a deep underground copper earth pole. The lightning conductor should be taller than the house to be protected. When lightning strikes the conductor, electric charges flow along the wire and are dissipated to the ground, where they cause no harm and thereby protect the building.

Task 1.4

Examine Figure 1.47, then summarise your observations. Discuss with your colleagues for more understanding.

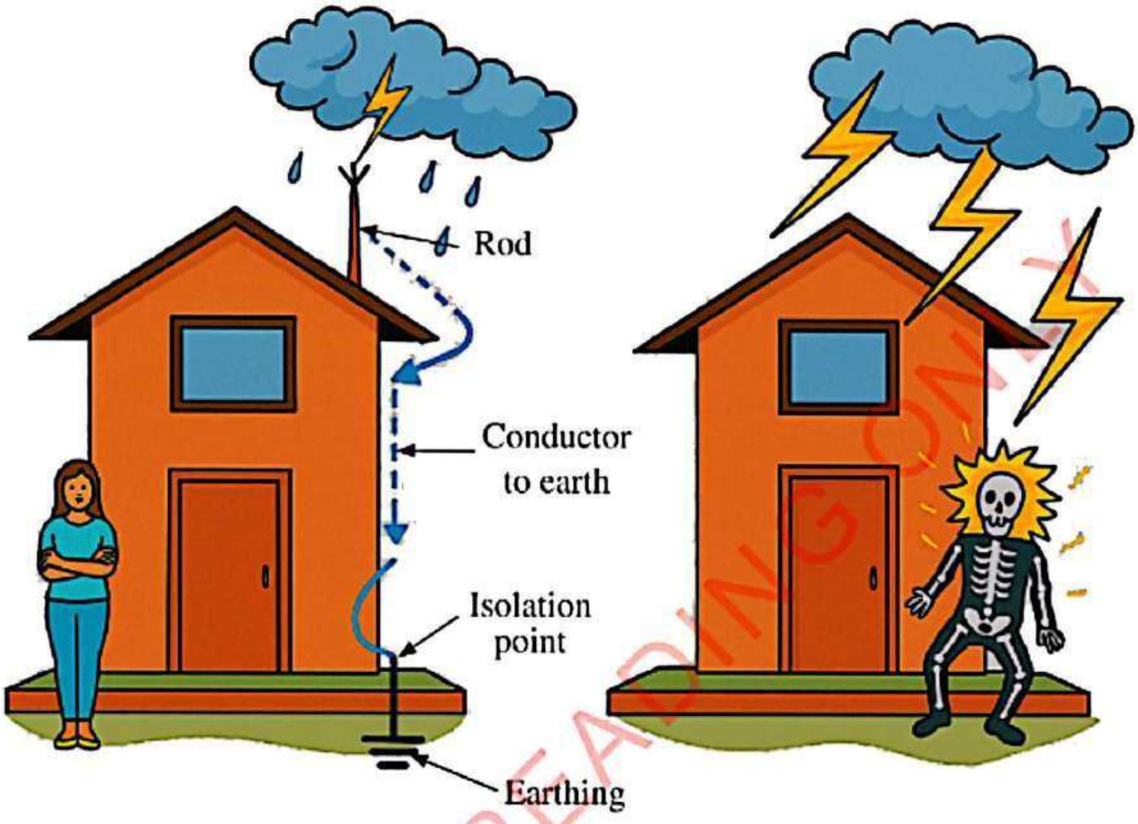


Figure 1.47

Mode of action of a lightning conductor

A negatively charged cloud passing overhead causes the sharp spikes of the conductor to become positively charged by induction. The acquired charge on the spikes is safely conducted to the ground; hence, no lightning occurs, and no harm is caused to the building.

Project 1.3

Study how lightning conductors are installed on buildings around you, then develop a simple lightning conductor for your Physics laboratory.

Task 1.5

Practical applications of static electricity

1. Use the Internet, your school, or your community library to find information about the practical applications of static electricity.
2. Research one useful effect of static electricity and one problem caused by static electricity.
3. Write a short paragraph explaining your research.

Chapter summary

1. Static electricity is the accumulation of excess electric charges in a region that does not conduct electricity, allowing the charge to remain in place.
2. Every atom contains a positively charged central part known as the nucleus, which attracts all the electrons firmly to itself. There are two types of charges: negative and positive charges.
3. An ebonite rod rubbed with fur becomes negatively charged. A glass rod rubbed with silk becomes positively charged.
4. The fundamental law of static electricity states that like charges repel, unlike charges attract.
5. Conductors are materials with electrons that flow freely from atom to atom. Any excess charge on a metallic conductor will distribute itself over the surface of the metal.
6. Insulators are materials that hinder the free flow of charge.
7. Excess charge on an insulator will remain in the location where it was introduced.
8. Capacitors are devices for storing charge. They are used in computers, radios and other electronics.
9. The SI unit of capacitance is the Farad.
10. Charge is normally concentrated on the sharp points of conductors.
11. Charges on a conductor will distribute themselves to reduce as much as possible the force of repulsion.
12. Hollow conductors have their excess electrostatic charge distributed on their outer surfaces.
13. Lightning is a large discharge of static electric charge within a cloud, between two clouds or between a cloud and the ground.

Revision Exercise 1

1. Choose the most correct answer in items (a) to (e).

   (a) Capacitors of 1 μF, 4 μF and 2 μF are connected in series. Calculate the capacitance that could replace them (equivalent capacitance).

   (i) $\frac{9}{4}\,\mu$F (ii) $\frac{4}{7}\,\mu$F

   (iii) $\frac{7}{4}\,\mu$F (iv) $\frac{7}{4}$ F

   (b) When a capacitor is charged and disconnected from a battery, what will happen to its charge and voltage if the distance between the plates is increased?

   (i) The charge will remain constant, but the voltage will increase.

   (ii) Both charge and voltage will decrease.

   (iii) The charge will decrease, but the voltage will remain constant.

(iv) The charge will remain constant, but the voltage will decrease.

(c) Object 1 is given a negative charge and placed on a beam balance. Object 2, which is also charged, is brought close to body 1, and the balance reading changes, as shown in Figure 1.47.

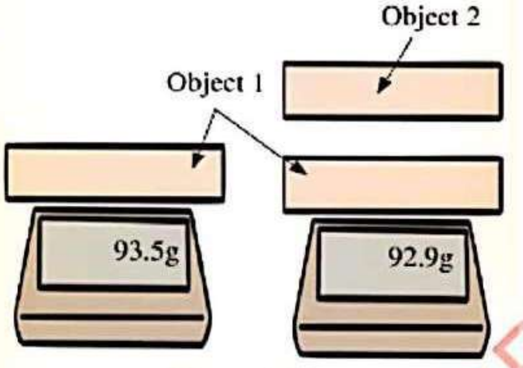


Figure 1.48

Which action would decrease the reading on the balance furthest?

(a) Adding the same number of electrons to both objects
(b) Remove the same number of electrons from the bodies
(c) Transfer electrons from body 1 to body 2
(d) Transfer of electrons from body 2 to body 1

(d) What should you do if you find yourself outdoors during a severe thunderstorm?

(a) take shelter under the nearest tree.
(b) stand under power lines.
(c) move to higher ground.
(d) hide in a ditch.

(e) A negatively charged metal rod is brought near side P of a neutral metal sphere PS. Which diagram in Figure 1.48 correctly shows the resulting charge distribution on the metal sphere?

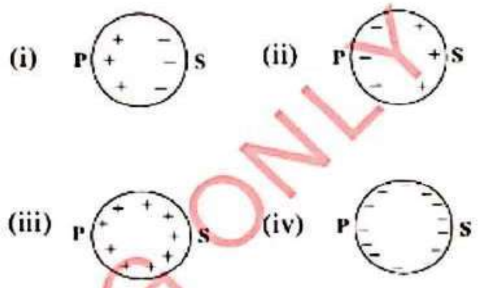
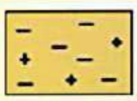
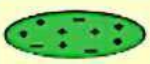


Figure 1.49

2. Match each item in **column A** against its corresponding item in **column B** by writing the correct response in the space provided.

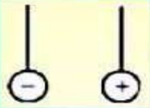
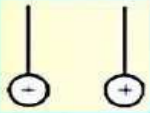
Column A	Answer	Column B
(a) Stores charge		(i) Repel
(b) $C=C_1+C_2$		(ii) Capacitor
(c) Glass		(iii) Metal cap
(d) Similar charges		(iv) Positive charge
(e) Detect charges		(v) Leaf electroscope
		(vi) Insulator
		(vii) Attract
		(viii) Capacitor in parallel
		(ix) Capacitor in series
		(x) Negative charges

3. (a) When a glass rod is rubbed with a piece of cloth, what type of charge does the glass rod acquire? Considering electron transfer, why does this happen?
   (b) Describe what happens when an ebonite (or plastic) rod is rubbed with fur. What charge does the rod gain, and why?
   (c) What happens when a charged electroscope is touched with a finger? What is the name of this process, and how does it work?
4. Identify those which could become negatively charged for each of the following pairs of materials being rubbed together.
   (a) Glass and silk
   (b) Fur and glass
   (c) Comb and hair
   (d) Fur and hard rubber
5. Complete the table by working out the overall charge on each object. Show your calculations. State whether the object is positively charged, negatively charged or neutral and why.

Object	Overall charge	Why is it positive, negative or neutral?
		
		
		

6. (a) The fundamental law of static electricity governs how charged objects behave. State this law, and provide at least one real-life example or experimental observation that demonstrates it.
   (b) Explain how a balloon rubbed against your hair can be attracted to small pieces of paper.
7. (a) Draw a well-labelled sketch of a gold-leaf electroscope.
   (b) How is the electroscope used for testing the types of charges?
8. If a metal rod is given a negative charge and brought near another neutral metal rod,
   (a) Will there be an electric force between them?
   (b) If there is a force, will it be attractive or repulsive? Why?
   (c) What could happen if the first rod were given a positive charge instead of a negative one?
9. Two rubber balloons are rubbed with hair; will the electric force between one of the balloons and the hair be attractive or repulsive? Or, will the electric force between the two balloons be attractive or repulsive? Explain.
10. State what happens in the following conditions:
   (a) An ebonite rod is rubbed with fur.
   (b) A negatively charged electroscope's cap is touched by a neutral glass rod.
   (c) A proof plane is inserted in a hollow sphere and tested for charge.

11. Look at the following images in the table. Redraw the images in the second column to show how the spheres will move because of the nature of the charges. Write an explanation in the last column.

Charged spheres	Draw how they will move	Explanation
		
		

12. (a) Why is lightning attracted to tall structures? Explain the factors that make certain objects more likely to be struck by lightning during a thunderstorm.
    (b) List and describe at least three types of capacitors, including their construction, properties, and typical applications.
    (c) Identify and explain the function of at least three household or industrial appliances that use capacitors

13. A capacitor of two parallel plates separated by air has a capacitance of 15 pF. A potential difference of 18 volts is applied across the plates.
    (a) Determine the charge on the capacitor.
    (b) If the space between is filled with mica, the capacitance now increases to 240 pF. How much more charge can be put on the capacitor using the 18 V supply?

14. A sharp needle was brought close to the cap of a charged leaf electroscope. Explain why the leaf collapsed.

15. (a) Determine the effective capacitance of the circuit shown in Figure 1.50.
    (b) How much charge is stored?

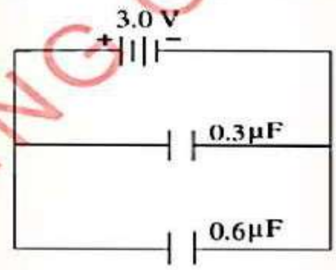


Figure 1.50

16. After walking on a carpeted floor, you sometimes get a mild electric shock when you touch a metal door knob. Explain how this happens.

17. The ruler Figure 1.51 has been rubbed with a cloth. Describe what is happening in itand why.

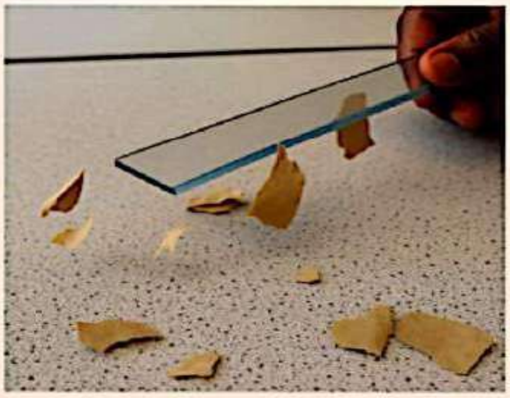


Figure 1.51

Chapter Two

Current electricity

Introduction

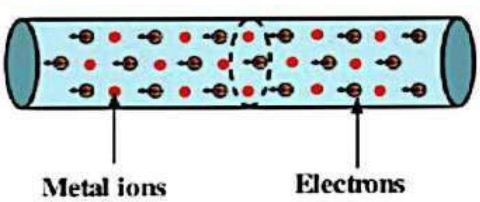
Current electricity is a fundamental aspect of engineering science that is crucial for designing, analysing, and enhancing electric circuits, electronic devices, and power systems in various technological fields. In this chapter, you will learn the concepts of current electricity, voltage, Ohm's law, electrical components, electrical energy and power. The competencies developed will enable you to design and make simple electric circuits for various applications. It will also enable you to utilise electrical appliances efficiently in various contexts.

Think

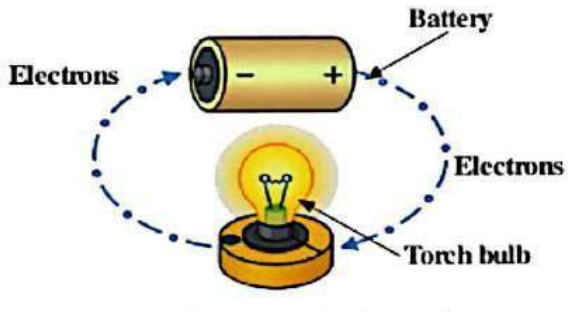
How would life on Earth be without electricity?

Concept of current electricity

A conductor, such as an electric wire (Figure 2.1(a)), contains charges (negative or positive); when these charges are compelled to move, they constitute an electric current. To initiate this movement, we must establish a potential difference across the conductor ends. Various methods have been utilised to create a potential difference; one employs a battery as shown in Figure 2.1 (b), while another involves connecting a charged capacitor. To ensure a steady flow of current, we must use a battery, as the capacitor discharges immediately once the current flows.



(a) Electric wire



(b) Simple conducting path

Figure 2.1: Flow of charges

Electric current (I) is defined as the rate of flow of electric charge (Q) through a conductor over time (t). This relationship is expressed mathematically as

$$I = \frac{charge(Q)}{time(t)}$$

But, $Q = ne$,

where n is the number of electrons and e is the charge of an electron.

Therefore,

$$I = \frac{ne}{t}$$

In simpler terms, current measures the amount of charge that passes a given point in a circuit per unit of time. This charge is carried by charged particles such as electrons or ions. A higher current indicates a greater flow of charge.

Example 2.1

Given that the charge of an electron is 1.6×10^{-19} C find the number of electrons that pass in one second through any cross-section of a conductor with a steady current of 1 ampere.

Solution

$$I = \frac{ne}{t}$$

$$n = \frac{It}{e} = \frac{1\ \text{A} \times 1\ \text{s}}{1.6 \times 10^{-19}\ \text{C}} = 6.25 \times 10^{18}$$

Therefore, the number of electrons is 6.25×10^{18}.

Electromotive force

The electromotive force (e.m.f) is the potential difference across the terminals of a source when no current is flowing. It provides the energy required to move electrons through a conductor, leading to an electric current. Note that the word "force" in this case does not mean the force of interaction between bodies. One may draw an analogy of e.m.f to water pressure. When the pressure is high, more water flows through a pipe. Similarly, with higher e.m.f, more electrons flow through a conductor. Sources of e.m.f include electrochemical cells such as dry cells and car batteries, thermoelectric devices, solar cells and electric generators. Labels of potential difference values written on a battery or cell refer to its e.m.f. Figure 2.2(a) shows a dry cell whose e.m.f is 1.5 V, and (b) a car battery whose e.m.f is 12 V.

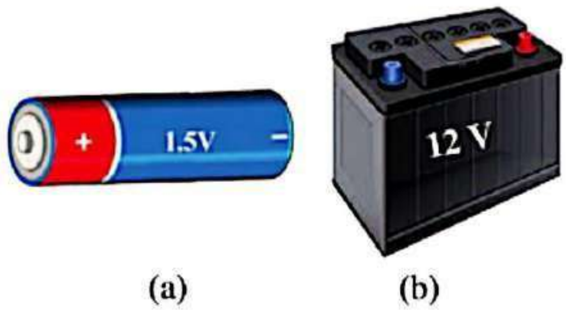


Figure 2.2: *A dry cell and a car battery*

Potential difference (p.d)

When an electric device such as a bulb is connected to a cell, electric current flows through the device, and some of the electrical energy is converted into light and heat. The amount of energy converted per unit charge equals the potential difference (p.d) across the device. Alternatively, electric potential difference (p.d) is the work done in moving a unit charge in a circuit from one point to another. Potential difference (p.d) is also called voltage.

$$p.d\,(V) = \frac{work\ done(W)}{charge(Q)}$$

Like the e.m.f., the SI unit for p.d is the volt (V). One volt is equivalent to one joule per coulomb. Figure 2.2 shows a circuit diagram with the dashed box indicating a region where the potential difference between two points of a resistor can be measured.

The difference between e.m.f. and p.d is that e.m.f is the potential difference across the cell terminals when no current flows or no load is connected. In contrast, p.d is measured when current flows through the circuit or when a load is connected. The load here refers to the resistance, R, of the electrical appliance connected to the source of e.m.f. Figure 2.3 shows a circuit with an e.m.f source and a resistor as a load.

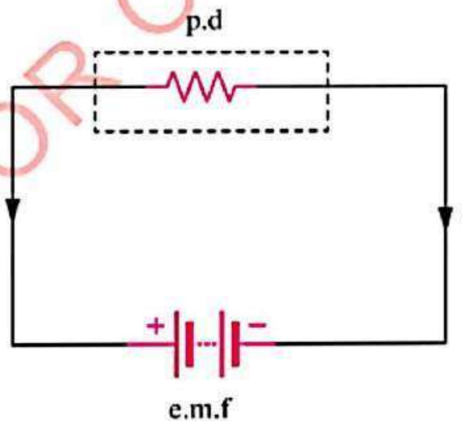


Figure 2.3: *Electromotive force (e.m.f) source and potential difference (p.d)*

Measurement of the e.m.f of a cell and the p.d across a conductor

The e.m.f. of a cell and p.d are measured using a high resistance device called a voltmeter. A voltmeter measures the difference in potential between two points. It is always connected in parallel with the cell or the load because the e.m.f. of a cell is compared to the p.d across the voltmeter's terminals. To measure e.m.f. and p.d, the positive terminal of the voltmeter is connected to the positive terminal of a cell, and the negative terminal of the voltmeter is connected to the negative terminal of the cell. Note: Measuring e.m.f by a voltmeter only provides an estimated value, since a small amount of current is drawn by the meter contrary to the requirement that no current is drawn for e.m.f measurement. Activity 2.1 will assist on understanding how one can measure of a cell and potential difference of a conductor.

Activity 2.1

Aim: To measure the e.m.f. of a cell and the potential difference of a conductor

Materials: dry cell (1.5 V), voltmeter, bulb, two switches, connecting wires

Procedure

1. Connect the circuit as shown in Figure 2.4.

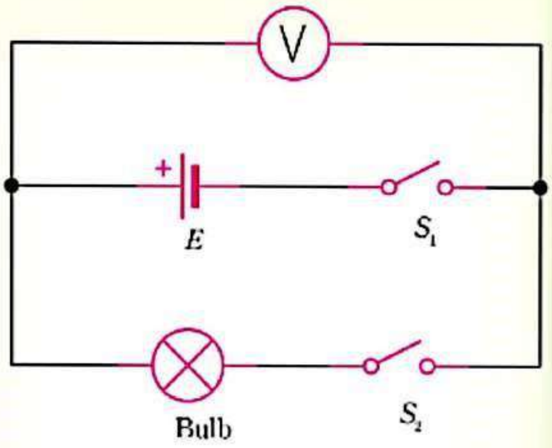


Figure 2.4

2. Close switch S_1, then note the voltmeter reading.
3. Close both switches (S_1 and S_2) and record the voltmeter reading.

Questions

(a) Compare the voltmeter reading when only S_1 is closed and when both S_1 and S_2 are closed. Explain your results.

(b) What is the e.m.f. of the cell?

(c) What is the potential difference across the bulb?

The voltmeter reading when the current flows through the bulb (when both switches are closed) is less than when no current flows through the bulb (only switch S1 is closed). When no current flows out of the cell or battery, the voltmeter reading is the cell's e.m.f. When both switches are closed and the current flows through the circuit, the voltmeter reading is the potential difference across the bulb.

Electric circuits and symbols

Circuit diagrams are visual representations of electrical circuits, using circuit symbols to represent electrical components and their connections. You can create these diagrams by placing components and connecting them with lines. These diagrams are crucial for understanding and building electrical circuits. Various IT tools, such as virtual labs and Smart Draw, may assist in developing the skills to construct an electric circuit.

Task 2.1

Draw a circuit with components A, B, C, and D as shown in Figure 2.5 using online interactive simulation software such as Phet simulation.

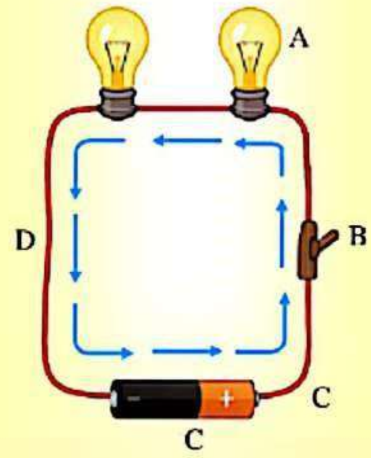


Figure 2.5

Principles for constructing an electric circuit

When drawing a circuit diagram, follow the following steps.

Voltmeter connection: A voltmeter must be connected in parallel with the component across which the voltage is being measured.

Ammeter connection: An ammeter, which measures current, is always connected in series with the circuit component(s) to ensure that the current flowing through the component(s) also flows through, and is measured by, the ammeter.

Components: For beginners, connect a single component, e.g., a resistor, bulb, in series with a source of e.m.f. However, depending on the requirement, if multiple components are used, they may be connected in parallel and/or series configurations, and then the system is connected in series with the source of e.m.f.

Other rules

1. Draw the circuit symbols first.
2. Using a ruler, draw all the connecting wires.
3. Make all the connecting wires and leads straight lines with corner angles of 90 degrees as shown in figure 2.6.
4. Do not cross any of the lines representing conducting wires.

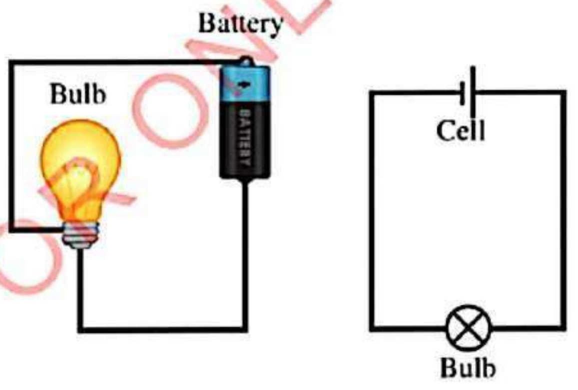
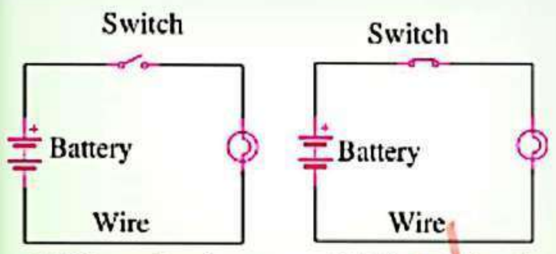


Figure 2.6: *Simple electric circuit*

Example 2.2

Draw an open and a closed electric circuit using a bulb, battery, switch and wire using the circuit symbols.

Solution



(a) Open circuit (b) Closed circuit

Figure 2.7

Resistance to an electric current

The flow of charge through a wire in a circuit can be compared to the flow of water through a pipe connecting two water reservoirs. Water flows through the pipe if there is a pressure difference between the two reservoirs. As it flows through a pipe, it loses energy due to friction between the moving water molecules and the pipe's inner walls. Similarly, electric charges will flow between two points of a conductor if one point has a higher electric potential than the other; that is, there is a potential difference. As charges flow in a material, they encounter numerous collisions with atoms, resulting in a resistance to the flow of charges. This is known as electrical resistance, denoted by the letter R. In other words, electrical resistance is the opposition to the flow of electrical current through a material.

Any material that offers low resistance to the current flow is termed a conductor. On the other hand, a material is said to be an insulator if it does not allow the flow of electric current through it. Some materials, known as semiconductors, have resistance between that of conductors and insulators. The SI unit of electrical resistance is the ohm, denoted by the symbol Ω. It is worth noting that electrical current loses its energy as it flows through a conductor.

Types of resistors

A resistor is an electrical component with two terminals used to restrict the flow of electric current in a circuit. That is, resistors control the magnitude of the current in a circuit in accordance with Ohm's law. There are two basic types of resistors depending on their applications and characteristics. These are fixed resistors and variable resistors.

Fixed resistors

The most commonly used type of resistor is the fixed resistor. A fixed resistor has a constant value of resistance. Applications of fixed resistors include protecting electrical components from excess current, dividing voltage in a circuit, and controlling the working of some circuits. In a circuit, the fixed resistor is represented by the symbols shown in Figure 2.8.

Figure 2.8: *Circuit symbols for fixed resistors*

Diverse resistor materials are used to fabricate fixed resistors. These materials influence the resistor's properties, such as tolerance and noise. Fixed resistors can be made of carbon, wound wire, metal oxide and metal films.

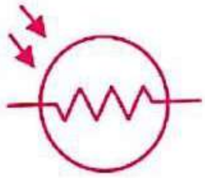
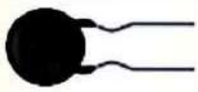
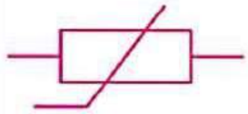
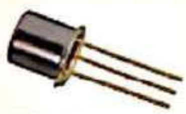
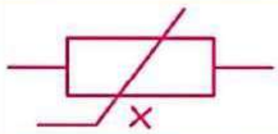
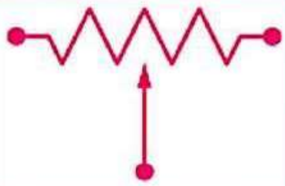
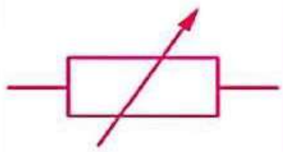
Task 2.2

Use library or online resources to outline characteristics, internal structure, and applications of carbon, wound wire, metal oxide and metal films resistors.

Variable resistors

These are resistors whose electric resistance can be adjusted (from zero to its maximum value) to suit the requirements of a circuit. Examples of variable resistors include rheostats, voltage dividers, thermistors, photoresistors and magneto-resistors. Some types of variable resistors and their circuit symbols are shown in Table 2.5.

Table 2.5: *Variable resistors and their symbols*

Appearance of a resistor	Symbol
 Photoresistor	
 Thermistor	
 Force resistor	
 Magneto-resistor	
 Potentiometer	
 Rheostat	

Equivalent resistors

Depending on the purpose, fixed resistors can be connected in either a parallel or a series configuration. The resultant resistance in the circuit is called total resistance, effective resistance, or equivalent resistance.

Resistors in series

When two or more resistors are connected end to end consecutively, and the same current flows through each resistor, such a connection is said to be a series connection. A single-loop circuit with series combination of resistors and a battery, is shown in Figure 2.9.

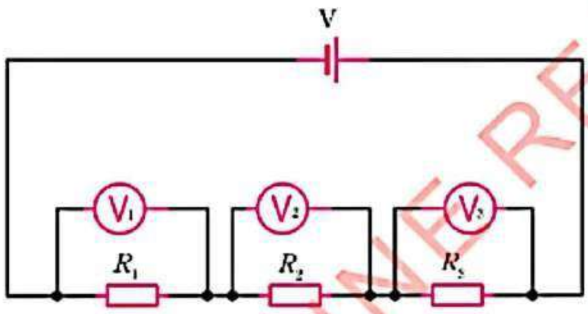


Figure 2.9: *A circuit with resistors connected in series*

The current flowing in the circuit is the same at all points. The sum of the potential difference across all the resistors equals the potential difference across the battery.

Therefore,

$$V = V_1 + V_2 + V_3$$

From Ohm's law, the current, I, in the circuit is given by,

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

where R_T is the total resistance, thus,

$$V = IR_T$$

$$IR_T = IR_1 + IR_2 + IR_3$$

$$IR_T = I(R_1 + R_2 + R_3)$$

$$R_T = R_1 + R_2 + R_3$$

When resistors are connected in series, the total resistance in the circuit is the sum of the individual resistances. Therefore, for n resistors connected in series, the total resistance is given by,

$$R_T = R_1 + R_2 + R_3 + ... + R_n$$

Note that when resistors are identical, the total resistance is given by $R_T = nR$, where R is the resistance of an individual resistor and n is the number of identical resistors.

Resistors in parallel

Resistors are said to be in parallel connection when two or more resistors are placed side by side with their corresponding ends joined together, such that the same p.d is applied to each resistor. Figure 2.10 shows a circuit with parallel connection of resistors and a battery.

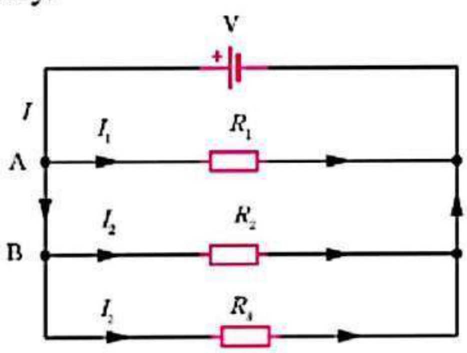


Figure 2.10: *A circuit with resistors connected in parallel*

When resistors are connected in parallel, the p.d. across each resistor is the same as the total voltage in the circuit. Though the voltage is the same for all branches, the currents flowing in each branch are different. Thus, Ohm's law can be applied in each branch. To find the different currents, one considers the current through each junction. The sum of the currents in each resistor in Figure 2.10 equals the total current in the circuit. That is,

$$I = I_1 + I_2 + I_3$$

From Ohm's law, the current, I, in the circuit is given by,

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

Where, R_T is the equivalent resistance.

Applying Ohm's law to each resistor gives:

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

$$\frac{V}{R_T} = V\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right)$$

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

When resistors are connected in parallel, the reciprocal of the total resistance is equal to the sum of the reciprocals of the individual resistances. Generally, when n resistors are connected in parallel, the reciprocal of the equivalent resistance is given by,

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

For identical n resistors connected in parallel, $R_1 = R_2 = R_3 = \ldots = R_n = R$. The reciprocal of total resistance is given by $\frac{1}{R_T} = \frac{n}{R}$. Therefore, the total resistance is given by $R_T = \frac{R}{n}$.

It should be noted that when resistors are connected in series, their total resistance is higher than that of individual resistors. However, for resistors connected in parallel, the total resistance is lower than that of individual resistors. Activity 2.2 will help in practical learning on effect of arrangement of resistors.

Activity 2.2

Aim: To investigate the effective resistance for resistors in series and in parallel

Materials: two dry cells of 1.5 V each, connecting wires, bulbs

Procedure

1. Connect two cells, each of 1.5 V in series and then connect them to one of the bulbs, A, as shown in Figure 2.11

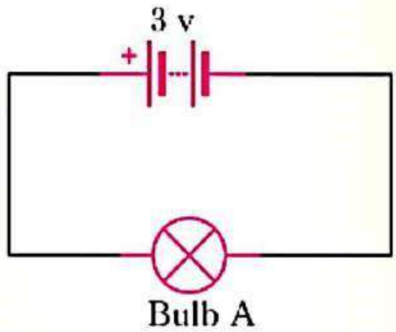


Figure 2.11

Observe the brightness of the bulb.

2. Connect another bulb, B, in series with bulb A as shown in Figure 2.12.

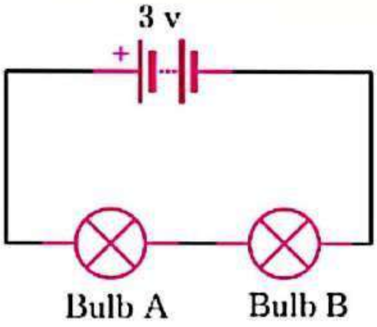


Figure 2.12

Observe the brightness of the bulbs.

3. Connect another bulb, C, in series with bulbs, A and B as shown in Figure 2.13. Observe how the brightness of bulbs A and B changes.

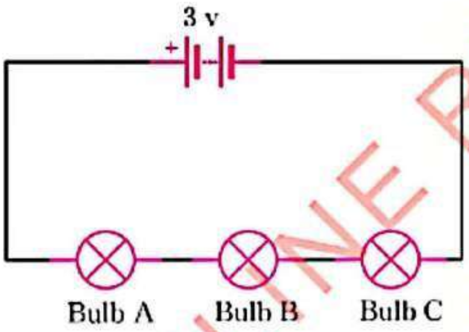


Figure 2.13

4. Connect bulb B in parallel with bulb A as shown in Figure 2.14. Observe the brightness of the bulbs compared to the initial brightness of bulb, A.

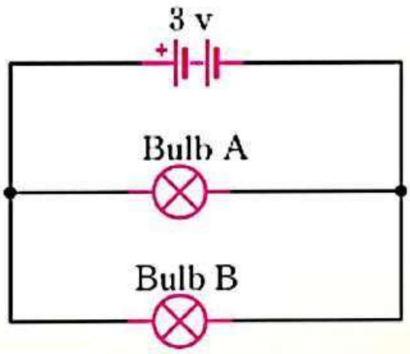


Figure 2.14

5. Connect bulb C in parallel with bulbs A and B as in the circuit shown in Figure 2.15. Observe how the brightness of the bulb's changes. Disconnect the circuit.

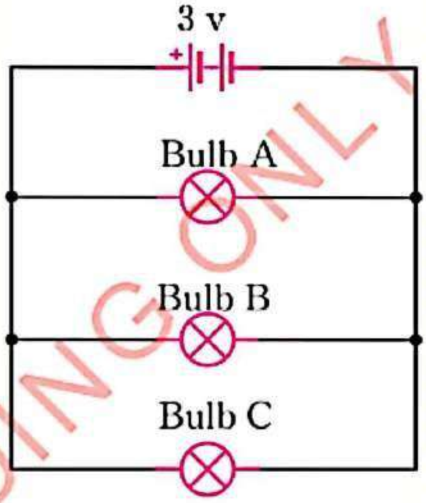


Figure 2.15

Questions

(a) What happened to the brightness of the bulbs as more bulbs were added in series?

(b) What happened to the brightness of the bulbs as more bulbs were added in parallel?

The brightness of the bulbs was reduced as more bulbs were added in series. This is because the total resistance increases when more bulbs (resistors) are added in series and consequently, the potential difference across individual bulbs is reduced. When bulbs are connected in parallel, the brightness of individual bulbs remains the same with an increase in the number of bulbs in the circuit. This is because the potential difference across each bulb remains the same when the number of bulbs is increased in a parallel connection. One might wrongly perceive that bulbs connected in a parallel connection are brighter only because of the combined brightness of all the bulbs.

Example 2.3

Figure 2.16 shows an electric circuit where, $V_B = 9\ V$, $R_1 = 4\ \Omega$, $R_2 = 5\ \Omega$, and $R_3 = 6\ \Omega$.

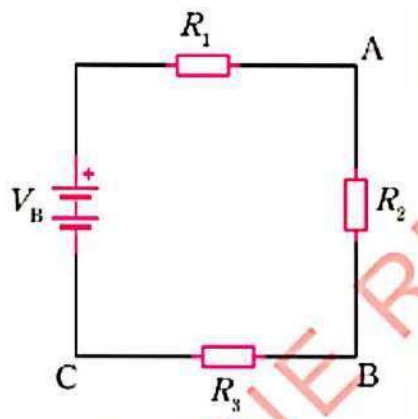


Figure 2.16

(a) What is the total resistance of the circuit?
(b) What is the value of the current flows in the circuit?
(c) What is the potential drop across each resistor?
(d) What is the electric potential at point A?

Solution

(a) $R_T = R_1 + R_2 + R_3 = 4\ \Omega + 5\ \Omega + 6\ \Omega$

$$= 15\ \Omega$$

(b) $I = \dfrac{V}{R_T}$

$$= \frac{9\ V}{15\ \Omega} = 0.6\ A$$

(c) p.d across R_1

$$V_{R_1} = IR_1$$
$$= 0.6\ A \times 4\ \Omega = 2.4\ V$$

p.d across R_2

$$V_{R_2} = IR_2$$
$$= 0.6\ A \times 4\ \Omega = 3.0\ V$$

p.d across R_3

$$V_{R_3} = IR_3$$
$$= 0.6\ A \times 5\ \Omega = 3.60\ V$$

(d) To find the electric potential at point A, take note that, the potential is measured with reference to the negative terminal of the source. This becomes our reference, 0 V. Therefore, we start at the negative terminal of the battery, where the potential is 0 V. Travelling around the circuit in the direction of electron flow, we pass through R_3 where there is a voltage drop of 3.6 V, then pass R_2 where the p.d is 3.0 V up to point A. Therefore, the potential at point A is,

$$V_A = V_{R_3} + V_{R_2}$$
$$= 3.6\ V + 3.0\ V$$
$$= 6.6\ V$$

Example 2.4

In the circuit shown in Figure 2.17 the battery has a voltage $V = 10$ V, $R_1 = 4\ \Omega$, $R_2 = 5\ \Omega$, $R_3 = 6\ \Omega$.

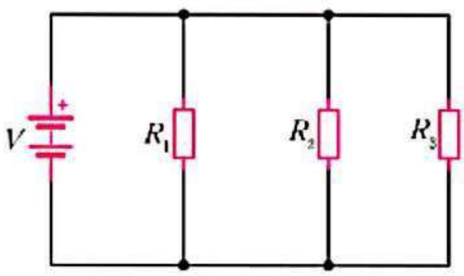


Figure 2.17

From the given circuit, find:

(a) Effective resistance and total current flowing.

(b) Current flowing through each resistor.

(c) Sum of currents flowing through the circuit.

Solution

Given $V = 10$ V, $R_1 = 4\ \Omega$, $R_2 = 5\ \Omega$, $R_3 = 6\ \Omega$;

Required to find the total resistance R_T. Using:

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

$\frac{1}{R_T} = \frac{1}{4\ \Omega} + \frac{1}{5\ \Omega} + \frac{1}{6\ \Omega} = \frac{37}{60\ \Omega}$

$R_T = 1.62\ \Omega$

Total current, I, is given by

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

$= \frac{10\ \text{V}}{1.62\ \Omega} = 6.17$ A

The total current flowing in the circuit is 6.17 A.

(b) The current flowing through each resistor is given by;

$I_1 = \frac{V}{R_1}$, $I_2 = \frac{V}{R_2}$ and $I_3 = \frac{V}{R_3}$

$I_1 = \frac{10\ \text{V}}{4\ \Omega} = 2.5$ A; $I_2 = \frac{10\ \text{V}}{5\ \Omega} = 2$ A

and $I_3 = \frac{10\ \text{V}}{6\ \Omega} = 1.67$ A

The current flowing through R_1 is 2.5 A, R_2 is 2 A and R_3 is 1.67 A.

(c) The total current flowing through the circuit is,

$I = I_1 + I_2 + I_3$

$I = 2.5\ \text{A} + 2\ \text{A} + 1.67\ \text{A}$

$= 6.17$ A

The total current flowing through the circuit is 6.17 A.

Example 2.5

Determine the current reading on the ammeter in the circuit shown in Figure 2.18.

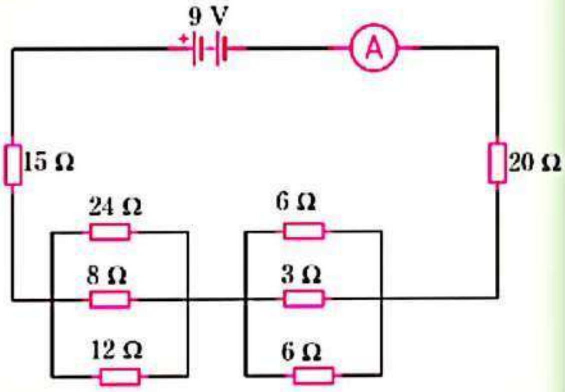


Figure 2.18

Solution

For three resistors in parallel,

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

For the first set of three resistors in parallel,

$$\frac{1}{R_T}=\frac{1}{24\ \Omega}+\frac{1}{8\ \Omega}+\frac{1}{12\ \Omega}=\frac{1}{4\ \Omega}$$

$$R_T=4\ \Omega$$

For the second set of resistors in parallel,

$$\frac{1}{R_T}=\frac{1}{R_4}+\frac{1}{R_5}+\frac{1}{R_6}$$

$$\frac{1}{R_T}=\frac{1}{6\ \Omega}+\frac{1}{3\ \Omega}+\frac{1}{6\ \Omega}=\frac{2}{3\ \Omega}$$

$$R_T=1.5\ \Omega$$

The effective resistance of the resistors in parallel, i.e., 4 Ω and 1.5 Ω, is now in series with resistors of 15 Ω and 20 Ω.

Therefore, the total resistance is given by,

$$=4\ \Omega+1.5\ \Omega+20\ \Omega+15\ \Omega$$

$$=40.5\ \Omega$$

The current is obtained through,

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

$$=\frac{9\ \text{V}}{40.5\ \Omega}=0.22\ \text{A}$$

Therefore, the current reading on the ammeter in the circuit is 0.22 A.

Internal resistance of a cell

A cell always resists the passage of current in a circuit. This resistance is called internal resistance. The internal resistance of a cell acts as if it is a resistor connected in series with the cell, so when current flows through the cell, there is a potential drop across this resistor. Consider a cell of e.m.f, E, and internal resistance, r connected across an external resistor, R, as shown in Figure 2.19 (a).

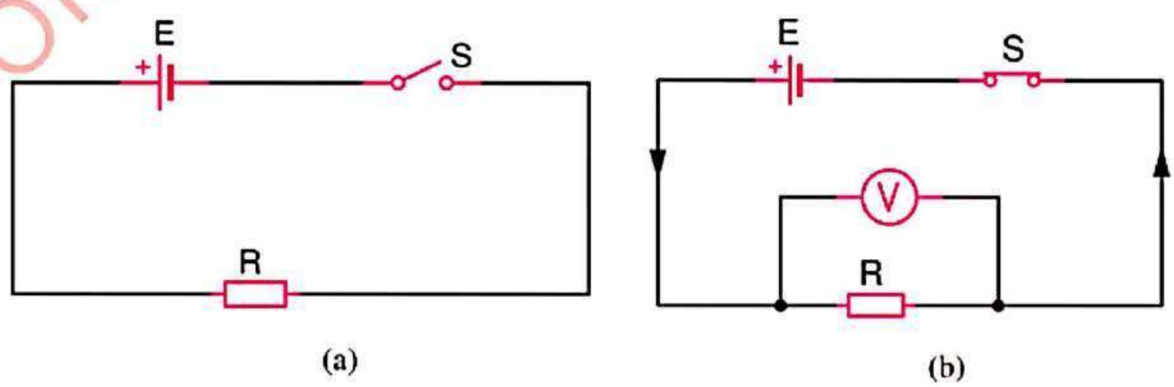


Figure 2.19: *A simple circuit; (a) switch open and (b) switch clossed*

Suppose the switch is closed as shown in Figure 2.19 (b), current, I, flows through the circuit. From Ohm's law, the p.d, V, across the resistor, R, is given by,

$$V = IR$$

The potential drop (V_1) caused by the cell's internal resistance is given by,

$$V_1 = Ir$$

The total voltage in the circuit is the sum of the potential drop due to the cell's internal resistance and that of the resistor, R. That is,

$$E = V + Ir$$

When no current is drawn in the circuit, e.m.f is equal to p.d across the cell $E = V$. Generally, the total e.m.f of the cell (s) is given by,

$$E = V + V_1$$

$$= IR + Ir$$

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

The equation $E = I(R + r)$ can be used to determine the internal resistance of a cell and the e.m.f of the cell experimentally. From Figure 2.19, different $R(\Omega)$ values can be used to give different values of current, I (A), and the two sets of values are plotted as shown in Figure 20.20 based on the equation:

$$R = E\left(\frac{1}{I}\right) - r$$

With R in the vertical axis and the reciprocal of current in the horizontal axis.

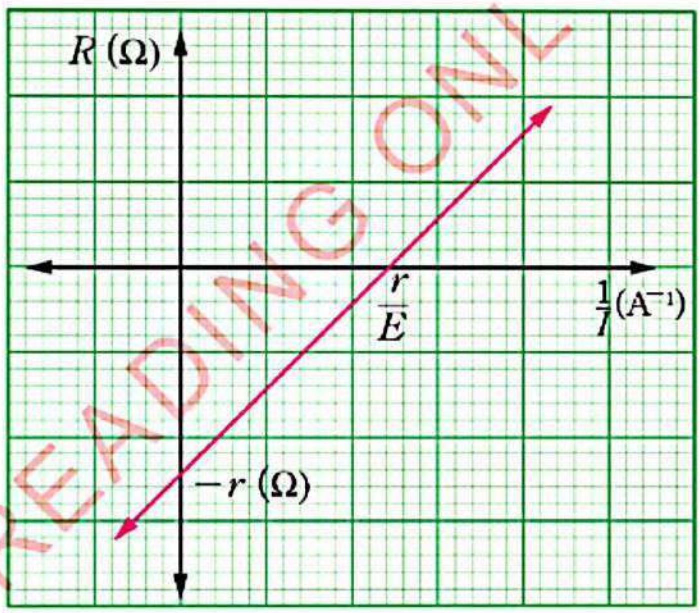


Figure 2.20: *The graph of resistance, R, against the reciprocal of current,* $\frac{1}{I}$

The numerical value of e.m.f and r can be determined from the graph. The slope of the graph represents the value of e.m.f, E, and the vertical intercept represents the value of internal resistance, r, of the cell. Similarly, when the axes of the variables are interchanged, the equation becomes:

$$\frac{1}{I} = \frac{1}{E}R + \frac{r}{E}$$

Therefore, the slope of this graph (Figure 2.21) represents the reciprocal of the cell's e.m.f, and the vertical intercept represents the product of the slope and the cell's internal resistance.

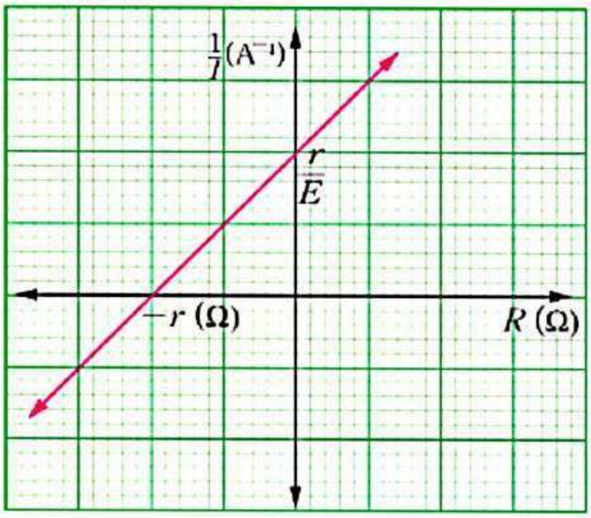


Figure 2.21: *The graph of the reciprocal of current, $\frac{1}{I}$ against resistance, R*

The following activity 2.3 will aid on practical understanding in measurement of e.m.f and internal resistance.

Activity 2.3

Aim: To determine the electromotive force, E, and internal resistance, r, of a cell

Materials: A cell, a set of standard resistors (2-10 Ω), an ammeter, a switch

Procedure

1. Connect the circuit as shown in Figure 2.22.

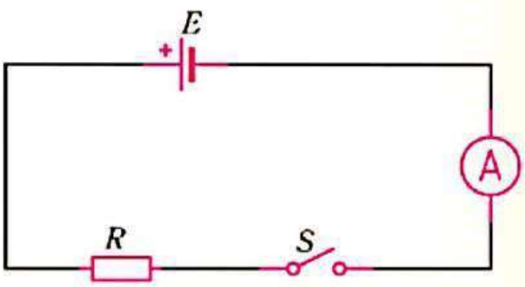


Figure 2.22

2. Set R at 10 Ω, close switch S and read the ammeter and record current, I.
3. Repeat step 2 for R = 8 Ω, 6 Ω, 4 Ω and 2 Ω.
4. Using a spreadsheet or otherwise, record results as shown in Table 2.6.

Table 2.6

Resistance, R (Ω)	Current, I (A)	$\frac{1}{I}(A^{-1})$
10		
8		
6		
4		
2		

Questions

(a) Use ICT software or otherwise to plot a graph of R against $\frac{1}{I}$.

(b) Determine the vertical intercept.

(c) What is the value of r?

(d) Determine the slope of the graph.

(e) What is the value of E?

Example 2.6

An electric cell with minimal voltage, E_m, has a resistance of 3 Ω connected across it. If the voltage falls to 0.6 E, calculate the internal resistance of this cell.

Solution

Given:

$E_m = E,\ R = 3\ \Omega,\ V = 0.6E$

From

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

$$E = 0.6E + Ir$$

$$Ir = E - 0.6E$$

$$Ir = 0.4E \qquad (1)$$

From Ohm's law

$$V = IR$$

$$3I = 0.6E$$

$$I = \frac{0.6E}{3} \qquad (2)$$

Substituting Equation (2) into (1) and solving for r, you get $r = 2\ \Omega$.

Exercise 2.1

1. A student measures the voltage of a cell in two scenarios. In scenario 1, he connects the voltmeter directly to the cell and records a value of 1.5 V. In scenario 2, he adds an unknown resistor to the circuit and records a voltage of 1.32 V.
   (a) What conclusions can be drawn from these results?
   (b) Explain the terms associated with the values recorded in scenarios 1 and 2.
2. The following results were obtained in an experiment to determine the value of resistance.

Voltage (mV)	0.04	0.08	0.2	0.21	0.22
Current (mA)	5.5	10.5	20.3	28.9	30

From the experimental results, using ICT tools or otherwise:
   (a) Plot a graph of V against I
   (b) Determine the value of resistance R
3. Study Figure 2.23 and the given instructions to answer the questions that follow.

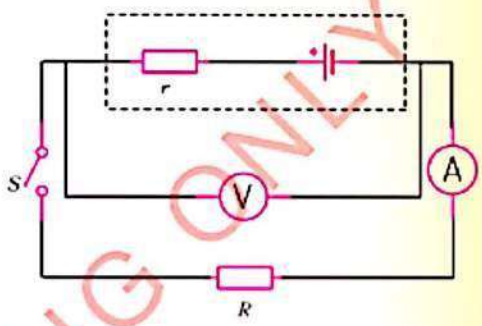


Figure 2.23

Switch condition	Ammeter reading (mA)	Voltmeter reading (V)
Open	0	9
Closed	250	7

   (a) Why does the reading on the voltmeter drop when the switch is closed?
   (b) Calculate the unknown external load resistance R.
   (c) Calculate the internal resistance
4. A student sets up the schematic diagram as in Figure 2.24 to investigate the internal resistance of a cell where $R = 2\Omega$ is a fixed resistor, r is the internal resistance of the cell, A is an ammeter and V is a voltmeter across the cell. When the switch is closed, the ammeter reads 0.4 A, the voltmeter reads 1.2 V. If the emf, E of the cell is known to be 1.6 V:
   (a) Draw the circuit diagram clearly

using circuit symbols and label all components.

(b) Calculate the effective resistance of the entire circuit.

(c) Use the readings to calculate the internal resistance r of the cell.

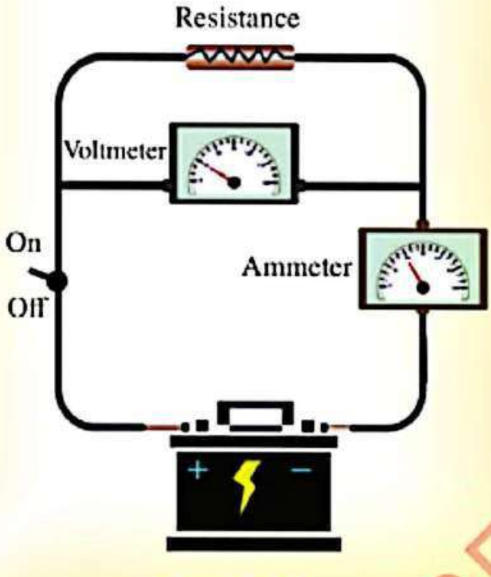


Figure 2.24

Potential difference across a conductor, current and resistance

Performing Activity 2.4 can determine the relationship between p.d across a conductor, the current flowing through the conductor, and the conductor's resistance and performing activity 2.5 one can determine the unknown resistance in circuit by ohms law.

Activity 2.4

Aim: To determine the relationship between potential difference, current and resistance

Materials: a d.c. power supply or 1.5 V cell, ammeter, bulb, switch, voltmeter, rheostat, connecting wires

Procedure

1. Connect an electric circuit as shown in Figure 2.25.

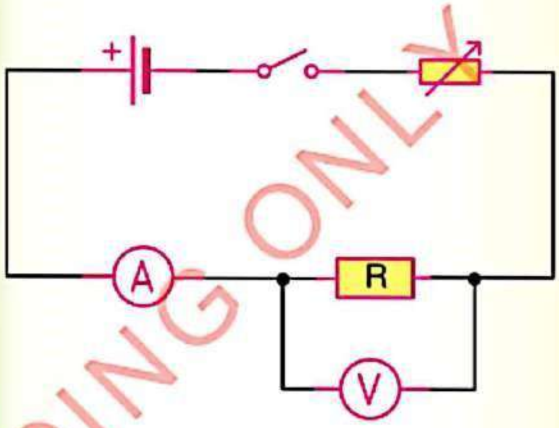


Figure 2.25

2. With the switch open, measure and record the potential difference across the bulb and the current through the circuit by using the voltmeter and ammeter, respectively.
3. Close the switch and adjust the rheostat until the voltmeter reads 0.2 V.
4. Measure and record the current through the bulb. Observe the brightness of the bulb.
5. Continue increasing the p.d at intervals of 0.2 V up to 1.2 V by adjusting the rheostat. Read the corresponding current value in each case.
6. Using a spreadsheet or otherwise, record the results as shown in Table 2.1.

Table 2.1

P.d. (V)	Current (A)
0.2	
0.4	
0.6	
0.8	
1.0	
1.2	

Questions

(a) What happened to the bulb's brightness as the p.d was increased?

(b) Use an ICT software or otherwise to plot a graph of p.d against current.

(c) Explain the shape of the graph. What does the nature of this graph imply?

Current flows when a cell is connected across the ends of a conductor. For a conductor such as copper wire, the current flowing through it is directly proportional to the potential difference across the ends of the conductor. This complies with Ohm's law, which states that "The current passing through a conductor at constant temperature is proportional to the potential difference between its ends."

That is,

$$I \propto V \text{ or } I = kV$$

where k is the constant of proportionality called conductance of a conductor, denoted by G. Hence,

$$G = \frac{I}{V}; \frac{1}{G} = \frac{V}{I}$$

Nevertheless, the reciprocal of conductance is the resistance of the conductor. That is,

$$\frac{1}{G} = R.$$

Similarly, Ohm's law can be expressed as:

$V \propto I$ it implies $V = IR$

where R is the constant of proportionality called resistance of a conductor. Hence,

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

The ohm can be defined as the resistance of a conductor such that, when a potential difference of 1 volt is applied to two points of a conductor, a current of 1 ampere flows through it. Therefore,

$$ohm = \frac{volt}{ampere}$$

By keeping temperature and other physical properties constant, the resistance (R) of a conductor remains constant. This relationship enables us to determine currents and voltages in electric circuits.

Activity 2.5

Aim: To determine the value of the unknown resistance by using Ohm's law

Materials: battery (E), ammeter (A), unknown resistance (R), switch (S), voltmeter (V), rheostat (Rh) of at least 500 Ω, and connecting wires

Procedure

1. Connect an electric circuit as shown in Figure 2.26.

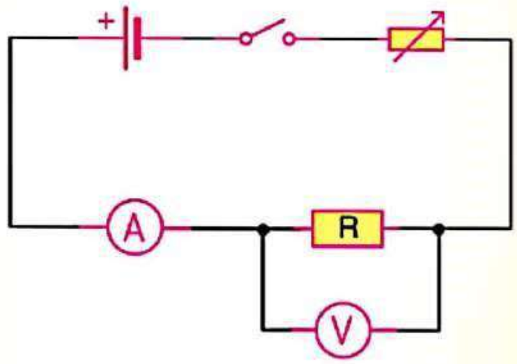


Figure 2.26

2. Close switch S and adjust the rheostat, Rh, so that a current of 0.1 A passes through the unknown resistor, *R*.
3. Use a spreadsheet or otherwise to record the current, *I* and p.d, *V*.
4. Adjust the *Rh* to get a current of 0.2 A passing through *R*. Record *I* and *V* as in step 3.
5. Repeat step 4 to obtain at least five more readings.
6. Record the results in a table similar to Table 2.2.

Table 2.2

Currently, *I* (ampere)	p.d. *V* (volt)
0.1	
0.2	
0.3	
0.4	
0.5	
0.6	
0.7	

Questions

(a) Use an ICT tool or otherwise to plot the graph of p.d, *V* against the current, *I*.

(b) What does the nature of the graph imply?

(c) Deduce the value of the unknown resistor, *R*.

Example 2.7

A cell develops a potential difference of 2 V across a resistor of 4 ohms. Calculate the current flowing through the resistor and the conductance of the resistor.

Solution

Using Ohm's law,

$$V = IR, \quad I = \frac{V}{R}$$

$$I = \frac{2\ \text{V}}{4\ \Omega} = 0.5\ \text{A}$$

Conductance G is the reciprocal of resistance

$$G = \frac{1}{R} = \frac{1}{4\Omega} = 0.25\Omega^{-1}$$

Therefore, the current flowing in the resistor is $0.5\,\text{A}$ and the conductance of the resistor is $0.25\Omega^{-1}$.

Factors that determine the resistance of a conductor

The resistance of a conductor is determined by its temperature, length, cross-sectional area and type of material.

Temperature

As temperature rises, the atoms in the conductor vibrate more, leading to increased collisions between electrons and atoms, which raises resistance. In some materials, the resistance varies almost linearly with temperature. For instance, the resistance of copper (Cu) varies approximately linearly with temperature. For some other materials, resistance does not vary linearly with temperature. However, the effect of temperature on the resistance of some alloys, such as constantan and manganin, is minimal.

Length of a conductor

When the length of a conductor is increased, while other factors are kept constant, the resistance of the conductor also increases. This is because electrons and atoms collide more in a long conductor than in a short conductor. This means that the resistance (R) of the wire is proportional to the length (l) of the wire. That is,

$$R \propto l$$

Cross-sectional area

A conductor with a larger cross-sectional area has more charge carriers to carry the electrical current than of a smaller cross area. This means the resistance R of a conductor is inversely proportional to the cross-sectional area A of the conductor, that is,

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

Nature of material

The resistance of a conductor also depends on the material used to make the conductor. For example, a conductor made from steel will have higher resistance than one made of copper of identical dimensions at the same temperature. For example, steel has a higher resistivity than copper. A material's property that resists current flow is known as the material's resistivity, denoted by ρ. Since, $R \propto l$ and $R \propto \frac{1}{A}$; then,

$$R \propto \frac{l}{A}$$

Hence,

$$R = \frac{l}{A}$$

where r is the constant of proportionality. This constant of proportionality is the resistivity of the material, given as:

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

Resistivity is, therefore, the measure of the ability of a material to oppose the flow of an electric current. The SI unit of resistivity is the ohm-metre (Ωm). Activity 2.6 will aid in developing practical knowledge on determination of resistivity of wires.

Activity 2.6

Aim: To determine the resistivity of constantan wire

Materials: battery, ammeter, switch, voltmeter, rheostat, connecting wires, micrometer screw gauge, a constantan wire of length 20 cm

Procedure

1. Connect an electric circuit as shown in Figure 2.27.

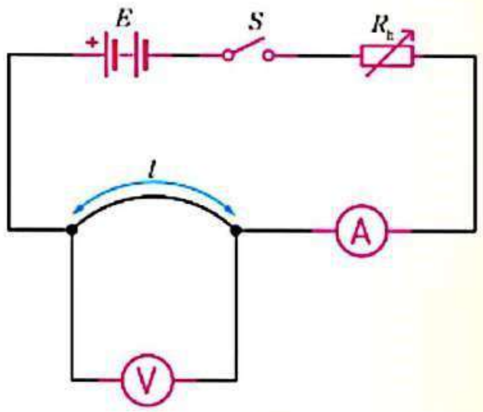


Figure 2.27

2. Close the switch S and adjust the rheostat so that the ammeter reads 0.2 A.
3. Record the current, I and potential difference, V.
4. Repeat steps 2 and 3 with current, I = 0.3 A, 0.4 A and 0.5 A.
5. Use a spreadsheet to record the results in the format shown in Table 2.3.

Table 2.3

Current, I (ampere)	p.d., V (volt)
0.2	
0.3	
0.4	
0.5	

6. Measure the diameter, D, of the constantan wire and calculate its cross-sectional area, A.

Questions

(a) What happened to the potential difference as the current was increased?

(b) Using ICT software, or otherwise, plot the graph of p.d, V against current, I and determine the slope of the graph.

(c) Deduce the resistivity of the constantan wire.

Different materials have different values of resistivity. The resistivities of some materials are given in Table 2.4.

Table 2.4: *Resistivities of some materials*

Material	Resistivity in Ωm (at 20 °C)
Silver	1.6×10^{-8}
Copper	1.68×10^{-8}
Aluminium	2.7×10^{-8}
Tungsten	5.6×10^{-8}
Iron	9.71×10^{-8}
Steel	1.05×10^{-7}
Platinum	1.06×10^{-7}
Chromium	1.3×10^{-7}
Manganin	4.8×10^{-7}
Constantan	4.9×10^{-7}
Lead	2.1×10^{-7}
Mercury	9.8×10^{-7}
Nichrome	1.0×10^{-6}
Glass	$1\times10^{9}-1\times10^{13}$
Rubber	$1\times10^{13}-1\times10^{15}$
Quartz	7.5×10^{17}

Example 2.8

What is the resistance of a copper wire of length 20 m and a diameter of 0.080 cm? (Resistivity of copper, $\rho_{cu} = 1.68\times10^{-8}\Omega\text{m}$.

Solution

Given that

$l = 20\ m$; for copper,

$\rho_{cu} = 1.68\times10^{-8}\ \Omega\text{m}$

$$R = \frac{\rho l}{A}$$

But $A = \pi r^2$

$= 3.14\times(4\times10^{-4}\ \text{m})^2$

$= 5.024\times10^{-7}\ \text{m}^2$

Hence,

$$R = \frac{1.68\times10^{-8}\ \Omega\text{m}\times20\ \text{m}}{5.024\times10^{-7}\ \text{m}^2}$$

$= 0.67\ \Omega$

Therefore, the resistance of the wire is $0.67\ \Omega$.

Example 2.9

A nichrome wire has a cross-sectional area of $4\times10^{-8}\ \text{m}^2$ and a resistivity of $1.0\times10^{-6}\ \Omega\text{m}$. If a resistor of resistance 11 Ω is to be made from this wire, calculate the length of the required wire.

Solution

Given that,

$A = 4\times10^{-8}\ \text{m}^2$; $\rho = 1.0\times10^{-6}\Omega\text{m}$; and $R = 11\ \Omega$;

then,

$$l = \frac{AR}{\rho}$$

$$l = \frac{4\times10^{-8}\ \text{m}^2\times11\ \Omega}{1.0\times10^{-6}\ \Omega\text{m}} = 0.44\ \text{m}$$

Therefore, the length of the wire is 0.44 m.

Example 2.10

A constantan wire has a length of 45 cm, a diameter of 0.37 mm and a resistivity of $4.9\times10^{-7}\ \Omega\text{m}$.

(a) What is the resistance of the wire?

(b) What will be the current flowing in the wire if it is connected to a 1.5 V cell?

Solution

(a) $\rho = 1.0\times10^{-6}\Omega\text{m}$; and $l = 0.45\ \text{m}$

But, $R = \frac{\rho l}{A}$ and $A = \pi r^2$;

where,

$$r = \frac{0.37\ \text{mm}}{2} = 0.185\ \text{mm}$$

$= 1.85\times10^{-4}\ \text{m}$,

hence,

$A = 3.14\times(1.85\times10^{-4}\ \text{m})^2$

$= 1.075\times10^{-7}\ \text{m}^2$

$$R = \frac{4.9\times10^{-7}\ \Omega\text{m}\times0.45\ \text{m}}{1.075\times10^{-7}\ \text{m}^2} = 2.05\ \Omega$$

Resistance of the wire is $2.05\ \Omega$.

(b) Given, $V = 1.5\ \text{V}$ and $R = 2.05\ \Omega$, then,

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

$$= \frac{1.5\ \text{V}}{2.05\ \Omega} = 0.73\ \text{A}$$

Therefore, the current flowing in the wire will be 0.73 A.

Measurement of resistance

Resistance measurement is essential in electrical circuits. Two accurate methods used are the Wheatstone bridge, which balances known and unknown resistances, and the potentiometer, which compares voltage drops to determine resistance. These methods are clearly explained in the sections below, providing step-by-step procedures, principles of operation, and practical applications to enhance understanding.

Wheatstone bridge

From Activity 2.5, Ohm's law was used to determine the value of the unknown resistance of a conductor. A similar approach cannot be applied to accurately measure a very low value of resistance in the milli-Ohms (mΩ) range. However, when resistors are connected in the series-parallel arrangement as shown in Figure 2.28, the value of the unknown resistance of a conductor, even in mΩ, can be measured. This diamond-like arrangement is called the Wheatstone bridge circuit. It consists mainly of four resistors known as the bridge arms and a galvanometer in between them.

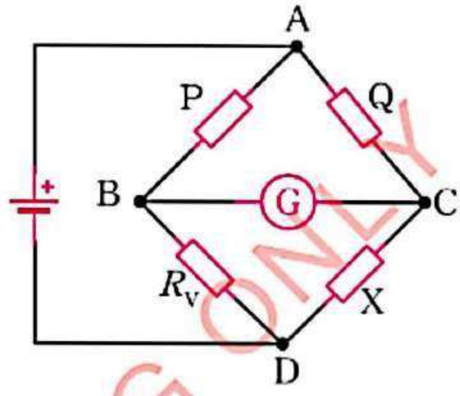


Figure 2.28: *The Wheatstone bridge*

Working principle of a Wheatstone bridge

To understand how the Wheatstone bridge works, let us consider a bridge circuit in Figure 2.29.

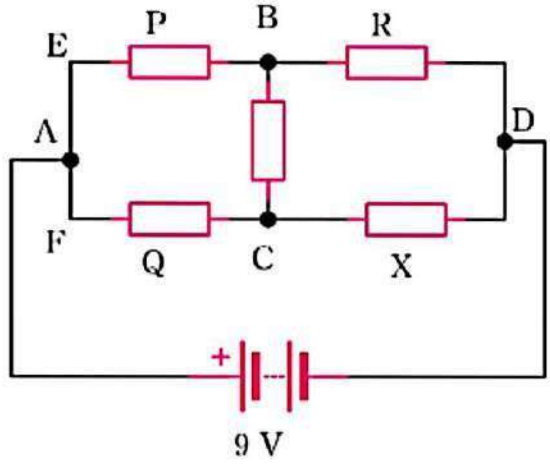


Figure 2.29: *Wheatstone circuit*

If the resistors, P = 5 Ω, Q = 1 Ω, R = 10 Ω, X = 2 Ω and J = 6 Ω, what is the current flowing through the circuit?

The circuit in Figure 2.29 does not have any resistors arranged in series or in parallel. Thus, one cannot reduce the circuit to an equivalent resistance using parallel and series formulae. However, if you observe the circuit carefully, you realize that, the resistors on one side of the joint resistor, J, are in the same ratio as the resistor on the other side of J. That is,

$$\frac{P}{Q}=\frac{5\ \Omega}{1\ \Omega} \text{ and } \frac{R}{X}=\frac{10\ \Omega}{2\ \Omega}=5.$$

Therefore, $\frac{P}{Q}=\frac{R}{X}$.

A bridge circuit that has this property is said to be a balanced Wheatstone bridge. Now, suppose the resistor J, is removed from the circuit so that resistor P, is in series with resistor R, and resistor Q is in series with resistor X. Moreover, the resistors P and R are in parallel with resistors Q and X. Therefore, the voltages at points E and F are the same. Since,

$$\frac{P}{Q}=\frac{R}{X},$$

the voltage drop at P is the same as the voltage drop at Q, meaning that voltage at point B (V_B) is the same as voltage at point C (V_C). This means the potential difference between points B and C is zero. Thus, when the resistor J is connected, current through it is zero. That is, when the bridge circuit is balanced, $I_J = 0$ A.

Suppose a resistor J is replaced with a galvanometer G as shown in Figure 2.29. The variable resistor R_V, can be varied to a point where the current through the galvanometer $I_G = 0$ A.

At this point, the bridge circuit is balanced, and therefore,

$$\frac{P}{Q}=\frac{R_V}{X},$$

which means,

$$X=\frac{QR_V}{P}$$

Performing activity 2.7 gives more understanding on Wheatstone bridge.

Activity 2.7

Aim: To determine the resistance of an unknown resistor X, using a Wheatstone bridge.

Materials: zero centred galvanometer, a dry cell, decade resistance box R_V, known resistors P and Q (ranging from 1 Ω to10 Ω), the unknown resistor X whose values range from 4 Ω to 10 Ω, a switch, and connecting wires

Procedure

1. Use the materials provided to set up the Wheatstone bridge circuit as shown in Figure 2.29.
2. Switch ON the circuit to allow current to flow through the circuit. Ensure that the amount of current flowing through the galvanometer does not deflect it out of range.
3. Adjust the resistance, R_V, until the reading on the galvanometer, G is zero. At this point the bridge is balanced.

4. Determine the value of the unknown resistor X using the formula:

$$X = \frac{QR_V}{P}$$

5. Repeat steps 3 and 4 by using different values of P and Q to obtain several values of X. Calculate the average value of the unknown resistor X.

Questions

(a) What is the value of the unknown resistor X ?

(b) What are the possible sources of errors in this activity?

Slide wire bridge (Metre bridge)

A slide wire bridge (Metre bridge) is a modified Wheatstone bridge. It is made of one known resistor R, an unknown resistor R_X, and a wire of uniform cross section area, as shown in Figure 2.30

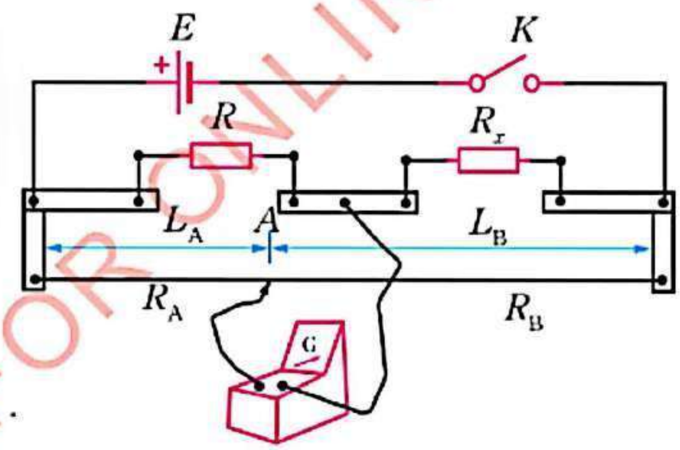


Figure 2.30: *Metre bridge*

The ratio $\frac{R_B}{R_A}$ is adjusted by sliding a jockey along the length of the wire. Because the wire has a uniform cross-sectional area, the ratio $\frac{R_B}{R_A}$ is equivalent to respective lengths L_B and L_A. That is,

$$\frac{R_B}{R_A} = \frac{\frac{\rho L_B}{A}}{\frac{\rho L_A}{A}} = \frac{L_B}{L_A}$$

But

$$\frac{R_B}{R_A} = \frac{R_X}{R} \Rightarrow \frac{L_B}{L_A} = \frac{R_X}{R}$$

This expression can therefore be written as,

$$R_X = \frac{L_B}{L_A} \times R$$

This expression can be used to determine the value of the unknown resistor.

Activity 2.8 aids on performing experiments regarding finding unkown resistor by meter bridge.

Activity 2.8

Aim: To determine the resistance of an unknown resistor using the metre bridge

Materials: a resistor with unknown resistance, a cell, galvanometer, metre bridge, decade resistance box, switch, jockey, connecting wires

Procedure

1. Set up the metre bridge circuit as shown in Figure 2.31. Let the resistance box be R.

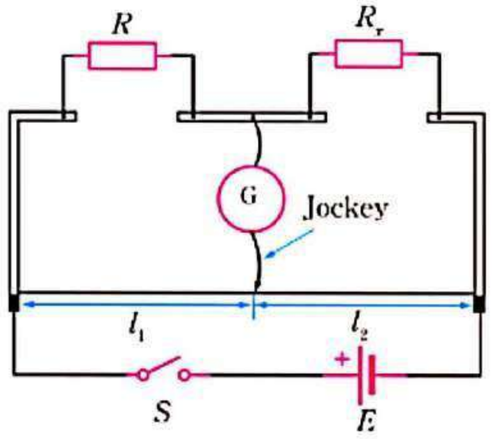


Figure 2.31

2. Set R to 1 Ω, then close the switch, S, and slide the jockey over the metre bridge wire until the galvanometer reads zero. Record length l_1 and l_2.
3. Repeat step 2 for R = 2 Ω, 3 Ω, 4 Ω and 5 Ω. Read and record the value of l_1 and l_2 in each case.
4. Use spreadsheet or otherwise to record results using Table 2.7.

Table 2.7

Resistor, R (Ω)	l_1 (cm)	l_2 (cm)	$\frac{l_1}{l_2}$
1			
2			
3			
4			
5			

Questions

(a) Using ICT software or otherwise, plot a graph of R against $\frac{l_1}{l_2}$.

(b) Deduce the value of unknown resistance, R_X.

Example 2.11

A metre bridge is set up as shown in Figure 2.32 using a standard 10 Ω resistor. The galvanometer shows zero deflection when the Jockey contact is at 48 cm from end A. Determine the resistance of a resistor, X.

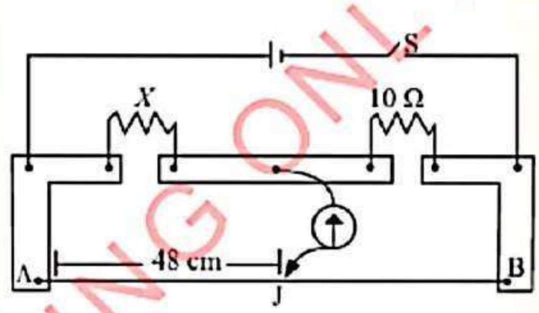


Figure 2.32

Solution

From the metre bridge expression,

$$X = \frac{L_A}{L_B} \times R$$

where

$R = 10\ \Omega$, $L_A = 48$ cm and

$L_B = 52$ cm

Hence,

$$X = \frac{48\text{ cm}}{52\text{ cm}} \times 10\ \Omega = 9.23\ \Omega$$

Therefore, the resistance X is 9.23 Ω.

Potentiometer

A potentiometer is a reliable tool for measuring e.m.f. It consists of a length AB of uniform resistance wire, with a steady current flowing through it from an accumulator C (Figure 2.33). Any length from A is read from a metre rule AB, and the length of AB may be one metre.

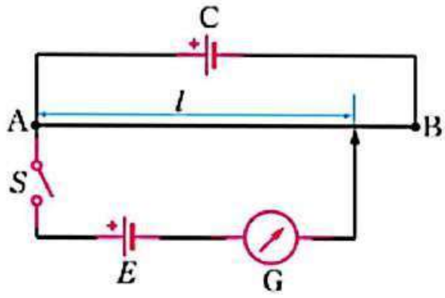


Figure 2.33: *A potentiometer*

On closing the switch, S, there will be a potential drop across AB and hence between point A and any other point along AB. This potential drop will produce a current in the galvanometer in the direction AGJ so that, in whatever position of J on AB, the galvanometer will be deflected. Suppose a second cell E, is introduced in series with the galvanometer, its current in the direction JGA, will now be opposed by the current due to the cell D flowing in the direction AGJ. There will now be two opposing p.d between A and J. It should be possible to find a position, J, of the jockey on AB for which the p.d across AJ due to E balances the p.d across AJ due to D. Activity 2.9 illustrate how one can compare e.m.f. of two cells by using potentiometer.

Activity 2.9

Aim: To compare the e.m.f of two cells using a potentiometer

Materials: A slide-wire potentiometer, galvanometer, 2 dry cells, jockey, connecting wires, switch, accumulator

Procedure

1. Set up the potentiometer circuit as shown in Figure 2.34 where C is an accumulator, E_1 and E_2 are the two cells for comparison.

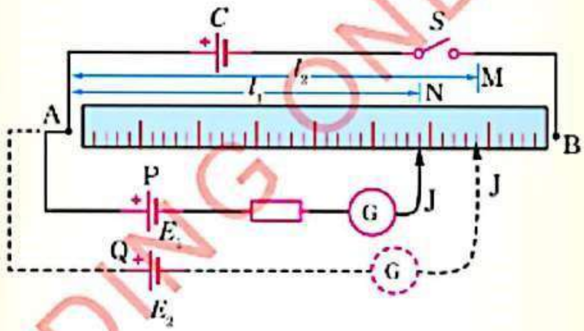


Figure 2.34

2. Join the positive terminal of P to A, the same terminal to which the positive terminal of C is joined.
3. Join the negative terminal of P to a slider, J, through a galvanometer, G.
4. Gently tap on the wire with J, find the point N (balance point) when no current flows in G. Measure the balance length AN or l_1 from the metre rule.
5. Disconnect the cell P (E_1) from the circuit, and replace it with cell Q (E_2), the other cell for comparison. As before, obtain the new balance point M and read off the length AM or l_2.

Questions

(a) Suppose the value of E_1 is known, find the value of E_2.

(b) It is clear from this activity that, as the e.m.f. increases, the length of the potentiometer wire increases as well.

Why does the length increase with an increase of e.m.f.?

Theoretically, the e.m.f E_1 *of cell P balances the p.d.* V_1 *on the wire* because no current flows in G at *the balance point N. As a result,* $E_1 = V_1$. *Similarly, if cell* E_2 *is the e.m.f of cell Q and* V_2 *is the p.d. between A and M,* $E_2 = V_2$. *As a result,* $\frac{E_1}{E_2} = \frac{V_1}{V_2}$.

The p.d. V *across any length,* l, *is directly proportional to* l *if the wire carries a constant current. As a result,* $\frac{E_1}{E_2} = \frac{l_1}{l_2}$. *Thus, the e.m.f of the two cells can be compared.*

Example 2.12

The balance length of a potentiometer wire for a cell of e.m.f, $E_1 = 1.63\ V$ *is 85 cm. If the cell is replaced by another one of e.m.f,* $E_2 = 1.07\ V$, *calculate the new balance length.*

Solution

Given

$E_1 = 1.63\ V$, $l_1 = 85\ cm$, $E_2 = 1.07\ V$

Then, the new length l_2 *is obtained from the formula:*

$$\frac{E_1}{E_2} = \frac{l_1}{l_2}$$

Therefore,

$$l_2 = \frac{E_2}{E_1} \times l_1$$

$$= \frac{1.07\ V}{1.63\ V} \times 85\ cm$$

$$= 55.79\ cm$$

The new balance length is 55.79 cm.

Exercise 2.2

1. *A wire of length 1.2 m and diameter* 0.64 mm has a resistance of 2.4 Ω. *Calculate the resistance of a wire of length 0.80 m and diameter 0.32 mm of the same material.*
2. *A wire of length 2 m and a cross sectional area of 0.5* mm^2, *has a* resistance of 2.2 Ω. Calculate the *resistivity of the material making up the wire.*
3. *A battery of e.m.f 12 V and internal* resistance 1.5 Ω is connected to a 4 Ω resistor. Calculate the:
   (a) *total resistance of the circuit*
   (b) *current through the battery*
   (c) *p.d across the cell terminals*
4. *The p.d across the terminals of a cell is 1.1 V when a current of 0.20 A is being drawn from the cell. If the p.d across the cell is 1.3 V when a current of 0.10 A is being drawn, determine the:*
   (a) *internal resistance of the cell.*
   (b) *cell's e.m.f.*

5. Two batteries, V_1 and V_2, are connected in series with an 8 Ω resistor as shown in Figure 2.35.

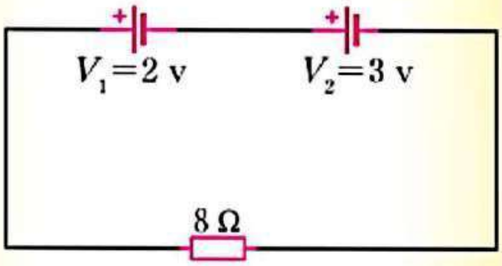


Figure 2.35

Given that the internal resistances of the two batteries are 2 Ω and 1 Ω, respectively, determine the p.d across the 8 Ω.

6. Look at the three circuit diagrams in Figure 2.36. Rank the circuits from brightest bulb(s) to dimmest bulb(s). Explain your choices.

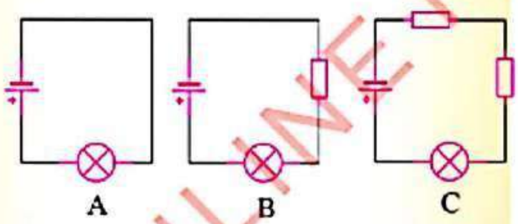


Figure 2.36

7. A sub-woofer needs a household voltage of 220 V to push a current of 5.5 A through its coil. What is the resistance of the coil?

Heating effect of an electric current

When an electric current flows through a conductor, the electrical energy is converted into thermal energy, and the conductor heats up. This is a demonstration of the heating effect of an electric current. In an electric iron, the electrical energy is converted to heat, making the iron hot. Other electrical appliances that work on the heating effect of electric current include immersion water heaters, hot plates, electric kettles and filament lamps. Activity 2.10, 2.11 and 2.12 illustrates on how one can investigate heating effects of an electric current.

Activity 2.10

Aim: To investigate the heating effect of an electric current

Materials: Battery, thermometer, resistive wire, ammeter, voltmeter, rheostat, stopwatch, calorimeter with jacket, connecting wires, water, switch

Procedure

1. Determine the resistance, R, of the resistive wire using a meter bridge procedure.
2. Set up the apparatus as shown in Figure 2.37.

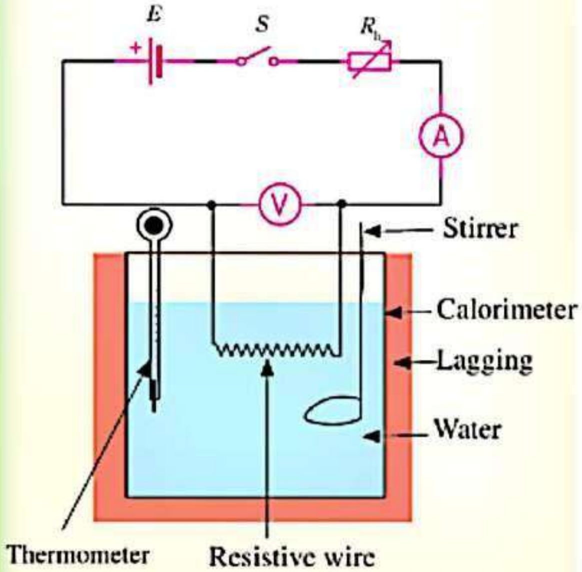


Figure 2.37

3. Close switch S and adjust the rheostat, R_h, to give appropriate current, I, and voltage, V.
4. Record the initial temperature θ_1 of water and leave the circuit ON for a time, t, which is monitored by a stopwatch.
5. After time, t, record the final temperature θ_2. The change in temperature will be $\theta = \theta_2 - \theta_1$.
6. Adjust R_h to obtain different values of I and V and repeat steps 4 and 5, to obtain at least two or more sets of I, V and θ.
7. Using spreadsheet or otherwise, record results as shown in Table 2.8.

Table 2.8

Current, I (A)	Voltage, V (V)	Temperature change, θ(°C)	Square of constant, I^2(A^2)

Questions

(a) Use ICT software to plot a graph of change in temperature, θ, against the square of current, I^2.

(b) What is the nature of the graph? Explain its physical meaning. The amount of heat, H, absorbed by the water is proportional to the increase in its temperature. The plot of θ against I^2 indicates that, $\theta \propto I^2$. Since $H \propto \theta$, therefore, $H \propto I^2$.

Activity 2.11

Aim: To demonstrate the effect of time on heating effect of an electric current

Materials: Battery, calorimeter with jacket, thermometer, resistive wire, ammeter, voltmeter, rheostat, stopwatch, switch, stirrer, water, connecting wires

Procedure

1. Connect the apparatus as shown in Figure 2.37. Close switch S and adjust the rheostat to obtain suitable current, I, and voltage, V.
2. Record an initial temperature of the water together with I and V. Leave the circuit ON for a known time, t.
3. At the end of time, t, record the value of the temperature change. Leave the circuit ON as in step 2, then record the change in temperature with the corresponding time.
4. Repeat step 3 and obtain at least 2 more values of change in temperature with time.
5. Using spreadsheet or otherwise, record results as shown in Table 2.9.

Table 2.9

Time, t (minutes)				
Temperature change, θ(°C)				

Questions

(a) Use ICT tools or otherwise, to plot the graph of temperature, θ, against time, t.

(b) Explain the nature of a graph.

Heat absorbed by water is proportional to the increase of heating time. The graph of θ against t shows that, $\theta \propto t$, and $H \propto t$.

Activity 2.12

Aim: To observe the effect of resistance on the heating effect of an electric current

Materials: Battery, calorimeter with jacket, thermometer, resistive wire, ammeter, voltmeter, rheostat, stopwatch, water, switch, stirrer, connecting wires

Procedure

1. Set up an arrangement as shown in Figure 2.37.
2. Close switch S and adjust a rheostat to obtain suitable values of I and V. Record the initial temperature of water.
3. Leave the current ON for a known time and record the change in temperature.
4. Change the resistance of the wire by varying its length, then, repeat steps 2 and 3.
5. Repeat step 4 and obtain at least 2 more readings of change of temperature with the corresponding resistance of wire.
6. Determine the resistance of each length of the wire and record the results as shown in Table 2.10.

Table 2.10

Length of the wire, l	
Resistance of the wire, $R(\Omega)$	
Temperature change, θ(°C)	

Questions

(a) Using ICT tools, plot a graph of change in temperature, θ, against resistance, R.

(b) Comment on the nature of the graph.

The heat absorbed by water is proportional to the increase in temperature. From the plot of change in temperature against resistance, it is observed that, θ, is proportional to the resistance of the wire, thus, $\theta \propto R$. Hence, $H \propto R$. Therefore, from Activities 2.10 - 2.12, it can be concluded that,

$$H \propto I^2Rt$$

Hence,

$$H = kI^2Rt$$

If the current of 1 A flows through a resistor of 1 Ω in 1 second, then the heat generated in water is 1 J. Thus, $k = 1$. Hence,

$$H = I^2Rt$$

This equation gives the relationship between the resistance of a conductor, current passing through a conductor, time a current flows and electrical energy generated. The electrical energy generated is measured in Joules. Thus, this equation is referred to as Joule's law of heating. The law states that, "*When an electric current is passed through a conductor, the heat generated in a given time is directly proportional to the resistance of the conductor in ohms, the square of current in amperes and the time in seconds for which the current flows*". Since the unit of electrical energy is joule, then the Joule is defined as the work done when a charge of 1 coulomb flows through a conductor with a p.d of 1 volt across it in 1 second.

By Ohm's law, $V = IR$. Then,

$$H = \frac{V^2}{R}t$$

Also,

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

Thus,

$$H = IVt$$

These are forms of stating up Joule's law.

Example 2.13

A resistor of 100 Ω is connected across a battery of 12 V. How much heat is dissipated across the resistor in 5 s? (Ignore the internal resistance of the battery).

Solution

Given: voltage, $V = 12\ \text{V}$, resistance, $R = 100\ \Omega$, time $t = 5\ \text{s}$

From,

$$H = \frac{V^2}{R}t$$

$$= \frac{12^2 \times \text{V}^2}{100\ \Omega} \times 5\ \text{s} = 7.2\ \text{J}$$

The heat dissipated across the resistor is 7.2 J.

Example 2.14

A bulb draws a current of 0.5 A from a 240 V source. Calculate the energy dissipated in 10 minutes.

Solution

Given:

$I = 0.5\ \text{A}$, $V = 240\ \text{V}$,

$t = 10 \times 60\ \text{s} = 600\ \text{s}$

Using the equation

$$H = IVt$$

$$= 0.5\ \text{A} \times 240\ \text{V} \times 600\ \text{s}$$

$$= 72000\ \text{J}$$

Therefore, the energy dissipated is 72000 J or 72 kJ.

Electric power

In many circuits, it is essential to know the rate at which electrical energy is transferred into other forms of energy. The rate of doing work or the rate at which energy is dissipated is called power.

$$electric\ power = \frac{electric\ energy\ dissipated}{time\ taken}$$

$$= \frac{energy\ transfer}{time\ taken}$$

$$= \frac{I^2Rt}{t} = I^2R$$

By Ohm's law, $IR = V$

Therefore,

$$P = IV$$

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

$$P = \frac{V^2}{R}$$

The SI unit of power is joule per second (Js^{-1}) or watt (W). The power is assumed to be 1 watt if 1 ampere current flows against a potential difference of 1 volt, that $1\ watt = 1\ ampere \times 1\ volt$. Likewise, if 1 joule of energy is being spent per second, the power consumed by an electrical appliance is said to be 1 watt (1 watt = 1 joule/second).

Example 2.15

If a lamp on a 240 V supply draws a current of 0.25 A, calculate the power the lamp uses to transfer electrical energy into heat and light energy.

Solution

$P = IV$

$P = 240\ V \times 0.25\ A = 60\ W$

Therefore, the lamp transfers 60 J of electrical energy into heat and light energy each second.

Power rating of electrical appliances

Every electrical appliance should carry a label stating the potential difference for which it has been designed and the power an appliance can convert when operating at the stated potential difference. The rate at which an appliance dissipates energy is called the rating of an appliance and is usually marked on the body of an appliance. For example, an appliance marked 3000 W, 240 V, dissipates energy at the rate of 3000 joules per second when connected to a 240 V supply. Figure 2.38 shows an electric iron marked 220 - 240 V, 1000 W, indicating that, the appliance dissipates energy at the rate of 1000 joules per second when connected to a 220 - 240 V supply.

It is worth noting that, if the appliance is connected to a higher voltage than the one indicated, it may be damaged, and if connected to a lower voltage it will not function properly.

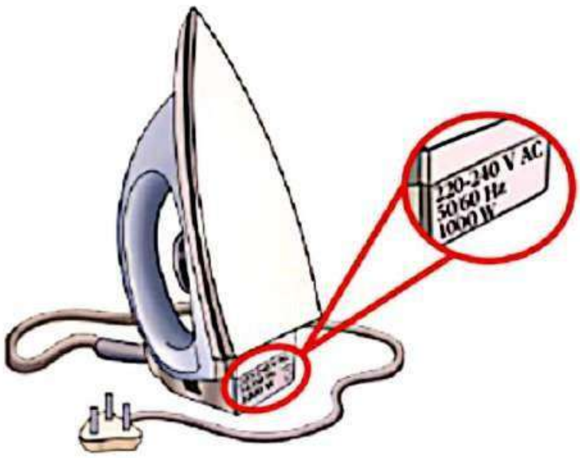


Figure 2.38: *An electric iron*

Task 2.3

(a) Identify the electrical appliances found at your home; list them and discuss their power ratings.

(b) Suppose the appliances you listed are used for 1 hour, what will be the total energy used?

Commercial unit of electrical energy

You have learnt that, the unit of electrical power is watt, and thus, unit of electrical energy should be watt-second. However, watt-second unit is too small as an electrical energy unit for everyday commercial purposes.

Thus, to resolve this challenge, a larger unit, the kilowatt-hour (kWh), is used. One kWh is the energy consumed in one hour by an appliance working at the rate of 1 kW. Commercially, 1 kWh is named as a unit of electricity. For example, if the user consumes 5 units of electricity, it means that, electrical energy of 5 kWh has been consumed.

1 kWh = 1 kilowatt × 1 hour

$= 1\,000 \text{ W} \times 3\,600 \text{ s}$

$= 36\,000\,000$ watt-second or 3.6×10^6 J

$= 3.6$ MJ

The unit of kWh is used to determine the cost of electrical energy consumed by electricity users. Normally, electricity cost is calculated by taking the price of a unit of electricity times the consumed electrical energy in kWh (total units). That is;

$$cost = price \times total\ units$$

In Tanzania, electricity users buy units of electricity before using the energy. Therefore, the Tanzania Electric Supply Company Limited (TANESCO) distributes special electricity meters that enable one to pay before consuming. These meters are famously known as "Lipa Umeme Kadiri Utumiavyo" abbreviated as LUKU. Figure 2.39 shows a picture of LUKU meter distributed by TANESCO.

Figure 2.39: *An example of a LUKU meter with 3.35 kWh (units)*

Example 2.16

A television set (TV) rated 40 W is switched ON for 5 hours every day.

(a) How much electrical energy in kWh does this TV consume in 30 days?

(b) If the price of a unit of electricity is Tsh 229.60, what is the total electricity cost of watching this TV in 30 days?

Solution

(a) $Energy = power \times time$

$$= 40 \text{ W} \times \frac{5 \text{ h}}{\text{days}} \times 30 \text{ days}$$

$$= 6\,000 \text{ Wh} = 6 \text{ kWh}$$

Therefore, the electrical energy consumed for 30 days is 6 kWh.

(b) To determine the electricity cost of watching this TV, we use the formula;

$$cost\ (Tsh) = price \times total\ units$$

Therefore,

$$cost\ (\text{Tsh}) = \frac{229.60 \text{ Tsh}}{1 \text{ kWh}} \times 6 \text{kWh}$$

$$= 1\,377.60 \text{ Tsh}$$

Hence, the cost of watching this TV for 30 days is Tanzanian shillings 1377.60.

Exercise 2.3

1. A 120 V circuit is equipped with a 20 A fuse. What is the least resistance that can be plugged into the circuit without causing the fuse element to melt?
2. A car's headlights consume a power of 40 W when on low beam and 50 W when on high beam. Given that the headlights are connected to a 12 V battery, determine:
   (a) The current that flows through the headlight in each case.
   (b) The resistance of the headlight in each case.
3. A generator at a power station has an output of 100 MW at 132 kV.
   (a) What is the current in the generator?
   (b) What is the daily energy output of the generator in joules and kilowatt-hours?
4. An electric motor draws a current of 10 A when connected to a 120 V supply. Calculate:
   (a) The motor's power consumption.
   (b) The energy used by the motor (in joules and kilowatt-hour) during 5 hours of operation.
5. A house has five rooms, each with a 60-W, 240-V bulb. If the bulbs are switched ON from 7.00 p.m. to 10.30 p.m., determine the power (in kilowatt-hour) consumed per day.
6. A light bulb has a rating of 240 V, 60 W. Determine:
   (a) The amount of current a bulb filament would carry when switched ON.
   (b) The resistance of the bulb filament.
7. In a car electrical system, the battery of an emf of 12.0 V and internal resistance r of 0.05 Ω is connected across a 12 V, 48 W headlight and a starter motor of resistance 0.12 Ω as shown in Figure 2.40.

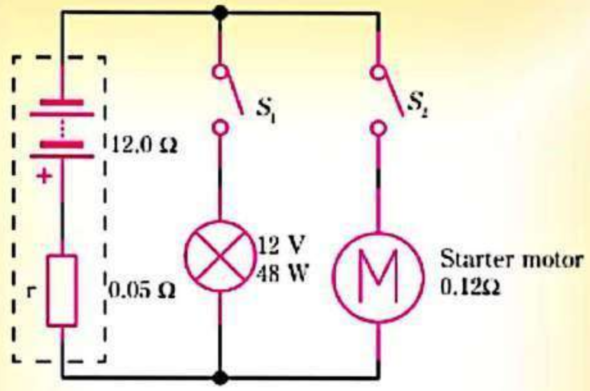


Figure 2.40

(a) State what is meant by "the battery emf of 12.0 V".

(b) What is the resistance of the headlamp when used at its rated voltage?

(c) Assuming that the resistance of the headlamp does not change, and all switches are closed, calculate:

(i) The effective resistance of the circuit.

(ii) The current from the battery.

(d) (i) Show that there is a p.d of 11.8 V across the headlamp when switch S_1 is closed and switch S_2 is open.

(ii) Calculate a p.d across starter motor when both switches S_1 and S_2 are now closed.

Electrical installations

Electricity is a highly convenient and clean source of power. Electricity is supplied in houses by low-resistance wires (copper or aluminium) insulated with rubber. The cables are rated according to the maximum current they can carry.

Live, Neutral and Earth

Domestic electricity is supplied through two cables: the live cable (L), coloured brown or red, and the neutral cable (N), usually coloured blue or black. For a single-phase system, the live cable is at a potential of 240 V relative to the neutral line. The current in the cable alternates 60 times a second (60 Hz). The neutral cable is earthed; it is connected to the ground at the power station. This ensures that even though current flows through this cable, it remains at zero potential. In this situation, it cannot give an electric shock when touched. To provide extra safety, especially in electrical appliances, a third cable called earth (E), coloured yellow or green, is also provided and is earthed by connecting it to the ground via a thick copper rod. This cable connects the metal body of an electrical appliance to the ground through a three-pin plug. A three-pin plug and electrical wiring cables are connected as shown in Figure 2.41.

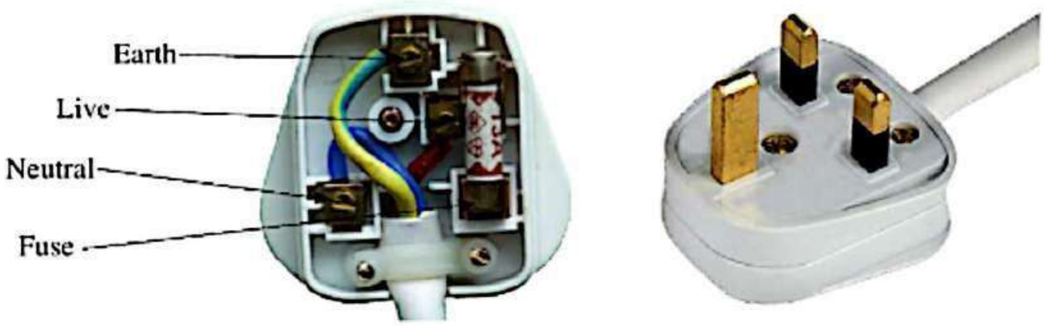


Figure 2.41: *A three-pin plug*

A fuse is connected to the live cable to ensure that if it blows, the appliance's body is cut off from the live electrical connection, preventing potential danger to users. The earth pin on the plug is generally longer than the other two pins, enabling it to open the safety shutter to the terminals of the socket. It also ensures an appliance is earthed before being connected to a power source. When connecting a three-pin plug, the colour code must be strictly adhered to avoid an electric shock. The switch must be OFF when pushing the plug into the socket. The two-pin plug does not have a fuse or an earth pin. Thus, an appliance using a two-pin plug does not have its body connected to the earth. Figure 2.42 shows a two-pin plug. The connections for this plug follow the same colour code as the three-pin plug.

Figure 2.42: *A two-pin plug*

A fuse and a circuit breaker

When an electric current exceeds the rated value of an electrical appliance, it causes damage to the device. To protect an appliance against this damage, a fuse or a circuit breaker is used. A fuse consists of an element, usually a piece of copper or tin-lead alloy wire, that melts when current exceeds a predetermined value. The element is contained in a suitable casing and placed in series with the circuit to be protected.

Fuses are categorised into two types; rewirable fuses and cartridge fuses. In rewireable fuse, the fuse element is carried in a removable fuse link that is made of porcelain or other suitable insulating material. This ensures no danger to an operator when removing the fuse link. Figure 2.43 shows a rewirable fuse.

Figure 2.43: *Rewireable fuse*

Cartridge fuses consist of a porcelain tube with metal end caps attached to the fuse element. Figure 2.44 shows a cartridge fuse.

Figure 2.44: *Cartridge fuse*

Action of a fuse

Blowing (melting) of a fuse occurs when a circuit is overloaded or a short circuit occurs. A short-circuit fault is an unwanted connection allowing current to flow along a path not part of a circuit design. The new path might re-route some or all of the current flows from the designed path. Short-circuit faults can be identified because the circuit or a section of the circuit draws an unusually high current (leading to fuse blowing). The potential difference between two points joined by a short circuit is zero or much lower than expected. Activity 2.13 illustrate melting of fuse.

Activity 2.13

Aim: To demonstrate the melting of a fuse

Materials: two fuse wires 3 A, 3 size-D dry cells, rheostat, ammeter (0 – 5 A), two 2.5 V torch bulbs with bulb holders, connecting wires, switch, crocodile clips

Procedure

1. Connect the apparatus to make a circuit as shown in Figure 2.45.

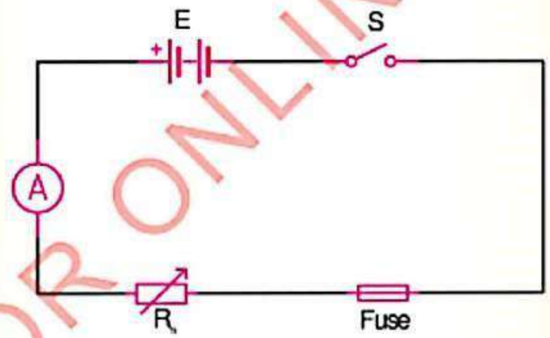


Figure 2.45

2. Start with the rheostat set at maximum resistance.
3. Close the switch and adjust the rheostat to raise the current. Observe both the ammeter and the fuse wire. Continue adjusting until the fuse wire melts. Open the switch.
4. Now disconnect the rheostat from the circuit and replace it with the two 2.5 V torch bulbs, also replace the melted fuse with a new one as shown in Figure 2.46.

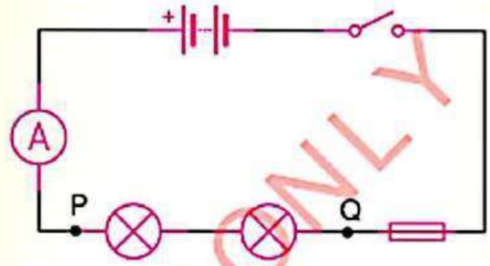


Figure 2.46

5. Close the switch and observe the ammeter reading and the brightness of the bulbs.
6. Short-circuit the bulbs by connecting a lead wire across PQ with crocodile clips. Observe the ammeter reading, the brightness of the bulbs and the fuse wire.

Questions

(a) Determine the current required to melt the fuse in Step 2.

(b) What was your observation on the ammeter reading and the bulbs' brightness when the switch was closed in Step 3?

(c) What was the result of short-circuiting in Step 6?

When a current in the circuit exceeds the current rating of a fuse wire, the fuse wire melts. Putting a lead wire across PQ causes an increase in the ammeter reading. It also causes bulbs to go off. These two observations are an indication of a short circuit. The lead wire across PQ is an unwanted connection which diverts current through a different path. The lead wire has much lower resistance than the bulbs. This results in a large current flow, hence, the melting of a fuse wire.

A circuit breaker like the ones shown in Figure 2.47 is a type of switch that cuts off the flow of current when the current in a circuit exceeds a specific value. It operates by opening the circuit in the event of excess current. Unlike a fuse, a circuit breaker can be reset once the current in a circuit has returned to normal. However, like a fuse, a circuit breaker is connected in series with the circuit it controls.

In a circuit breaker, switch contacts are held closed by a latch mechanism that releases the contacts quickly to open the circuit.

Figure 2.47: Examples of circuit-breakers

Domestic wiring

The power company connects power to a house up to the meter and leaves cables to be connected to the consumer unit where the house wiring starts. A consumer unit is a type of distribution board that distributes electricity from the main supply to separate circuits. From the consumer unit, the cables branch into several parallel circuits which carry current to the various parts of the house. There are two methods of wiring a house from the main switch: the ring and tree systems.

Ring main system. In many houses, the main sockets are connected to a ring main. This cable begins and ends at the consumer unit. It has live, neutral, and earth wires, each forming a ring around the house or part of the house. In a circuit, the current has two parts, so thin cables can be used. The sockets usually have a 30 A fuse at the consumer unit. Figure 2.48 shows a typical ring main circuit.

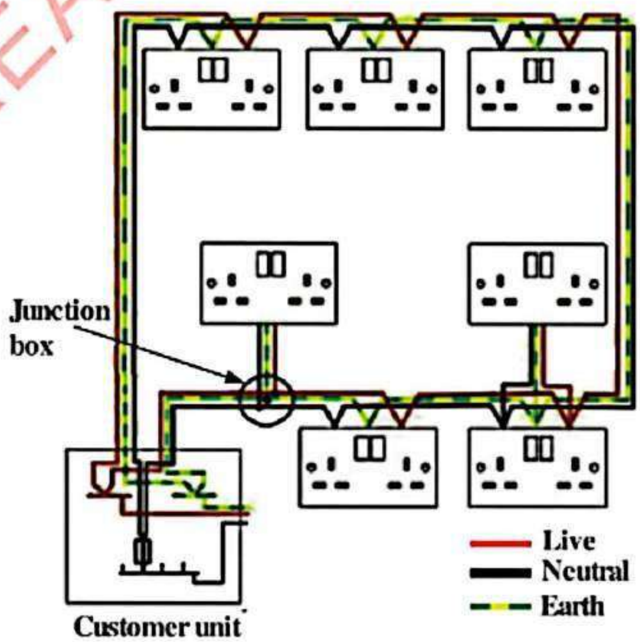


Figure 2.48: Consumer unit and a ring main in a house

The tree system method uses a cable from the main switch to the distribution box as shown in Figure 2.49. Of these two methods of wiring, the ring system is more convenient for wiring modern houses than the tree system.

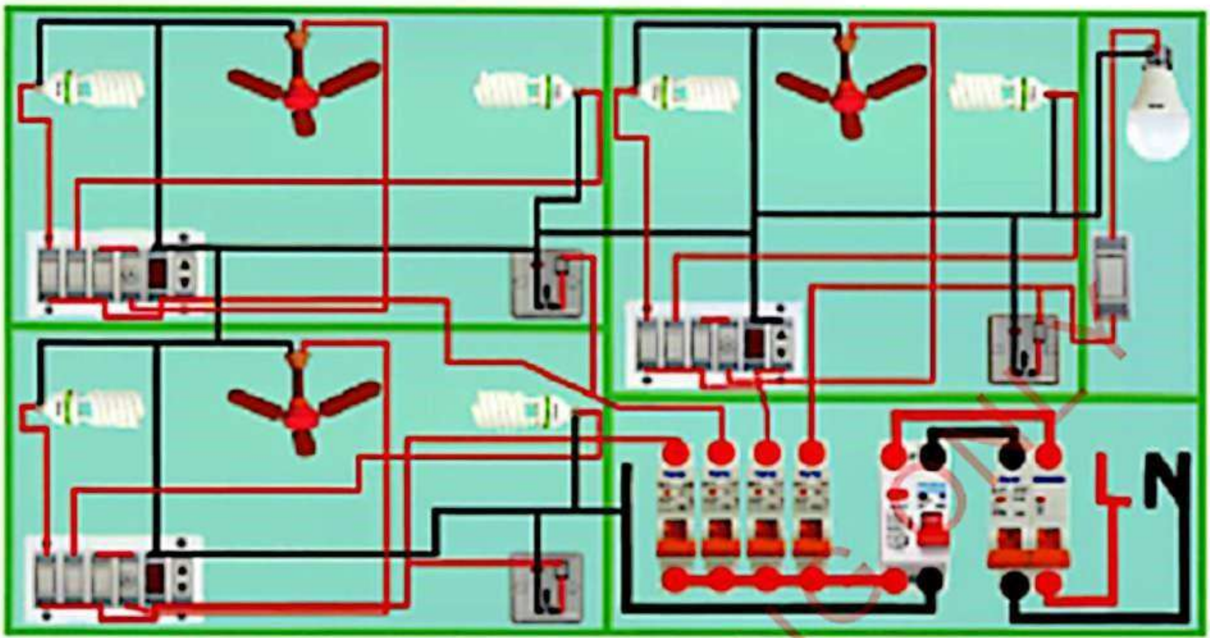


Figure 2.49: *The tree system method of house wiring*

In the distribution box, there are lighting fuses and power fuses. For example, there are separate fuses for lighting in corridors, bedrooms, the living room and the kitchen. Most houses have light fuses rated 5 A and fuses for power sockets usually rated 15 A. Hence, cables for power points are different from those for lights. Lighting circuits control the lighting fixtures in a house. Unlike the ring circuit, the lighting circuit does not form a loop returning to the consumer unit. Instead, the consumer unit is normally connected to the first lamp, which in turn is connected to the second lamp, and so on. There are two types of lighting circuits: loop-in lighting circuits and junction box lighting circuits.

In the loop-in lighting circuit, the live, neutral, and earth wires run from the consumer unit to each of the ceiling designs, one after the other. From each rose, another set of wires runs to the switch, which operates the light. Figure 2.50 illustrates the loop-in circuit.

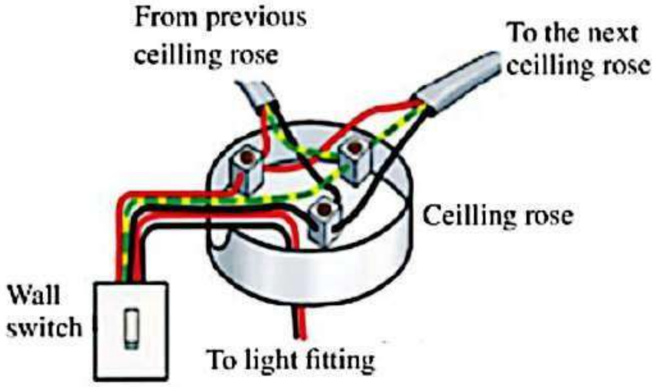


Figure 2.50: *Loop-in circuit*

In the junction box lighting circuit, neutral and earth wires run to one junction box after another. From the junction box, one wire runs to the light and the other runs to the switch for that light. Figure 2.51 illustrates the junction box lighting circuit.

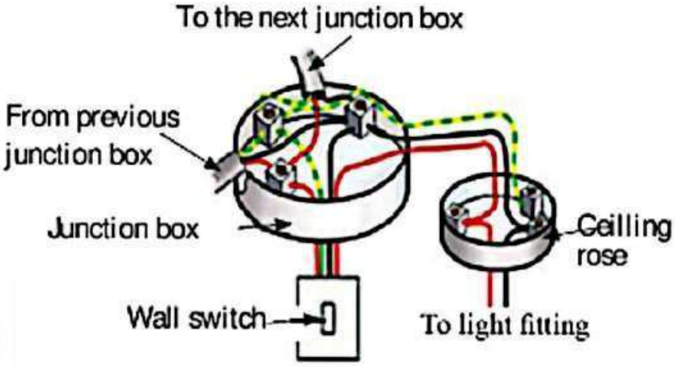


Figure 2.51: **Junction box lighting circuit**

Task 2.4

1. Open up a three-pin plug and fix it to a cable and a fuse. Ask the teacher to check before you close it up.
2. Open the two-pin plug and fix it to the cables as instructed. Ask the teacher to check before you close it up.

Project 2.1

Aim: To demonstrate a ring and tree wiring on an electrical board

Materials: two switches, wire cutters, electrical board, bulb, red or brown, black or blue and yellow or green cables, each about 2 metres long

Procedure

1. Draw a schematic diagram of a ring in the circuit on a sheet of paper. Use the diagram to connect the circuit to the electrical board. Ask your teacher to check your connections before dismantling.
2. Draw a loop-in circuit to carry lamps. Use the diagram to connect the circuit to the electrical board. Ask your teacher to check your connection before dismantling it.

Checking electrical faults in domestic appliances

Identifying electrical faults in domestic appliances is essential for ensuring safety and optimal performance. Common issues like short circuits and faulty wiring can lead to malfunctions and pose hazards, making regular inspections and maintenance crucial. Two devices are useful when checking electrical appliance faults. These are the multimeter and the live mains lead indicator. Multimeters are tools used for measuring a variety of electrical variables. The most basic parameters measured are voltage and current (both a.c and d.c.). They also have a range switch so that precise readings can be taken. There are moving coils and digital multimeters. The moving-coil multimeters (analogue) (Figure 2.52 (a)) have some disadvantages as they involve various settings when in use. The digital multimeter (Figure 2.52 (b)), has no moving parts, thus, easy to use.

(a) Analogue (b) Digital

Figure 2.52: **Multimeters**

The live mains lead indicator, commonly called a tester, is made up of a form of a screwdriver with a hollow insulating handle containing a tiny neon discharge tube. One electrode of the neon tube is usually in contact with the metal probe of the screwdriver. The other is connected to the metal cap of the handle through a high-carbon resistor. When one inserts the metal probe into a live socket and touches a metal cap with a finger, current leaks to the earth through the body and the neon tube glows. Owing to the high resistance, this current is very low, so there is no risk of electric shock. Figure 2.53 shows a typical tester.

Figure 2.53: *Live mains lead indicator(tester)*

Most of the faults that occur in electrical appliances are simple and can be repaired easily. If, for example, an electric kettle fails to work, the first thing to check is whether there is power in the socket. This is done using the tester. The next step is to check the cable from the socket to the appliance. The plug should be opened to check the fuse if no fault is detected. Also, check each cable for continuity using a multimeter. If these components function correctly, the heating element is the next thing to check for faults. This can be checked for continuity or short circuits using a multimeter.

If the element is faulty, it must be replaced, as repair may not be possible. If the element is not faulty, then look for loose connections. Connections should be made firm and/or cleaned of rust and other dirt.

Repairs in electrical appliances should be limited to connections to the power supply only. Beyond that, an electrical technician should be consulted. Care should be taken to avoid electric shocks during such repairs. Simple repairs on electrical connections in a domestic system can also be carried out. When a fuse blows, it is very likely to be due to a fault in an appliance. If the fault is detected and corrected, then the fuse can be replaced (or the circuit breaker switched ON).

Other faults occur due to wire cutting or joining, sockets getting dirty and switch breakage. All repairs should be done with the mains switched OFF. When replacing switches and sockets, the colour code should be followed strictly.

Exercise 2.4

1. Explain the properties and functions of a fuse. How does a fuse in a lighting circuit differ from that in a heating or power circuit? What is the importance of using a fuse in an electrical appliance?
2. (a) A refrigerator is marked 250 V; 400 W. Calculate the maximum current that can flowthrough it.

(b) Discuss what might happen to the refrigerator if it is connected to a supply of:
   (i) 280 V.
   (ii) 110 V.

3. (a) Why are the electrical appliances earthed?
   (b) Explain the precautions to take during electrical wiring of a house.
   (c) Describe how electricity from a fuse box is distributed to other parts of a house.
4. (a) Explain briefly why most plugs have three pins.
   (b) In a three-pin plug, we find wires labelled N, L and E:
      (i) What do these letters mean?
      (ii) At present, what is the internationally accepted colour for wires labelled N, L and E?
5. Give the differences between the tree system and ring system methods of wiring a house.
6. Why is the earth thicker and longer in a three-pin plug?

Cells

A cell is a set-up used to cause a flow of electric current in a conductor. The flow of current is caused by reactions releasing and accepting electrons at different ends of a conductor. There are two common types of electrochemical cells, namely primary cells and secondary cells.

Primary cells

Primary cells, also known as voltaic cells, are formed by dipping two different electrodes (usually made of metals) into an electrolyte. In a primary cell, reactants are used up after some time and must be replaced. Figure 2.54 shows features of a simple primary cell.

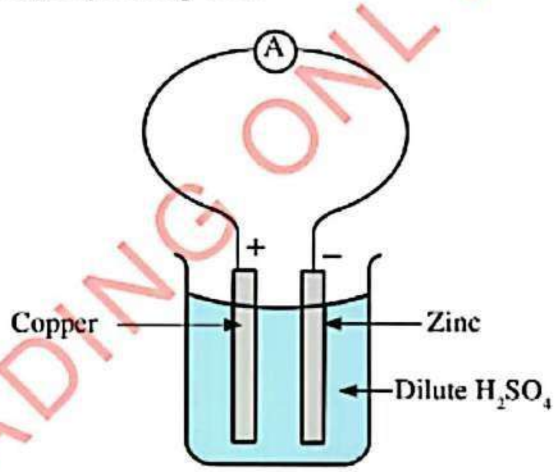


Figure 2.54: **A simple cell**

Electrodes of a simple cell can be made of copper (positive) and zinc (negative) while an electrolyte is dilute sulphuric acid.

The following are the processes that occur when the cell is in operation:

The dilute sulphuric acid ionises into sulphate ions (SO_4^{2-}) and hydrogen ions (H^+):

$$H_2SO_4 \rightarrow 2H^+ + SO_4^{2-}$$

Zinc goes into solution as zinc ions (Zn^{2+}), releasing two electrons which travel along the wire (external circuit) to the copper electrode. The zinc ions combine with the sulphate ions to form zinc sulphate $(ZnSO_4)$. At the same time when zinc ions go into solution, an equivalent number of hydrogen ions move to the copper electrode where they gain electrons and are liberated as hydrogen gas (bubbles):

$$2H^{+} + 2e^{-} \rightarrow H_2(g)$$

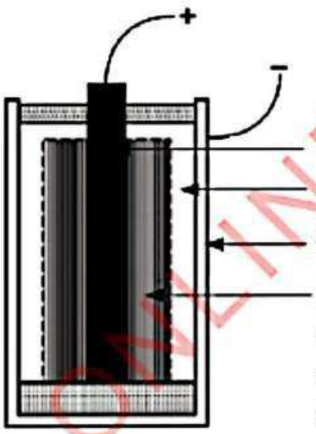
By losing electrons, copper becomes positively charged and enables it to attract electrons from Zinc through connecting wire. This movement of electrons through the wire is called the electric current.

The conventional direction of electric current is from the positive terminal to the negative terminal of the cell, which is the opposite of the direction of flow of electrons.

Mode of action of a dry cell (Leclanché cell)

The Leclanché cell consists of carbon as a positive electrode and zinc as a negative electrode. The electrolyte in this cell is ammonium chloride (NH_4Cl) (Sal-ammoniac)

The dry cell is a modified Leclanché cell in which the main electrolyte can be a liquid or a paste. If the electrolyte is a liquid, the cell is said to be a wet cell. Thus, the Leclanché cell is wet. If the electrolyte is a paste, the cell is referred to as a dry cell. Figure 2.55 Shows internal structure of a dry cell and an assortment of dry cells.



(a) Internal structure

(b) Assortment of dry cells

Figure 2.55: *Dry cells*

The components of a dry cell are the same as those of the Leclanché cell, except that instead of ammonium chloride solution, a cell is filled with a paste of manganese dioxide, ammonium chloride and zinc chloride. The two salts (ammonium chloride and zinc chloride) act as the electrolyte. The negative electrode (zinc) is the one containing the electrolyte and depolarizer.

Arrangement of cells in series and parallel

Cells are often used in combination. A battery is formed when two or more cells are connected. Cells can be connected in either series or parallel.

Cells in series

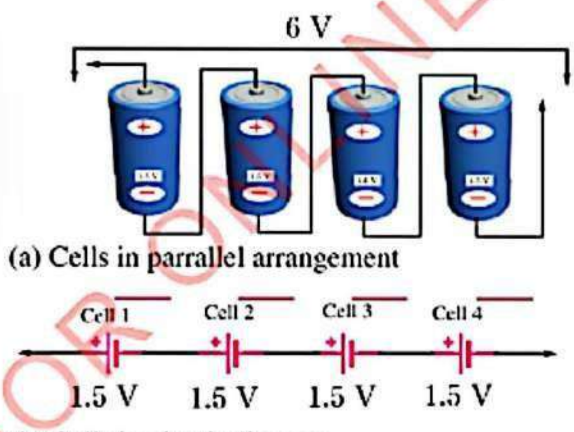
To obtain a larger e.m.f, cells are arranged in series as shown in Figure 2.56. The current flowing through the cells is the same. The total voltage E_T across the cells is equal to the sum of the voltage of the individual cells. This is:

$$E_T = E_1 + E_2 + E_3 + E_4$$

The total voltage, E_T for cell arrangements in Figure 2.56 is;

$$E_T = 1.5\ V + 1.5\ V + 1.5\ V + 1.5\ V = 6\ V$$

In the case of n cells, each of volts E, $E_T = nE$.



(a) Cells in parrallel arrangement

(b) Cells in circuit diagram

Figure 2.56: *Cells in series*

If cell 3 is reversed in Figure 2.56, then the equivalent e.m.f. is given by,

$$E_T = E_1 + E_2 + E_3 + E_4$$

$$E_T = 1.5\ V + 1.5\ V - 1.5\ V + 1.5\ V = 4.5\ V$$

Therefore, $E_T = 4.5\ V$.

The sum of individual internal resistances, r equals total internal resistance, r_T. If the four cells in Figure 2.56 are identical and have the same e.m.f and internal resistance, then,

$$r_T = r_1 + r_2 + r_3 + r_4$$

$$r_T = 1\ \Omega + 1\ \Omega + 1\ \Omega + 1\Omega = 4\ \Omega$$

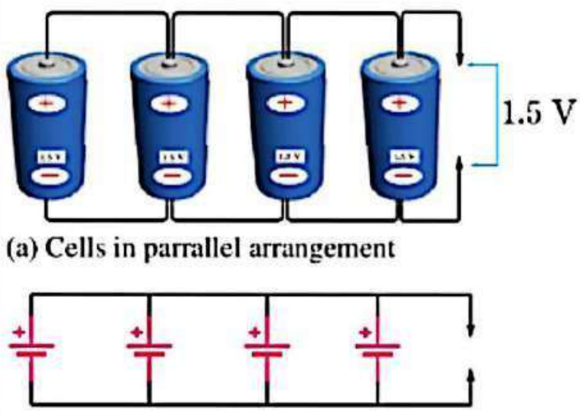
where $r_1 = r_2 = r_3 = r_4$

In the case of n cells:

$$r_T = nr$$

Cells in parallel

Suppose four identical cells, each of e.m.f. 1.5 V and internal resistance 1 Ω, are arranged in parallel as shown in Figure 2.57. The total e.m.f. recorded when a voltmeter is connected to terminals P and Q is the e.m.f of one of the four cells. This is because the four cells operate together as a single cell whose component materials are the sum of those in the individual cells. This is because the e.m.f. of a cell is determined by the nature of the chemicals used and not by their amount. As a result, the e.m.f. equals that of one of the cells.



(a) Cells in parrallel arrangement

(b) Cells in circuit diagram

Figure 2.57: *Cells in parallel*

The internal resistance of the battery is different from that of a single cell. In this case, the internal resistances of four cells are parallel, as shown in Figure 2.57. As a result, the total internal resistance is given by,

$$\frac{1}{r_T} = \frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3} + \frac{1}{r_4}$$

$$\frac{1}{r_T} = \frac{1}{1\,\Omega} + \frac{1}{1\,\Omega} + \frac{1}{1\,\Omega} + \frac{1}{1\,\Omega} = \frac{4}{1\,\Omega}$$

$$\frac{1}{r_T} = \frac{4}{1\,\Omega}$$

$$r_T = 0.25\ \Omega$$

Thus, the battery has an e.m.f. of 1.5 V and an internal resistance of $0.25\,\Omega$.

Example 2.7

Determine the voltage across AB in the circuit shown in Figure 2.58.

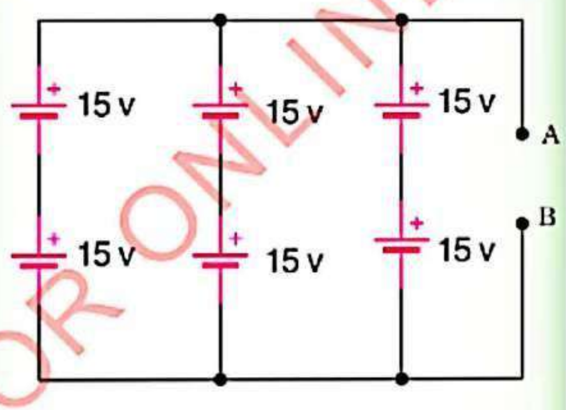


Figure 2.58

Solution

Note that, all the internal loops are connected in series while the external loops are connected in parallel.

For the internal loops, the total voltage in each loop = (1.5 + 1.5) V = 3 V. This means that the external loop is made up of 3 batteries, each with a voltage of 3 V. The total voltage (across AB) is the same as that of a single battery (3 V).

Cell defects

When the simple cell is in operation, the current drops to a very small value after some time. A simple cell has two main defects which cause the current to diminish quickly when the cell is being used. These defects are local action and polarization.

Local action

The local action of a cell is the deterioration of the battery due to currents that are flowing from and to the same electrode. The deterioration is caused by embedded impurities such as iron, lead and carbon in a zinc electrode. The impurities act as positive electrodes and create electric currents between zinc and this positive (impurities) electrode. Local action can be reduced by using pure zinc or by rubbing mercury on the zinc plate to form an amalgam.

Polarization

Polarization is a defect that occurs in simple electric cells due to the accumulation of hydrogen gas around a positive electrode. The hydrogen gas produced in chemical reactions inside the cell can accumulate around the electrodes resulting in insulation. Polarization in cells can be minimized using depolarizers such as potassium dichromate or manganese oxide, which oxidizes hydrogen to water. Simple cells, Daniel and Leclanché cells, are all called primary cells. In this type of cell, the current is produced from non-recoverable or irreversible chemical reactions. For example, when all zinc has been dissolved in a simple cell, it will never be recovered to its original form by passing a current through the cell in the opposite direction.

Secondary cells

Unlike primary cells, secondary cells can be recharged after they have run down. Examples of secondary cells are the lead-acid cell and the nickel-ferrous cell. Secondary cells are also called accumulators.

Mode of action of lead-acid accumulator

The lead-acid battery consists of several lead-acid cells. Each cell has two groups of lead plates. One group forms a positive terminal while the other group forms a negative terminal. All positive terminal plates are connected with a connecting strap. This is also the case for negative terminal plates. The positive and negative terminal plates are connected so that they alternate. Between the plates are sheets of insulating material called separators. These are made up of porous wood or fibreglass. The separators prevent the positive and negative plates from coming into contact thereby avoiding the production of a short circuit. The positive plates are made of lead dioxide while the negative plates are made of porous lead metal. The two sets of plates with the separators between them are placed in a container filled with a dilute solution of sulphuric acid. The term lead-acid refers to the lead plates and the sulphuric acid which are the main components of the battery. Figure 2.59 illustrates the components of the lead-acid accumulator.

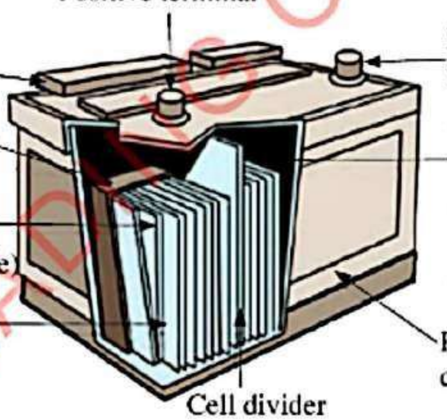


Figure 2.59: *Lead-acid accumulator*

Charging and discharging the lead-acid battery

When the battery is providing energy, it is said to be discharging. The energy is produced when the acid (electrolyte) gradually combines with the active material of the electrodes. This lowers the concentration of sulphuric acid.

Charging the lead-acid battery is to drive all the acid out of the plates and return it to the electrolyte. During charging (Figure 2.60(b)), a direct current is passed through the battery in the opposite direction to that during the discharge (Figure 2.60(a)). The negative terminal of the battery charger is connected to the negative terminal of the battery, while the positive terminal of the charger is connected to the positive terminal of the battery. This reverses the action of discharge and restores the battery to its original charged condition. When the battery is fully charged, the active material of the positive plates is lead peroxide while that of the negative plate is porous lead metal. The concentration of the acid is maximum in the charged state.

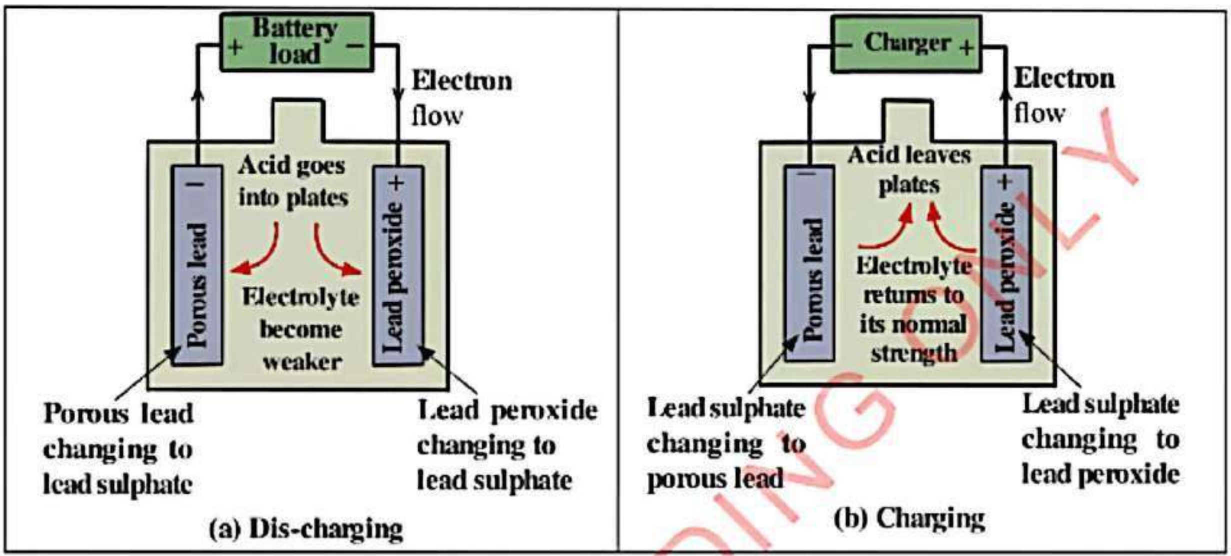


Figure 2.60: Lead-acid battery

If the battery is only partially discharged, it can be recharged using a battery charger as shown in Figure 2.61(b). Lead-acid batteries should never be allowed to become completely discharged. The maximum recommended discharge is 75% of the maximum voltage depending on the type of the battery. When the battery is completely discharged, both electrodes are completely converted to lead sulphate. In this state, the battery is said to be sulphated, meaning that it will no longer function as it cannot be recharged. The main advantage of the lead-acid accumulator is its ability to be recharged. Its major disadvantages are its large size and weight. Activity 2.14 demonstrates on how one can charge and discharge a lead-acid cell.

Activity 2.14

Aim: To charge and discharge a lead-acid cell

Materials: power pack (or a pack of 4 dry cells), two lead plates (3 cm × 5 cm each), dilute sulphuric acid, rheostat, ammeter, bulb, voltmeter, connecting wires, switch

Procedure

1. Connect a circuit as shown in Figure 2.61.

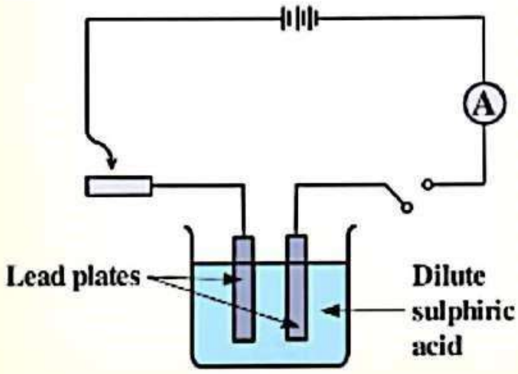


Figure 2.61

2. Close the switch and adjust the rheostat so that the reading on the ammeter is 1.5 A. Let the current flow for about one minute.
3. Open the switch and use the voltmeter to measure the potential difference across the plates.
4. Connect a 2.5 V bulb across the plates and observe its brightness.
5. Disconnect the circuit, pull out the plates and note the colour of both the positive and the negative plates.

Questions

(a) What was the voltage across the lead plates when a 1.5 A current was allowed to flow for one minute?
(b) What was the colour of each plate at the end of an experiment?

The plates produce a potential difference of approximately 2.0 V or slightly more after running a constant current for a short time. For a short period of time, this voltage causes the bulb to glow brightly. The plate that is linked to the positive terminal of a power source becomes the positive terminal of this cell. The cell is being charged when the current passes through the plates. The positive plate changes its colour to brownish red. This is due to lead dioxide (or red lead) which is formed from lead during the charging process.

Lead-acid accumulators are commonly used as car and photovoltaic system batteries. Although it is rechargeable, the accumulator does not last forever. After some time, the cells can no longer be recharged. If well taken care of, however, lead-acid batteries can last for a long time. The following are some guidelines on how to care for lead-acid batteries:

1. The cells should be charged regularly and should never be left discharged. Cars have alternators that automatically charge the batteries.
2. The acid level should be maintained by adding distilled water when necessary. Never add acid.
3. The terminals should be kept clean and greased.
4. Rough handling should be avoided, for example, dropping the battery down.
5. The cells should not be short-circuited, that is, they should not be allowed to drive very large currents.
6. When charging, the rate specified by the manufacturer should not be exceeded.

Uses of cells and accumulators in daily life

The following are some of the uses of cells and lead-acid batteries:

Dry cells are used for operating radios, electronic calculators and other small electrical devices. On the other hand, accumulators offer a lot of use in our daily life as follows:

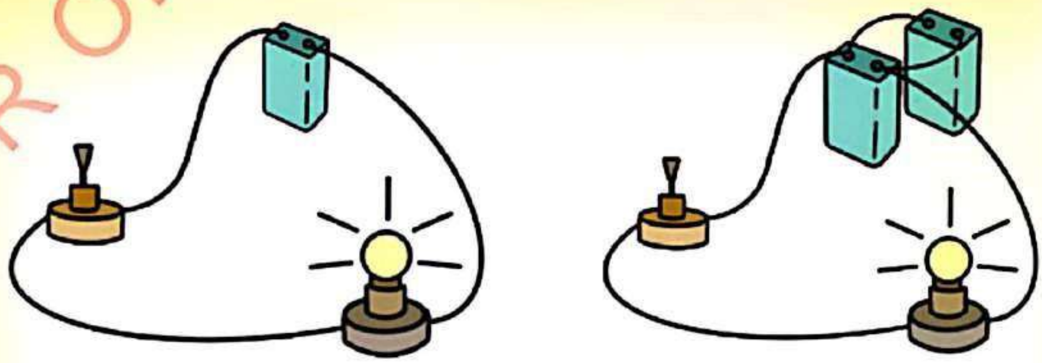
1. They are used to provide power to motor vehicles. Figure 2.62 shows a typical car battery.

Figure 2.62: *A car battery*

2. They are used to provide energy to power domestic appliances such as radio, television and lighting fixtures.
3. They are used to store electrical energy produced by solar panels.

Exercise 2.5

1. With the aid of a diagram and chemical equations, describe the construction and operation of a simple cell.
2. State the defects of a simple cell and explain how these defects can be minimised.
3. Describe, with the aid of a diagram, the construction of a typical lead-acid accumulator.
4. Use appropriate diagrams to illustrate how an accumulator may be charged and discharged.
5. Three cells of e.m.f 1.5 V, 1.6 V, and 1.3 V are connected in series to supply current to an external resistor of 1.6 Ω. The internal resistances of the three cells are 0.26 Ω, 0.35 Ω and 0.42 Ω, respectively. Determine the current through an external resistor.
6. Four cells each of e.m.f 1.48 V and internal resistance 0.51 Ω are connected in parallel across an external resistor of 2.6 Ω. Determine the current supplied by the battery.
7. Figure 2.63 (a) and (b) show two identical bulbs connected to one cell and two dry cells respectively. The bulb connected to two dry cells lights up brighter



(a) (b)

Figure 2.63

(a) What is meant by the value "9 V" labelled on the dry cell?
(b) Explain why the bulb connected to two dry cells is brighter.

Uses of current electricity in daily life

Domestic use of current electricity

Electricity is essential for domestic tasks like cooking, preserving food, and doing laundry. It powers appliances such as stoves, refrigerators, washing machines, and irons. It also provides lighting, entertainment through TVs and computers, and comfort using fans, heaters, and air conditioners. Other common devices include kettles, vacuums, and hairdryers.

Transport use of current electricity

Current electricity is used in transportation to power various electric vehicles. For example, standard gauge railway trains use electricity for efficient and eco-friendly travel. Additionally, electric cars like the Tesla Model 3, electric buses in urban areas, trams in cities, and electric scooters also rely on current electricity for operation. Figure 2.64 shows a train which use electricity for transportation.

Figure 2.64. *Standard Gauge Railway electric train.*

Industry use of current electricity

Industries use current electricity to power machines and equipment essential for manufacturing and production. For example, textile mills use electric looms, car factories operate robotic arms and conveyor belts, and food processing plants run mixers and packaging machines. Welding machines, and electric drills also rely on current electricity.

Project 2.2

In groups, identify 3 other uses of current electricity apart from what is mentioned in this part.

Chapter summary

1. Electromotive force (e.m.f), is the maximum potential difference between two terminals of a battery or a cell when no current is drawn from the battery or cell. In other words, it is the electrical intensity or pressure developed by a source of electrical energy.
2. Electric potential difference (p.d) is the work done per unit charge in moving the electric charge from one point to another point of a conductor.
3. Electric current, I, is defined as the rate at which electric charge, Q, passes a given point by a unit of the ampere, A, and is measured by an instrument called an ammeter.
4. Resistance is the opposition to the flow of electric current in a conductor. It is measured in ohms (Ω).
5. The resistance of a conductor is affected by: temperature, its length, cross-sectional area and material of the conductor.
6. When resistors are connected in series, the total resistance in the circuit is equal to the sum of the individual resistances.
7. When resistors are connected in parallel, the reciprocal of the total resistance is equal to the sum of the reciprocals of the individual resistances.
8. When an electric current flow through a conductor of high resistance, the electrical energy gets converted into thermal energy and heats the conductor. This is known as the heating effect of an electric current.
9. Every electrical appliance should carry a label stating the potential difference for which it has been designed and the power it can convert when operating at the stated potential difference.
10. Electricity is supplied in consumers' places by low-resistance wire made up of either copper or aluminium material insulated with plastic.
11. The wires used in electrical installation are rated according to the maximum current they can carry.
12. Domestic electricity is supplied by two cables; the live cable (L), coloured brown or red, and the neutral cable (N) usually coloured blue or black.
13. The rate at which an appliance dissipates energy is called the rating of that appliance and is usually marked on the body of the appliance.
14. There are two common types of electrochemical cells, namely primary and secondary cells.
15. The total voltage across cells connected in series is equal to the sum of the voltages of the individual cells while in parallel connection, the effective voltage is equal to the voltage of one of the cells (for identical cells).

Revision Exercise 2

1. For each of the items (i) - (iv), choose the correct answer among the given alternatives and write its letter.

(a) The given circuit diagram in Figure 2.65 is for the experiment to determine the equivalent resistance of two resistors connected in series. The components X, Y and Z shown in the circuit respectively represent.

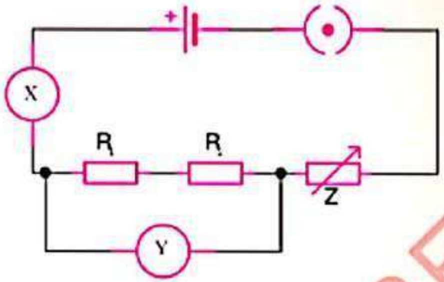


Figure 2.65

(i) Rheostat, resistor, ammeter
(ii) Voltmeter, ammeter, rheostat
(iii) Ammeter, voltmeter, rheostat
(iv) Rheostat, ammeter, voltmeter

(b) The electric current as a function of voltage across a resistor is presented by the graph in Figure 2.66. What is the resistance of the wire?

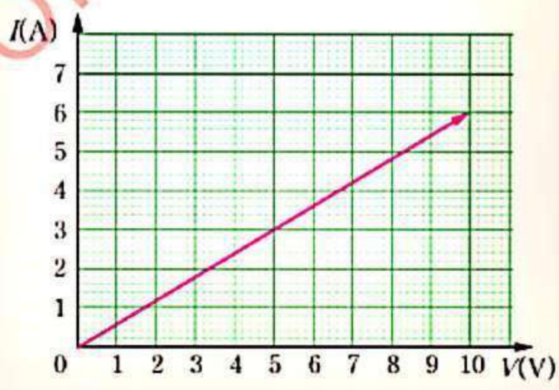


Figure 2.66

(i) 1 Ω (ii) 0.8 Ω
(iii) 1.7 Ω (iv) 0.4 Ω
(v) 0.2 Ω

(c) What is the power dissipated in the resistor in revision exercise 1 (b) when the applied voltage is 5 V?

(i) 5 W (ii) 10 W
(iii) 15 W (iv) 20 W
(v) 25 W

(d) Three resistors: $R_1 = 3\ \Omega$, $R_2 = 6\ \Omega$, and $R_3 = 9\ \Omega$ are connected in series and to a 36 V battery as shown in Figure 2.67. What is the ammeter reading when the switch is closed?

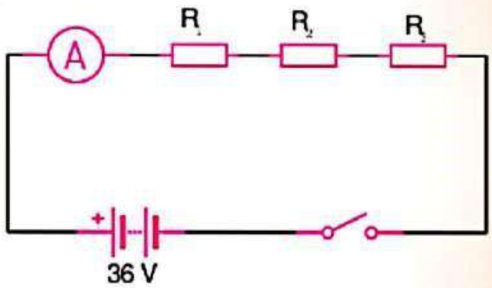


Figure 2.67

(i) 6 A
(ii) 5 A
(iii) 4A
(iv) 2 A

2. A child, while inserting an electric plug into the socket, did not see that there was a thin piece of aluminium foil stuck between the pins of the plug. When he turned the switch on, he noticed a spark at the plug, and at the same time, the lights went out. What could have happened to cause the spark and to make the lights go out?

3. Calculate the resistivity of a wire of length 2 m and cross-sectional area 0.004 cm^2 if its resistance is 3.0 ohms.
4. When a 6 V battery is connected to a lamp, a current in the circuit is measured to be 0.4 A. What is the resistance of the lamp?
5. The e.m.f of a cell is 9 V. How much work is required to move one electron from the negative terminal to the positive terminal? Ignore the internal resistance of the cell.
6. A bulb with a resistance of 5 Ω is connected to an 8 V battery. If the internal resistance of the battery is neglected:
   (a) How much current will flow through the bulb?
   (b) How much light and heat energy does the lamp produce in one hour?
7. (a) Look at the following photo of a light bulb in Figure 2.68. Label the filament and explain why it glows.

Figure 2.68

   (b) A 12 V battery is connected to two bulbs as shown in Figure 2.69.

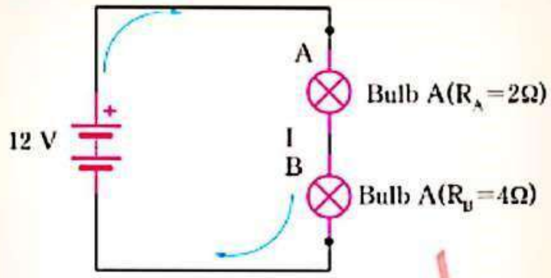


Figure 2.69

   Determine the voltage across:
   (i) bulb A.
   (ii) bulb B.
   (c) How much current will flow in the circuit?
8. A 12 V battery is connected to two bulbs as shown in Figure 2.70.

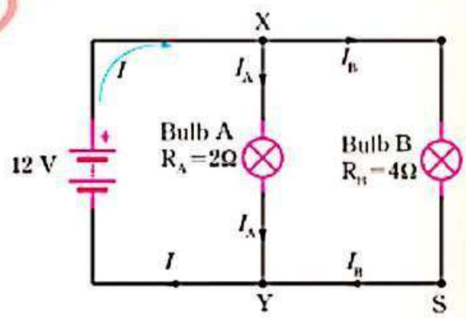


Figure 2.70

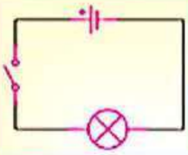
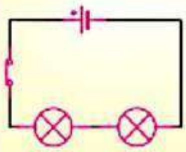
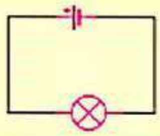
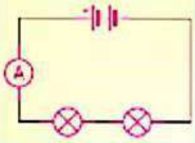
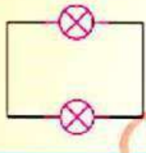
   (a) What is the voltage across:
   (i) bulb A?
   (ii) bulb B?
   (b) What is the current flowing through:
   (i) bulb A?
   (ii) bulb B?
   (c) What is the total current, I?
9. (a) What is the benefit of using a circuit breaker rather than a fuse?
   (b) An electrician wants to replace a faulty fuse with a normal piece

of conducting wire. Should you let him? Why or why not?

10. A wire of length 28 cm and radius 0.75 mm is wound around a cylindrical tube to form a solenoid. If the resistivity of the wire is 5.6×10^{-8} Ω m, Calculate its resistance.

11. Three identical resistors each with a resistance of 10 Ω are connected in series to a 12 V battery with an internal resistance of 2 Ω:
    (a) What is the total resistance of the circuit?
    (a) How much power is supplied by the battery?
    (b) How much power is dissipated in each of the external resistors?
    (c) How much power is dissipated by the battery's internal resistance?

12. Look at the circuits below. If the bulb(s) will glow, place a tick next to the picture and explain why it will glow. If the bulb(s) will not glow, place a cross next to the picture and explain why it will not glow.

Circuit	Glow/ Not Glow	Explanation
		
		
		
		
		

13. The diagram in Figure 2.71 shows an electric circuit containing three resistors.

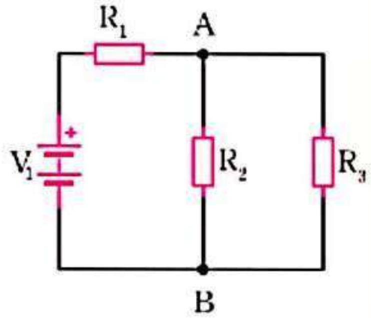


Figure 2.71

Given that, the battery has a voltage of 24 V and a negligible internal resistance and that
$R_1 = 5$ Ω, $R_2 = 10$ Ω, $R_3 = 10$ Ω
determine:
(a) the total resistance in the circuit.
(b) the current that flows through R_1.
(c) the current that flows through R_2.
(d) how much current flows through R_3.
(e) the potential difference between points A and B.

14. Figure 2.72 shows three resistors connected in parallel to a cell with negligible internal resistance.

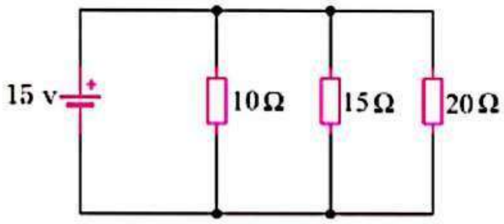


Figure 2.72

(a) What is the total resistance in the circuit?

(b) What is the total current flowing in the circuit?

(c) What current flows in each resistor?

(d) How much power is supplied by the battery?

(e) How much power is dissipated in each resistor?

15. An electrical circuit in a domestic house is protected by a 6 A fuse. The circuit is connected to the 240 V mains. The following appliances in Table 2.11 are connected to the circuit.

Appliance	Bulb 1	Bulb 2	TV	Heater	Iron
Power rating (W)	100	75	300	1500	900

List several groups of these appliances that could be turned ON at the same time without blowing the fuse. Justify your answer.

16. Look at the circuit diagram in Figure 2.73. Each light bulb is identical.

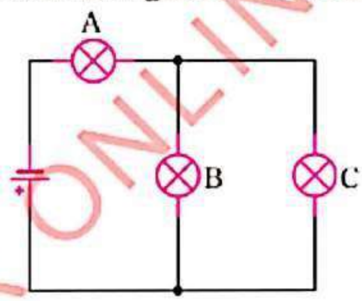


Figure 2.73

(a) Is this a series or parallel circuit? **Explain your answer.**

(b) How do the brightness of bulbs A, B and C compare? (which is the brightest?)

(c) What would happen to the brightness of the bulbs if the switch was opened? Explain **your answer.**

17. Study the following diagram of Figure 2.74.

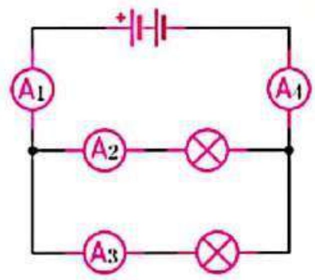


Figure 2.74

(a) What is the relationship between the ammeter readings on A1 and A4? **In other words, how do the current strengths compare at these points in** the circuit? Explain your answer.

(b) What is the relationship between the ammeter readings on A_1, A_2 and A_3? In other words, how do the current strengths compare at these points in the circuit? Explain your answer.

Chapter Three

Magnetism

Introduction

Knowledge of magnetism has provided several useful applications in daily life, starting from the historical navigation by the Greeks to the present-day digital world. In this chapter, you will learn the concept of magnetism and how materials can be magnetised or demagnetised. You will also learn about magnetic fields, including the Earth's magnetic field. The competencies developed will enable you to apply the knowledge of magnetism in various contexts.

Think

Life without the existence of magnetism

Concept of magnetism

Magnetism is a phenomenon produced by the motion of electric charges that results in an attractive and repulsive force between objects. The earliest observation of magnetism was recorded in 600 BC by the Greek philosopher Thales. He observed that pieces of iron were attracted to a natural mineral iron ore called magnetite. The lodestone is an example of a magnetised piece of the mineral magnetite. Figure 3.1 shows an iron ore.

Figure 3.1: *Iron ore*

The lodestone tends to attract certain metals more strongly at specific points on its surface than others. Any material that has properties similar to those of the lodestone is called a magnet. When magnets attract or repel each other, they exert a force called magnetic force. Magnetism arises from two types of electron motion as shown in Figure 3.2. The first is the motion of electrons around the nucleus of an atom. The second type of motion is the spin of electrons about their axes. These motions of charged particles independently impart a magnetic effect, causing an atom to behave like a tiny magnet.

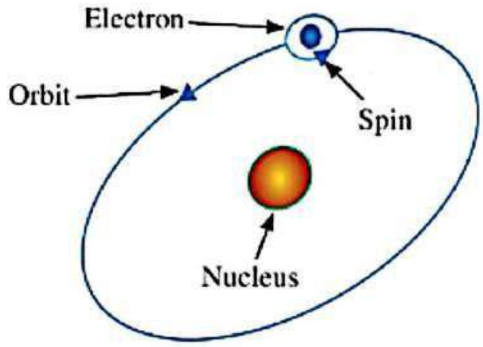


Figure 3.2: *Orbit of a spinning electron around the nucleus of an atom*

In many atoms, these magnetic effects cancel each other, while in other atoms they do not cancel completely.

Magnetic and non-magnetic materials

When a magnet is brought near different objects, some will be attracted or repelled, and others will not. Objects that are attracted are said to possess induced magnetism. The process by which a material becomes a magnet due to its closeness or contact with a magnet is called induction. The induced magnetism can be temporary or permanent upon the removal of the magnet in contact. The nature of the material being magnetised determines how long the induced magnetism lasts. For example, iron exhibits temporary magnetism while materials like steel tend to retain their magnetism for a long time. Materials which are not affected by a magnet are called non-magnetic materials.

Activity 3.1

Aim: To classify magnetic and non-magnetic materials

Materials: bar magnet, knife, blade, copper rod, paper, glass rod, iron nail, water, wooden toothpick, chalk, aluminium foil, lead (graphite) pencil, some sand

Procedure

1. Place each of the materials close to a bar magnet.
2. Note down your observations.

Questions

(a) Which materials were attracted to the magnet, and what do they have in common?
(b) Why do you think some metals are attracted to the magnet while others are not?
(c) Based on your observations, how can you classify magnetic and non-magnetic materials?

Metallic materials like iron, nickel and cobalt become magnetised when exposed to the influence of a magnet. They are thus magnetic. Magnetic materials are those which can be magnetised by even weak magnets. Materials that are attracted to a magnet and can be strongly magnetised are called ferromagnetic materials. Ferromagnetic materials contain either iron, nickel or cobalt. These materials are grouped as magnetically hard or soft depending on how well they retain their magnetism when magnetised.

Magnetically hard materials such as steel do not readily lose their magnetism, though they are difficult to magnetise. They are used to make permanent magnets. On the other hand, soft magnetic materials like iron can be easily magnetised, but they tend to lose their magnetism easily. As a result, they are used in the cores of electromagnets and transformers. Brass, copper, tin, zinc and aluminium are non-magnetic materials. These materials are not attracted by a magnet. Non-metals, for example, plastic, rubber, water, wood and ceramics are also non-magnetic. These materials cannot be magnetised.

Types of magnets

Magnets are categorised according to their sources of magnetism. They include:

1. **Temporary magnets.** These acquire magnetism due to an applied external magnetic field but lose their magnetism when the external field is removed. These magnets retain magnetism in a short time (i.e., the time during which the magnetising field is present). For example, the magnetism that is induced in iron is temporary and is lost once the external magnet is withdrawn. Iron nails and paper clips shown in Figure 3.3 (a) are good examples of objects that can be temporarily magnetised. An electromagnet used in magnetic cranes, as shown in Figure 3.3 (b), is an example of a temporary magnet.

(a) Iron paper clips and nails

(b) Magnetic crane

Figure 3.3: **Temporary magnets**

Other examples of temporary magnetism are **electromagnets**. These are temporary magnets created by an electric current flowing through a coil, often with an iron core to enhance the magnetic field. They can be quickly turned on and off, and their magnetic strength can be adjusted by changing the current. However, they require a continuous power supply to maintain magnetism, which disappears when the current stops. Electromagnets are widely used in applications needing strong, controllable magnetic fields, such as railroad tracks, electric motors, microphones, hard drives, MRI machines, security systems, cranes, and various computer and television hardware.

Figure 3.4: **Electric Motor**

2. **Permanent magnets**. These retain some magnetism even after the external magnetic field is removed. Such materials include an alloy composed of aluminium, nickel and cobalt (Alnico), or ceramic-like material made from a mixture of iron oxides with nickel, strontium, or cobalt (ferrites) that become magnetised in a magnetic field. These magnets may be naturally occurring "rare earth" elements or chemical compounds. An example of a permanent magnet is the bar magnet shown in Figure 3.5.

Figure 3.5: *Bar magnet*

Properties of magnets

When you closely examine a bar magnet, you see one end marked N and the other end marked S. Every magnet, regardless of its shape and size, has two poles. N represents a North pole and S represents a South pole as shown in Figure 3.6.

Figure 3.6: *Bar magnet showing the N and S poles*

These poles are always marked during the process of manufacturing for easy identification. Colouring is also used to mark the poles as shown in Figure 3.6.

Activity 3.2

Aim: To investigate the properties of magnets

Materials: bar magnets, block of wood, iron filings, water, string, compass needle, retort stand

Procedure

1. Perform the following steps:
   (a) Position the north pole of one bar magnet close to the south pole of another bar magnet.
   (b) Bring the two north poles close, then do the same with the two south poles.
   (c) Make a note of what you observe.
   (d) Spread some iron filings onto a piece of paper, then hold the north pole of a magnet near the filings without touching them.
   (e) Repeat this by bringing the south pole close to the filings, again without contact.
   (f) Lastly, bring the centre part of the magnet near the filings, but do not let them touch.
   (g) Record your observations.
2. Tie a string around the middle of a bar magnet and suspend it in the air as shown in Figure 3.7.

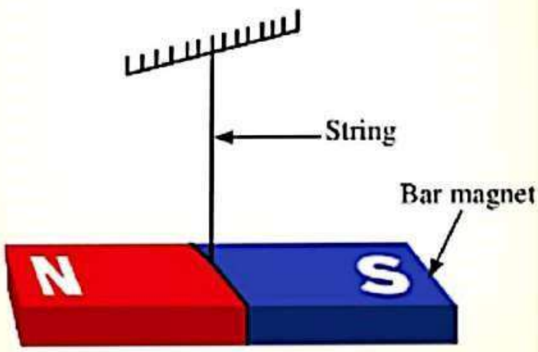


Figure 3.7

3. Gently push one end of the magnet so that it slowly spins and comes to rest. Note the direction in which the magnet's north pole is pointing.
4. Push the magnet again and wait for it to come to rest.
5. Place a block of wood in a pan of water and lay the bar magnet on top as shown in Figure 3.8. Note what happens.

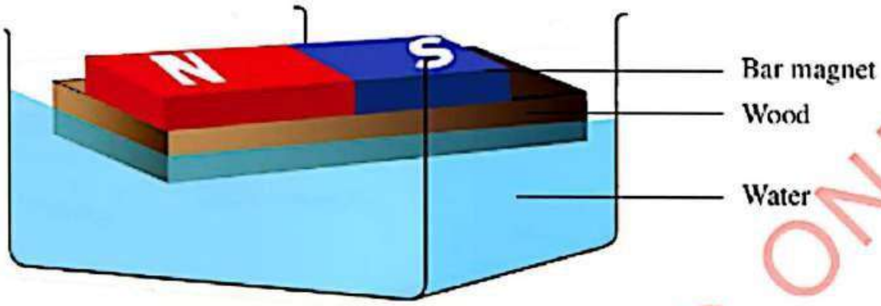


Figure 3.8

Questions

(a) Did the iron filings stick to the magnet while picking up more filings?
(b) Did the magnet always point in the same direction?
(c) Compare the direction of the suspended magnet with that of a compass needle. Does the magnet line up with the compass needle?
(d) Describe your observations.

Some of the properties of magnets and magnetism include:

1. All magnets have two poles, the north and south poles.
2. Magnets exert a force on some materials and do not on others.
3. Magnets attract ferromagnetic materials such as iron, nickel and cobalt.
4. The magnetic force is an action-at-a-distance force.
5. In a bar magnet, more iron filings stick to the poles, meaning that the magnetic force is the strongest near the poles of a magnet, and that the poles have equal strength.
6. When two magnets are brought together, like poles repel each other while unlike poles attract, as shown in Figure 3.9. This is the basic law of magnetism.

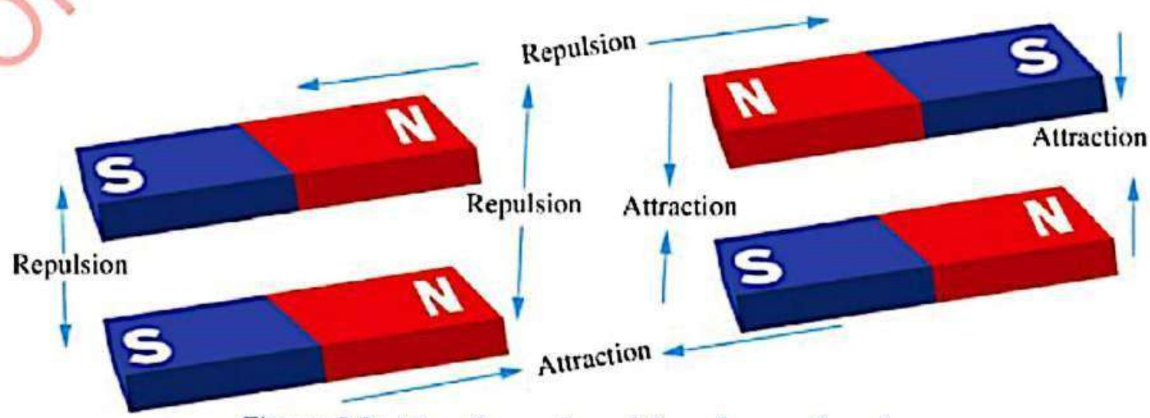


Figure 3.9: Attraction and repulsion of magnetic poles

7. A freely suspended bar magnet always points in a north–south direction. The north pole of a freely suspended magnet points in the north direction, and the south pole points in the south direction of the Earth. Likewise, the arrow of a compass needle points towards the north.

Shapes of magnets

Magnets are of different types, and they work in different ways. They differ in materials, shapes, sizes, functions, forces and applications. For example, magnets can have different shapes, which include bar, horseshoe and disc as shown in Figure 3.10. Magnets also vary in size from tiny discs used in speakers to large magnets used in commercial power-generating plants. One of the largest magnets is perhaps the Earth itself.

Figure 3.10: *Types of magnets according to their shapes*

Applications of magnets

Magnets are widely used in various electronic devices, as described in the following examples:

1. Magnetic recording media

Magnetic recording is a technology that stores information on a magnetic medium. Examples of magnetic recording media include computer hard discs as shown in Figure 3.11. In the hard disc, the magnetic material is coated with aluminium or glass. The recorded information can be retrieved by playing back, using a special head.

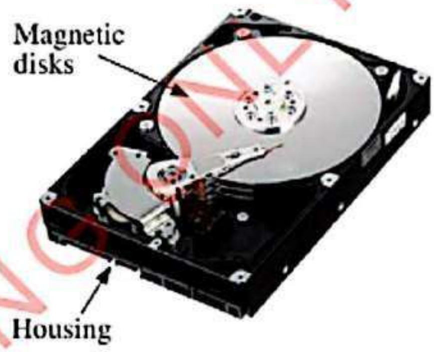


Figure 3.11: *Magnetic recording media*

2. Credit, debit and ATM cards

These have a magnetic strip on one of their sides. This strip contains the necessary information to contact an individual's financial institution and connect with their account. These automatic cash cards also use magnetic ink to store information. Figure 3.12 shows an example of an automatic cash card.

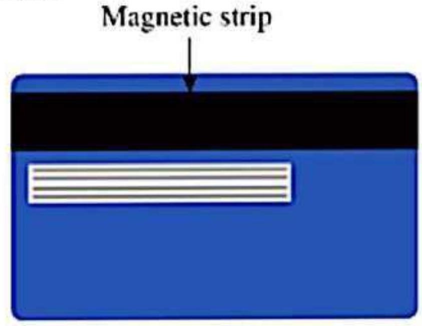


Figure 3.12: *ATM card*

3. CRT (Cathode Ray Tube) television and computer monitors

These employ an electromagnet in their inputs to assist in producing an image on the screen (see Figure 3.13).

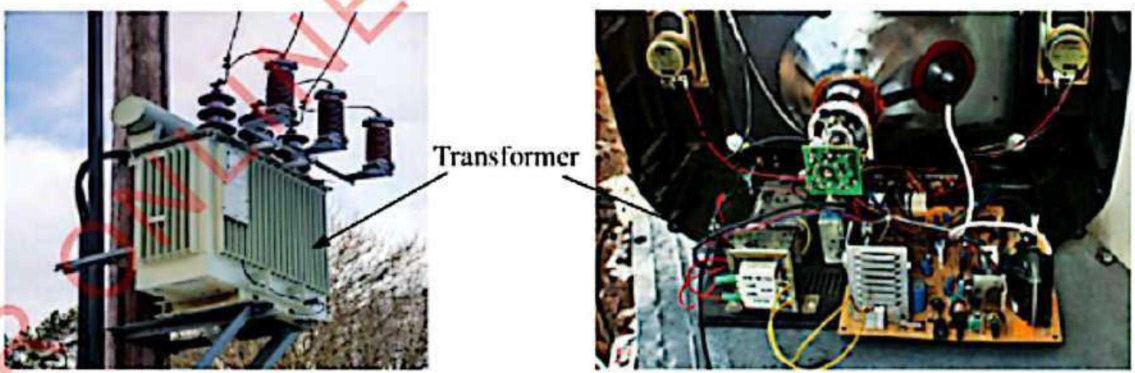
Figure 3.13: *CRT TV screen*

4. Speakers and microphones

These use permanent magnets and current-carrying coils to convert electric energy into sound and sound energy into electrical energy, respectively. For example, hi-fi stereo speakers (see Figure 3.14) have very powerful magnets to produce high-quality sound and sufficient volume.

Figure 3.14: *Speaker*

5. **Electric generators**
   These use permanent magnets to convert mechanical energy to electrical energy.
6. **Transformers**
   These are used in power transmission and many electronic devices, as shown in Figure 3.15 (a) and (b).



(a): *Transformer on electric poles* **(b):** *Small transformer in a television set*

Figure 3.15: *Transformer for power transmission*

Transformers are used in electronic devices to reduce the standard 240 V AC mains voltage to lower levels suitable for operating equipment such as radios, high fidelity hi-fi systems, computers, televisions, and doorbells

7. **Electromagnets.** These are used in hospitals when dealing with eye injuries caused by iron or steel splinters. They are also used in Magnetic Resonance Imaging (MRI) to diagnose brain tumours, haemorrhage, nerve injury and stroke injury. Electromagnets are also applicable in steelworks and cranes.

8. **Moving coil meters.** A horseshoe magnet is used in voltmeters and ammeters. It is an inbuilt part of these devices that enables the pointers to move in a direction of increasing voltage or current.

Task 3.1

In groups, search the internet or other sources, then describe other applications of magnets. Write a report on your findings and present your work to the class.

Exercise 3.1

1. In a certain primary school, a teacher demonstrated how magnets work by giving students different objects like a nail, plastic ruler, coin, wooden pencil, and paperclip, along with a bar magnet. The students were asked to identify objects that were attracted to the magnet and those which are not.
   (a) Why could some objects be attracted to the magnet and others not?
   (b) Which of the objects could be attracted by the magnet? What are their characteristics?
   (c) Which of the objects could not be attracted by the magnet? Why?
2. A magnet is cut into two equal pieces. What happens to the magnetic poles of each piece, and why?
3. A student argues that all metals are magnetic. Do you agree or disagree? Explain your answer with examples.
4. You are asked to design a simple tool for separating magnetic materials from a pile of mixed waste at a recycling centre. The pile contains nails, plastic wrappers, glass pieces, iron rods, and paper. Describe the tool you would design and the method by which it operates.

Magnetisation and demagnetisation

Magnets are manufactured by aligning the tiny atomic magnets of a material. The process of making a magnet is called magnetisation. Likewise, demagnetisation is the process of destroying or removing the magnetism in a magnetised material.

Magnetisation

The atoms of most materials act like tiny magnets called atomic dipoles. If the material is not yet magnetised, its atomic dipoles randomly align, forming magnetic domains as shown in Figure 3.16.

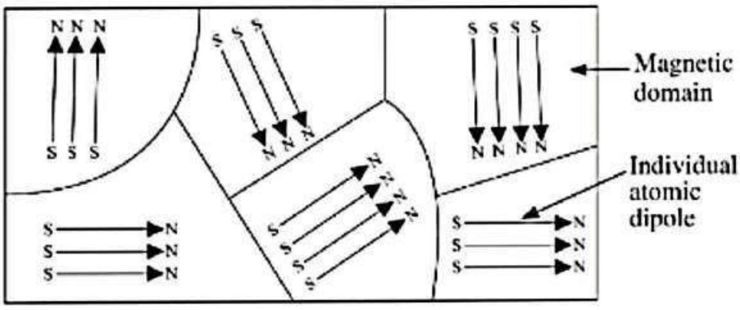


Figure 3.16: *Random alignment of atomic dipoles in unmagnetised material*

If atomic dipoles arrange in such a way that N poles of all the dipoles face in one common direction, the material is said to be magnetised.

***Magnetisation* is the process of aligning the atomic dipoles in a material in one direction to produce a net effect of attraction or repulsion.**

The domains may show a net magnetic behaviour in the absence of an external magnetic field. On applying an external magnetic field, all dipoles align themselves in the direction of the applied field. In this way the material is strongly magnetised in the direction parallel to the magnetising field as shown in Figure 3.17.

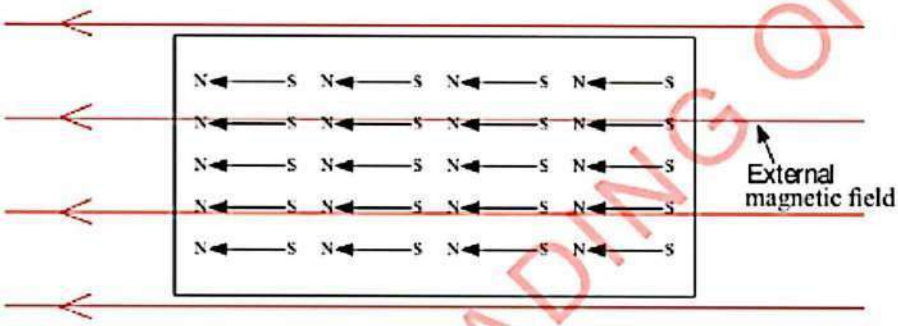


Figure 3.17: Aligned atomic dipoles in a magnetised material

Materials in which it is possible to cause this alignment are either ferromagnetic or paramagnetic. Ferromagnetic materials such as steel, nickel and cobalt can form permanent magnets, while paramagnetic materials such as aluminium and chromium can only be weakly magnetised and do not retain any magnetism once the external field is removed. The alignment of domains in these materials can be achieved through one of the following: heating or vibration, stroking, and the electric method.

In the first method of magnetisation, an external magnetic field is required. Placing an object in an external magnetic field will result in some degree of alignment. Vibrating or heating the object can increase the amount of alignment by causing the atomic dipoles to move and eventually become aligned. Many natural magnetic materials start out as part of lava (molten rock). If the lava contains ferromagnetic minerals, the atoms align with the Earth's magnetic field which is subject to vibration while the rock is still liquid. As the rock cools and solidifies, the alignment becomes permanent.

Activity 3.3

Aim: To demonstrate magnetic alignment

Materials: a small glass or plastic jar, iron filings, bar magnet, magnifying glass (or smartphone with magnification app), computer or tablet with image analysis software

Procedure

1. Fill in the small glass or plastic jar with iron filings.
2. Examine the filings using a magnifying glass, a digital magnifying camera, or a smartphone with a magnification app, and take clear images or videos.
3. Now, place the jar of filings alongside a strong bar magnet and gently shake the jar for a few seconds.
4. Use the magnifying device again to observe the images or videos as shown in Figure 3.18 and use image analysis software to compare the arrangement of filings before and after magnetisation.

Figure 3.18

Questions

(a) What did you observe from the recorded images or videos?

(b) Explain your observations based on the behaviour of magnetic materials.

In the second magnetisation method, a piece of unmagnetised material is stroked using a magnet. An existing magnet is moved from one end of the material to the other in the same direction. This process is repeated several times. The pole produced at the end of the stroke is always the opposite of that at the end of the magnet used for stroking. For example, if the north pole of the magnet is used for stroking, then the rod will be magnetised such that its starting end will act as the north pole and the other end as the south pole, as shown in Figure 3.19.

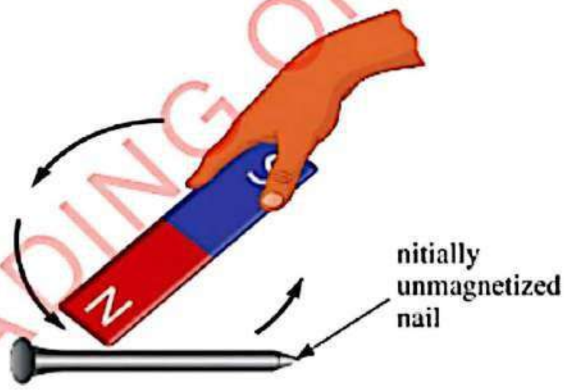


Figure 3.19: *Single-touch method*

After completing stroking, care has to be taken not to move the magnet close to the nail because this is taken as a repeat stroke. It disorganises the already aligned dipoles. The stroking method, whereby only one magnetising magnet is used, is called a single-touch method. When two magnets are used, the method is called a double-touch method. In this process, the ends of two magnets of different polarities are positioned at the middle of the iron nail. The two magnets are then moved in a curved motion in the opposite directions as shown in Figure 3.20. The iron nail is stroked a few times along its length. This procedure must be done with care to ensure the proper magnetisation of the iron nail.

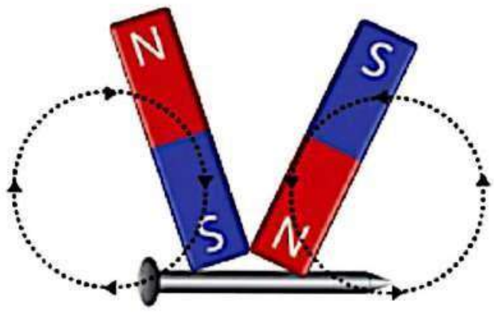


Figure 3.20: *Double touch method*

Activity 3.4

Aim: To magnetise a steel rod by a single-touch method.

Materials: Steel rod, bar magnet, pins, smartphone or tablet with camera, tripod or phone stand, video recording or time-lapse app, computer or smartboard

Procedure

1. Place the steel rod on a flat surface and set up a smartphone or tablet on a tripod to record the entire magnetisation process.
2. Drag the pole of a bar magnet from one end of the rod to the other.
3. After reaching the far end, lift the magnet and return it to the starting point.
4. Repeat step 2 ten times. The stroking should involve wide loops.
5. After magnetising, use pins to test for magnetism by hanging them one below the other from the rod, and record or photograph the result.
6. Use a computer or projector to play back the video and analyse the magnetisation process, highlighting key actions and effects.

Questions

(a) Why must step 2 be repeated during the magnetisation process?

(b) Why are wide loops important when stroking with the magnet?

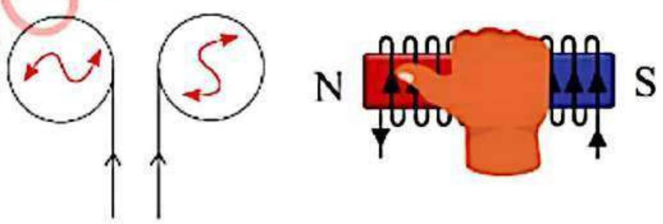
(c) Explain the significance of loading the pins one below the other.

For each stroke, several dipoles align themselves in one direction. Stroking is repeated to ensure that a maximum number of dipoles have aligned themselves to such a level that the end product is a magnet. A state where no further alignment takes place is known as saturation. A load of pins placed one after the other is used to test for saturation. If the magnet can hold the pins, then it has reached its saturation. During stroking, a wide loop is advised so that the alignment of the dipoles is not disturbed.

The third method of magnetisation relies on the fact that an electric current produces a magnetic field. A long wire is wrapped around an object, such as a nail and connected to a battery as shown in Figure 3.21. The direct current supplied in the wire produces a magnetic field that magnetises the nail. The combined effect of all the turns of wire produces a field similar to that of a bar magnet. A wire coil of several turns is called a solenoid. To increase the field strength of the magnet formed by a solenoid, a soft iron core is inserted in the solenoid, and a large current is passed through the wire. The number of turns of the wire is also increased. This is an industrial way of making a magnet. The solenoid produces an electromagnet that acts like a bar magnet.

Figure 3.21: *Electric method of magnetisation*

Polarity of a magnet can be determined by the direction of the current. When looking at the nail, the end that has current flowing in a clockwise direction is the S pole. If it flows anticlockwise, the end acts as the N pole. See Figure 3.22 (a). This is the rule for magnetic polarity. Also, a right-hand grip rule can be used to indicate the polarity of the magnetised material. The rule states that "if the fingers of the right hand grip the solenoid in the direction of the current, then the thumb points to the N pole of the solenoid" as shown in Figure 3.22 (b).



(a) Rule of magnetic polarity

(b) Right-hand grip rule

Figure 3.22: *Rules of polarity*

Activity 3.5

Aim: To magnetise a steel bar

Materials: steel bar, battery, switch, solenoid of copper wire, iron filings

Procedure

1. Test the steel bar for magnetic properties by using iron filings.
2. Connect the battery to the solenoid and the switch.
3. Place the steel bar inside the solenoid as shown in Figure 3.23.

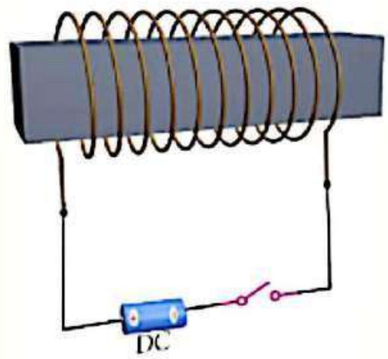


Figure 3.23: *Making a steel bar magnet*

4. Switch on the current for 10 seconds and then switch off.
5. Remove the bar from the solenoid and test it again for magnetism using the iron filings.

Questions

(a) Why is the current switched on for only a few seconds?

(b) What is observed when the steel bar is brought near the iron filings?

The current is switched on for a short time only because overheating can damage the coil. Moreover, the bar does not become more strongly magnetised if the current is left on for a long time. The steel bar attracts the iron filings, showing that it has been magnetised. In each of the methods mentioned, if the object is composed of ferromagnetic materials, it will remain magnetised for a while after removing the external field. However, if it is composed of paramagnetic materials, it will lose its magnetism immediately when the magnetising field is switched off.

Demagnetisation

Demagnetisation is the process of destroying the magnetic property of a material.

The process involves the destruction of the dipole alignment in the magnetised material. This process can be done in the following ways:

1. If a permanent magnet is heated or vibrated in the absence of an external field, the magnetisation can be destroyed.
2. Randomly stroking one magnet with another can demagnetise the magnet being stroked.
3. Wrapping a wire coil around the magnet and connecting the coil to a source of alternating current will eliminate the magnetic alignment.
4. Repeated hammering or dropping the magnet in the absence of external magnetic field can also distort dipoles alignment.

Note; During heating, the dipoles gain thermal energy and start to vibrate randomly losing alignment. Randomly stroking makes the individual dipoles orient in different directions. Alternating current repeatedly realign the dipoles in different directions making them settle in random orientations. Hammering or dropping induce physical force into dipoles that disaligns them.

Activity 3.6

Aim: To demagnetise a bar magnet using alternating current and a rheostat

Materials: bar magnet, solenoid wire, rheostat, iron filings, AC power source

Procedure

1. Test a bar magnet for magnetism using iron filings.
2. Set up an electric circuit by connecting the solenoid wire to a low voltage AC power source, ensuring the rheostat is connected in series to control the current flow
3. Adjust the rheostat to regulate the current to a safe and effective level for demagnetisation.
4. Place the solenoid with its axis pointing in an east-west direction as shown in Figure 3.24.

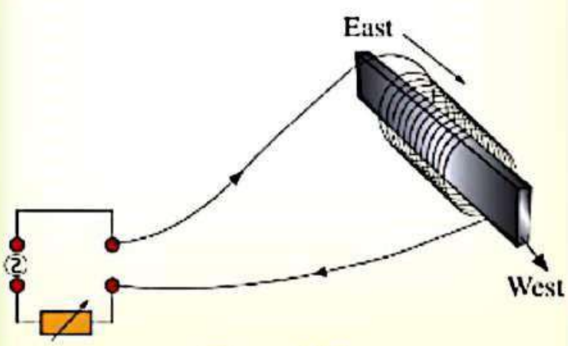


Figure 3.24

5. Place the bar magnet inside the solenoid and switch on the current.
6. After about 10 seconds, gradually reduce the current using the rheostat and slowly withdraw the bar magnet from the solenoid in the east-west direction while the current is still flowing.
7. Check the magnet's magnetic strength by using iron filings.

Questions

(a) Why is the solenoid and bar magnet placed in an east-west direction?

(b) What is observed when the bar magnet is brought near the iron filings?

The magnet is placed in an east-west direction so that it is not left with any magnetism due to the induction in the Earth's magnetic field. When this bar is brought near some iron filings, it does not attract them. This proves that a bar magnet has been demagnetised.

Storage of magnets

Magnets become weaker with time because free poles near the ends repel each other and upset the alignment of the tiny magnets. Magnets gradually lose strength over time because the free poles at their ends repel one another. This upsets the alignment of the small magnetic domains inside the magnet. Likewise, various external factors can contribute to a magnet losing its magnetism. Therefore, it is important to store magnets properly to ensure they stay effective for a longer period.

Task 3.2

Do a library search to find out ways in which magnets should be stored and handled so that they do not lose their magnetic strength. Write a report and present it to the rest of the class. Use your findings to design systems for storing magnets in your laboratory.

In order to maintain the magnetism in magnets for a long period, the following practices have to be observed:

1. Avoid storing magnets in places where they may come into contact with ferrous objects, such as steel shelves and tools.
2. Store magnets in pairs with the unlike poles facing each other. Pieces of magnetic keepers are used at the ends to preserve the strength of the magnets. Note: A magnetic keeper is a ferromagnetic bar placed across the poles of a permanent magnet. It preserves the strength of the magnet by completing the magnetic loop as shown in Figure 3.25.

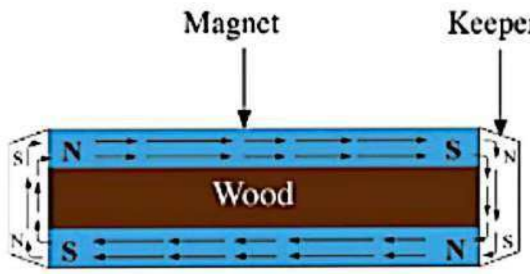


Figure 3.25: *Magnetic keeper*

3. Do not overheat magnets. This may cause harmful structural changes in the magnet.

4. Do not store or keep magnets near strong magnetic or electric fields.
5. Do not subject magnets to any form of severe stress, such as vibrations or mechanical impacts. These can physically damage the magnet. Permanent magnets are hard but brittle at the same time.

ICT Corner

Use ICT tools to research, design, and present how magnetisation and demagnetisation processes work, including their methods and real-life applications.

Exercise 3.2

1. (a) Briefly explain the origin of magnetism.
   (b) State the basic law of magnetism.
2. (a) Explain the concept of ferromagnetic and paramagnetic materials.
   (b) Explain three materials which are classified as ferromagnetic and paramagnetic.
3. (a) Differentiate between magnetisation and demagnetisation.
   (b) Describe three methods through which a magnetic material can be magnetised.
4. (a) Explain four ways in which magnets are used in daily life.
   (b) In which part of a fridge or a microwave oven are magnetic strips installed? Why?
5. How can you store magnets for effective and durable use of their magnetism?

Magnetic field of a magnet

A magnetic field exerts a force on a magnetic material placed in it. Physicists use magnetic field patterns to describe the action of magnetic forces from a distance. If a magnet is dipped in iron filings, the filings tend to cling around its ends. Similarly, if the filings are sprinkled on a paper over a bar magnet, they will be pulled to the poles of the magnet. The filings thus become magnetised and aligned, revealing the magnets field pattern as shown in Figure 3.26.

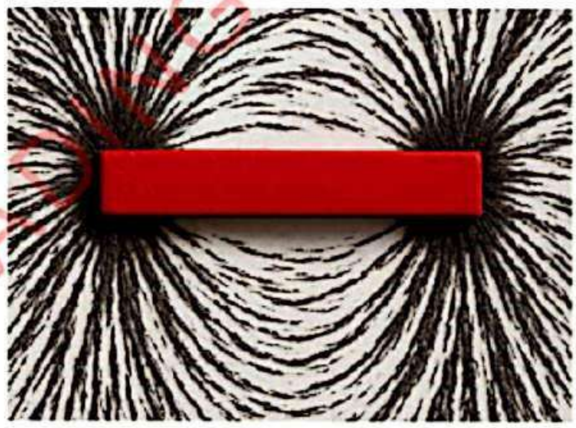


Figure 3.26: *Iron fillings around a bar magnet*

A magnetic field is the region around **a magnet in which magnetic force can be experienced by magnetic materials.**

It is therefore, the indication of the strength and direction of the force a magnet exerts on magnetic materials. If the magnetic field is stationary, it is referred to as a magnetostatic field. At any given point, its magnitude and direction remain the same.

One application of a magnetic field is in the banking industry. Banks use magnetic ink on cheques and cheque deposit slips so that the cheques are sorted out automatically by machines. These machines can detect the magnetic field around each number on a cheque and cheque deposit slips. Figure 3.27 shows a cheque deposit slip containing a magnetic field.

Magnetic ink character

Figure 3.27: *Magnetic ink on a cheque deposit slip*

Activity 3.7

Aim: To demonstrate the existence of a magnetic field

Materials: magnifying glass, bar magnet, iron filings, cylindrical magnet, plastic bottle, test tube, masking tape, sheet of paper

Procedure

Part I

1. Lay a strong bar magnet on a table as shown in Figure 3.28.

Figure 3.28

2. Cover the magnet with a sheet of white paper and trace the magnet.
3. Label the north and south poles as shown in Figure 3.29.

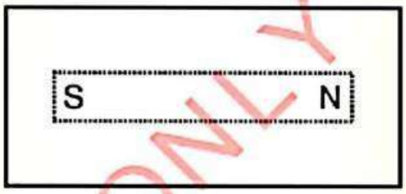


Figure 3.29

4. Sprinkle iron filings onto the paper in the area around the outline.
5. Gently blow any loose filings aside.
6. Examine the pattern formed by the filings with a magnifying glass as shown in Figure 3.30.

Figure 3.30

Part II

1. Fill a plastic bottle to about one fifth with iron filings.
2. Wrap the top part of the test tube with masking tape so that the tube fits tightly into the mouth of the bottle.
3. Fit the test tube into the mouth of the bottle and

slide the cylindrical magnet into the test tube as shown in Figure 3.31.

4. Put the bottle cap on. Turn the bottle on its side and rotate it.

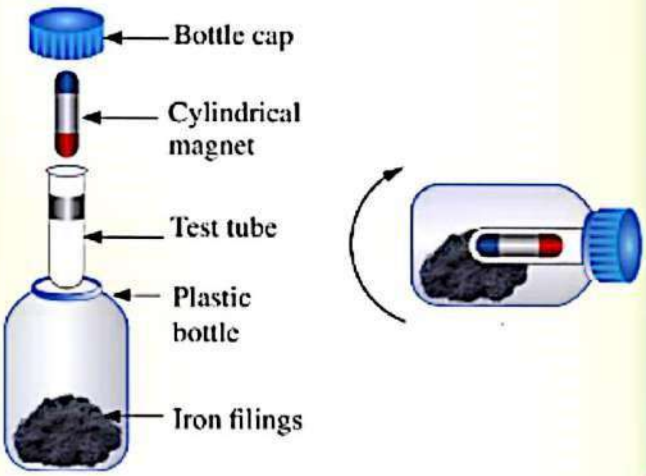


Figure 3.31

Questions

(a) What did you observe in the procedure of part I above? Sketch the pattern.

(b) What is your observation in the procedure of part II?

(c) Explain your observations.

Magnetic lines of force

Recall that iron filings become aligned in the presence of a magnetic field. This alignment displays the lines of force in a magnetic field. The magnetic lines of force emerge from the north (N) pole to the south (S) pole of a magnet. They are crowded together or become denser at the poles of a magnet, showing that the magnetic field is strong at the poles. Away from the poles, the field is weak, hence, magnetic lines formed are less dense. Magnetic lines of force show the direction of the magnetic force. The direction of the magnetic lines of force at any point is the direction in which the north pole of a small magnet points when located at that point, as illustrated using arrows in Figure 3.32.

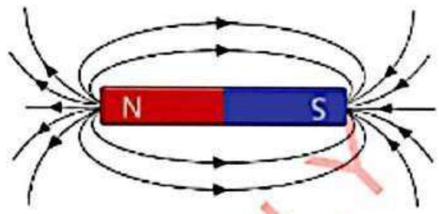


Figure 3.32: *Magnetic field lines around a bar magnet*

The lines of force point away from the north pole of a magnet and towards the south pole. The direction at any point along a line of force is therefore defined as the path that a magnetic north pole would tend to take. The north end of a compass needle could also point in the same direction as shown in Figure 3.33.

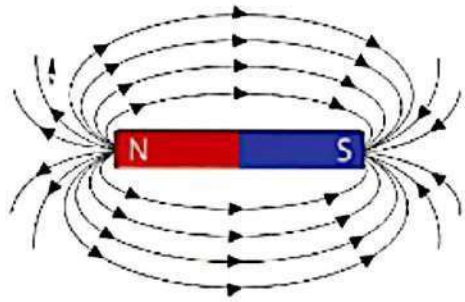


Figure 3.33: *Compass needle direction around a bar magnet*

Properties of magnetic lines of force

Some of the properties of magnetic lines of force are as follows:

1. Magnetic lines of force are continuous and always form closed loops.
2. Lines of force from the bar magnet leave the north pole

and enter the south pole, and back to the north pole, forming a closed loop.

3. Magnetic lines of force are close together where the magnetic force is stronger, and they are far apart where the magnetic force is weaker.
4. Magnetic lines of force never cross one another.
5. Parallel magnetic lines of force in the same direction repel one another. Parallel magnetic lines of force in opposite directions attract one another as shown in Figure 3.34.

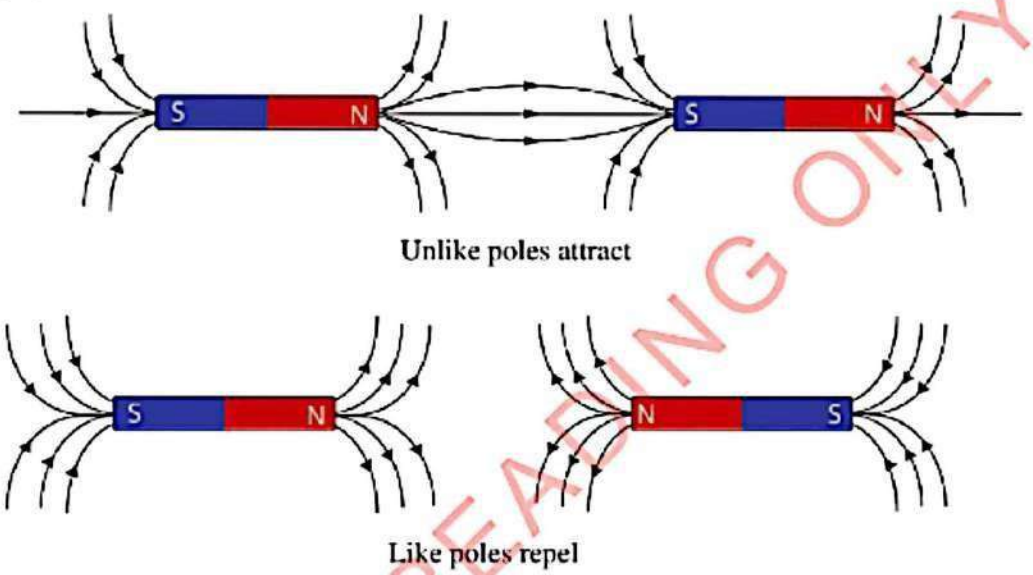


Figure 3.34: *Unlike poles attract and like poles repel*

6. Magnetic lines of force pass through magnetic and non-magnetic materials.
7. Magnetic lines of force always enter or leave a magnetic material at right angles to the surface.

Neutral points in a magnetic field

At any point where two different magnetic fields exist, a stronger field is created if they are in the same direction, but a weaker field arises if they are in opposite directions. The two fields can balance each other at one point.

> *A neutral point is a location where the total magnetic field equals zero.*

For instance, if two bar magnets are positioned close to each other as illustrated in Figure 3.35, their magnetic fields oppose one another. At a certain spot, these fields exactly cancel out, creating a neutral point labelled X. As a result, there is no magnetic force present at neutral points.

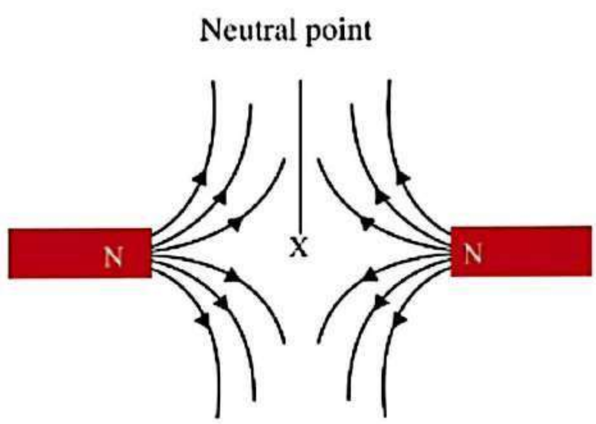


Figure 3.35: *Neutral point*

Activity 3.8

Aim: To locate the magnetic neutral points

Materials: large sheet of cardboard, tape, two bar magnets, a compass

Procedure

1. On the large sheet of cardboard, draw a line along the N-S direction as indicated by a compass needle.
2. Tape the bar magnets on the board with their axis along the N-S line as shown in Figure 3.36.
3. Place a compass at point A near the bar magnet, then record your observations.

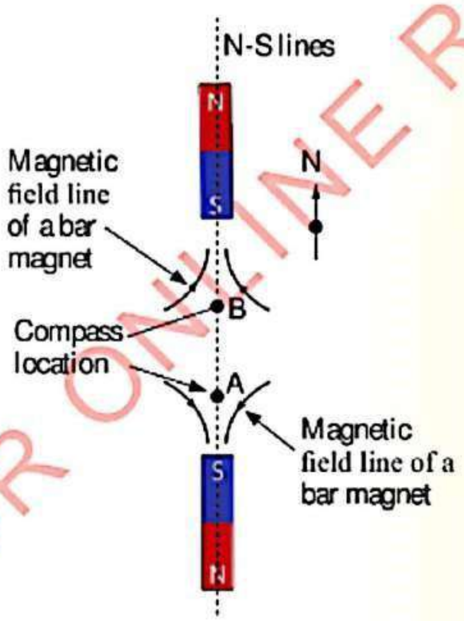


Figure 3.36

4. Slowly slide the compass along the N–S line toward point B until the compass needle spins to point in the opposite direction. Then, record your observations.
5. Use your compass to locate a neutral point.
6. Repeat Activity 3.8 with the bar magnets aligned in the W-E direction (in a line perpendicular to the drawn N-S line).

Questions

(a) Why did the compass change direction?

(b) Could you locate any neutral point on the N–S or E–W lines? Explain.

Magnetic shielding

Magnetic shielding is the process of limiting the flow of magnetic fields between two locations, or across an object, by separating them with a barrier made of conductive ferromagnetic materials. Without a shield, the magnetic field lines will pass through a region as in Figure 3.37.

Figure 3.37: *Magnetic field lines through a region*

Field lines from the north pole cannot be stopped from moving to the south pole of a magnet, but they can be redirected. In this case, the channel is a length of ferromagnetic material such as soft iron. When magnetic field lines reach the iron, they flow along it rather than through the magnet itself. Materials that can redirect magnetic field lines are said to be permeable. Suppose a region is to be shielded from magnetic effects; it could be enclosed with a ring made up of soft iron. The field lines could follow the iron ring around the shielded region as shown in Figure 3.38.

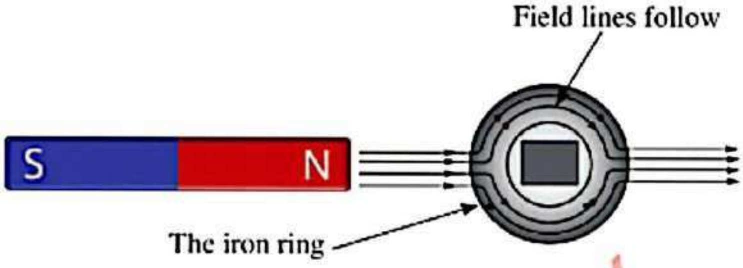


Figure 3.38: *Magnetic shielding redirects field lines*

Activity 3.9

Aim: To demonstrate magnetic shielding

Materials: two pencils, bar magnets, index cards, sellotape, paper clips, drinking straws, iron nails

Procedure

1. Place two pencils on the sides of an index card.
2. Lay a second index card on top of the pencils as shown in Figure 3.39.

Figure 3.39

3. Tape a strong bar magnet to the top index card as shown in 3.40.

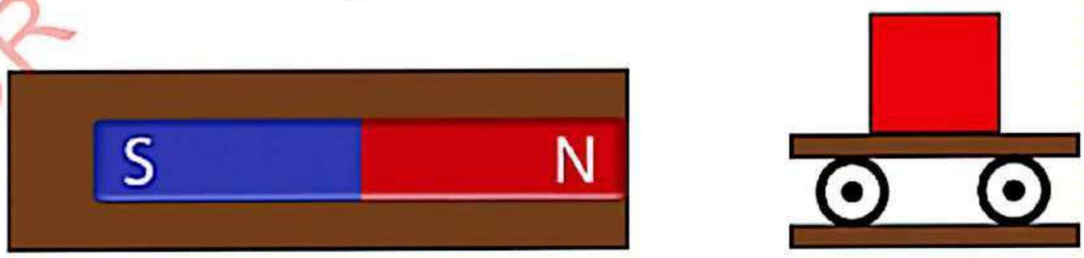


Figure 3.40

4. Use the assembly to pick up several small paper clips with the bottom card as shown in Figure 3.41.

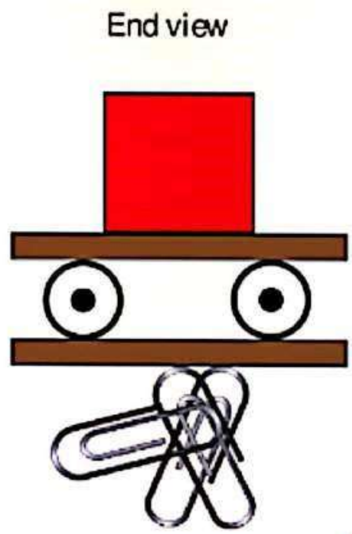


Figure 3.41

5. Tape several drinking straws together side by side and insert them into the space between the two index cards as shown in Figure 3.42, then repeat step 4.

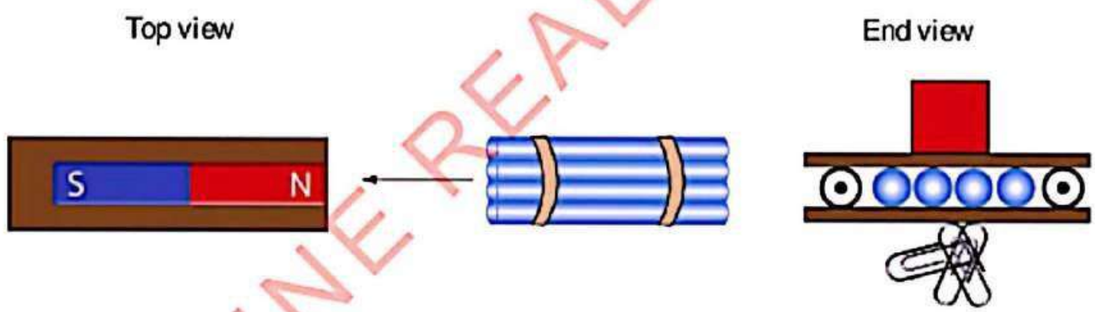


Figure 3.42

6. Tape several iron nails side by side and insert them into the space between the two index cards as shown in Figure 3.43, then repeat step 4.

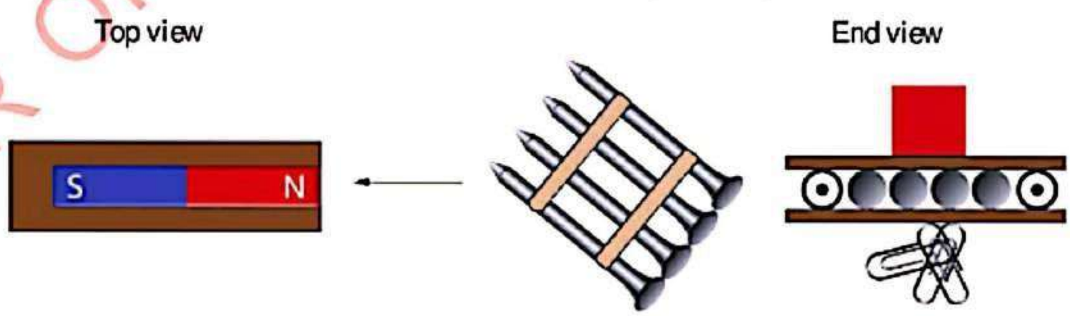


Figure 3.43

Questions

(a) For each case, what happened to the paper clips? Why?

(b) Explain your results using the concept of magnetic shielding.

Exercise 3.3

1. A student wants to turn an iron nail into a temporary magnet to pick up small pins. What should the student do to magnetise the nail, and how will the student know it has become magnetic?
2. Two students tried to magnetise two similar iron nails. Student A used the stroking method, and Student B placed the nail inside a solenoid and passed an electric current. Later, Student A's magnet picked up fewer paper clips than Student B's. Describe the methods used. Why were the results different?
3. A technician suggests heating a magnet to make it stronger. Do you agree or disagree? Give reasons.
4. Suppose you are helping in designing a magnetic tool for lifting nails in a workshop. However, the magnet gets demagnetised frequently due to rough handling. Propose an improved design or method that ensures the tool stays magnetised for a longer time, and explain why your design would work better.
5. A student places a bar magnet under a sheet of paper and sprinkles iron filings on top. What pattern will the filings form, and what does this show about the magnetic field?
6. Two magnets, one bar magnet and the other a horseshoe magnet, are placed on a table. A student uses a compass to trace the field lines around both. Compare the magnetic field patterns of the two magnets.
7. A student claims that magnetic field strength is the same all around a bar magnet. Do you agree or disagree? Justify your answer.

Earth's magnetic field

The Earth behaves as if it has a short bar magnet inside it (See Figure 3.44). This apparent magnet is inclined at a small angle to the Earth's axis of rotation, with its south pole pointing in the northern hemisphere. This is inferred from the fact that the compass needle points towards the true north only at certain locations.

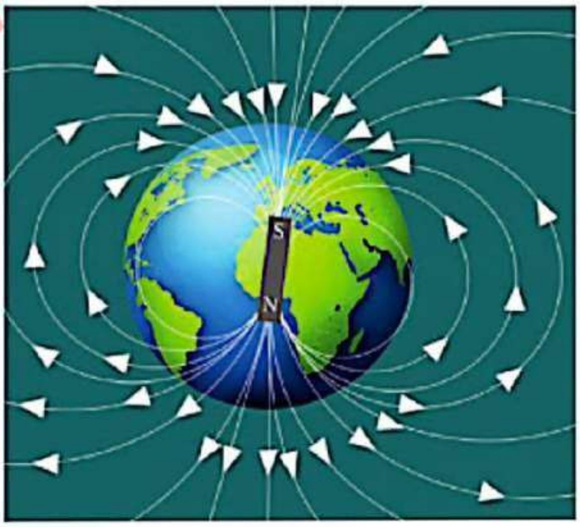


Figure 3.44: *Earth's imaginary magnet*

The source of the Earth's magnetism remains uncertain and lacks a straightforward explanation. However, it is believed that the generation of the magnetic field is linked to the rotation of the Earth. This leads to the rotation of the metallic iron fluid that makes up a large portion of the interior of the Earth. The Earth has two sets of poles, the north and south geographic poles as defined by its axis of rotation, and the north and south magnetic poles that are defined by its magnetic field. The magnetic pole in the Northern Hemisphere is magnetically a south pole called the Magnetic South Pole (MSP), and in the Southern Hemisphere, the magnetic pole is called the Magnetic North Pole (MNP) as shown in Figure 3.45.

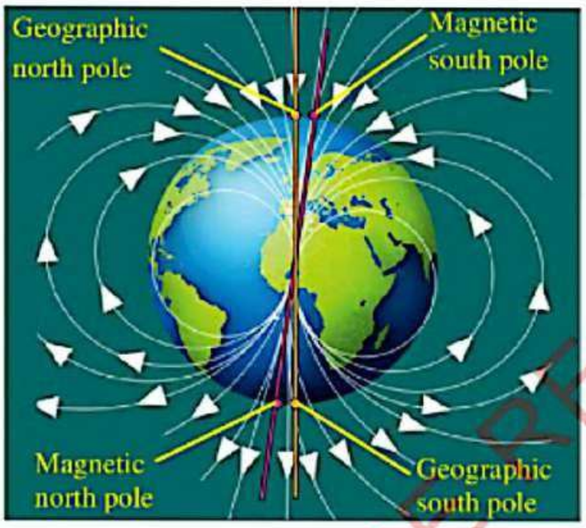


Figure 3.45: *Earth's geographic and magnetic poles*

Direction of the Earth's magnetic field

Magnetic fields have both magnitude and direction. The SI unit for magnitude of a magnetic field is the Tesla, T. The magnitude of the Earth's field varies from one location to another, ranging from $25 \mu T$ to $65 \mu T$. A compass may be used to determine the direction of the Earth's magnetic field. A compass is a device with a magnetised needle that is free to rotate in a horizontal plane and align itself with the horizontal component of the Earth's magnetic field. The head of a compass needle is a magnetic north pole, and the tail is a magnetic south pole. The compass needle points toward the north pole, which means it will point toward the Earth's MSP. Therefore, a compass needle points in the general north direction of the Earth as shown in Figure 3.46. For this reason, the magnetic north pole of the compass needle is referred to as a north-seeking pole, and the general direction it indicates is often called the "magnetic north".

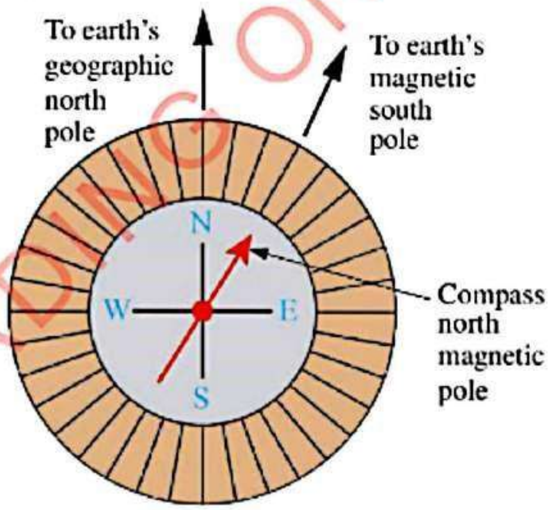


Figure 3.46: *Magnetic compass*

When a magnet is hung so that it can swing freely in a horizontal direction, it will move back and forth for a short time before it comes to rest in an approximate N–S direction. The magnet comes to rest with its axis in a vertical plane called the magnetic meridian.

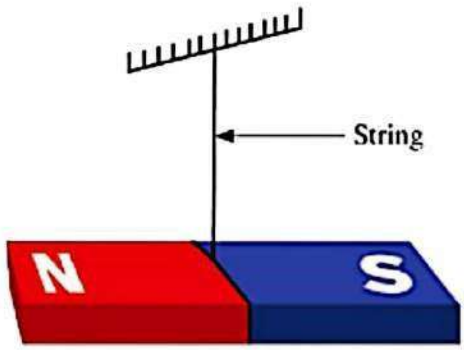


Figure 3.47: *Freely suspended magnet*

Just as with the compass needle, the pole which points towards the north is the north-seeking pole (N pole), and the other is the south-seeking pole (S pole).

Activity 3.10

Aim: To demonstrate the presence of the Earth's magnetic field

Materials: a nail or pin, water, bar magnet, stopper (cork), water dish

Procedure

1. Using the north pole of a bar magnet, stroke a nail or straight pin from head to tip 10 to 15 times. This magnetises the nail with a south pole (SP) at the tip and a north pole (NP) at its head as shown in Figure 3.48.

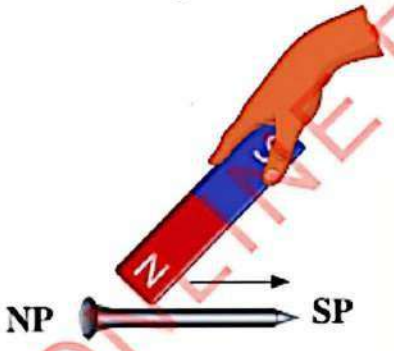


Figure 3.48

2. Float a cork or rubber stopper in a dish with shallow water. Place the nail on the cork as shown in Figure 3.49.

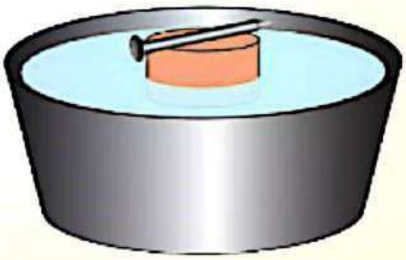


Figure 3.49

3. Push one end of the nail slightly horizontally so that it rotates slowly. When the nail comes to rest, its tip will be pointing toward the earth's MSP.
4. Place a piece of tape on the edge of the dish to mark this direction.
5. Push the nail slightly, then observe its orientation when it stops moving. Repeat this several times.

Questions

Does the needle always point in one direction? Why?

If a bar magnet is suspended horizontally from its centre, it will point to the north-south direction. The bar magnet is free to turn and lines up along the field lines of the Earth's magnetic fields.

Earth's magnetic lines of force about a bar magnet

The Earth's magnetic field around the equator consists of parallel lines that point toward the north, as shown in Figure 3.50. This forms a 'uniform field' in which the direction and strength of the lines of force are constant.

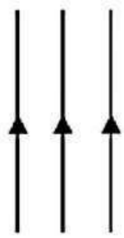


Figure 3.50: *Earth's field*

The Earth's magnetic lines of force about a bar magnet are a resultant of two magnetic fields, one due to the bar magnet and the other due to the Earth. Figures 3.51 illustrates the resulting field when the two fields combine. At certain location, the Earth's field neutralises the field due to the bar magnet. This results into neutral points (x).

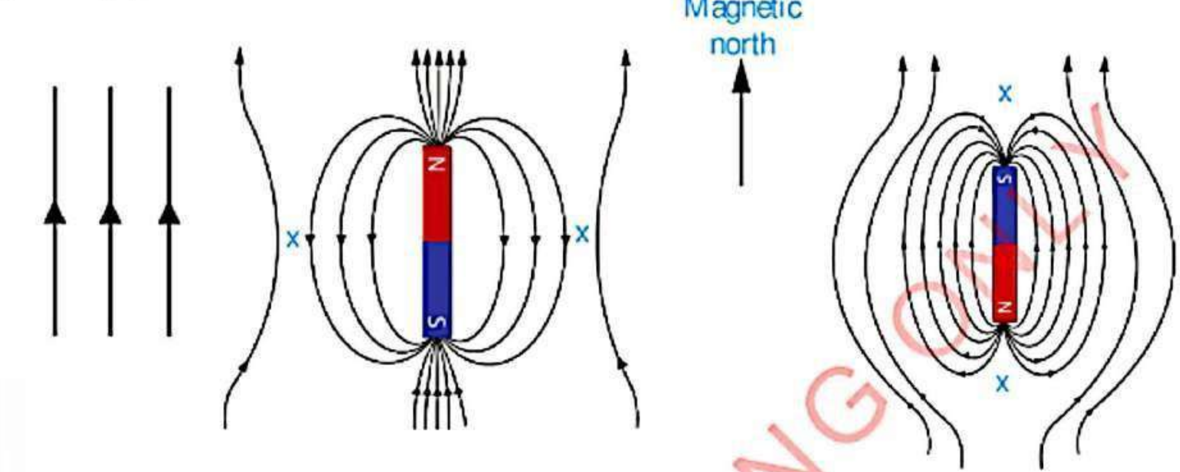


Figure 3.51: *Fields of a bar magnet against the earth's magnetic field*

Angle of declination

As mentioned earlier, the Earth's Magnetic North Pole (MNP) and Geographic North Pole (GNP) are not in the same plane. Generally, the Earth's axis of rotation does not coincide with the magnetic axis as shown in Figure 3.52.

The angle between the two axes is called the angle of declination, D or angle of deviation

Figure 3.52: *Angle of declination*

Additionally, the Earth's magnetic field changes slowly over time so that the MNP moves. There have been times through the Earth's 4.5-billion-year history that the Earth's magnetic field was completely reversed. Table 3.1 shows a list of the latitude and longitude of the MSP for some years from 2001.

Table 3.1: *Location of MSP for some years*

Year	2001	2002	2003	2004	2005	2006
Latitude	81.3°N	81.6°N	82.0°N	82. 3°N	82. 7°N	86.50°N
Longitude	110.8°W	111.6°W	112.4°W	113.4°W	114.4°W	164.0°E

The angle of declination also indicates whether the magnetic south is east or west of the geographic north.

Angle of inclination (dip angle)

If we position a compass on its side so that its needle can rotate within a vertical plane, the needle will align itself with the Earth's magnetic field.

The angle formed between the direction of the resulting magnetic field and its horizontal component is known as the angle of inclination, or dip angle, denoted by I.

This angle is positive when the magnetic field vector points downward (as in the Northern Hemisphere) and negative when it points upward (as in the Southern Hemisphere). The angle of inclination ranges from 0° at the magnetic equator to 90° at the magnetic poles. It is measured using a dip needle, which is a magnetised needle mounted on a pivot allowing it to rotate freely in a vertical plane, as shown in Figure 3.53.

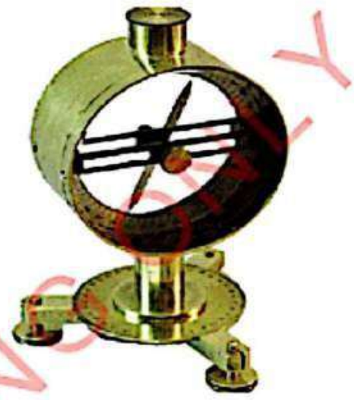


Figure 3.53: *Dip needle*

In practice, a compass is used to align the dip needle with the horizontal component of the magnetic field, and the dip needle rotates vertically to align with the total field. The magnetic dip produces a vertical moment, causing the needle in a compass to rotate vertically. This produces friction in the pivot, which hinders the free rotation of the needle. To compensate for the dip, a small mass is added to one end of the needle to produce an opposite gravitational moment so as to maintain the needle in vertical equilibrium. A compass to be used in the northern hemisphere, whereby the vertical component points down, has the mass added to the tail end of the needle. A compass to be used in the southern hemisphere, whereby the vertical component points up, has the mass added to the head end of the needle. Figure 3.54 (b) shows the various magnetic field components in the northern and southern hemispheres.

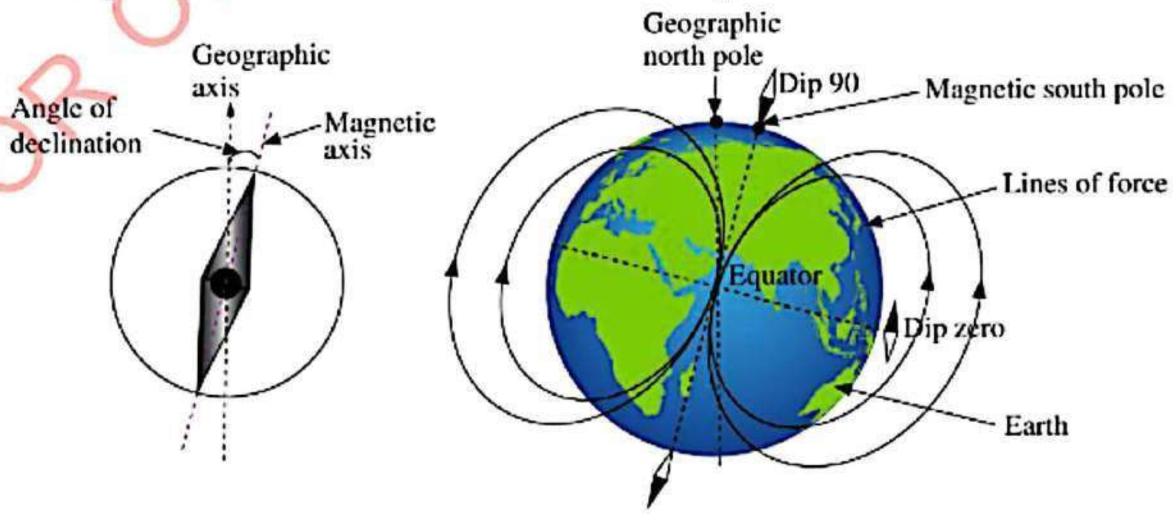


Figure 3.54: *(a) Compass showing angle of declination (b) Compass showing dip angle*

Use a compass and dip needle to determine the angles of declination and inclination at your location.

Applications of the Earth's magnetic field

The Earth's magnetic field has very important applications in our daily life.

1. It is used by map-readers to find locations of different places.
2. It gives useful information in the search for minerals.
3. Reversals of the Earth's magnetic field provide the basis for dating rocks and sediments.
4. Map-readers with a magnetic compass can locate the direction of the magnetic north using the compass.
5. It protects the Earth from cosmic radiation (potentially damaging high-energy particles from the sun).

ICT Corner

Use ICT tools to find your school, the nearest hospital, police station, a bus station or airport, and any mountainous region. Document each place's name, location, direction from your school (e.g., north, south-west), and distance in kilometres. Then, use the "directions" feature to plan a route from your home to each of the identified places, including the means of transport you would use (such as walking, driving, or taking a bus) and the estimated travel time for each journey.

Exercise 3.4

1. Briefly explain the following terms as applied in magnetism.
   (a) A magnetic field.
   (b) A magnetic line of force.
2. (a) Draw a magnetic field around a bar magnet using magnetic lines of force.
   (b) Draw magnetic fields around the pairs of magnets shown in Figure 3.55:

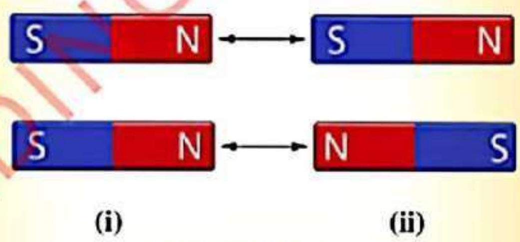


Figure 3.55

3. The earth is a magnet. Explain.
4. Describe the applications of the Earth's magnetic field.

Chapter summary

1. Magnetism was known to the early Greeks since 600 BCE.
2. Some materials have magnetic properties and can be made into permanent (ferromagnetic) magnets or temporary (paramagnetic) magnets. All magnets have a north pole and a south pole.
3. Magnets exert a force on some materials but not on others. The force is strongest at the poles of the magnets, and it can act from a distance.

4. Like poles repel and unlike poles attract.
5. The 'tiny magnets' in a material are called dipoles. A group of dipoles forms a domain.
6. A magnetic field is the region around a magnet within which magnetic force can be experienced. Magnetic fields are represented by lines of action of magnetic force called field lines.
7. Points at which the net magnetic field is zero are called neutral points.
8. Materials that can redirect field lines are called permeable materials.
9. The angle between the resultant magnetic field direction and horizontal component of the field is called *the angle of inclination, I,* or *dip angle.*

Revision Exercise 3

Choose the most correct answer in questions1-2.

1. Why are magnets often fitted to the doors of refrigerators and some cupboards?
   (a) To keep away heat.
   (b) To keep the inside environment warm.
   (c) To keep the door tightly closed.
   (d) To keep iron away.
2. The following are applications of magnetism in daily life, EXCEPT:
   (a) Magnets are used to trap non-metallic objects during flour packing.
   (b) VHS tapes are manufactured as a result of magnetism.
   (c) Banks make use of magnetic ink on cheques.
   (d) Magnets are used to lift scrap metals.
3. Match each item in column A against its corresponding item from column B by writing the correct response in the space provided.

Column A	Answer	Column B
(a) Magnetic materials		(i) Like poles attract, unlike poles repel
(b) Law of polarity		(ii) Magnetic field is zero
(c) Magnetic shielding		(iii) Redirects magnetic lines of force
(d) Neutral point		(iv) Strong magnet
(e) Aluminium		(v) Iron nail
		(vi) Paramagnetic
		(vii) Direct neutral point

4. Why is the core of an electromagnet made of ferromagnetic material?
5. Where on the surface of the earth is the earth's magnetic field perpendicular to the surface of the earth?

6. Differentiate between a force due to a magnet from the force due to gravity on the earth.
7. (a) How do you know that a certain material is magnetic in nature?
   (b) State the law of polarity and illustrate it using sketch diagrams.
   (c) Suppose you are in the physics laboratory and you are given a bar magnet whose poles are not labelled. Describe how you could determine which end of the bar is the north pole.
8. (a) State three applications of magnets.
   (b) Draw the following sketch diagrams:
      (i) Arrangement of domains of dipoles in unmagnetised iron bar.
      (ii) Arrangement of domains of dipoles in a magnetised iron bar.
   (c) Explain what would happen if you cut a bar magnet into half.
9. (a) Describe the magnetisation process.
   (b) How can a permanent magnet be demagnetised?
   (c) Explain the type of force that a magnet experiences.
10. (a) What are magnetic lines of force?
   (b) Analyse the properties of lines of force.
   (c) Describe the process of magnetic shielding.
11. Suppose you mount a bar magnet on a set of rubber wheels as shown in Figure 3.56.

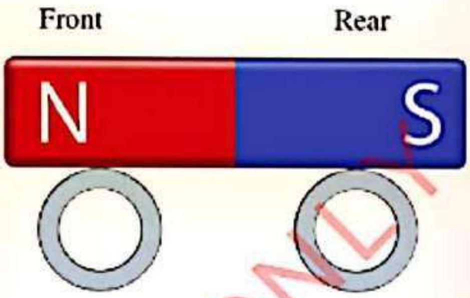


Figure 3.56

If you place the 'magnetic car' on the magnetic N–S line with the front of the car pointing to the geographic north, would it roll towards the north or towards the south? Explain your answer.
12. (a) You are given 4 strong bar magnets; is it possible to build the objects shown in Figure 3.57?

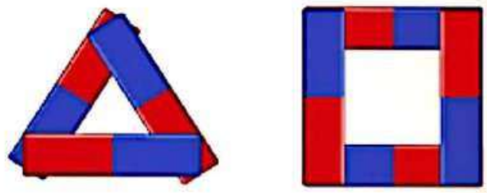


Figure 3.57

   (b) Draw diagrams indicating each magnet's north and south poles.
13. You are given two iron bars, A and B, that look identical as shown in Figure 3.58. One of them is a strong permanent magnet.

Figure 3.58

Explain how you can determine which bar is a strong permanent magnet.

14. Bar magnet P is twice as strong as bar magnet Q.
    (a) The two magnets are arranged with the N-pole of P 1m from the S-pole of Q as shown in Figure 3.59.

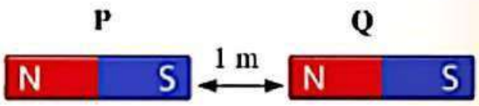


Figure 3.59

Is there a neutral point between the two magnets? If there is, how far from magnet P is it located? If there is no neutral point, explain why.

    (b) Magnet Q in Figure 3.59 is flipped so that the two north poles are 1 m apart as shown in Figure 3.60.

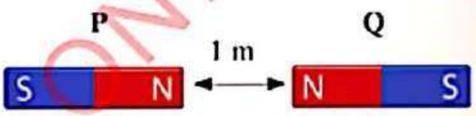


Figure 3.60

Is there a neutral point between the two magnets? If there is, how far from magnet P is it located? If there is no neutral point, explain why not.

15. The two magnets described in Question 14 are placed parallel to each other as shown in Figure 3.61.

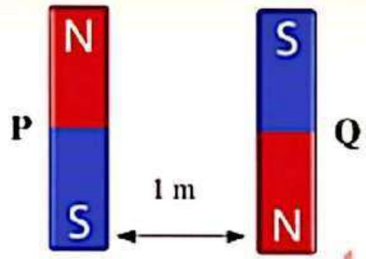


Figure 3.61

Is there a neutral point between the two magnets? If there is, how far is it from magnet P? If there is no neutral point, explain why.

16. Copy the image of a horseshoe magnet shown in Figure 3.62 and sketch 8 to 10 field lines.

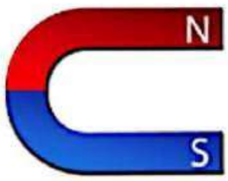


Figure 3.62

17. Compasses designed to be used in cars are equipped with a suction cup so that they can be mounted on the dashboard. Why?

18. Suppose that in Figure 3.63 (a) the nail becomes magnetised, with the head of the nail becoming a north magnetic pole. What could happen if the battery was reversed as in Figure 3.63 (b)?

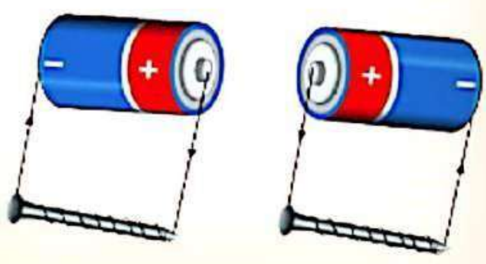


Figure 3.63

Chapter Four

Nature and reflection of light

Introduction

Light is essential for many everyday activities, most notably our ability to see objects around us. It allows us to perceive colours, shapes and details and navigate our environments safely. In this Chapter, you will learn the concept of light, sources of light, propagation and transmission of light, reflection of light through plane mirrors and curved mirrors, and uses of curved mirrors in daily life. The competencies developed will enable you to analyse and describe the characteristics of images formed by plane and curved mirrors. Also, you will be able to apply the principles of light reflection in different everyday situations.

Think
Life without reflection of light

Concept of light

Light is a fundamental aspect of our universe, influencing both the physical world and our perception of it. It is a type of energy that we can see with our eyes, which helps us understand what is around us. When light encounters different materials, it can be absorbed, reflected, or refracted, leading to various visual effects.

The concept of light extends beyond mere visibility; it shapes our experiences, influences our environment, and carries profound significance in both science and culture. Understanding light allows us to appreciate its role in our lives and the world around us.

Light is a form of energy which stimulates the sense of vision.

Light has some distinct features that differentiate it from other forms of energy. These features include:

1. Light is given out from its source. Lines known as light rays are used to show the direction of light.
2. Light travels in a straight line. This means that light can be observed as a beam of light. A beam is a bundle of rays.
3. Light transfers energy. Objects gain energy when they absorb light. For example, solar panels absorb light

from the Sun (solar energy) and convert it into electrical energy.

4. Light travels in a vacuum. Light does not require a material medium to travel.
5. Light travels at the speed of 3×10^8 m/s, which is the highest speed recorded on Earth.

Sources of light

Light sources can be classified into two main types: natural and artificial. Some objects are luminous, meaning they produce their own light, whereas others are non-luminous and only reflect or scatter light from other sources. Bioluminescence is a natural occurrence in certain glowing organisms, especially in dark forest settings.

Task 4.1

(a) Classify objects from Table 4.1 as natural or artificial light sources.

(b) Identify objects which emit their own light (luminous) and those which do not emit light (non-luminous).

Table 4.1: *Natural and artificial luminous and non-luminous objects*

 (a) Uhuru torch	 (b) The Sun	 (c) Lamp	 (d) Match box
 (e) Fire	 (f) Light bulb	 (g) Plane mirror	 (h) Lightning
 (i) TV screen	 (j) Bioluminescence eyes	 (k) Volcano	 (l) Firefly

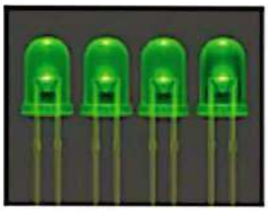
(m) Stars

(n) Candle

(o) Traffic light

(p) Moon

(q) Watasenia plants



(r) Light emitting diodes

(s) Lighter

(t) Torch

Propagation and transmission of light

The propagation and transmission of light are foundational concepts in understanding how light behaves as it travels and interacts with different media. Light moves at incredible speeds and interacts with various materials in unique ways. This phenomenon encompasses a variety of processes, including reflection, refraction, and absorption, all of which play a crucial role in how we perceive our surroundings.

Rays and beams of light

To explore the concept of a ray and a beam of light, perform Activity 4.1 and Activity 4.2

Activity 4.1

Aim: To explore rays and beams of light

Materials: a flashlight or small handheld torch (can use a phone flashlight if available), piece of cardboard or stiff paper, small mirror, piece of thin cloth or plastic (like a transparent bag or thin cotton), needle or sharp object to create holes, dust, chalk powder, or flour to make light paths visible (optional)

Procedure

1. Create a single small hole at the centre of the cardboard. Ensure the hole is just big enough for a narrow beam of light to pass through. We will use this narrow beam of light as a model of a ray of light.
2. Turn on the flashlight and place the cardboard in front of it, allowing the light

to pass through the hole. Observe the ray of light coming through the hole.

3. If available, sprinkle some dust or flour in the air around the light to make the ray more visible. If it is still difficult to see the ray, a thin cloth or a semitransparent plastic may be used.
4. Remove the cardboard with a single hole and replace it with another cardboard piece that has 3-5 small holes arranged in a cluster.
5. Shine the flashlight through the multiple holes and observe how several rays combine to form a 'beam' of light.

Questions

Focusing on observations in Steps 2 and 5:

(a) What insights did you gain from the observations?

(b) Highlight the key differences between the two observations.

(c) Analyse any patterns in Steps 2 and 5.

(d) What relationships can you identify between them?

Activity 4.2

Aim: To explore the rectilinear propagation of light

Materials: candle, matches, 3 cardboards of equal size (about 20 cm by 8 cm), sellotape, string, nail, ruler, screen

Procedure

1. Take three square cardboards of equal size. Locate the centre of each piece of cardboard by drawing the diagonals.
2. Using a nail, make a hole at the centre of each cardboard.
3. Fix the three cardboards so that they are upright as seen in Figure 4.1.
4. Arrange the cardboards as A, B and C, one behind the other, so that their centres are in the same horizontal line. You may pass a knitting needle through to confirm that they are in a straight line.

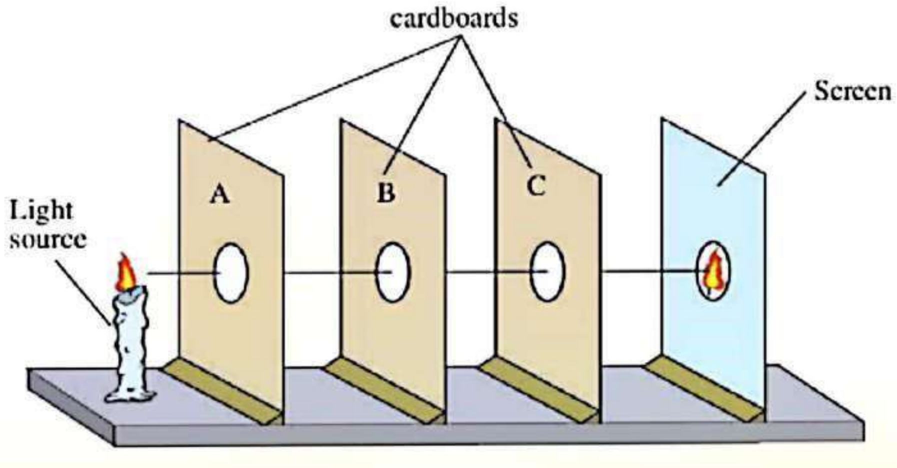


Figure 4.1

5. Now, place a burning candle in front of board A and look through the hole in board C. Then, move board B sideways slightly and again look through the pinhole in board C.

Questions

Focusing on observations in steps 4 and 5:

(a) What insights did you gain from steps 4 and 5?

(b) Draw patterns or themes from your observations in steps 4 and 5.

The rectilinear propagation of light is a fundamental principle which states that light travels in straight lines in a uniform medium. This principle is crucial in designing optical devices like cameras, telescopes, and lasers, where precise light paths are necessary for functionality. The concept of rectilinear propagation of light helps to understand the behaviour of light, making it important in both science and practical applications.

Task 4.2

Hold the straight tube in front of the light source and note what you observe (Figure 4.2 (A)). Next, hold the curved tube (Figure 4.2 (B)) in front of the light source and again note your observation.

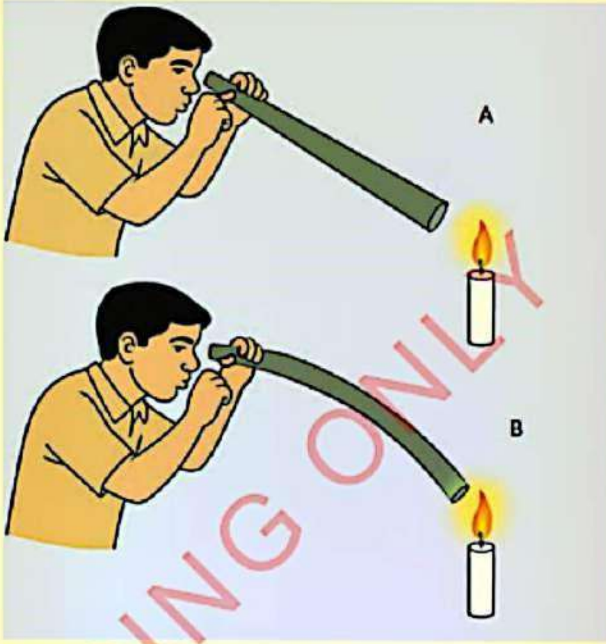


Figure 4.2

(a) What did you observe about the path of the light in the straight tube?

(b) How did the light behave when it travelled through the curved tube?

(c) What conclusions can you draw about how light travels through different shapes of tubes?

Transmission of light

The ability of light to travel through matter varies from one substance to another. When light travels through matter, it is said to be transmitted (passed through). When discussing light transmission, materials are classified into three categories, namely: transparent materials, translucent materials, and opaque materials.

Transparent materials are materials that allow light to pass through them. You can see through transparent materials without obstruction, as shown in Figure 4.3. These materials appear to be clear. Examples of transparent materials are glass panes of windows, glass slabs, prisms, and clear plastics.

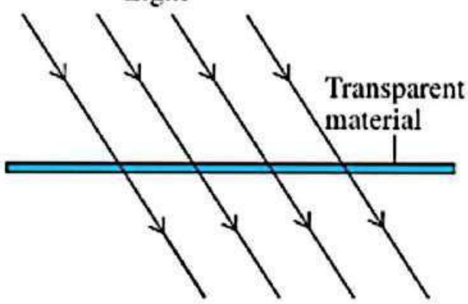


Figure 4.3: *Transmission of light through transparent material*

Translucent materials allow only part of the light to pass through them but not enough to make a defined image. This happens as light rays get scattered when passing through the material as shown in Figure 4.4. Oiled paper and tinted frosted glass are examples of translucent materials. Tinted glass is used in car windows. Some glass windows in houses are frosted to provide privacy. You cannot see clearly through a translucent material.

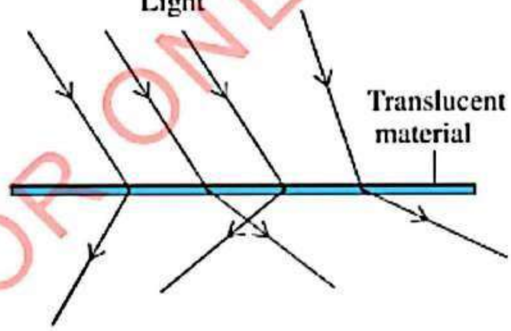


Figure 4.4: *Transmission of light through translucent material*

Opaque materials are materials which totally block the light, as shown in Figure 4.5. A block of concrete, wood, a book, a wall, and a human body are examples of opaque materials.

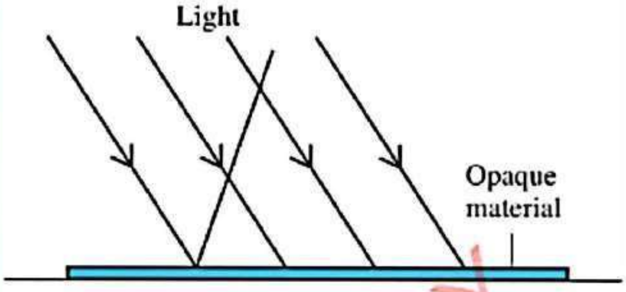


Figure 4.5: *Light falling on an opaque material*

Task 4.3

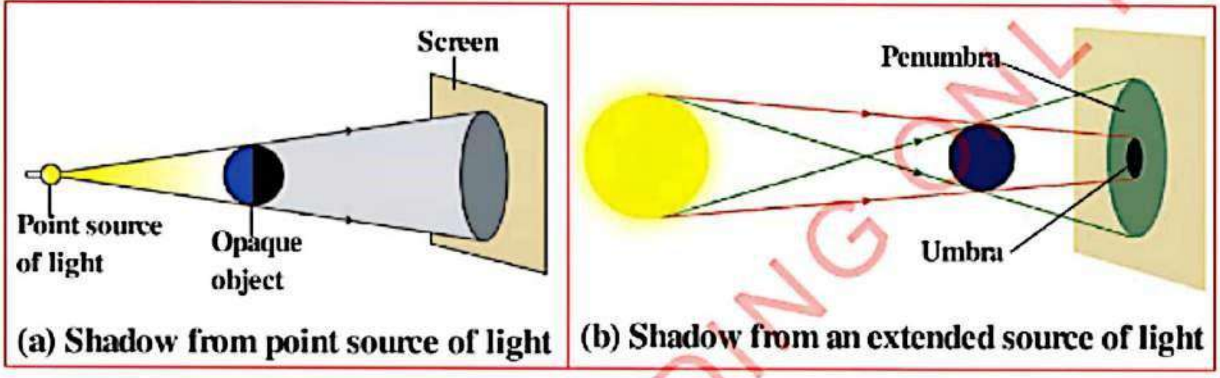
From your school and home environment, collect and identify transparent, translucent and opaque materials. What is the importance of each material in your daily life?

Shadows

When an opaque object is in the path of a beam of light, a darkened region is formed behind the object. Little or no light reaches this region because the opaque object does not allow light to pass through it. This region is called a shadow. The shadow is formed because light travels in straight lines. Shadows have sharp edges as shown in Figure 4.6.

Figure 4.6: *Tree shadow cast*

The type of shadow formed varies depending on the size of the source of light. Point sources of light such as the ray box produce a sharp shadow (Figure 4.7 (a)). An extended source of light produces a shadow that is not uniform. A shadow has two main parts. One part is totally dark and is called total shadow or umbra, and the other part is partially dark and is called partial shadow or penumbra (Figure 4.7 (b)). An example of an extended source of light is the Sun. The shadow formed by an extended source of light is blurred at the edges. To explore the concept of light, perform Activity 4.3.



(a) Shadow from point source of light (b) Shadow from an extended source of light

Figure 4.7: *Shadow formation*

Activity 4.3

Aim: To demonstrate the formation of a shadow from a point source of light

Materials: piece of cardboard, torch, white screen, and object hanging on a string

Procedure

1. Make a small hole (2 to 5 mm) in the cardboard (to simulate a point source).
2. Place the white screen about 30 cm from the cardboard.
3. Suspend the object between the cardboard and the white screen as in Figure 4.8.

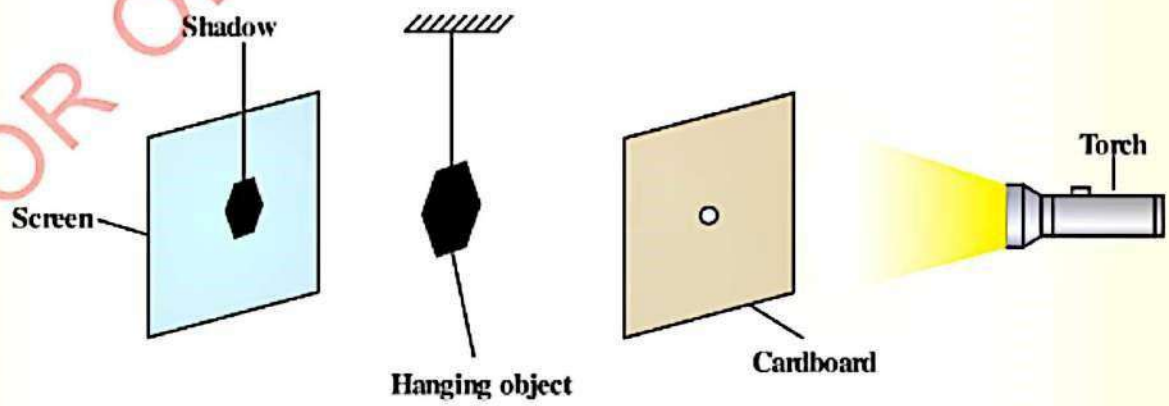


Figure 4.8

4. Place a light source close to the hole in the cardboard and observe the shadow of the object that forms on the screen.

Questions

(a) What type of shadow was formed on the screen?

(b) Where can similar shadow effects be found in daily life?

Project 4.1

Set up a light source and various objects at different distances to explore how shadows change with different light sources and object positions. Investigate the size and clarity of shadows formed. Write the report of your findings.

Exercise 4.1

1. You are in a room at night, and the light is turned on. You can see the furniture, walls, and other objects even though they do not produce light. Explain how you are able to see non-luminous objects in such a situation.
2. Imagine you are helping your school administration to design an energy-saving lighting system. Would relying only on sunlight be effective for classrooms? Justify your answer based on daily lighting needs.
3. During a science club presentation, a student shines a torch through a hole in a cardboard. Describe the difference between the terms "ray of light" and "beam of light" in relation to this demonstration.
4. Your parents are planning to build new classrooms and has asked for your input on design choices. Which roofing materials would you recommend to help reduce electricity usage for lighting during the day? Explain your choice.
5. Explain how the umbra and penumbra are formed when light is blocked by an object.
6. You are asked to create sharp shadows of different objects using a torch during a science exhibition. Identify and explain the factors that will affect how sharp the shadows appear

Reflection of light through the plane mirror

We see objects because they reflect the light falling on them. When light rays fall on the surface of an object, they are either absorbed, transmitted, or reflected. Sometimes, a combination of the above processes may occur. When light strikes a surface, how it is reflected depends on the nature of the surface.

Reflection of light is the phenomenon in which light rays are bounced back when they strike a highly polished surface like a mirror.

While one cannot usually see behind oneself, by the use of a mirror, one can see an object which is approaching from behind. This is possible because the light from the object, on falling on the mirror, is thrown back to the observer's eyes.

Therefore, this throwing back of light from the mirror is called reflection. It is *possible to see an object because it either* emits or reflects light.

When using a plane mirror, a reflected ray bounces off the mirror. A plane *mirror is a thin glass whose surface (the bottom/back) is silvered to obtain a shiny* reflecting surface. Figure 4.9 shows the reflection of light rays from a plane *mirror. A polished metal surface can also* reflect light rays like a plane mirror.

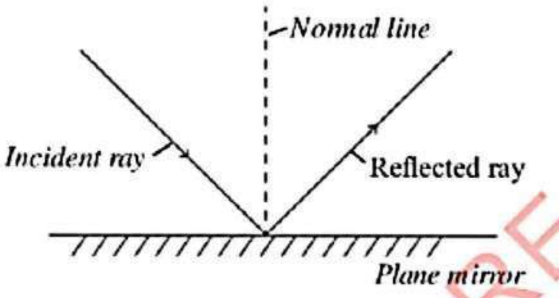


Figure 4.9: *Reflection of light on a plane mirror*

Regular and irregular reflection of light

There are two types of reflection: regular or specular reflection, and irregular or diffuse reflection.

Regular reflection

In regular reflection, the reflecting *surface is so smooth that an image of the* object that reflects the light is very clear. In regular reflection, all the reflected *rays are in one direction. The rays are also parallel, as shown in Figure 4.10. Examples of such surfaces are mirrors and polished metal surfaces like highly* reflective aluminium sheets.

When viewing the image of an object in a plane mirror, rays of light originate from the object and travel parallel along a straight line to the mirror. The same rays reach the eye after reflection, appearing *as if originating from the image, resulting in a very sharp image.*

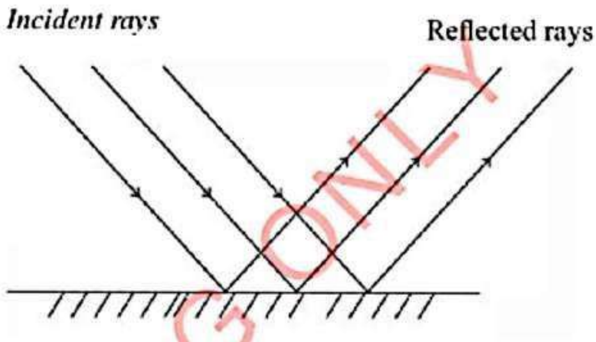


Figure 4.10: *Regular reflection of light*

Irregular reflection of light

Irregular reflection is the type of reflection in which light rays meet a rough reflecting *surface. This is shown by the incident* light rays reflected in different directions *as shown in Figure 4.11. In irregular* reflection, the reflected rays are not *parallel, causing them to scatter in many directions. This results in the formation of distorted images.*

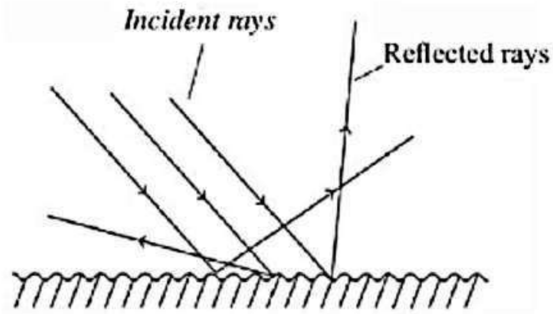


Figure 4.11: *Diffuse reflection of light*

Laws of reflection

The phenomenon of reflection is *fundamental to the behaviour of light and serves as a foundation in the study of* light. When light encounters a surface, it predictably changes direction, following specific principles known as the laws of reflection. These laws govern how light interacts with reflective surfaces, such as mirrors (Figure 4.12) and determine the path of the reflected rays. They are essential for understanding the behaviour of optical systems and have practical applications in fields ranging from astronomy to everyday technologies like periscopes, cameras, and fibre optics. Activity 4.4 aids in experimental exploration on laws governing reflection of light.

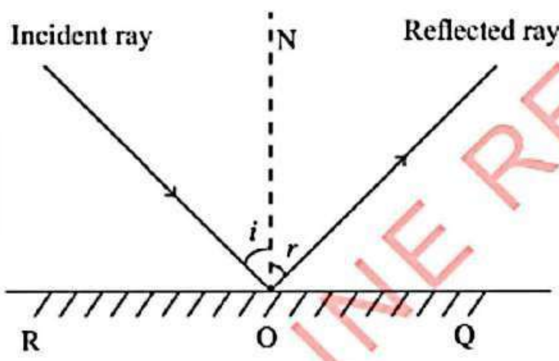


Figure 4.12: *Reflection of light from the plane mirror*

There are two laws of reflection that can be stated as follows:

1. **The angle of incidence is equal to the angle of reflection.** This means the angle at which the incoming light ray strikes a surface (the angle of incidence) is identical to the angle at which it is reflected away (the angle of reflection).
2. **The incident ray, the reflected ray, and the normal to the reflective surface all lie in the same plane.** This ensures that the reflection is constrained to a two-dimensional plane defined by the light ray and perpendicular to the surface at the point of incidence.

Activity 4.4

Aim: To investigate the laws of reflection

Materials: pins, soft board, plain paper, optical pins, mirror

Procedure

1. Fix a plane paper on a soft board using a pin, then draw a horizontal line across it.
2. Align a mirror vertically on the line.
3. Place an optical pin in front of the mirror so that you can see its image in the mirror.
4. Line up the pin and its image and place a second pin in front of the mirror along the line of sight, as shown in Figure 4.13.

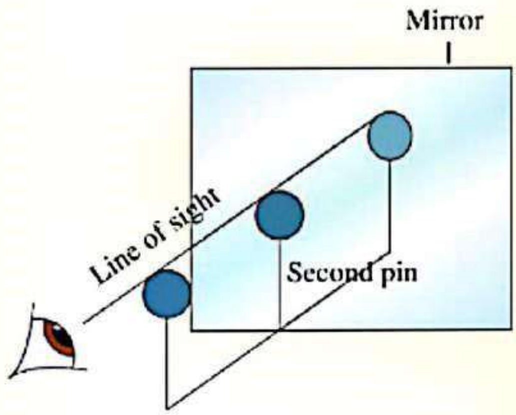


Figure 4.13

5. Look at the image in the mirror from another direction and place two pins

along your line of sight, as shown in Figure 4.14.

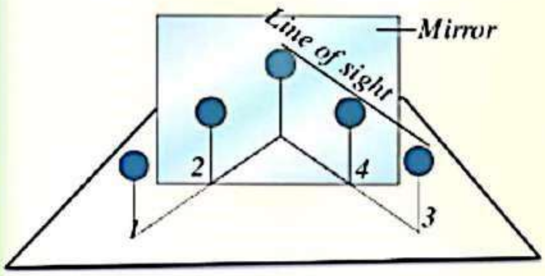


Figure 4.14

6. Remove the mirror and use a ruler to draw a line through the positions of pins 1 and 2. This represents the incident ray.
7. Draw a line through the positions of pins 3 and 4. This represents the reflected ray.
8. Extend the lines until they intersect. The point of intersection is where the image appears, as shown in Figure 15.

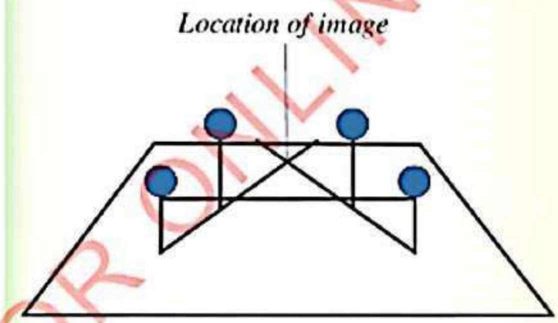


Figure 4. 15

9. Measure the shortest distance from pin 1 to the mirror line. Also, measure the shortest distance from the location of the image to the mirror line.
10. Draw a line through the midpoint of the mirror line and the point representing the location of the image. This line will be perpendicular to the mirror line and therefore the normal.
11. Using a protractor, measure the angle of incidence and the angle of reflection.

Questions

(a) Compare the object's size with the size of the image formed in Step 3.

(b) Discuss your results in step 9.

(c) Compare the two angles formed by the rays and discuss your results.

(d) Comment on the position of the incident ray, the reflected ray and the normal.

The image of the pin in the mirror is identical in size and shape to the actual pin. This shows that both the object and its image have the same size. Also, the distances of the object and its image from the mirror are equal. The activity also demonstrates that the angle at which light hits the mirror (angle of incidence) equals the angle at which it reflects (angle of reflection). Furthermore, the incident ray, reflected ray, and the normal line all lie within the same plane.

Image formed by plane mirrors

When we look in a mirror, we do not see the actual object but rather an image created by light rays reflecting off the mirror's surface. These reflected rays adhere to the laws of reflection. Although the image forms in our eyes, it appears to be located behind the mirror, despite the fact that no light comes from that spot. The position of the image can be determined by drawing and extending the reflected rays behind the mirror until they intersect, as shown in Figure 4.16. In other words, the image seems to be the point from which all the reflected rays emerge. Moreover, the incident ray, reflected ray, and the normal all lie in the same plane.

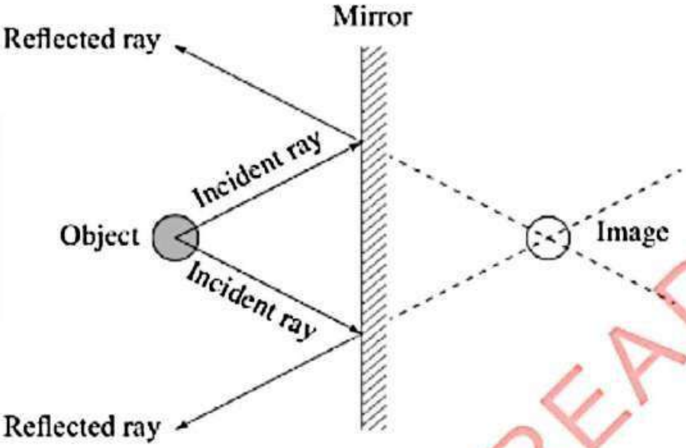


Figure 4.16: *Image formation by a plane mirror*

Characteristics of images formed in a plane mirror

A plane mirror is a simple glass with a flat surface. The only difference from other types of glass is that its back has been silvered. The image formed by a plane mirror has several characteristics. These include the following:

1. The image formed is virtual (not real).

   When an object is placed in front of the plane mirror, its image will appear to be in a position behind the mirror. This image is said to be virtual, that is not real, since it is in a location where the light does not reach, even though it appears like it does. It only appears to the observer as though the light is coming from this point.

2. The image is upright.

   If you stand in front of a plane mirror, your image appears upright; that is, the image of your head appear at the top and that of your feet at the bottom. This is because plane mirrors form upright images, not inverted images.

3. The image is the same size as the object.

   The image of an object placed in front of a plane mirror is the same size as the object. The ratio of the image size to the object size is called magnification. Plane mirrors produce images which have a magnification of 1.

4. The image is the same distance behind the mirror as the object is in front of the mirror.

   If you stand a distance of three metres from the plane mirror you must focus at a location three metres behind the mirror to view your image.

5. The image has a left-right reversal.

   If you view your image in a plane mirror, you will notice that it appears to be laterally inverted. This means that when, for example, you raise your left hand, the image appears to indicate a raised right hand. If you are wearing a shirt with lettering, for example, WAY, it would appear as YAW. Note that both the order and orientation of the letters are reversed. They are laterally inverted. The alphabets that will have the image appear the same as the alphabet when kept in front of a plane mirror are A, H, I, M, O, T, U, V, W, X, and Y. These letters are vertically symmetric. That means if we cut the letters in half, both halves will look similar. There won't be any change in appearance when the letter is flipped sideways.

Lateral inversion is the phenomenon in which the image of the object turns 180° about the vertical axis, such that the right side of the object appears as the left side of the object and vice versa. For example, a card printed with word, REEL when viewed through the mirror the word would appear as ⅃ƎƎЯ.

Task 4.4

The following tasks should be done in pairs.

(a) On an index card or sheet of paper, write the word 'SCHOOL'. Look at the word reflected in a mirror.
  (i) What is the size of the image compared to the object?
  (ii) What do you observe about the position of the letters?

(b) Raise your right hand while standing in front of the mirror. Which hand does your image appear to raise? If a person were facing you, which hand would she raise to look like your image in the mirror? Present your findings to the class members.

Rotating a mirror

If a mirror is rotated by a certain angle, what changes can occur to the reflected ray? You know that when light reflects off a plane mirror, the angle of incidence is equal to the angle of reflection. Now, if a specific angle turns the plane mirror, how will this affect the angle of reflection? To explore reflection of ray of light by rotating mirror, perform Activity 4.5.

Activity 4.5

Aim: To investigate the reflection of a ray of light by rotating a mirror

Materials: ray box, plane mirror, soft board, protractor, plain paper, pins

Procedure

1. Fix a sheet of paper on the soft board and draw on it a line $L_1 L_2$.
2. Place a plane mirror vertically with one of its sides along the mirror line $L_1 L_2$ to be perpendicular to the soft board.
3. Introduce a ray of light to strike the mirror at a given angle, say 30°.
4. Mark the paths of the incident ray and the reflected ray.
5. Without moving the ray box, rotate the mirror slightly through an acute angle, and mark the new line of the mirror as $L_3 L_4$.
6. Mark the path of the incident ray as $L_3 L_2$ and that of the reflected ray as $L_3 L_1$.

7. Measure and record the size of the angles of incidence and reflection.

Questions

(a) By what angle was the mirror rotated?

(b) By what angle did the reflected ray change its direction?

The reflected ray changes direction by an angle that is double the angle through which the mirror is rotated. Therefore, if the mirror is rotated by an angle θ the reflected ray will rotate by an angle 2θ.

Multiple mirrors

Sometimes, systems are made up of two or more mirrors and can create multiple images of a single object. A common example of this is a right-angle mirror.

Right-angle mirrors

Right-angle mirrors refer to two mirrors that are 'joined' at their edges at an angle of 90°. Suppose we take two mirrors and set them at right angles to each other. You will see a typical image in mirror 1 and another image in mirror 2. The two plane mirrors each produce a left-right reversal of the images, that is, 1 and 2. These images are sometimes referred to as primary images. If you look carefully, you see that a third image is formed by the rays reflecting off mirror 1 and then off mirror 2 to your eyes (Figure 4.17). This third image is identical to the other two except that it results from two reflections, thus, it does not show right-left reversal. Image 3 is usually referred to as the secondary image. To explore the concept of images formed by multiple mirrors, perform Activity 4.6.

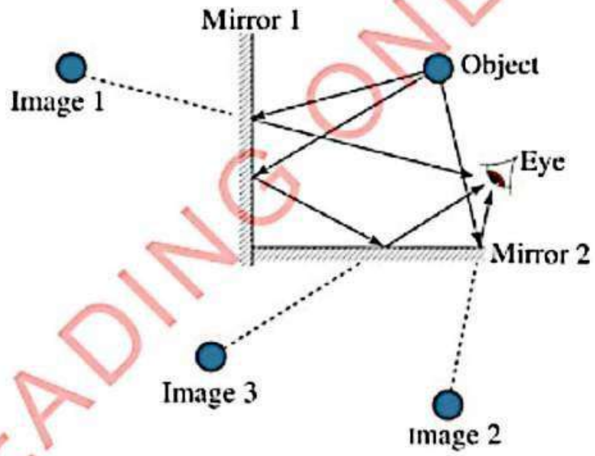


Figure 4.17: *Multiple images in right-angle mirrors*

Activity 4.6

Aim: To determine the number of images formed by multiple mirrors

Materials: two plane mirrors, one object, four drawing pins, an optical board, protractor, ruler, plain paper

Procedure

1. Using drawing pins, fix a plain paper on an optical board.
2. Draw two lines that are perpendicular (90°) to each other on plain paper.
3. Place the two mirrors along the lines
4. Place an object in front of the mirrors as shown in Figure 4.18.

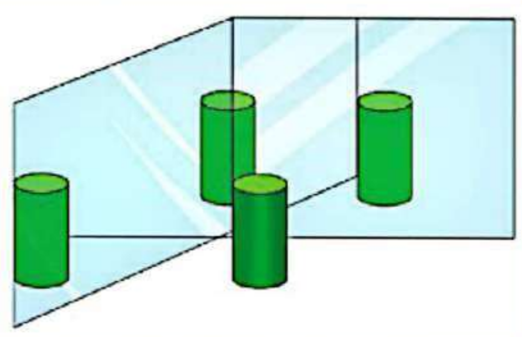


Figure 4.18: *Plane mirrors placed at a right angle*

5. Observe and count the number of images formed.
6. Reduce the angle by closing the mirrors gradually onto each other, such that the angle between them is 60°, 45°, 30° and 0°. Note that at 0° the mirrors are parallel to each other.
7. Record your results using a table as shown in Table 4.2.

Table 4.2: *Number of images for various angles between the mirrors*

Angle between the mirrors	Number of images
90°	
60°	
45°	
30°	
0°	

Questions

(a) What happened to the number of images when the angle is reduced?

(b) Account for the number of images formed in the mirror.

The number of images will increase as the angle between the mirrors becomes smaller. When the angle is 0°, the mirrors are parallel to each other and the number of images (n) is infinite. The number of images formed in multiple mirrors relates to the angle θ between two mirrors, as follows:

$$n = \frac{360^{\circ}}{\theta} - 1,$$

For $\theta = 90^{\circ}$,

$$n = \frac{360^{\circ}}{90^{\circ}} - 1, \; n = 3$$

From the explanation above, we can see that as the angle between the mirrors decreases, the number of images increases. As the angle between the mirrors approaches zero, the number of images approaches infinity. That is, there is a very large number of faint images. Parallel mirrors are commonly used in salons and barbershops.

Example 4.1

An object is placed 2 cm from a plane mirror. If the object is moved by 1 cm toward the mirror, what will be the new distance between the object and the image?

Solution

Given an initial distance of the object from the plane mirror = 2 cm and the object moves 1 cm toward the mirror:
Then, the new distance of the object from the mirror = 2 cm – 1 cm = 1 cm.
Since in a plane mirror, the image is formed at the same distance behind the

mirror as the object is in front of the mirror, therefore, the new distance between the object and its image will be:

$$\text{distance between object and image} = 2 \times (\text{distance of object from mirror})$$
$$= 2 \times 1\text{ cm} = 2\text{ cm}$$

Therefore, the new distance between the object and its image is 2 cm.

Example 4.2

Two plane mirrors are placed at an angle of 60° to each other. When an object is placed between them, find the number of images formed due to repeated reflections.

Solution

Given $\theta = 60^\circ$

Substitute into the formula

$$n = \frac{360^\circ}{\theta} - 1$$

$$n = \frac{360^\circ}{\theta} - 1 = n = \frac{360^\circ}{60^\circ} - 1$$

$$n = 6 - 1 = 5$$

Therefore, 5 images are formed due to repeated reflections.

Exercise 4.2

1. Some letters are provided in the following boxes. Create meaningful words related to the reflection of light by selecting the horizontal and vertical sequences.

N	E	P	R	E	C	T
O	P	X	V	R	T	U
R	L	V	I	R	T	U
M	A	L	R	E	A	L
A	N	I	T	C	A	R
L	E	O	U	T	A	E
A	I	M	A	G	E	J
N	K	N	L	E	N	C

2. The distances and heights of an object placed in front of a plane mirror are provided in columns A and B, respectively. In columns C and D, the distances and heights of the image are listed, but not in the correct order. Correct the order.

Column A	Column B	Column C	Column D
10 cm	5 cm	5 cm	10 cm
5 cm	10 cm	10 cm	8 cm
6 cm	8 cm	6 cm	5 cm

3. An object is placed in front of a plane mirror. The mirror is moved away from the object at a speed of 0.25ms^{-1}. What is the speed of the image with respect to the mirror and to the object?

4. A ray of light strikes a plane mirror such that the angle with the mirror is 20°. What

is the value of the angle of reflection? What is the angle between the incident ray and the reflected ray?

5. A girl in Figure 4.19 stands 80 cm away from the plane mirror. If the girl moves 20 cm towards the mirror, what is the distance between the girl and her image? Give a reason for your answer.

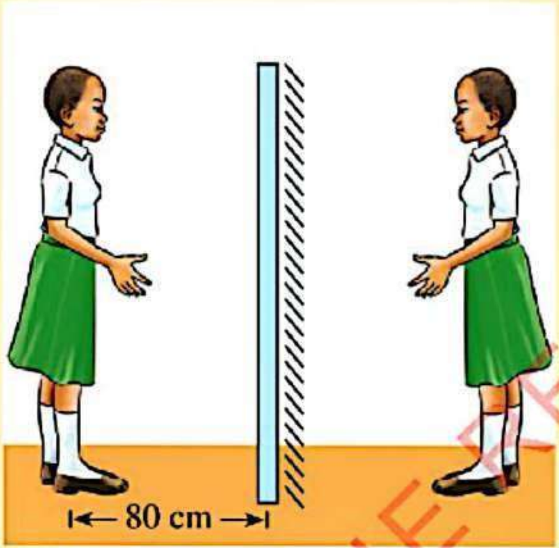


Figure 4.19

6. A regular polygon has an exterior angle of 45°. Determine how many times it can be rotated through the angle 45° and still coincide with itself, excluding the starting position.

Reflection of light from curved mirrors

Have you ever observed that a car side mirror makes objects look smaller than their real size? Why does this happen? A mirror with a curved reflecting surface is called a curved mirror. It is formed by silvering a piece of curved glass. If the glass is considered a portion of a hollow sphere, then the resulting mirror is called a spherical or curved mirror. The type of curved mirror depends on which side of the curved glass is silvered. If the outer side of the curved glass is silvered such that the inner side becomes reflective, the mirror is called a concave mirror (Figure 4.20(a)). Conversely, if the inner side of the curved glass is silvered so that the outer surface becomes reflective, the mirror is called a convex mirror (Figure 4.20 (b)).

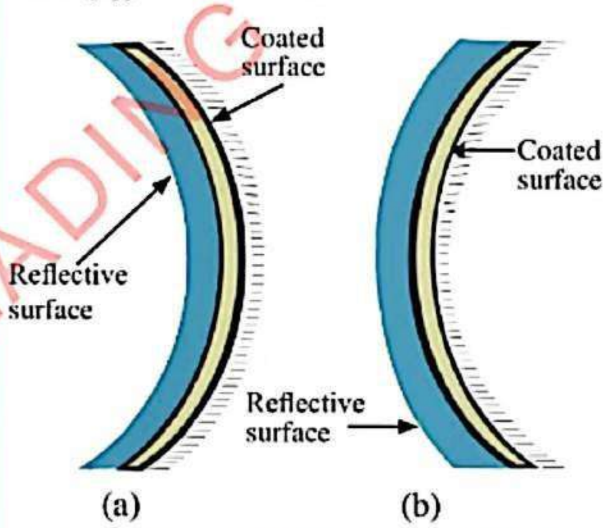


Figure 4.20: *(a) Concave, and (b) convex mirrors*

Terminologies used in spherical mirrors

Understanding spherical mirrors involves key terms such as **principal axis, focal point, mirror vertex, focal length,** and **centre of curvature.** The centre of curvature (C) is the centre of the sphere from which the mirror is derived. The principal axis is the line through the sphere's centre that intersects the mirror at the pole (P), which is the mirror's vertex. These concepts are essential for understanding how light reflects off curved mirrors.

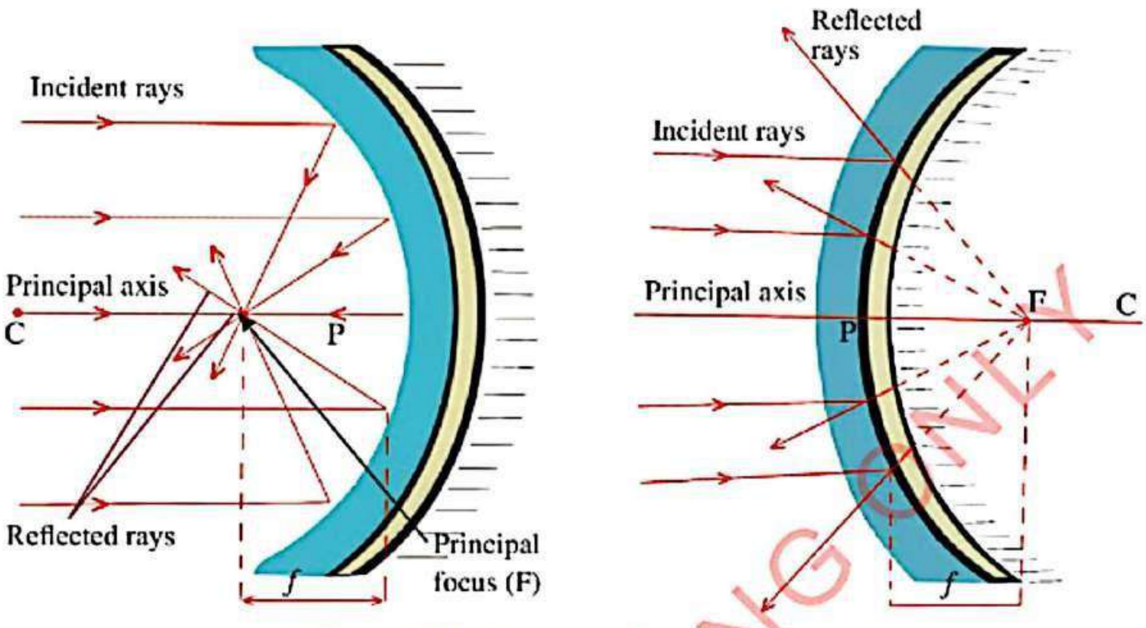


Figure 4.21: *Geometry of curved mirrors*

The pole acts as the centre of the mirror, with the principal focus (F) positioned halfway between the pole and the centre of curvature (C). In concave mirrors, the focal point is where all parallel rays of light come together; in contrast, for convex mirrors, the focal point appears as a location from which light rays spread out. The radius of curvature (R) refers to the radius of the sphere from which the mirror originates, and the focal length (f) is half that radius, indicating the distance from the mirror to the focal point. Figure 4.21 shows the geometry of curved mirrors.

A virtual image is formed when light rays appear to originate but cannot be focused onto a screen, while a real image is created where actual light rays intersect and can be projected onto a screen. The image distance v is the distance from the image point to the pole, and the object distance u is the distance from the object to the pole. Magnification m is the ratio of the image height h_i to the object height h_0, and it can also be expressed as the ratio of the image distance to the object distance. We perceive an image because light from the object reflects off a mirror and travels to our eyes, similar to how we see the object itself.

Relationship between focal length and radius of curvature

Consider the reflection of light ray I from a concave mirror at point M. CM is a line normal to the mirror surface and passes through the centre of curvature, and MF is the reflected ray, which passes through the focal point. Performing Activity 4.7 develops knowledge on practical solving for radius of curvature of curved mirrors.

$\angle i = \angle r$ (as we know that the angles of incidence and reflection are equal)

$\therefore$ In ΔCMF, $MF = CF$

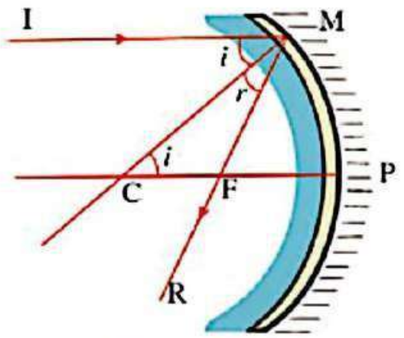


Figure 4.22:

For a small aperture of the mirror around the vertex,

$$MF = PF$$

$$PC = PF + CF = PF + PF = 2PF$$

$$R = 2f$$

Therefore, $f = \frac{R}{2}$

Activity 4.7

Aim: To determine the approximate value of the radius of curvature of a concave mirror

Materials: concave mirror, black carbon paper, metre rule

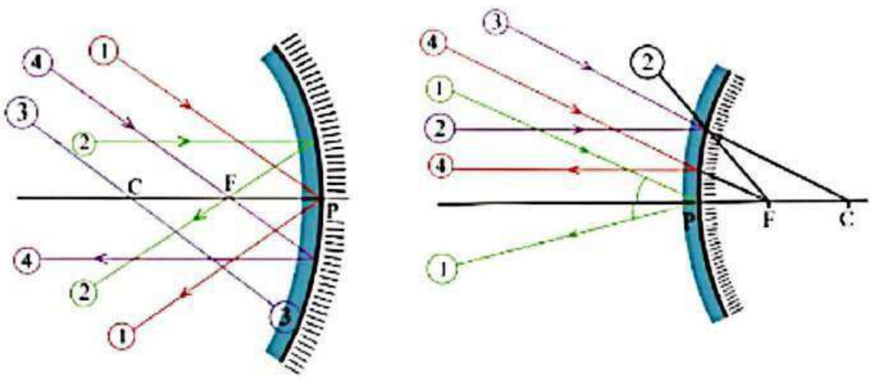
Procedure

1. Hold a concave mirror in such a way that its reflecting surface faces towards the Sun.
2. Adjust the position of the concave mirror so that the Sun's image falls on the piece of carbon paper after reflecting from the mirror.
3. Adjust the position of the carbon paper until you find a bright, sharp spot of light on the paper sheet.
4. Measure the distance between the mirror and the paper with the help of the metre rule.
5. Hold both the mirror and the paper for a few minutes in the same position and observe what happens.

Questions

What is the length of the radius of curvature of the mirror?

What happened to the black carbon paper in step 5? Determining the image location for curved mirrors is essential when using mirrors for various purposes. Methods for locating images formed by curved mirrors include the geometrical method and the mirror formula. The geometrical method involves using ray diagrams, which are valuable tools for determining the path light takes from the object to our eyes through the mirror. Figure 4.23 shows the reflection of light rays by curved mirrors.



(a) a concave mirror *(b) a convex mirror*

Figure 4.23: *Ray diagrams for spherical mirrors*

Images formed by concave mirrors

The rules of reflection for concave mirrors are used to locate an image formed by a concave mirror. These rules are as follows:

1. An incident ray that travels parallel to the principal axis of the mirror is reflected through the focal point.
2. An incident ray that passes through the focal point is reflected parallel to the principal axis.
3. An incident ray that passes through the centre of curvature is reflected along its path.
4. An incident ray striking the pole of the mirror at an angle to the principal axis is reflected such that the angle of incidence equals the angle of reflection, measured with respect to the principal axis.

In Figure 4.24, the incident rays are drawn along with their corresponding reflected rays. Each reflected ray converges at the image location and then diverges to the eye of an observer. Every observer can observe the same image location, and every light ray follows the laws of reflection. However, only two of these rays are needed to determine the image location since it only requires two rays to find the intersection point. Figure 4.23 shows the rays used to locate images formed by concave mirrors.

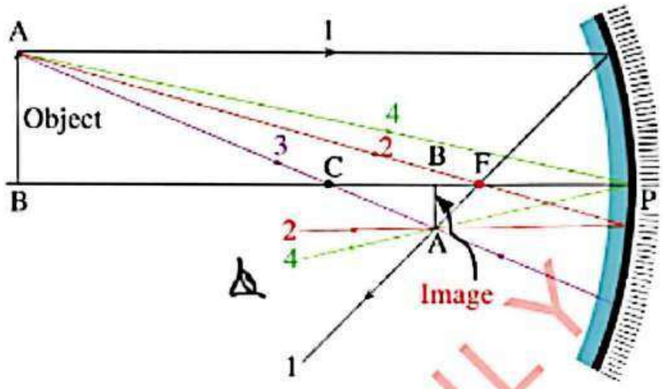


Figure 4.24: *Rays used to locate images formed by concave mirrors*

In drawing ray diagrams, when the light rays diverge, they are extended backwards to locate the image. In such cases, the image formed is virtual because it is formed by virtual rays of light, which are represented by dotted lines. The image is real when it is formed by the intersection of real rays of light. Activity 4.8 assists on experimental determination on behaviours of image formed by concave mirrors.

Activity 4.8

Aim: To determine the images formed by concave mirrors

Materials: graph paper, a sharp pencil, a ruler

Procedure

1. Choose an appropriate scale so that the ray diagram fits on the available space.
2. Draw a concave mirror at the centre of the graph paper.
3. Draw a horizontal line passing through the centre of the concave mirror. This is the principal axis.
4. Locate the centre of curvature and the focal point on the principal axis. Choose the

centre of curvature such that there is a considerable distance to the pole of the mirror.

5. Using the chosen scale, draw an upright arrow at a point far beyond C. The arrow represents an object.
6. Draw a ray diagram from the tip of the arrow parallel to the principal axis. This ray will be reflected through the focal point.
7. Draw another ray through the focal point from the same point on the object. This ray is reflected parallel to the principal axis. You may also choose to draw a ray that strikes at the pole and is reflected with the same angle as that of incidence.
8. Locate the point at which the reflected rays intersect and draw an arrow from the principal axis to the point of intersection. This represents the image and its location.
9. Measure the object distance, the image distance, the object size, and the image size. Determine the enlargement of the image using the formula:

$$magnification = \frac{image\ size}{object\ size}$$

Repeat steps 5 to 9 for different positions of the object. That is an object at the centre of curvature, C, an object between C and F, an object at F, an object between F and P.

10. Record your results as shown in Table 4.3.

Table 4.3

u (cm)	v (cm)	h_0 (cm)	h_1 (cm)	Nature of image	Magnification
Beyond C					
At C					
Between F and C					
At F					
Between F and P					

Questions

(a) What are the positions of the images formed for different object positions?

(b) Describe the nature of the images formed. That is, whether the images for various object positions are real or virtual, upright or inverted.

(c) Are the images for objects at different positions enlarged, the same size as the object or diminished?

It is observed that, depending on the object position, an image formed by a concave mirror can be virtual or real, enlarged or diminished, upright or inverted. The amount by which the size of the object is enlarged or diminished is called magnification, and is given by:

$$m = \frac{image\ size}{object\ size} = \frac{image\ distance}{object\ distance}$$

Example 4.3

An object 20 cm high is placed 40 cm in front of a concave mirror of focal length 15 cm. Determine the position, nature, size and magnification of the image formed using a ray diagram.

Solution

1. Choose a scale of 1 cm to represent 5 cm.
2. Draw the principal axis of the mirror and mark the focal point as shown in Figure 4.24 (a).
3. Draw the object position. Using the chosen scale, the object will be 4 cm high at a distance of 8 cm from the mirror as shown in Figure 4.25 (b).

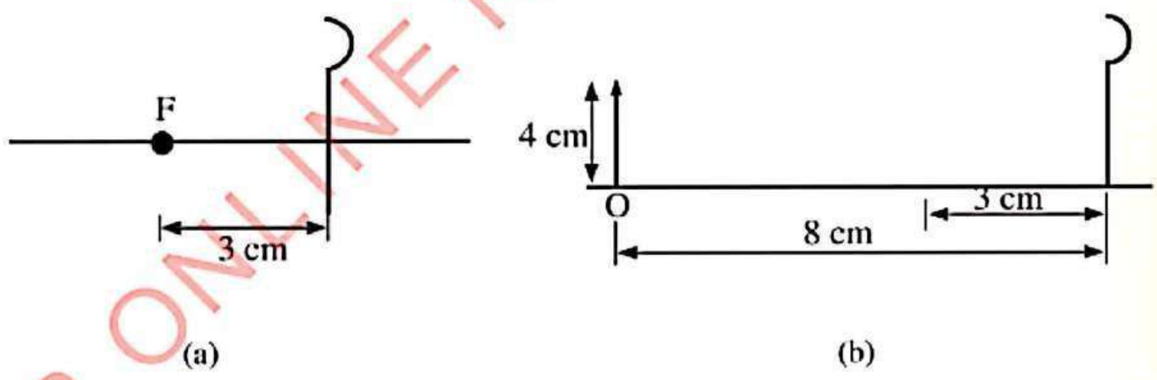


Figure 4.25

4. Locate the position of the image by drawing rays from the object to the mirror and the reflected rays as follows:
   (a) From the head of the object, draw ray 1 parallel to the principal axis. This ray will be reflected through the focal point.
   (b) From the head of the object, draw ray 2 through the focal point. This ray will be reflected parallel to the principal axis.
   (c) At the point of intersection of the two reflected rays, construct the image as shown in Figure 4.26.

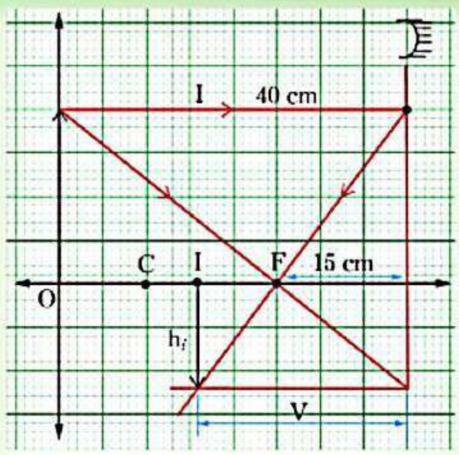


Figure 4.26

5. Using the chosen scale, the nature, size and position of the image can be determined. Thus,
   (a) The measured height of the image, $h_i = 2.4$ cm, which corresponds to the actual height of 12 cm (1 cm represents 5 cm).
   (b) The measured image distance, $v = 4.8$ cm, which corresponds to the actual image distance of 24 cm from the mirror.
   (c) True rays form the point of intersection, so the image is real.
   (d) The image is inverted.
   (e) $Magnification\,(m) = \frac{12\text{ cm}}{20\text{ cm}} = 0.6$, the image is diminished.

Task 4.5

Use a ray diagram to observe what happens when the object is located very far beyond the centre of curvature of a concave mirror. Discuss with your classmates about your observations.

Images formed by convex mirrors

In convex mirrors, the the centre of curvature, C, and the focal point, F, are located behind the mirror, that is, on the side of the mirror opposite the reflecting surface. Thus, a convex mirror has a negative focal length.

A convex mirror is sometimes referred to as a diverging mirror because incident light rays diverge upon reflection from the mirror surface. As a result, the reflected light rays never intersect on the object side (front side) of the mirror; instead, they appear to converge behind the mirror when extended backwards. For this reason, convex mirrors produce virtual images that are located somewhere behind the mirror. To determine the image location, only a pair of incident and reflected rays needs to be drawn. These rays are the same as those used in concave mirror ray diagrams, except that in this case, the rays appear to diverge from a point behind the convex mirror. The divergence point can be determined using the laws of reflection for convex mirrors (Figure 4.27), stated as:

1. Any incident ray travelling parallel to the principal axis will be reflected in such a manner that the reflected ray extended backwards pass through the focal point of the mirror.
2. Any incident ray travelling toward a convex mirror such that its extension passes through the focal point will be reflected parallel to the principal axis.
3. An incident ray, not parallel to the principal axis, that strikes the pole of the convex mirror is reflected such

that the angle of incidence equals the angle of reflection.

4. Any incident ray travelling toward a convex mirror such that its extension passes through the centre of curvature will be reflected along its path.

Note: The image of an object can be located by drawing any two of the stated rays.

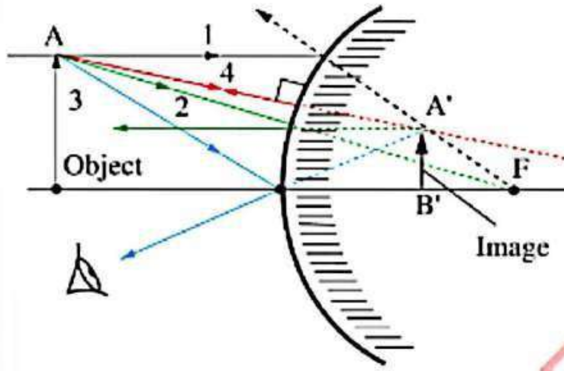


Figure 4.27: *Image formed by a convex mirror*

Activity 4.9 Aids in understanding characteristics of image formed by convex mirrors.

Activity 4.9

Aim: To determine the images formed by a convex mirror

Materials: graph paper, a sharp pencil, a ruler

Procedure

1. Choose an appropriate scale so that the ray diagram fits on the available space, and draw a convex mirror at the centre of the graph paper.
2. Draw a horizontal line passing through the centre of the convex mirror. This is the principal axis. Locate the centre of curvature, C and the focal point, F on the principal axis such that there is a considerable distance between C and P.
3. Use the scale to draw an upright arrow at a point far from the mirror. The arrow represents an object at a position far from the mirror.
4. Draw a ray from the tip point of the arrow towards the focal point, which is on the opposite side of the mirror. This ray will strike the mirror before reaching the focal point; stop the ray at the point of incidence with the mirror.
5. Draw the second ray such that it travels exactly parallel to the principal axis. Remember to place arrowheads upon the rays to indicate their direction.
6. Once the incident rays strike the mirror, they are reflected according to the rules of reflection for convex mirrors. For example, the ray that travels towards the focal point will be reflected and travel parallel to the principal axis. The incident ray that travels parallel to the principal axis is reflected and travels in a direction such that the reflected ray, extended backwards, passes through the focal point.

7. Use dashed lines to extend the reflected rays behind the mirror until they intersect. The point of intersection is the image point of the top of the object.
8. Use an arrow to draw the image by joining the point of intersection of extended rays and the principal axis.
9. Measure the image distance v, the object distance u, the image height, h_i and the object height, h_o. Note that, distances measured behind the mirror are considered to be negative.
10. Repeat Steps 3 to 9 for different positions of the object.
11. Summarise the results in a table.

Questions

(a) What are the characteristics of the images formed by a convex mirror?

(b) Do the characteristics of the image formed by a convex mirror change with the change of object position?

From this activity, we observe that the image of an object in front of a convex mirror will be located behind the convex mirror. Furthermore, the image will be upright, reduced in size and virtual.

Example 4.4

An object 5 cm long is placed on and perpendicular to the principal axis of a convex mirror of radius of curvature 20 cm. Use a scaled diagram to find the position, size and nature of the image when the object is 10 cm from the pole of the mirror.

Solution

The height of the object is 5 cm, the object distance is 10 cm, the radius of curvature is 20 cm, and the focal length is −10 cm.

Scale: 1 cm represents 5 cm.

From the scale:

Height of object = 1 cm, object distance = 2 cm and focal length −2 cm

1. Draw a convex mirror with the pole P.
2. Locate the focal point and object position by using the provided values.
3. Draw any two of the rays stated in the laws of reflection for a convex mirror as shown in Figure 4.28.

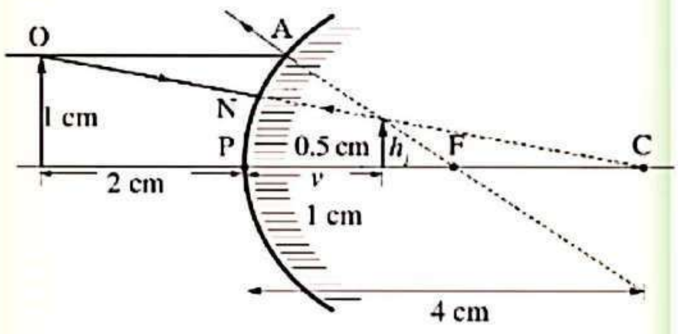


Figure 4.28

4. The object's image is constructed by considering the reflection of the rays OA and ON. After reflection, the ray OA appears

to diverge from the principal focus F, while the ray ON is reflected along its original path, hence appearing to come from C.

5. The image of the object is formed at the point of intersection of lines AF and NC.
6. Measure the image distance, v and height of the image, h_i.
7. Since the scale is 1 cm to 5 cm, it then follows that:

image distance,

$$v = \frac{1\text{ cm} \times 5\text{ cm}}{1\text{ cm}} = 5\text{ cm}$$

height of image,

$$h_i = \frac{0.5\text{ cm} \times 5\text{ cm}}{1\text{ cm}} = 2.5\text{ cm}$$

8. Virtual rays form the point of intersection, so the image is virtual.
9. The image is upright and diminished.

Curved mirror formula

Ray diagrams provide valuable information for determining the approximate location and size of the image. However, they do not deliver accurate numerical information concerning image distance and size. This is due to several errors that can arise from various sources when creating ray diagrams. Therefore, to obtain more precise numerical information, one should use the mirror equation and the magnification equation. The mirror equation provides the quantitative relationship between the object distance (u), the image distance (v), and the focal length (f). This equation is derived using the geometry of either concave or convex mirrors.

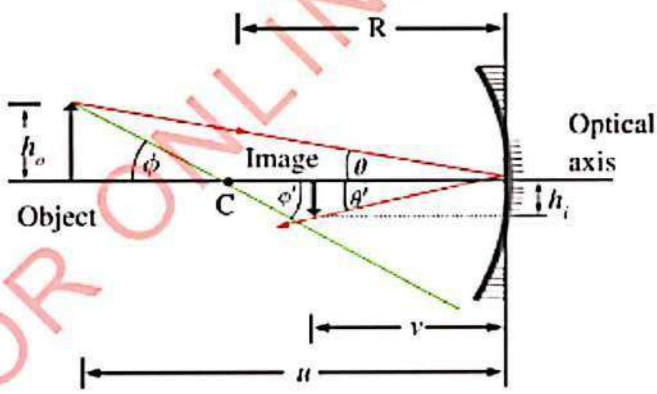


Figure 4.29: *(a) Image formed by a concave mirror*

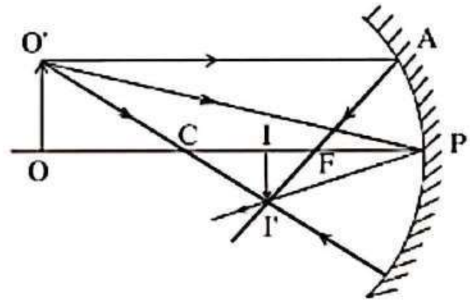


Figure 4.29: *(b) Concave mirror-real image*

From Figure 4.29 (a), the angles ϕ and ϕ' are alternate interior angles thus they have the same magnitude. However, they differ in sign if we measure angles from the optical axis. Therefore, $\phi = \phi'$. On the other hand, an analogous scenario holds for the angles θ and θ', which have equal magnitudes following the laws of reflection by concave mirrors. However, if measured from the optical axis, $\theta = -\theta'$. Now, considering the trigonometric identity;

$$\tan(-\theta) = -\tan\theta,$$

We find that;

$$\tan\theta = -\tan(\theta')$$

$$\tan\theta = \frac{h_0}{u} \text{ and } \tan\theta' = \frac{h_i}{v}$$

This implies to obtain $\frac{h_0}{u} = \frac{h_i}{v}$, which can also be rearranged to obtain:

$$\frac{h_i}{h_0} = \frac{v}{u} = m$$

This is the image magnification equation for spherical mirrors. Note that, h_0, h_i, u, v and m are respectively, the object height, the image height, the object distance, the image distance and magnification.

Therefore:

$$m = \frac{\textit{image height}(h_i)}{\textit{object height}(h_0)}$$

$$m = \frac{\textit{image distance from the mirror}(v)}{\textit{object distance from the mirror}(u)}$$

Note that, magnification is a ratio and, therefore, has no units. When the value of m is negative, the image is inverted. The image formed by a curved mirror can be larger, smaller or the same size as the object. When the ratio, m, *is greater than one, the image is enlarged; when it is less than one, the image is diminished;* and when it is equal to 1, the image and object sizes are equal. Similarly, from Figure 4.29, we observe that:

$$\tan\phi = \frac{h_0}{u-R} \text{ and } \tan\phi' = \frac{h_i}{R-v}$$

Since $\tan(\phi) = -\tan(\phi')$, then,

$$\frac{h_0}{u-R} = -\frac{h_i}{R-v}$$

This implies that;

$$-\frac{h_0}{h_i} = \frac{u}{v} = \frac{u-R}{R-v}$$

Further algebraic manipulation yields:

$$uv - vR = uR - uv$$

$$2uv = uR + vR = R(u+v)$$

$$\frac{2}{R} = \frac{u+v}{uv} = \frac{1}{u} + \frac{1}{v}$$

Since, $R = 2f$, it follows that: $\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$

Alternatively

To derive the equation $\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$, we analyse the geometry of a concave mirror using the principle of similar triangles.

Assumptions

1. Distances are measured from the mirror's pole.
2. Sign conventions
   (a) the distance in the direction of incidence light is positive
   (b) distances below the principal axis are negative.

Derivation

3. Consider the ray diagram setup of Figure 4.30
   (a) Place an object AB at a distance u from the pole.
   (b) The image A_1B_1 forms at a distance v.
   (c) The focal length f is the distance from P to F (principal focus).

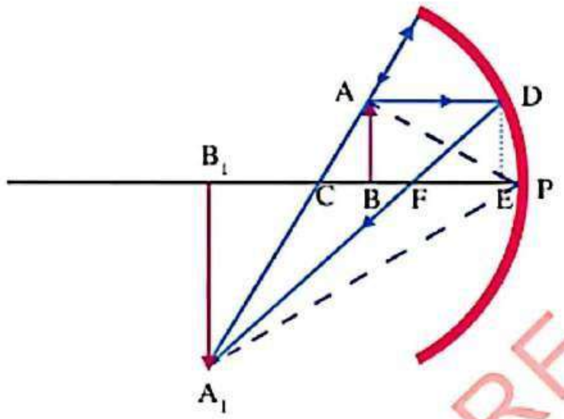


Figure 4.30: *Geometry of a concave mirror*

4. Identify similar triangles
   (a) (Triangle 1): ΔABP (object triangle) and ΔA_1B_1P (image triangle) are similar
      (i) $\angle APB = \angle A_1PB_1$ (from angle of incidence = angle of reflection).
      (ii) Both are right-angled.
   (b) (Triangle 2): ΔDEF (Mirror-focal triangle) and ΔA_1B_1F (Image-focal triangle) are similar
      (i) $\angle EFD = \angle B_1FA_1$ (Vertically opposite angles)
      (ii) Both are right-angled.

5. Set up a ratio

   From $\Delta ABP : \Delta A_1B_1P$

$$\frac{A_1B_1}{AB} = \frac{B_1P}{BP} \Rightarrow \frac{h_i}{h_0} = \frac{v}{u} \qquad (1)$$

   $\Delta DEF : \Delta A_1B_1F$

$$\frac{A_1B_1}{DE} = \frac{B_1F}{FE} \Rightarrow \frac{h_i}{h_0} = \frac{v-f}{f} \qquad (2)$$

6. Compare Equations (1) and (2) :

$$\frac{v}{u} = \frac{v-f}{f}$$

$$vf = uv - uf$$

$$\frac{vf}{uv} = \frac{uv}{uv} - \frac{uf}{uv}$$

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

$$f\left(\frac{1}{v} + \frac{1}{u}\right) = 1$$

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

This equation applies to both concave and convex mirrors with both convention signs.

Sign convention for the mirror equation

Recall, the characteristics of images formed by spherical mirrors depend on whether the mirror is concave or convex. The size, position and nature of the image also depend on the position of the object in front of the mirror. To determine the image properties, there is a need to indicate the signs of values such as image distance, image height, and focal length. Two sign conventions, namely the new Cartesian convention and the real is positive convention, are commonly used. The two sign conventions are summarised in Table 4.4.

Table 4.4: *Sign conventions*

New Cartesian convention	Real is positive
1. All distances are measured from the mirror as the origin	1. All distances are measured from the mirror as the origin
2. Distances measured in the opposite direction of the incident light are negative	2. Distances of real objects and images are positive
3. Distances measured along the direction of the incident light are positive	3. Distances of virtual objects and images are negative

Generally, the sign conventions for the given quantities in the mirror equation and magnification equations are as follows;

(a) f is positive if the mirror is concave.

(b) f is negative if the mirror is convex.

(c) v is positive if the image is real and located on the same side of the mirror as the object.

(d) v is negative if the image is virtual and located behind the mirror.

(e) h_i is positive if the image is upright and, therefore, virtual.

(f) h_i is negative if the image is inverted and, therefore, real.

Example 4.5

A 4.0 cm light bulb is placed 8.3 cm from a concave mirror with a focal length of 15.2 cm. Determine the image distance and the image size.

Solution

Given $h_0 = 4.0$ cm , $u = 8.3$ cm, $f = 15.2$ cm

Using formula

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

Upon rearranging the formula

$$v = \frac{fu}{u - f}$$

$$v = \frac{15.2 \text{ cm} \times 8.3 \text{ cm}}{8.3 \text{ cm} - 15.2 \text{ cm}} = -18.28 \text{ cm}$$

From $m = \frac{h_i}{h_0} = \frac{-v}{u}$, hence, $h_i = \frac{-vh_0}{u}$

$$h_i = \frac{-(-18.28 \text{ cm}) \times 4 \text{ cm}}{8.3 \text{ cm}} = 8.81 \text{ cm}$$

Therefore, the image is formed at a distance of 18.28 cm from the mirror with a size of 8.81 cm. The negative sign of the image distance indicates that the image is formed behind the mirror.

Example 4.6

A 4.0 cm light bulb is placed 35.5 cm from a convex mirror with a focal length of 12.2 cm. Determine the image distance and the image size.

Solution

By the new Cartesian sign conversion;

$u = -35.5$ cm *(Measured against the direction of incident light),*

$f = +12.2$ cm

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

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

$$v = \frac{fu}{u - f}$$

$$v = \frac{-35.5\text{ cm} \times 12.2\text{ cm}}{-35.5\text{ cm} - 12.2\text{ cm}} = 9.08\text{ cm}$$

$$m = \frac{-v}{u} = \frac{-9.08\text{ cm}}{-35.5\text{ cm}} = 0.26$$

$$h_i = mh_o = 0.26 \times 4\text{ cm} = 1.04\text{ cm}$$

Therefore, the image size is 1.04 cm, and the image distance is 9.08 cm behind the mirror.

Example 4.7

An electric room heater uses a concave mirror to reflect infrared (IR) radiation *from a hot coil. Note that IR follows* the same law of reflection as visible *light. Given that the mirror has a radius of curvature of 50 cm and produces an image of the coil 3 m away from the* mirror, where is the coil located?

Solution

Using the new Cartesian convention,

$$f = \frac{-R}{2} = -25\text{ cm}, v = 300\text{ cm}$$

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

$$u = \frac{fv}{v - f}$$

$$u = \frac{-300\text{ cm} \times (-25\text{ cm})}{-300\text{ cm} - (-25\text{ cm})} = -27\text{ cm}$$

Therefore, the coil is 27.27 cm in front of the mirror.

Example 4.8

An object 3 cm high is placed at a point 30 cm from the pole of a concave mirror whose focal length is 12 cm. Using the mirror formula, find the *position, the height and the nature of the image formed.*

Solution

12 cm, $f = 30$ cm, $u = h_o = 3$ cm

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

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

$$\frac{1}{v} = \frac{1}{12\text{ cm}} - \frac{1}{30\text{ cm}}$$

$$= \frac{5\text{ cm} - 2\text{ cm}}{3} = \frac{1}{30\text{ cm}}$$

$$v = \frac{60\text{ cm}}{3} = 20\text{ cm}$$

Since the image distance is positive, the image is real. To find the height of the image, we apply the magnification formula: Activities 4.10, 4.11 and 4.12 aid in investigating properties that affects image formation on curved mirrors.

Activity 4.10

Aim: To investigate the characteristics of images formed in curved mirrors

Materials: concave and convex mirrors (f = 15.0 cm), candle, metre rule, white screen, a V-stand or mirror holder

Procedure

1. Mount the concave mirror on a V-stand or mirror holder.
2. Attach the white screen to a movable stand.
3. Light the candle and set up the apparatus as shown in Figure 4.31. Start by placing the lit candle 40 cm from the mirror pole, so the object is beyond the centre of curvature, C.

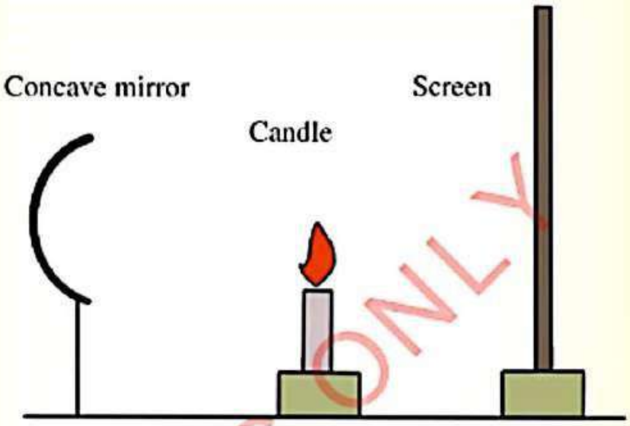


Figure 4.31

Note: The flame of the lit candle should be at the same level as the centre of the mirror and the screen.

4. Adjust the screen's position until a clear image of the candle flame is formed. Observe the nature of the image formed. Note whether it is enlarged, diminished, upright or inverted and record your observation.
5. Measure the distance between the screen and the mirror. This corresponds to the image distance; *verify* the measured image distance by calculating v using the mirror equation.
6. Move the candle to a point 35 cm from the mirror pole and repeat steps 4 and 5.
7. Repeat step 6 for the candle placed at 30 cm, 25 cm, 15 cm, 10 cm, and 5 cm from the pole of the mirror. Note that, in some cases, you may have to look in the mirror to see the image. Record your data in the form of Table 4.5.
8. Replace the concave mirror with a convex mirror of focal length 15 cm and repeat Steps 4 to 7.

Table 4.5

$f\,(cm)$	$\frac{1}{f}(cm^{-1})$	$u\,(cm)$	$\frac{1}{u}(cm^{-1})$	$v\,(cm)$	$\frac{1}{v}(cm^{-1})$	$\frac{1}{f}=\left(\frac{1}{u}+\frac{1}{v}\right)cm^{-1}$

Questions

(a) Describe the characteristics of the images for all object positions, using:
  (i) a concave mirror
  (ii) a convex mirror

(b) How do the measured image positions differ from the calculated image positions? Give a brief explanation for any discrepancies.

This activity has revealed the characteristics of various images formed by concave and convex mirrors. Although measurements of image and object distances are affected by some errors, the values can be correctly approximated by using the mirror equation. Other image characteristics can also be predicted using the mirror equation. This verifies the mirror equation.

Activity 4.11

Aim: To estimate the focal length of a concave mirror with an illuminated object.

Materials: concave mirror, metre rule, cross wires, lamp-box, white screen, a V-stand, bench, a source of light

Procedure

1. Fix the V-stand on a bench and mount the concave mirror on the stand so that the reflecting surface of the mirror faces a distant object. Ensure that the image of the distant object is clearly visible.
2. Place the white screen on the bench and move it until a sharp image of the distant object is focused on the screen.
3. Measure the distance between the mirror and the screen. This distance is the image distance, v, and it approximately corresponds to the focal length of the mirror.
4. Create a small round hole on one side of the lamp box and attach the crosswire so that the crossing point coincides with the centre of the hole.
5. Position the box on the bench outside the approximate focal length of the mirror.
6. Switch on the lamp in the box so that the crosswire is illuminated through the box hole.
7. Move the screen until a clear inverted image of the crosswire is formed on the screen.

8. Measure the image distance, v, from the screen to the mirror and the object distance, u, from the crosswire to the mirror
9. Change the object distance and measure the corresponding image distances. Obtain at least 5 sets of u and v.
10. Using the mirror equation,

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

    (a) Calculate the focal length of the mirror
    (b) Determine the average focal length of the mirror.

Question

Why did you obtain different values of f for different sets of u and v?

This activity has shown that the unknown focal length of a concave mirror can be determined by experimenting with an illuminated object. Although measurement errors can affect the experiment, the method can effectively estimate the focal length of a given concave mirror.

Activity 4.12

Aim: To determine the focal length of a concave mirror using a non-parallax method.

Materials: concave mirror, bench, optical pins, screen, metre rule, corks

Procedure

1. Mount the concave mirror on a bench.
2. Fix an optical pin on a cork, then fix it on a screen.
3. Move the pin (object) until an inverted (real) image appears in front of the mirror, as illustrated in Figure 4.32.

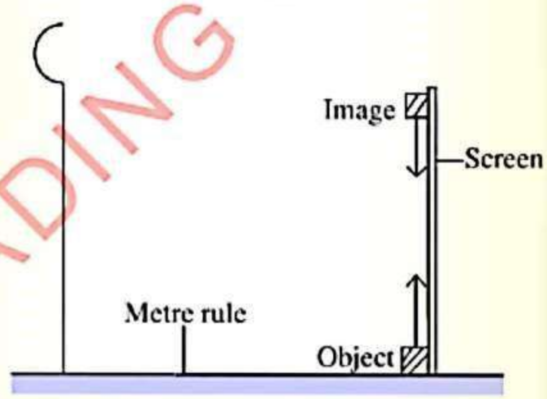


Figure 4.32

4. Adjust the position of the object pin until there is no parallax between it and its image.
5. Measure the distance between the mirror and the image formed at this point.

Questions

What is the significance of the distance between the mirror and its image?

From this activity, the position of the image pin is at the centre of curvature. The focal length of the mirror can be obtained from;

$f=\frac{R}{2}$.

Uses of curved mirrors

Curved mirrors have various applications in our daily lives. Depending on the purpose, some applications utilise concave mirrors while others utilise convex mirrors.

Uses of convex mirrors

Convex mirrors provide a wide field of view compared to other mirrors, forming diminished images. Therefore, they are used when a broad field of view is preferred over the size of the image. The following are some applications of convex mirrors:

Convex mirrors are used as side mirrors for cars. This allows the driver to gain a wide angle rear view, as shown in Figure 4.33. However, these mirrors have the disadvantage of making objects appear farther away than they actually are. This occurs because the image is always formed between the mirror and the focal point of the mirror, regardless of the object's distance. Hence, images appear small, and the brain interprets smaller images as farther away.

Figure 4.33: *A side mirror of a car*

Reflecting light in streetlights: A convex mirror is a reflector in street lamps. Due to the wide view offered by the diverging mirror, light from the lamp spreads over a larger area. Figure 4.34 illustrates light diverging from the streetlights.

Figure 4.34: *Divergence of light from a streetlight*

Seeing around corners: Convex mirrors are placed at road junctions and the corners of places like parking lots and supermarkets. This enables people to see around the corners to avoid collisions between vehicles or supermarket trolleys. Figure 4 .35 shows a convex mirror used as a safety mirror at a road junction.

Figure 4.35: *A safety convex mirror around a corner*

Security and investigation: Due to their wide field of view, convex mirrors are used to investigate business establishments and security installations. An example of a convex mirror employed for security purposes is illustrated in Figure 4.36.

Figure 4.36: *A security convex mirror in a shop*

Uses of concave mirrors

Concave mirrors are helpful because of their ability to produce enlarged images, focus faint light and produce a parallel beam of light. The following are some applications of concave mirrors:

Headlights in a car: A powerful light source is positioned at the focal point of a concave mirror in a small space at the back of a headlight. Any light that strikes the mirror from the focus will be reflected parallel to the axis of the concave mirror. This creates an intense beam of light in front of the car, as illustrated in Figure 4.37.

Figure 4.37

Dentist's mirror: A concave mirror helps the dentist to focus light on the tooth to be examined inside the mouth. Figure 4.38 shows a dentist mirror in use to examine a tooth.

Figure 4.38: *A dentist mirror in use*

Shaving mirrors: A concave mirror produces a magnified and upright image of the object when the object is positioned between the principal focus and the pole. Thus, concave mirrors are used as shaving mirrors, creating an enlarged reflection of the face when it is held within the focus of the mirror. A concave mirror, as shown in Figure 4.39, serves as an example of a shaving mirror.

Figure 4.39: *A shaving mirror*

Reflecting telescopes: A concave mirror (primary mirror) forms images of distant stars at the focal point. A plane mirror (secondary mirror) is then used to project the rays to the side where the image can be viewed through a lens, as shown in Figure 4.40.

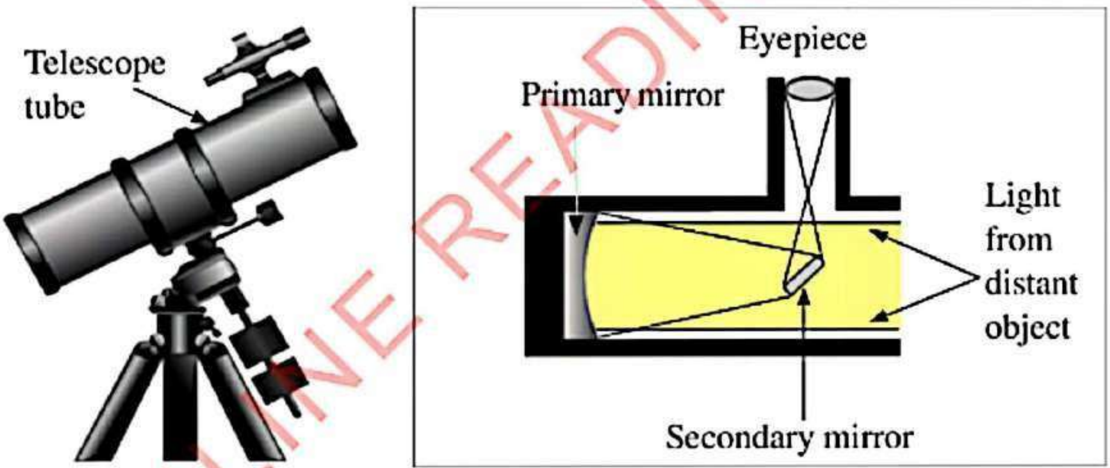


Figure 4.40: *Reflecting telescope*

In some cases, the concept of light reflection off concave surfaces is used for applications beyond light and image formation, outlined as follows:

Satellite dishes: Satellite dishes are specialized antennas designed to receive and transmit signals to and from satellites in orbit. Figure 4.41 shows a satellite dish.

Figure 4.41: *A satellite dish*

Parabolic solar cookers: These solar cookers convert sunlight directly into heat by concentrating it through a parabolic arrangement of reflectors. Figure 4.42 shows a parabolic solar cooker.

Figure 4.42: *A parabolic solar cooker*

Project 4.2

Design and construct a simple solar cooker using a concave mirror or a parabolic reflector. Utilise materials such as cardboard, aluminium foil, and a transparent cover. Test the cooker by attempting to heat or cook food items with sunlight. Document the process, results, and any challenges encountered.

Exercise 4.3

1. Why do concave mirrors produce both real and virtual images, but convex mirrors produce only virtual images?
2. A nail of 6 cm in height is placed 30 cm from a converging mirror of focal length 10 cm. Determine the position and height of the image. State also whether the image is real or virtual, enlarged or diminished.
3. An object is 15 cm in front of a diverging mirror. What is the focal length of the mirror if a virtual image is formed 10 cm behind the mirror?
4. A 4 cm tall object is placed 10 cm from a concave mirror with a radius of curvature of 12 cm. Determine the focal length of the mirror, image distance, image height, and nature of the image.
5. An object is placed 30 cm in front of a concave mirror with a 15 cm focal length. Determine the image distance and magnification. Is the image real or virtual, upright or inverted?
6. Name any three real life uses for each of the concave and convex mirrors.

Chapter summary

1. Light is a form of energy that is visible to the human eye and enables the perception of objects.
2. Propagation of light is the passage of light through different media, which can involve reflection, refraction, and absorption.
3. A plane mirror is a flat, reflective surface that creates virtual images of objects.
4. Laws of Reflection:
   (a) The angle of incidence equals the angle of reflection.
   (b) Incident rays, reflected rays, and the normal line lie in the same plane
5. A curved mirror has a curved surface, which can be concave or convex. A concave mirror is a mirror that curves inward, capable of focusing light and producing enlarged images.

6. A convex mirror is a mirror that curves outward, producing smaller images and a wider field of view.
7. A virtual image is formed by the apparent divergence of light rays, which cannot be projected onto a screen (e.g., images in a plane mirror).
8. Real image is an image formed by the actual convergence of light rays, which can be projected onto a screen.
9. Focal point is the point at which parallel light rays converge after reflecting off a concave mirror.
10. Magnification (m) is the ratio of the height of the image to the height of the object, indicating how much larger or smaller the image is compared to the object.

Revision Exercise 4

1. A parallel beam of light hits a plane mirror. Which diagram illustrates how the mirror reflects the beam?

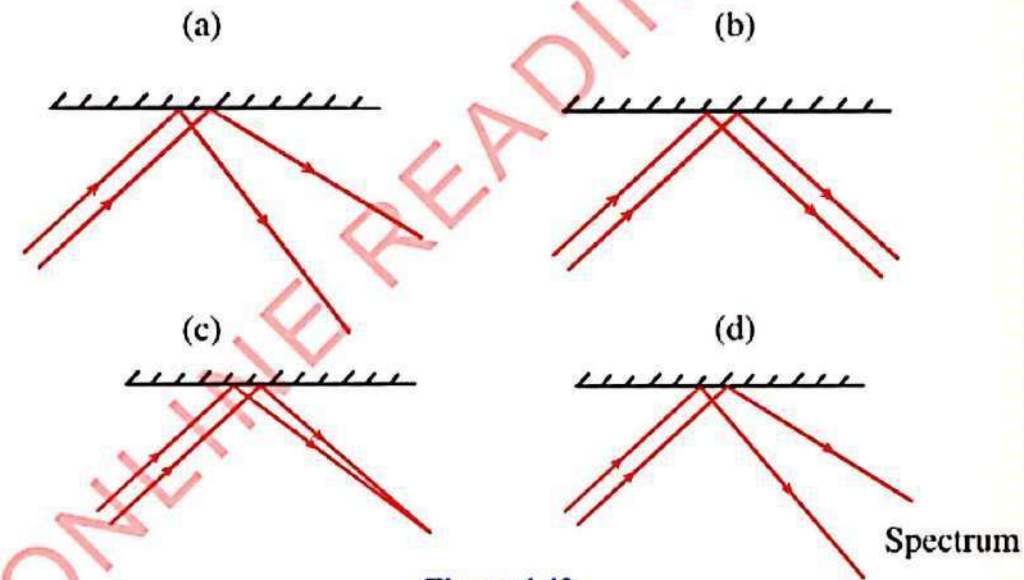


Figure 4.42:

2. The provided data displays the focal lengths of the three concave mirrors A, B, and C, along with the respective distances of various objects from these mirrors.

Mirrors	Object distance (cm)	Focal length (cm)
A	45	20
B	30	15
C	20	30

Answer the following questions:

(a) In the given positions of an object relative to the mirrors, which mirror will produce a diminished image of the object? Draw a ray diagram to demonstrate the image formation using this mirror.

(b) Which mirror can serve conveniently as a make-up mirror? Illustrate this function with a ray diagram.

3. A spherical mirror creates an image with a magnification of -1 on a screen positioned 50 cm away from the mirror.
   (a) Identify the type of mirror used.
   (b) Calculate the distance from the image to the object.
   (c) Determine the focal length of the mirror.
   (d) Illustrate the ray diagram to demonstrate how the image is formed in this scenario.
4. A student wants to project the image of the candle flame on a screen 80 cm in front of a mirror while keeping it 20 cm from its pole.
   (a) Which type of mirror should the student use?
   (b) Determine the magnification of the image produced.
   (c) Determine the distance between the object and its image
   (d) Draw the ray diagram to show the image formation in this case and mark the distance between the object and its image.
5. Draw a ray diagram to show the path of the reflected ray in each of the following cases. A ray of light incident on the convex mirror.
   (a) Strikes at its pole, making an angle θ from the principal axis.
   (b) Is directed towards its principal focus
   (c) Parallel to its principal axis
6. Draw a ray diagram to show the path of the reflected ray in each of the following cases. A ray of light incident on the convex mirror.
   (a) Passing through its optical centre
   (b) Is directed towards its principal focus
   (c) Parallel to its principal axis
7. Suppose you have three concave mirrors, A, B, and C, of focal lengths 10 cm, 15 cm, and 20 cm. For each concave mirror, you experiment with image formation for three values of object distances: 10 cm, 20 cm, and 30 cm. Provide reasons for each of the following:
   (a) For the three object distances, identify which mirror produces an image with a magnification of -1.
   (b) Out of the three mirrors, identify which one you would prefer to use for saving purposes or for applying makeup.
   (c) For mirror B, create a ray diagram to illustrate image formation for object distances of 10 cm and 20 cm.
8. A student has focused the image of a candle flame onto a white screen using a concave mirror. The situation is given:

   Length of the flame = 1.5 cm

   Focal length of the mirror = 12 cm

   Distance of flame from the mirror = 18 cm

   If the flame is perpendicular to the principal axis of the mirror, then calculate the following:
   (a) Distance of the image from the mirror
   (b) Length of the image

Chapter Five

Refraction and dispersion of light

Introduction

The principles, theories, and concepts surrounding the refraction of light are integral to our daily lives, significantly impacting both natural phenomena and technological advancements. Key applications include vision correction, the design of various optical instruments, the functionality of optical fibres, the creation of various colours by prisms and rainbows, and the development of magnification tools. In this chapter, you will explore how light refracts through glass prisms and lenses. The competencies developed will enable you to design optical instruments and use them in different contexts.

Think

Importance of optical fibres in our daily lives

Concept of refraction of light

In the previous chapter, it was learnt that, as light travels through a given medium, it travels in a straight line. However, when light passes from one medium to other medium, the light beam tends to bend. The bending of light is referred to as the refraction of light. The direction of a ray of light changes as it passes obliquely from one medium into another.

Refraction occurs because different media have different optical densities. If the speed of light in one medium is lower than that in the other medium, the first medium is said to have a higher optical density than the second medium. Thus, the optical density of a medium can be determined by using the speed of light in that medium. Refraction occurs only at a boundary. Once the light has crossed the boundary between the two media, it continues to travel in a straight line.

Activity 5.1

Aim: To investigate the refraction of light rays as they pass from air to water

Materials: coin, bucket, water

Procedure

1. Obtain a wide opaque container, such as a bucket.
2. Place a coin inside but at the bottom of the empty bucket.

3. In a straight line, slowly move away from the bucket to a point where the coin is just outside your line of view. That is, the coin is not visible. Mark this point as M.
4. Pour gently clear water into the bucket and try to view the coin while standing at point M.
5. Continue adding more water until the coin can be seen when viewed from point M as in Figure 5.1.

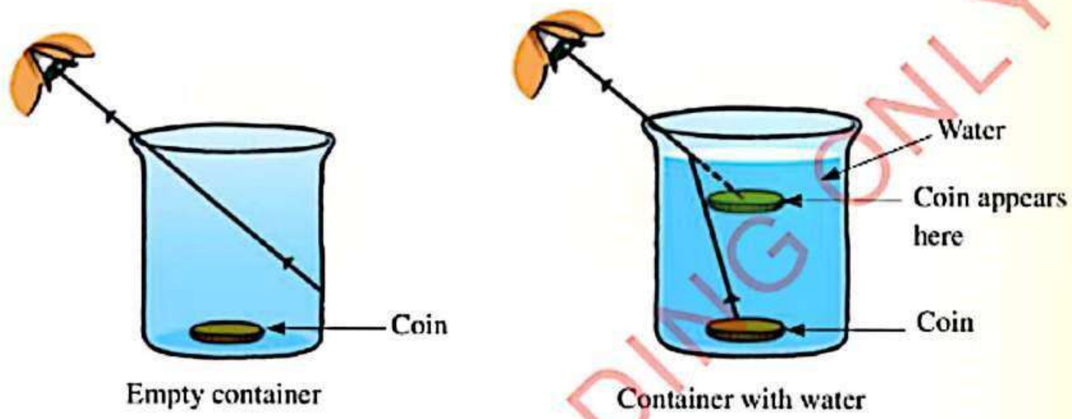


Figure 5.1

Questions

(a) Explain why the coin can be seen when the water is added, but not before?
(b) Why does the coin become visible from point M after filling the bucket with water?
(c) Does the coin appear raised? Explain.
(d) Suggest other materials that can be used to demonstrate the refraction of light, besides water used in this activity.

The coin appears raised due to the change of direction of rays of light at the boundary between water and air, as shown in Figure 5.1.

Angle of incidence and angle of refraction

When light passes from a medium such as air to another medium such as glass, which is optically denser than the first medium, its velocity decreases. Conversely, when light passes from an optically denser medium such as glass to a medium that is optically less dense like air, its velocity increases. The line that is perpendicular to the boundary between the two media through which light travels is called the normal line. The ray of light in the first medium is called the incident ray and the ray of light in the second medium is called the refracted ray. The angle between the incident ray and the normal line is known as the angle of incidence and is denoted by the letter i. On the other hand, the angle between the refracted ray and the normal line is called the angle of refraction, denoted by r. Figure 5.2, shows the normal line, the incident ray, the refracted ray, the angle of incidence (i) and the angle of refraction (r).

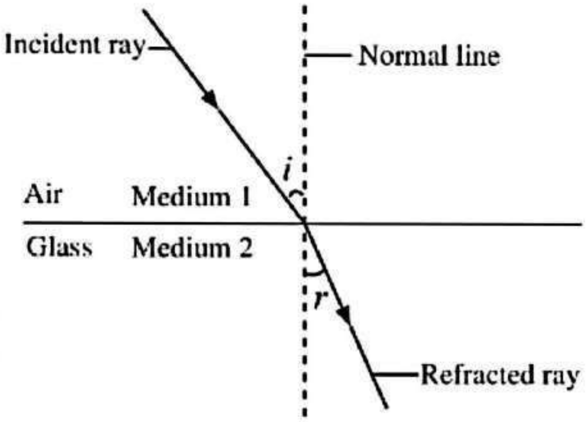


Figure 5.2: *Light travelling from air to glass*

Refraction of light by a glass prism

Glass prisms come in various types, including rectangular and triangular. Refraction occurs when light passes through the prism, bending at the interfaces due to changes in speed as it enters and exits the glass. When light enters the prism from air, it slows down and bends towards the normal line, which is perpendicular to the surface at the entry point. Conversely, as light exits the prism back into the air, it speeds up and bends away from the normal.

Refraction of light by a rectangular prism

When a light ray passes from air into a rectangular glass prism, it undergoes refraction at the point where it enters the glass. Inside the prism, the light travels in a straight line until it reaches the opposite boundary, where it is refracted again as it exits back into the air. Since the opposite sides of a rectangular glass prism are parallel, the emerging light ray continues in the same direction it had before entering the prism. As a result, there is no overall deviation in the path of the light. This behaviour is illustrated in Figure 5.3.

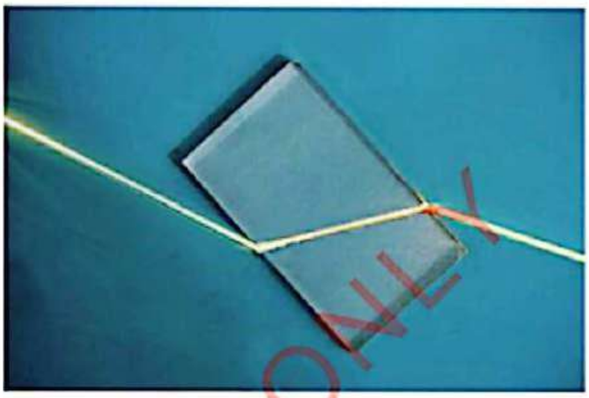


Figure 5.3: *Light refraction by a rectangular glass block*

Activity 5.2

Aim: To investigate the refraction of light as it passes from air to glass

Materials: transparent glass block, white piece of paper, a ray box

Procedure

1. Place a transparent glass block on a white piece of paper. Ensure that the block is fixed so that it does not move.
2. Place the ray box so that a ray of light falls on the side of the block at a small angle to the normal as shown in Figure 5.4. Draw a line tracing the beam of light and mark the point at which light enters the glass block as M.
3. Mark the point at which the ray of light emerges from the other side of the glass block as N and draw a line

tracing the ray of light as it leaves the glass block.

4. Remove the glass block and draw a line joining points M and N. Observe the direction of the line MN as compared to the line drawn in Step 2.

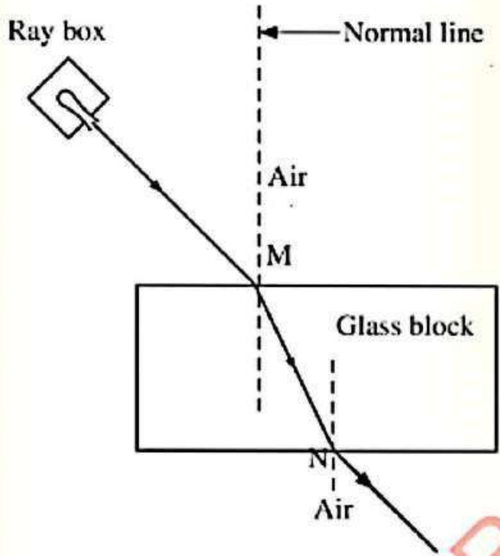


Figure 5.4

Question

Is there any change in the direction of the ray of light as it emerges from the other side of the glass block? Explain.

There is a change in the direction of light when it passes from air to glass (first boundary) and when it passes from glass to air (second boundary). This is because light is passing through different materials with different optical densities.

Activity 5.3

Aim: To measure the angles of incidence and refraction using a glass prism

Materials: plain paper, soft board, drawing pins, transparent glass block, protractor

Procedure

1. Place a plain paper on a soft board. Fix the paper firmly on the board using drawing pins.
2. Place a rectangular glass block on the paper and trace its outline. Draw a line perpendicular to the outline of the glass block. This is the normal line.
3. Draw a light ray that meets the side of a glass block such that it makes a small angle with the normal line. This is the angle of incidence (i). Mark the meeting point as M.
4. Stick two pins, P1 and P2 along the light ray drawn in step 3.
5. Observe the pins through the block from the opposite side.
6. Stick two other pins, P3 and P4, so that they appear in line with P1 and P2.
7. Draw a line joining the points of the two pins and the edge of the glass block at point N as shown in Figure 5.5.
8. Remove the glass block and draw a line, MN, joining point M and point N.
9. Draw a line perpendicular to the outline of the glass block at point N. This is also a normal line.
10. Measure the angle between the normal line and the refracted ray. This is the angle of refraction (r).

Note: Both the angle of incidence and the angle of refraction are measured from the normal line.

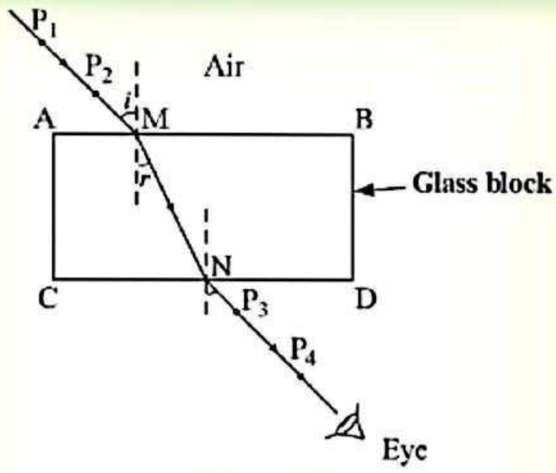


Figure 5.5

Question

Describe the path taken by a light ray travelling from the air into the glass block and the air again.

The lines P_1P_2, MN and P_3P_4 show the path that a light ray follows from air, through the glass block and to air again. Light rays are refracted as they pass from air to glass (at the first boundary) and again as they pass from glass to air (at the second boundary).

Laws of refraction

When a beam of light passes through two different media via an interface, it bends. The amount of bending depends on the optical densities of the two media and the angle of incidence of the light beam. Note that, the angle of incidence and the angle of refraction differ in proportion to the difference in the optical densities of the two media. If a light ray passes from the optically less dense medium to the optically denser medium, it is bent towards the normal. However, if the ray travels from a medium of higher optical density to a medium of lower optical density, it bends away from the normal. Following various experimental observations, two laws govern the behaviour of a light ray as it strikes the interface between two media of different optical densities. These laws are known as the laws of refraction of light.

Activity 5.4

Aim: To deduce the laws of refraction and determine the refractive index

Materials: A rectangular glass block, four optical pins, a white sheet of paper, a piece of soft board, a pencil, a protractor, paper pins, a computer or tablet with spreadsheet software

Procedure

1. Place the glass block on the sheet of paper and trace its outline using a pencil.
2. Remove the block.
3. At point E (near the centre of the longer edge of the outline), draw a normal to the outline as shown in Figure 5.6.

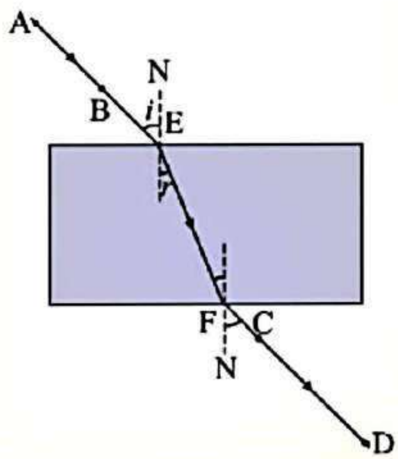


Figure 5.6

4. Draw a line at an angle to the outline, for example, 30°, to meet the outline at E.
5. Place the paper on the soft board and hold it in position with the help of paper pins.
6. Stick two optical pins, A and B on the line you drew. Replace the glass block back on the outline.
7. View through the block from the opposite side and place pins C and D so that all four pins appear in a straight line.
8. Remove the block and draw a line through the marks made by pins C and D. Mark the point of intersection of the line through C and D and the glass block outline as F.
9. Join points F and E with a straight line and then draw a normal line to the glass block outline at E and F as shown in Figure 5.6.
10. Measure the angle of incidence and the angle of refraction at the first boundary.

Repeat the experiment for different angles of incidence and record results in the format shown in Table 5.1.

Table 5.1

i (°)	r (°)	sin(i)	sin(r)	$\frac{\sin(i)}{\sin(r)}$

Questions

(a) Calculate the ratio $\frac{\sin(i)}{\sin(r)}$ for each pair of angles and record your result in the table.

(b) Use spreadsheet software to input your data from Table 5.1. Create a graph to visualise the relationship between the angle of incidence and the calculated ratio.

(c) What conclusion can you draw from the values of $\frac{\sin(i)}{\sin(r)}$ for the different angles of incidence i?

Several deductions can be made from the results of the above experiment:

1. Whenever the pins are set in line and viewed from one side, they appear to be in line. This is also the case when pins are viewed from the other side. This illustrates the principle of reversibility of light, which states that; "light will follow exactly the same path if its direction of travel is reversed". The implication of the law of reversibility of light in a rectangular glass prism is that, if i is the angle of incidence from air to glass and r is the angle of refraction, then, r becomes the angle of incidence for glass to air and i becomes the angle of refraction.
2. As a ray of light travels from air to glass (from an optically less dense medium to a denser medium), it is bent towards the normal at the boundary between the two media. Conversely, when a ray of light travels from glass to air (from an optically denser

medium to a less dense medium), it is bent away from the normal.

3. The ratio $\frac{\sin(i)}{\sin(r)}$ is the same (constant) for the different angles of incidence.
4. The points E and F, the normal line, the incident ray and the refracted ray lie on the same plane. This may not have been obvious. However, you can observe this if you lift one edge of the glass block above the other edge of the block after setting the pins in a line. You will immediately notice that the linearity of pins A, B, C and D disappears. These important observations lead to two important conclusions that are essentially the laws of refraction of light. These laws state that;
   (a) At the point of incidence, the incident ray, the normal line and the refracted ray all lie on the same plane.
   (b) For a particular material, the ratio $\frac{\sin(i)}{\sin(r)}$ is constant. This law is also referred to as Snell's law of refraction.

Refractive index of a material

In Activity 5.4, you observed that, for a given material or medium, the ratio $\frac{\sin(i)}{\sin(r)}$ is constant regardless of the size of the angle of incidence. This constant is known as the refractive index of the material (medium). It is a dimensionless (it has no unit) constant denoted by the Greek letter η. The refractive index of a material is a measure of the influence of the material on the speed of light as it passes through it. Therefore, the refractive index of a material is also obtained from the ratio of the speed of light in vacuum, c, to the speed of light in the material, v.

That is, $\eta = \frac{c}{v}$.

To be specific, the ratio $\eta = \frac{c}{v}$ is known as *the absolute refractive index* of a material. If the ratio is obtained from the speed of light v_1 in one material, to the speed of light v_2 in the other material, then $\eta = \frac{v_1}{v_2}$. In this case, the ratio is called the *relative refractive index*.

Normally, the speed of light in air is considered as the speed of light in vacuum, c. Therefore, if light travels from air to water and from air to glass, it will have different speeds in water and glass because air, water and glass have different optical densities. Letting the speed of light in water be v_1 and its speed in glass be v_2 one can calculate the absolute refractive indices of water and glass as follows;

The absolute refractive index of water:

$$\eta_1 = \frac{c}{v_1}$$

This implies that, $c = \eta_1 v_1$.

The absolute refractive index of glass:

$$\eta_2 = \frac{c}{v_2}$$

This implies that, $c = \eta_2 v_2$.

Thus, $c = \eta_1 v_1 = \eta_2 v_2$

Hence, $\eta_1 v_1 = \eta_2 v_2$

This expression can be rearranged to read:

$$\frac{\eta_2}{\eta_1} = \frac{v_1}{v_2}$$

The ratio $\frac{\eta_2}{\eta_1}$ is the relative refractive index of glass to water. This ratio can also be related to the ratio of the sines of the angle of incidence and the angle of refraction as follows.

$$\frac{\eta_2}{\eta_1} = \frac{\sin(i)}{\sin(r)}$$

Therefore, $\eta_1 \sin(i) = \eta_2 \sin(r)$

Applying the law of reversibility of light shows that, ${}_g\eta_a = \frac{1}{{}_a\eta_g}$

where ${}_g\eta_a$ and ${}_a\eta_g$ are the relative refractive indices for light travelling from air to glass and from glass to air, respectively.

There are various methods of determining the refractive index of a given material. One important method is carrying out an experiment described in Activity 5.4. Another method of estimating the refractive index of liquids is based on a concave mirror method described in Activity 5.5.

Activity 5.5

Aim: To determine the refractive index of water using a concave mirror method

Materials: concave mirrors of different focal lengths (10 cm, 15 cm, 20 cm and 25 cm), water, retort stand, optical pin, clamp, meter rule, computer or tablet with spreadsheet software

Procedure

1. Place a concave mirror on a bench.
2. Clamp an optical pin on the retort stand above the concave mirror.
3. Position one eye vertically above the pin and look in the concave mirror for the real inverted image of the pin.
4. Adjust the position of the optical pin by moving it up or down until the pin image coincides with the real pin as shown in Figure 5.7. Ensure that there is no parallax.
5. Measure and record the height, *h* of the head of the optical pin from the pole of the mirror.

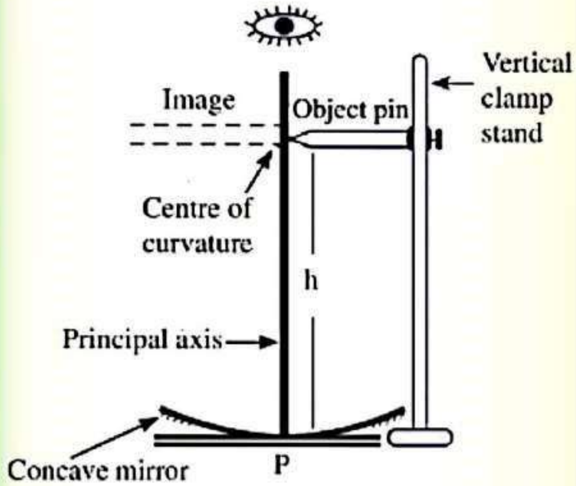


Figure 5.7

6. Fill the concave mirror with enough water to overcome the curvature of the concave mirror and the water

surface tension. Wait for some time until the water is still.

7. Repeat steps 3 and 4.
8. Measure and record the new height, h' of the optical pin from the pole (P) of the mirror.
9. Repeat the experiment using other concave mirrors of different focal lengths.
10. Record your results in a table similar to Table 5.2 and calculate the average refractive index of water.

Table 5.2

Focal length f (cm)	Height h (cm)	Height h'cm	Refractive index $\eta = \frac{h'}{h}$

Note: Use spreadsheet software to: Input your data from Table 5.2.

(a) Calculate the refractive index using the formula $\eta = \frac{h}{h'}$.

(b) Create a graph to visualise the relationship between focal lengths and the calculated refractive indices.

Questions

(a) Which mirror gives the most accurate value of the refractive index of water?

(b) What are the possible sources of uncertainties in determining the refractive index of water using the concave mirror method?

In this activity, the refractive index of water has been determined using a concave mirror method. As the known refractive index of water is 1.33, this method gives a good estimate of the refractive index of water. Therefore, the method can be useful in determining the refractive indices of different liquids.

Task 5.1

Use the apparent depth method to determine the refractive index of water. How accurate is your value of refractive index?

Example 5.1

Find the index of refraction for a certain medium, assuming light in air enters the medium at an incident angle of 30° and the angle of refraction is 22°.

Solution

Given, the incident angle $(i) = 30^o$, angle of refraction $(r) = 22^o$, $\eta = ?$

$$_a\eta_g = \frac{\sin(i)}{\sin(r)}$$

$$= \frac{\sin 30°}{\sin 22°} = 1.33$$

Therefore, the refractive index of the medium is 1.33.

Total internal reflection of light

It has been established that when light travels from a lighter medium to a denser one, $(\eta_1 < \eta_2)$ the refracted light ray bends towards the normal. Conversely, when light travels from a denser medium to a lighter one $(\eta_1 < \eta_2)$, the refracted light ray bends away from the normal. It is also known that the angle of refraction and hence the amount by which light bends away from the normal depends on the angle of incidence. Therefore, the larger the angle of incidence, the more the light bends away from normal. Yet, one could ask, when light travels from a denser medium to a less dense medium, how far away from normal can light bend?

The answer to this question is that the bending of light can only get as far as 90° without leaving the medium. Therefore, there is an angle of incidence of light for which the angle of refraction is 90°. This angle of incidence is known as the critical angle and is typically denoted by a letter c. When the angle of incidence becomes greater than the critical angle, light is not refracted anymore; instead, light is reflected back into the same medium from which it is coming. This phenomenon is known as total internal reflection. Therefore,

Total internal reflection (TIR) is a physical phenomenon in which all the light travelling in an optically denser medium is reflected back upon striking the interface with an optically less dense medium.

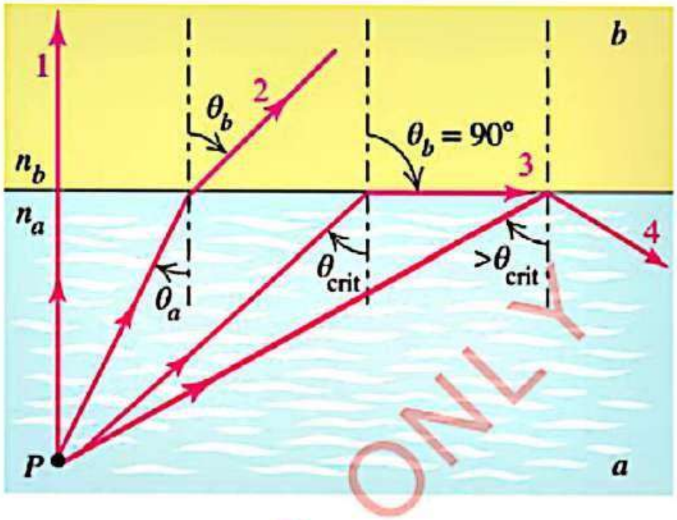


Figure 5.8: *Occurrence of the total internal reflection*

Total internal reflection only takes place when both of the following two conditions are met:

1. Light travels from an optically denser medium towards a less dense medium.
2. The angle of incidence is greater than the critical angle.

Total internal reflection will not take place unless the incident light is travelling within the more optically dense medium towards the less optically dense medium.

For example,
TIR will happen for light travelling from water towards air, but it will not happen for light travelling from air towards water. On the other hand, TIR occurs only if the angle of refraction exceeds 90°. When the angle of incidence equals the critical angle, the angle of refraction is 90° (Figure 5.9 (a)). Also, when the angle of incidence is greater than the critical angle, all the light undergoes total internal reflection as shown in Figure 5.9 (b).

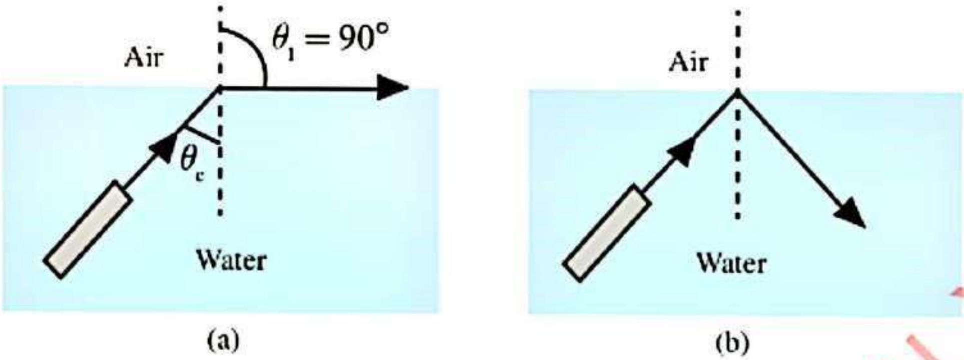


Figure 5.9: (a) *Critical angle and (b) total internal reflection*

ICT Corner

Access an online simulation, such as those on PhET Interactive Simulations, to explore total internal reflection. Adjust the angle of incidence for a laser beam in water and observe how the intensities of the reflected and refracted rays change. Identify the critical angle where total internal reflection occurs, and record your findings. Analyse the behavior of light at different incidence angles to deepen your understanding of this optical phenomenon.

Example 5.2

What must be the angle of incidence for total internal reflection to occur when a ray travels from glass to water?

Use $\eta_g = 1.52$ and $\eta_w = 1.33$.

Solution

For total internal reflection,

From

$$\eta_1 \sin(i) = \eta_2 \sin(r)$$

$$\eta_g \sin(i) = \eta_w \sin(r)$$

$$i = \sin^{-1}\left(\frac{\eta_w \sin(90°)}{\eta_g}\right)$$

$$i = \sin^{-1}\left(\frac{1.33 \times 1}{1.52}\right) = 61.04°$$

Therefore, the critical angle is $61.04°$. For total internal reflection to occur, the angle of incidence must be greater than the critical angle. That is $i > 61.04°$.

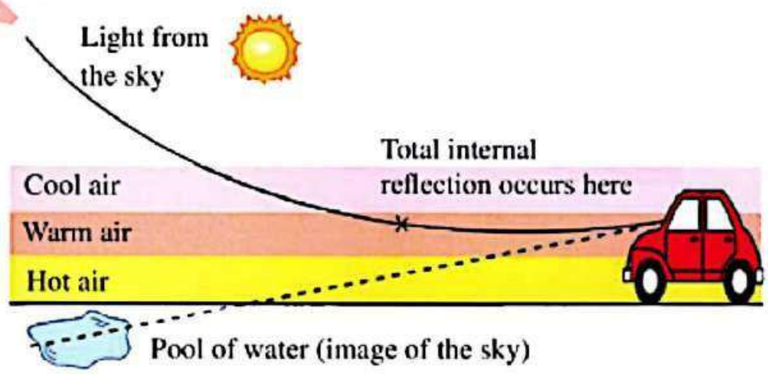
Mirages

In the previous discussion, it has been established that light tends to bend when it strikes an interface between two media that have different refractive indices. After passing the boundary, the light travels in a straight line within the new medium. However, the discussion has presumed that the media in which light travels are of uniform optical density. Nevertheless, not every medium is uniform and even air can sometimes form a non-uniform medium. When the medium is optically non-uniform, refraction of light can occur as the light travels within the medium. This leads to an interesting phenomenon; the formation of mirages. A mirage is an optical phenomenon that produces illusion images due to the refraction of light through a non-uniform medium.

Mirages can commonly be observed when you walk down a tarmac roadway on a sunny day. As you walk down the roadway, there appears to be a puddle of water on the road several metres (about 100 m) ahead of you. Yet, when you arrive at the perceived location of the puddle, you recognise that the puddle is not there. Instead, the puddle of water appears to be another one hundred metres before you. The appearance of the puddle of water is simply an illusion because of the mirage.

Mirages occur on sunny days because the sun heats the roadway to high temperatures. The heated roadway, in turn, heats the surrounding air, keeping the air just above the roadway at a higher temperature than the air above. Hot air tends to be optically less dense than cooler air. Thus, the layers of air just above the roadway are optically less dense than the air further above the roadway. This creates a non-uniform optical medium. Consequently, as light travels from the sun, it passes through the cooler air layers towards the hot air layers. This means light travels from an optically denser medium to a less dense medium. Thus, light will be refracted upon striking the boundary between the two layers of air. Therefore, light bends upwards. As the light continues to traverse different air layers, it is bent more upwards to the extent that it reaches your eyes instead of hitting the road. Your brain traces the light straight back along the direction from which it comes to your eyes. Figure 5.10 (a) shows an image of the sky, which is refracted by air with non-uniform optical density, appearing as a puddle of water just above the roadway. Figure 5.10 (b) illustrates the formation of an atmospheric mirage. The mirage phenomenon can also occur in bodies of water such as seas, lakes, ponds, and deserts.

(a) Mirage observed above the roadway



(b) Formation of an atmospheric mirage

Figure 5.10: **Road mirage**

Task 5.2

Organise a walk with your friends down the tarmac roadway (if any) on a sunny day and try to observe the occurrence of the mirage. Discuss the conditions necessary for the occurrence of a mirage.

Exercise 5.1

1. A coin is at the bottom of a trough containing three immiscible liquids of refractive indices 1.3, 1.4 and 1.5, poured one above the other at heights 30 cm, 16 cm, and 20 cm, respectively. What is the apparent depth at which the coin appears when observed from an air medium outside? In which medium will the coin be seen?
2. Light is incident on an air-water interface at an angle of 40°. Given that the refractive index of water is 1.33, determine the angle of refraction of the light in the water.
3. A stone is lying at the bottom of a pool of water 3 m deep. What would be the stone's depth as seen by an observer standing near the pool? Use $\eta_w = 1.30$.
4. (a) The speed of light in water and air is 2.8×10^8 m/s and 3.0×10^8 m/s, respectively. Determine the refractive index from air to water.
   (b) A ray of light travelling from air to water is incident at the surface of water at an angle of 30°. Calculate the angle of refraction in the water.
5. A swimming pool appears to be 1.5 m deep. If the refractive index of water is 1.3, determine the real depth of the pool.
6. Diamond has a refractive index of 2.42. Given that the speed of light in a vacuum is 3.0×10^8 m/s, determine:
   (a) Speed of light in diamond.
   (b) The critical angle for diamond.
7. The critical angle for a beam of light travelling between water and air is 49°.
   (a) A beam strikes the boundary between water and air and undergoes total internal reflection. Will the beam stay in the air or the water? Explain.
   (b) Explain what happens when a beam of light from the air strikes the surface of a calm lake at an angle of 50° from the normal.

Refraction of light by a triangular glass prism

A triangular glass prism is a transparent object having two triangular and three rectangular faces. The refraction of light by a triangular glass prism is different from the refraction by a rectangular glass prism. For a triangular glass prism, the emergent ray of light is not parallel to the incident ray of light. This is because, when a ray of light enters the glass prism, it gets deviated two times. First, light is refracted when it enters the glass prism and then refracted for the second time when it comes out of the prism as shown in Figure 5.11. This is possible because the refracting surfaces of the prism are not parallel to each other, therefore when the ray of light passes through the prism it bends towards the normal, which is oriented towards the prism's base. The amount by which light bends is dependent on the angle of incidence, the wavelength of the light, and the refractive indices of the materials through which light travels.

Angle of deviation

The angle of deviation is a measure of how much the incident ray has been deflected from its original direction by the prism. Consider a ray of light incident on a glass prism as shown in Figure 5.11.

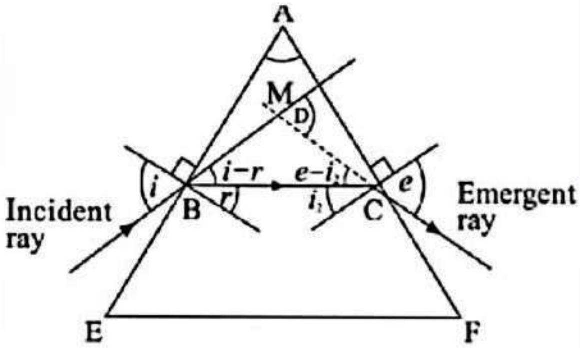


Figure 5.11: *Deduction of the angle of deviation*

where $B\hat{A}C$ = angle of prism or apex angle

i = angle of incidence

r = angle of refraction at the first surface

i_2 = angle of incidence at the second surface

e = angle of emergence from the prism

D = angle of deviation. This is the angle between the initial incident ray direction and the final emergent ray direction.

Consider triangle ABC in Figure 5.11. The sum of internal angles is 180^o that is,

$$A\hat{B}C + B\hat{A}C + A\hat{C}B = 180^o$$

$$90° - r + A + 90° - i_2 = 180°$$

$$180° + A - r - i_2 = 180°$$

$$A_2 = r + i \text{ ....(1)}$$

Now consider triangle MBC

$$M\hat{B}C + M\hat{C}B + B\hat{M}C = 180°$$

$$i - r + e - i_2 + 180° - D = 180°$$

$$i - r + e - i_2 = D \text{ ....(2)}$$

r and e can be calculated by Snell's law. Consider the first surface, by Snell's law

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

In order to determine the angle of deviation D, we must consider very small angles, that is, $\sin i \approx i$ and $\sin r \approx r$

Now

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

Then,

$$i = \eta r \text{ ....(3)}$$

Consider the second surface, by Snell's law

$$\eta = \frac{\sin e}{\sin i_2}$$

This implies that,

$$\frac{e}{i_2} = \eta, \text{ and } e = \eta i_2 \text{ ....(4)}$$

Substitute Equation (3) and (4) in Equation (2) we have, $r(\eta - 1) + i_2(\eta - 1) = D$

$$\eta r - r + \eta i_2 - i_2 = D$$

Simplifying this equation, you get,

$$D = (r + i_2) \times (\eta - 1) \text{ ....(5)}$$

Combining Equations (1) and (5) we finally have, $D = A \times (\eta - 1)$

Therefore, the angle of deviation is given by $D = A \times (\eta - 1)$.

Activity 5.6

Aim: To trace the path of the rays of light through a triangular glass prism

Materials: a white sheet of paper, soft board, thumb pins, triangular prism, pencil, protractor, drawing board

Procedure

1. Fix a white sheet of paper on a drawing board using drawing pins.
2. Place the triangular prism resting on its triangular base on the paper. Using a pencil, draw the outline the prism.
3. Draw a line NEN′ perpendicular to the face of the prism AB (Figure 5.12). This is the normal at point E.

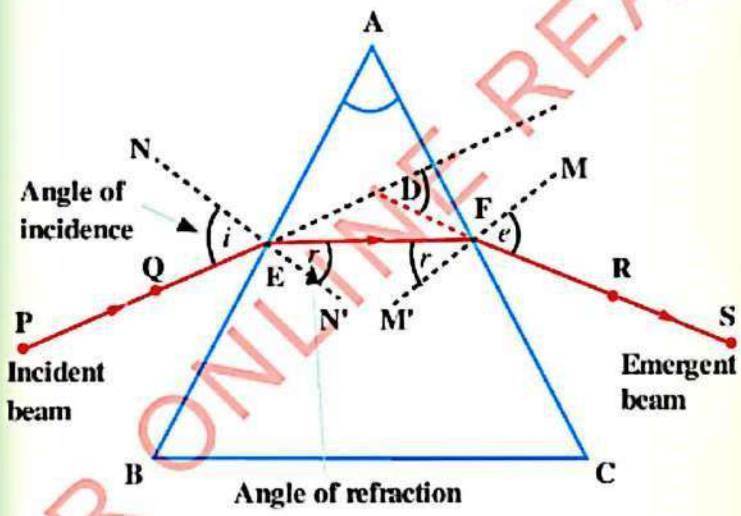


Figure 5.12

4. Draw a line PE such that it makes an angle between 30° and 60° with the normal NEN′ .This is an incident light ray.
5. On the line PE, fix two pins at a distance of 5 cm from each other and mark these as points P and Q. Replace the prism back on the outline.
6. Look for the images of the pins at P and Q through the AC face of the prism.
7. While looking at pins positioned at P and Q, fix two pins at points R and S such that they appear to be in a straight line with pins at P and Q. Remove the pins and the prism.
8. Let this line meet the prism at point F. Join and produce a line joining points R and SF.
9. Extend the direction of the incident ray PQE till it meets the face AC. Also, extend (backwards) the emergent ray SRF so that these two lines meet at point D.
10. Mark the angle of incidence (*i*), the angle of refraction (*r*), the angle of emergence (*e*) and the angle of deviation (*D*).

Questions

(a) What happens to the incident ray when it enters the prism?

(b) What factors depend on the angle of deviation through a prism?

The incident ray bends towards the normal when it enters the prism and bends away from the normal when it exits the prism. Moreover, the angle of deviation decreases with the increase in the angle of incidence.

Angle of minimum deviation of a prism

The value of the angle of deviation D depends on the angle of incidence, i. As the angle of incidence increases, the angle of deviation decreases to a minimum value called angle of minimum deviation (Dm), and then starts to increase again as shown in Figure 5.13.

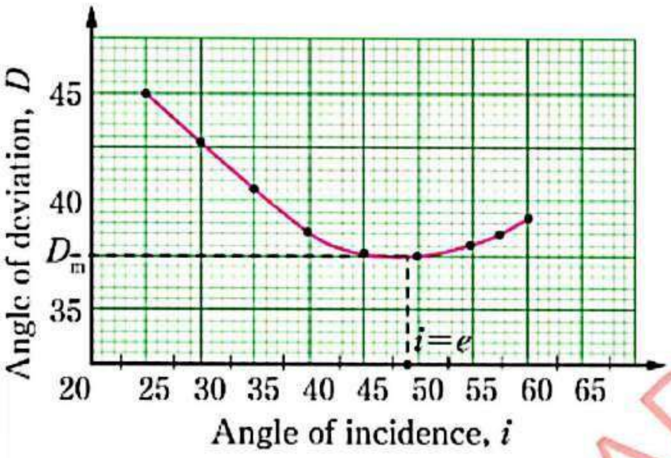


Figure 5.13: *Variation of the angle of deviation with the angle of incidence*

At the angle of minimum deviation, the angle of incidence and the angle of emergence are equal. That is, $i = e$. At the angle of minimum deviation, the refracted ray from the first surface travels through the prism perpendicular to the bisector of the apex angle A as shown in Figure 5.14.

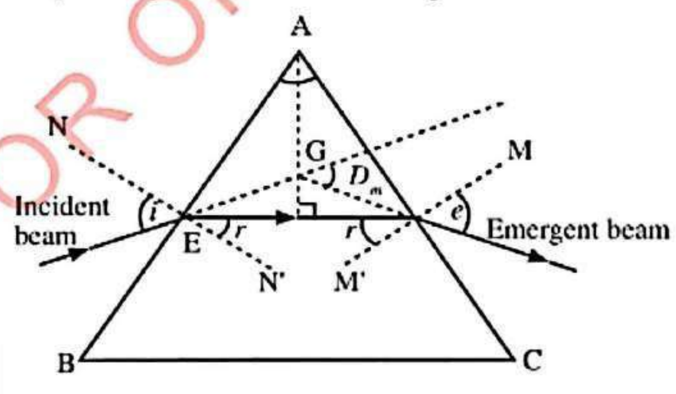


Figure 5.14: *Deducing the angle of minimum deviation*

Consider triangle ABC in Figure 5.14.

The sum of internal angles is 180°

$$A\hat{E}F + E\hat{A}F + E\hat{F}A = 180°$$

$$90° - r + A + 90° - i_2 = 180° \ldots..(6)$$

But we know that at a minimum angle of deviation, $i_2 = r$, then Equation (6) can be written as,

$$90° - r + A + 90° - r = 180°$$

$A = r + r = 2r$, this implies that,

$$r = \frac{A}{2}$$

Now consider triangle GEF

$$G\hat{E}F + G\hat{F}E + E\hat{G}F = 180°$$

$$i - r + e - r + 180° - D_m = 180°$$

But, $i = e$

$$i - r + i - r + 180° - D_m = 180°$$

By simplifying you get,

$$D_m = i - r + i - r$$

This becomes,

$$D_m = i - r + i - r = 2i - 2r.$$

This becomes,

$$D_m = 2i - A \text{ as } r = \frac{A}{2}$$

Therefore,

$$i = \frac{A + D_m}{2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(vii)}$$

Consider the first surface, by Snell's law

$$\eta = \frac{\sin i}{\sin r} = \frac{\sin\left[\frac{A + D_m}{2}\right]}{\sin\frac{A}{2}}$$

Activity 5.7

Aim: To determine the angle of minimum deviation of an equilateral triangular glass prism

Materials: a white sheet of paper, a drawing board, an equilateral triangular glass prism, drawing pins, a metre rule, a pencil, office pins, graph paper, a protractor, ICT Tools (computer or tablet with graphing software, digital camera, simulation tool)

$-D_m =$

Procedure

1. Place the white sheet of paper on the drawing board and fix it with the help of drawing pins.
2. Place an equilateral glass prism on top of the paper and trace its outline.
3. Remove the prism and label the outline as ABC.
4. On the side AC just above the centre of the outline, draw a perpendicular line NQ.
5. Measure the angle of incidence of 25° at the point of the perpendicular line and draw a line RQ.
6. Insert two pins P_1 and P_2 on the line RQ and replace the glass prism.
7. On the other side of a prism, trace the pins P_3 and P_4 which appear to be in line with P_1 and P_2 , and draw line TS as shown in Figure 5.15.

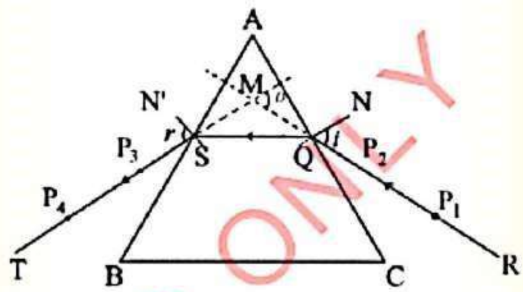


Figure 5.15

8. Extend line RQ and line TS with dotted lines to meet at a point M.
9. Measure the angle of deviation D.
10. Repeat steps 5 to 8 for other angles of incidence of 30°, 35°, 40°, 45°, 50°, 55° and 60°.
11. Record your results in a table similar to Table 5.3.
12. Use ICT tools or otherwise to;
    (a) input your recorded data into a graphing software, if ICT is used. If not, start at (ii)
    (b) create a graph of the angle of deviation (y-axis) against an angle of incidence (x-axis)
    (c) find the angle of minimum deviation, which corresponds to the lowest point on the graph.
13. Optionally, capture images of your experimental setup and results to document your process.

Table 5.3

Prism angle, A	
Angle of incidence (i)	Angle of deviation (D)
25°	
30°	
35°	
40°	
45°	
50°	
55°	
60°	

Questions

(a) When light passes through a triangular glass prism, what happens to the angle of deviation when the angle of incidence changes?

(b) Does the angle of minimum deviation (Dm) change when a different prism is used?

The angle of deviation first decreases to attain the minimum value of Dm and then increases as the angle of incidence increases. The angle of minimum deviation is important for calculating the refractive index of materials, using the equation:

$$\eta = \frac{\sin i}{\sin r} = \frac{\sin\left(\frac{A + D_m}{2}\right)}{\sin \frac{A}{2}}$$

Exercise 5.2

1. (a) Describe the angle of minimum deviation in a triangular glass prism and its relationship with the angle of incidence and the prism's angle.
   (b) Explain why a rectangular glass block does not cause dispersion of light.
2. Light travelling through transparent oil enters a glass with a refractive index of 1.5. If the refractive index of glass with respect to the oil is 1.25, what is the refractive index of the oil?
3. A monochromatic light is incident on an equilateral glass prism at an angle of 30^0 and emerges at an angle of 75°. What is the angle of deviation produced by the prism?
4. A light ray falls at normal incidence on the first face of an equilateral prism such that, the angle of incidence is 45^0, and emerges from the second face by making the same angle with the normal. What is the refractive index of the material of the prism?
5. The angle of minimum deviation for a prism is 37°. If the angle of the prism is 60°, find the refractive index of the material of the prism.
6. A rectangular glass block of thickness 10 cm and refractive index 1.5 is placed over a small coin. A beaker filled with water of refraction index 4/3 to the height of 10 cm is placed over the block.
   (a) Find the apparent position of the coin when viewed normally.
   (b) If the eye is slowly moved away from the normal, then at a certain position the object is found to disappear due to total internal reflection. At what surface does it happen and why?

Colours of light

The major source of light for the Earth is the Sun. What is the colour of sunlight? Sometimes we see in the sky a rainbow consisting of different colours. In addition, during sunset or sunrise, the sky appears orange or red. Can we conclude from these observations that sunlight is made of different colours?

Dispersion of white light

White light is known to consist of seven colours. If a beam of white light is passed through a triangular glass prism, it splits into a band of seven colours. Figure 5.16 shows a band of colours formed when white light passes through a triangular glass prism. This band is known as the spectrum of white light. Colours that form the spectrum of white light are red (R), orange (O), yellow (Y), green (G), blue (B), indigo (I) and violet (V). For the sake of remembering the arrangement of these colours, an abbreviation ROYGBIV is commonly used.

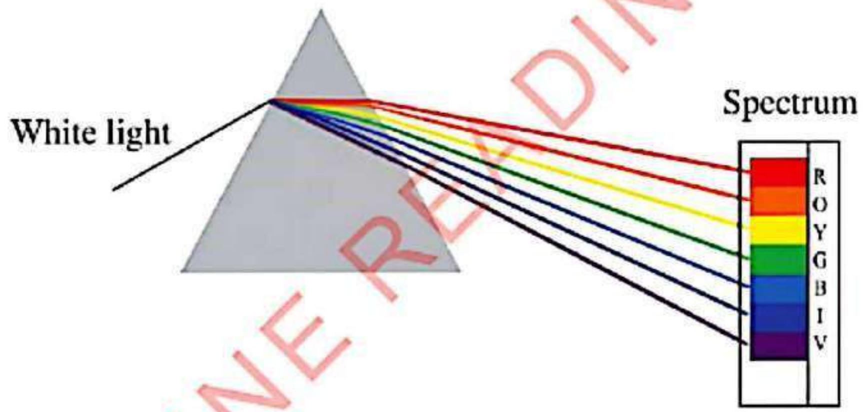


Figure 5.16: *Dispersion of white light by a triangular glass prism*

Dispersion of light is a phenomenon in which white light splits into its colour components upon passing through a medium such as a triangular glass prism. This phenomenon happens because when a beam of white light enters a transparent medium, each colour component is refracted at a different angle of refraction, resulting in different angles of deviation. For example, red colour deviates least while violet colour deviates most. The result is the splitting of the white light into its components to form a spectrum with red colour being at the upper part of the spectrum, and the violet colour being at the bottom of the spectrum, as shown in Figure 5.16. Each component has a different wavelength, which falls well within the visible part of the electromagnetic spectrum.

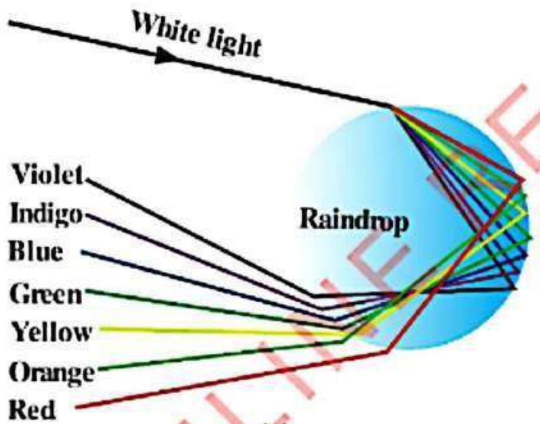
Rainbow

Light dispersion can also occur when light passes through other transparent materials, such as water droplets and soap bubbles. One consequence of light dispersion by water droplets in the atmosphere is the formation of a rainbow. A rainbow is a natural phenomenon caused by the dispersion of white light. It is caused by the refraction and reflection of white light by falling water droplets.

Formation of rainbow

The rainbow phenomenon can be observed when there are water droplets in the atmosphere as the sun shines from behind the observer at a low altitude. The rainbow's appearance is caused by the dispersion of sunlight as it is refracted by nearly circular raindrops. The white light from the sun is first refracted as it enters the surface of the raindrops.

When light travels from a less dense medium to a light denser medium, it bends towards the normal. However, not all colours bend equally. As in a glass prism, red light bends the least while violet bends the most. At the back of the raindrops, some of the dispersed light is reflected back over a wide range of angles and again refracted as it leaves the raindrop. In most cases, the violet light leaves the raindrop at a smaller angle relative to incident sunlight compared to red light as shown in Figure 5.17 (a). As a result, the observer sees an image of well-arranged coloured bands in the atmosphere called a rainbow, with red light appearing on top and violet at the bottom of the spectrum as shown in Figure 5.17 (b).



(a)

(b)

Figure 5.17: Formation of a rainbow

Activity 5.8

Aim: To observe the formation of a rainbow by spraying water into the air

Materials: water, a hose that can spray water, a sprinkler or a fountain

Procedure

1. Bring the water hose to an open space.
2. Open the water tap so that the hose sprays water into the air.
3. Stand near the spray of water drops with your back directed towards the sun.
4. Move around until you locate your shadow.
5. Look for a rainbow in the spray of water.

Questions

(a) Why does the sunlight shining through water drops make a rainbow?

(b) Why must you stand with your back toward the sun to see a rainbow?

(c) Can a person standing beside you also see the rainbow?

When you look at a rainbow, you see seven colours. They are always in the same order. That is red, orange, yellow, green, blue, indigo, and violet. An easy way to remember the colours and the order is to think of the name ROYGBIV, spelt from the first letter of each colour.

Primary rainbow

This rainbow forms at an angle of approximately 40° to 42° from the antisolar point. The light undergoes one internal reflection within the water droplets (see Figure 5.18(a)), creating the primary rainbow we observe. It is the brightest and most common rainbow with the red colour being on the outside (on top) and the violet colour in the inside (bottom);

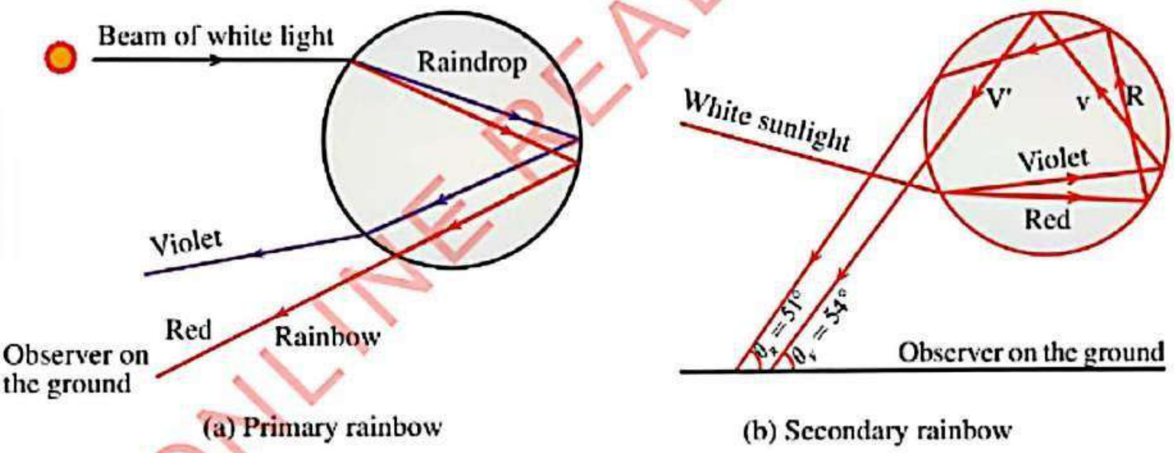


Figure 5.18: *Types of rainbows*

Secondary rainbow

A secondary rainbow forms outside a primary rainbow, resulting from light undergoing two internal reflections within raindrops (see Figure 5.18(b)). This double reflection causes the colours of the secondary rainbow to appear in reverse order compared to the primary rainbow. The secondary rainbow is also considerably fainter than the primary one. This phenomenon showcases the complex interaction of light with water droplets, demonstrating how multiple reflections alter the path and appearance of the light.

Recombining colours of white light

We have seen that upon falling on a transparent medium such as a triangular glass prism or water droplet, white light splits into its colour components. What happens when the components of white light are passed through a second prism that is identical to the first prism? If the second prism is arranged similarly to the first prism, no further splitting of white light can be observed. But if the second prism is inverted with respect to the first prism, a beam of white light is observed to emerge from the other side of the second prism. This means that the dispersed colours of white light can be recombined to form white light, as illustrated by Figure 5.19. This phenomenon is known as the white colour recombination.

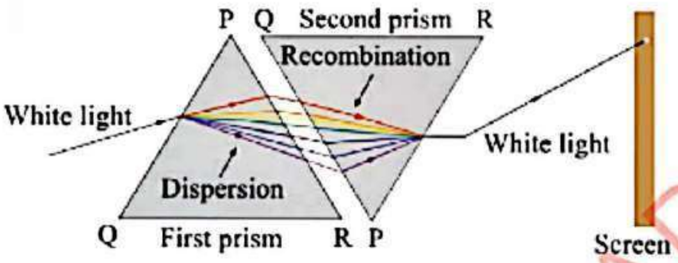


Figure 5.19: *Dispersion and recombination of white light*

The experiment of recombination of the spectrum of light can be extended to observe the recombination of two or more individual colours. Sir Isaac Newton did this for the first time using prisms and mirrors. He discovered that when the light from the red, green, and blue regions of the spectrum are recombined, they regenerate white light. Therefore, he called red, green, and blue the primary colours.

Newton also observed that when two primary colours are combined, other colours are formed. For example, when blue and green lights are combined, cyan light is formed. Furthermore, green and red lights combine to give yellow light, while red and blue lights combine to form magenta light. Newton named the colours that resulted from recombining two primary colours as secondary colours. Secondary colours include yellow, cyan and magenta. He finally organised his findings in a colour wheel showing the three "primary colours" separated by the three "secondary colours", as shown in Figure 5.20. This colour wheel is famously known as the Newton colour wheel or disc. When the disc is rotated about its axis at high speed, all the colours blend to form a white colour. However, as the disc slows down, individual colours are seen again.

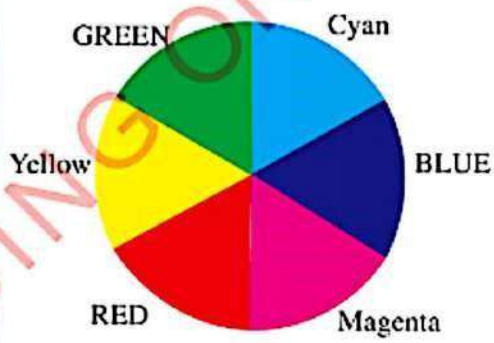


Figure 5.20: *A Newton's colour wheel*

Since magenta was not a part of the light spectrum, its origin posed a mystery. This mystery was resolved by Hermann von Helmholtz, who established that the human eye consists of three types of colour receptors. One of the primary colours (red, blue and green) can stimulate only one receptor type. Moreover, the eye perceives all of the variations in colour by internally combining the signals from these receptors. Therefore, white light is seen when red, blue and green light enters the eye. However, when both red and blue light but no green light enters the eye, magenta is seen even though the light is not magenta. Similarly, when red and green light enters the eye, a yellow light is seen, and when blue and green light enter the eye, a cyan light is seen.

Task 5.3

Use a cardboard to make Newton's colour wheel and observe the colours as the wheel spins at different speeds.

Appearance of objects under white light

When one looks at an object, the object is seen when it reflects light into the eye of the observer. Objects may absorb certain colours of the light falling on them and reflect other colours. Therefore, the colour appearance of objects depends on the colour of the light that the object reflects or absorbs and the colour of the light falling on the object. The selective absorption or reflection of light by an object gives the object its characteristic colour as perceived by an observer.

Coloured objects under white light

When white light falls on an object, and the object reflects the entire colour spectrum in the light, the object appears white. Conversely, the object appears black if it absorbs all colours of the white light falling on it. If the object reflects some of the colours and absorbs the others, the object appears coloured. For example, some flowers in Figure 5.21 appear yellow because they absorb all other colours except the yellow colour, which is reflected into the observer's eyes. Other flowers also absorb all the colours of white light except their respective colours, as seen in the Figure 5.21.

Figure 5.21: *Coloured flowers*

White objects under coloured light

An object is seen as white because it reflects all colours of the white light falling on it. Therefore, when a white object is viewed under the coloured light, it will reflect the coloured light and hence appear to have the colour of the light. For example, when a white object is viewed under the blue light, it appears as a blue object. Similarly, an object will appear red or green when viewed under red or green light, respectively.

Activity 5.9

Aim: To investigate the appearance of a white object under coloured lights

Materials: colour filters (red, yellow, green and blue), a white object

Procedure

1. Take filters of different colours (red, yellow, green and blue).
2. Let the light fall on the white object through each colour filter.

3. View the white object under the filtered light.
4. Observe and record the appearance of the white object under the filtered light.

Questions

(a) Describe the appearance of the white object as seen through each light filter.

(b) What happens when light from the blue filter is passed through a green filter?

When white light is transmitted through a colour filter, the filter allows only a specific light colour to pass through it. Therefore, the filtered light will have a colour depending on the colour of the filter. For example, the light will be yellow, green, blue or red if the filter used is respectively yellow, green, blue or red. Consequently, if light from one filter is passed through another filter of different colour, the light is absorbed by the second filter. Now, when the light through a filter of a given colour falls on the white object, the object reflects that light into the observer's sight. Therefore, the object appears to have the colour of the filtered light. Figure 5.22 shows the appearance of a white object under different coloured lights.

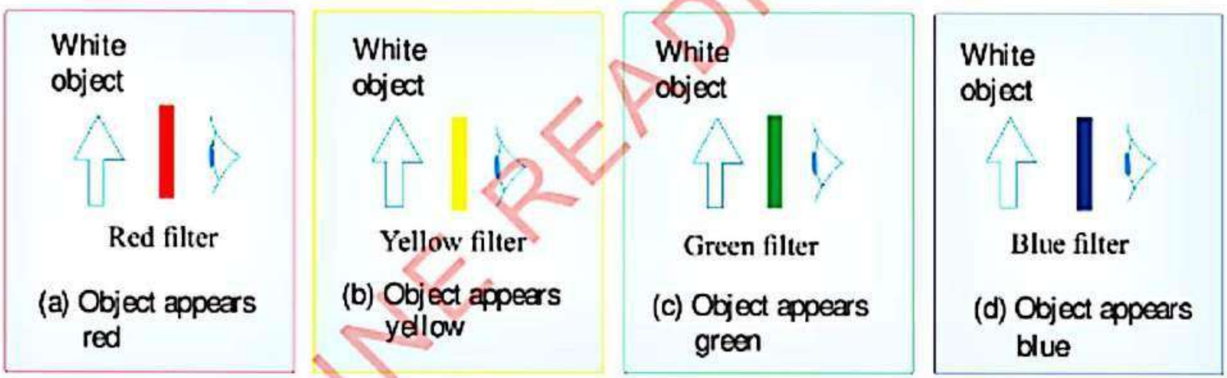


Figure 5.22: Appearance of a white object under coloured lights

Primary, secondary and complementary colours of light

What happens when a physicist simultaneously casts the blue, green and red light beams on a spot on a white screen?

Experiments with beams of various coloured lights have demonstrated that many colours in the light spectrum can be created by mixing other colours. For instance, when light from one end of the spectrum is combined with light from the middle, we can produce all the colours found in that half of the spectrum. Similarly, by mixing lights from both ends of the spectrum with light from the middle, we can generate all the colours that lie in between them.

White light can also be produced by combining only three distinct light colours, provided that they are widely separated on the visible light spectrum. Any three colours of light that produce white light when combined with the correct intensity are called primary colours. These include red (R), blue (B) and green (G) as shown in Figure 5.23. Moreover, mixing together two or all of these three primary light colours with varying degrees of intensity can produce a wide range of other light colours. Many television sets and computer monitors produce a wide range of colours on the monitor by using red, green and blue light-emitting phosphors.

Figure 5.23: *Primary light colours*

Light colours formed by combining the primary colours are referred to as secondary colours. These include cyan, magenta, and yellow, as shown in Figure 5.24.

Figure 5.24: *Secondary light colours*

On the other hand, white light can sometimes be formed by mixing any two colours of the light spectrum. Therefore, the two colours that mix in definite ratios to form white light are termed complementary colours. Examples of complementary colours are blue and yellow, red and cyan, and green and magenta.

Activity 5.10

Aim: To investigate the mixing of primary colours of light

Materials: three torches, light colour filters, a white screen, dark room

Procedure

1. Cover the opening of the first torch with a green filter, the second with a blue filter and the third with a red filter.
2. Switch on the torches and ensure that the first torch gives green light, the second gives blue light and the third gives red light.
3. Direct the torches to the white screen such that circles of green, blue and red light can be seen on the screen.
4. Slowly move the torches such that the blue and red circles intersect by half of their size and observe the image on the screen. Record your observation.
5. Repeat step 4 for different combinations of light circles on the screen.
6. Now, combine all the three circles such that there is a region of intersection for all three circles. Observe the image on the screen.

Questions

(a) What is the resulting colour in each case?

(b) What is the colour at the region of intersection when all the three colour circles were combined?

(c) What do your observations mean?

Different combinations of primary colours of light produce different secondary colours. For example, green and blue lights combine to produce cyan, which is the complement of red. green and red lights combine to produce yellow, which is the complement of blue, while blue and red combine to produce magenta, which is the complement of green. Thus, two primary colours combine to produce the complement of the third primary colour, whereas the three primary colours combine to produce white light. One can easily remember the combinations of primary colours of light by observing the circles in Figure 5.25.

Figure 5.25: *Mixing primary colours*

Addition and subtraction of light colours

When you look at an object and perceive a distinct colour, you are not necessarily seeing a single colour of light, rather a combination of different colours. Consider, for instance, that you are looking at a shirt that appears yellow. There may be several colours of light with varying intensity that strike your eye after being reflected by the shirt. Yet your eye-brain system interprets the colours that strike your eye, and the shirt is perceived to be yellow. Understanding how different colours are perceived requires knowledge of adding and subtracting light colours.

Addition of colours of light

Generation of various colours of light by mixing of the three primary colours of light is known as colour addition. The colour addition principles can be used to make predictions of the colours that would result when different coloured lights are mixed. For example, red (R) light and green (G) light add together to produce yellow (Y) light. Red light and blue light add together to produce magenta (M) light. Green light and blue (B) light add together to produce cyan (C) light. Finally, red light, green light and blue light add together to produce white light. Moreover, addition of complementary colours of light produces white light. The addition of light colours can be described by the following equations;

$$R + G = Y$$
$$R + B = M$$
$$G + B = C$$
$$R + C = R + (G + B) = W$$
$$B + Y = B + (G + R) = W$$
$$G + M = G + (R + B) = W$$

Note that, Figure 5.26 can conveniently summarise the colour addition equations.

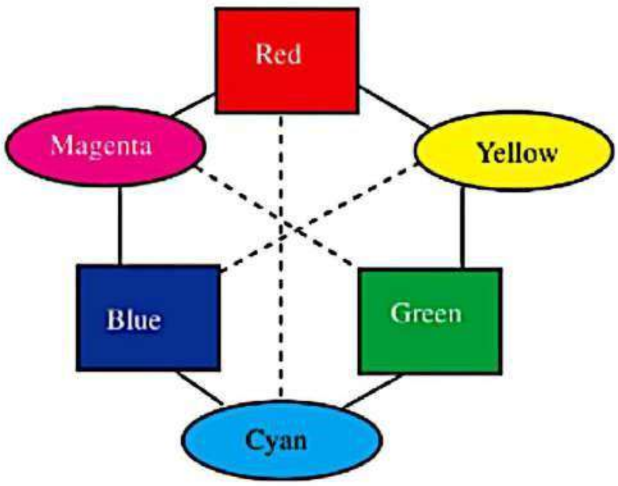


Figure 5.26: *Addition of light colours*

Subtraction of colours of light

The principles of colour addition govern the perceived colour resulting from mixing of different colours of light. However, *understanding colour perceptions cannot be complete without an understanding of the principles of colour subtraction. Some materials contain atoms and molecules that are capable of selectively absorbing one or more colours of light. Therefore, if a beam of white light falls on such a material, some light colours are absorbed and some are* reflected to the observer's eye. This is the *basis of subtraction of light colours. Figure 5.27 illustrates light colour subtraction.* Yellow filter absorbs blue light, magenta filter absorbs green light, and cyan filter *absorbs red light.*

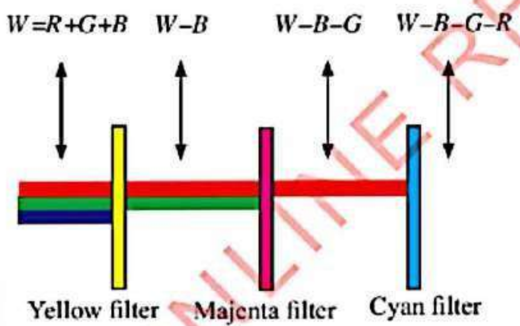


Figure 5.27: ***Subtraction of light colours***

Colour subtraction

Consider a piece of cloth that is made of materials capable of absorbing blue light. Such a cloth will absorb blue light and reflect the other colours. What appearance *will such a cloth have if illuminated with white light, and how can we account for* its appearance?

Suppose that a beam of white light made of blue, green and red colours falls on a shirt. If the shirt absorbs blue light, it will then reflect only red and green light. As we see through reflected light, and since, *R+G=Y , the shirt will appear yellow. . This example illustrates the process of colour subtraction. In this process, the colour appearance of an object is determined by identifying colours of light that are subtracted from the original set of colours, as depicted in Figure 5.28.*

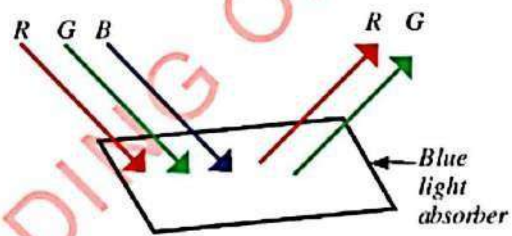


Figure 5.28: ***Process of subtraction of light colours***

The colour subtraction process illustrated by Figure 5.28 can alternatively be depicted using the colour subtraction equation:

$$W - B = (R + G + B) - B = R + G = Y.$$

Suppose that the same piece of cloth is illuminated by a cyan light. Since cyan consists of blue and green light, and the cloth absorbs blue light, then blue light is subtracted. The cloth will then appear green. This process is represented by the following equation:

$$C - B = (G + B) - B = G$$

This observation highlights the fact that an object's colour is not part of the object itself, but depends on the light colours it reflects. Hence, the cloth appears yellow because it reflects green and red lights from the white incident light. Generally, the rules of subtraction of light colour are:

1. Red colour absorbs green and blue light and reflects red light.
2. Blue colour absorbs green and red light and reflects blue light.
3. Green colour absorbs blue and red light while reflecting green light.
4. Cyan colour absorbs red light and reflects cyan light (blue + green).
5. Magenta colour absorbs green light and reflects magenta light (red + blue).
6. Yellow colour absorbs blue light and reflects yellow light (red + green).

These rules are very important concepts for understanding colour appearance in objects. Figure 5.29 summarises the colour subtraction rules.

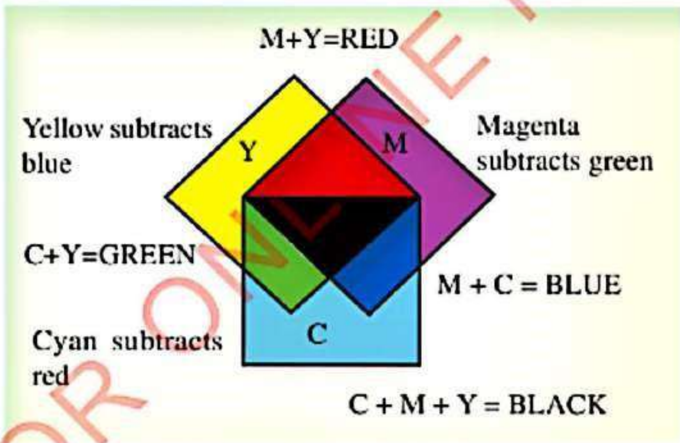


Figure 5.29: *Light colour subtraction using idealised primary filters*

Additive and subtractive mixing of colours

Following our discussion on the addition and subtraction of colours of light, you may have realised that objects can appear in different colours depending on the combination of light that reaches our eyes. This idea is very useful in the synthesis of colours, which we refer to as colour mixing. Since colour-mixing uses the concepts of addition and subtraction of light colours, there are two main types of colour mixing. These are additive colour mixing and subtractive colour mixing.

Additive colour mixing

Additive colour mixing is the process of creating a new colour by adding one set of colours to another set of colours. When we add all of the different colours of sunlight, we see white light rather than many individual colours. Thus, this type of colour mixing is called additive colour mixing because all of the wavelengths still reach our eyes, but the observed colour depends on the combinations of different colours.

Normally, primary colours used in additive colour mixing are red, blue and green and secondary colours are cyan, magenta and yellow. Additive colour mixing is commonly used to generate colours on televisions and computer monitors using RGB (red, green and blue) system. Activity 5.10 that you performed earlier demonstrates the process of additive mixing of colours.

Subtractive colour mixing

When colour pigments are mixed, both paints continue to absorb the same colours as they did before being mixed, the result is the colour that both pigments reflect in common. This process is therefore called subtractive colour mixing because, when colour pigments mix, each may absorb some of the colours that the other pigment reflects, reducing the range of colours seen compared to before mixing. Since we only see light that is reflected by the paints, the primary colours in the subtractive colour mixing are cyan, magenta and yellow while secondary colours are red, blue, and green. Even addition of primary colours gives black colour, which simply means all colours have been absorbed and no light is reflected. Subtractive colour mixing is commonly used in coloured printers and production of different paints using a CMY (cyan, magenta and yellow) system.

It is important to note that each primary colour of paint pigment absorbs one primary colour of light. The colour absorbed by a primary colour paint pigment is the complementary colour of that paint pigment. That is,

(a) Magenta paint absorbs green light.

(b) Cyan absorbs red light.

(c) Yellow absorbs blue light.

On the other hand, each secondary colour paint pigment absorbs two secondary colours of light. That is,

(a) Blue paint absorbs cyan and magenta.

(b) Green paint absorbs yellow and cyan.

(c) Red paint absorbs magenta and yellow.

Activity 5.11

Aim: To explore the subtractive colour mixing

Materials: three colours of paint (blue, red and yellow), plain white papers, a stick, a dropper

Procedure

1. Put a few drops of blue paint on the white paper.
2. Using a clean dropper, put a similar number of yellow paint drops on the same paper. This makes an even mixing ratio.
3. Gently mix the paints and observe the resulting colour. Record this observation.
4. Repeat the procedure for different paints, different number of paints and different mixing ratios.

Question

Explain how new colours have been generated by mixing different paints.

When different paints are mixed, each paint reflects the same light colours that it was reflecting before being mixed. However, in the mixture, each paint absorbs some of the colours that are reflected by the other paint. Consequently, only the remaining colours of light reach the observer's eye giving the mixture of paints a different colour appearance.

Note that, both additive and subtractive colour mixing are of paramount importance for understanding our perception of different colours.

Differences between additive and subtractive colour mixing

The easy way to remember the difference between additive and subtractive colour mixing is that, additive colour mixing is what happens when we mix lights of different colours whereas subtractive colour mixing occurs when we mix paints or other coloured material. Table 5.4 summarizes the differences between the two-colour mixing processes.

Table 5.4: *Comparison between additive and subtractive colour mixing*

Criteria	Additive mixing	Subtractive mixing
Definition	A process of creating a new colour by adding one set of colours to another of colours	A process creating a new colour by the removal of some colours from a broad light spectrum
Primary colours	red, green and blue	cyan, magenta and yellow
Secondary colours	cyan, magenta and yellow	red, blue and green
Colour combination	green + red = yellow blue + red = magenta blue + green = cyan red + blue + green = white	white - red = cyan white - green = magenta white - blue = yellow white - blue = yellow white - red - green = black
Application system	RGB	CMY
Applications	Used in colour television and computer monitors	Used in colour printers, paint pigments

ICT Corner

Use digital painting software to create a blank canvas and experiment with cyan, magenta, and yellow paints. Mix different proportions of these colours to create new shades, documenting your colour combinations and results by taking screenshots. Share your findings with classmates and discuss the mixing process.

Exercise 5.3

1. Determine the colour appearances of objects in the following conditions;
   (a) Yellow light falling on a shirt that can absorb blue light colour.
   (b) Yellow light falling on a sheet of paper that can absorb cyan light colour.
2. Suppose that light from a magenta spotlight and light from a yellow spotlight are mixed together, will white light be produced? Explain.
3. What do dispersion, the formation of rainbows,

and the whiteness of clouds reveal about the behavior of light?

4. Explain why an object which appears yellow in daylight, appears red when illuminated with a red light and black when illuminated with a blue light?
5. What is the difference between secondary and complementary colours in light?
6. Explain the appearance of a red tie with blue spots when observed in
   (a) red light.
   (b) green light.
7. Briefly describe two methods of combining spectrum colours to produce white light.

Refraction of light by lenses

A piece of glass or other transparent material may be shaped in such a way that, parallel incident light rays passing through it would either converge to a point or appear to diverge from a point. A piece of glass that has such a shape is referred to as a lens. Though most lenses are made of glass, it is possible to make lenses from various transparent materials. In recent times, the use of plastic for making lenses has been increasing. A lens is therefore a carefully molded piece of transparent material that refracts light rays in such a way that an image is formed. Lenses can be thought of as a series of tiny refracting prisms, each of which refracts light to produce their own image. When these prisms act together, they produce a bright image focused at a point as shown in Figure 5.30.

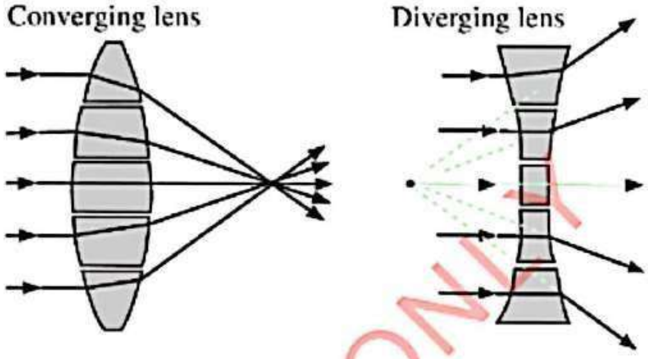


Figure 5.30: *A set of prisms packed to converge or diverge light rays*

Convex and concave lenses

Lenses differ from one another in terms of their shape and the materials from which they are made. Based on their shapes, there are two major types of lenses. These are the convex (converging) lenses and concave (diverging) lenses.

A convex lens is a lens that converges rays of light that pass through it. Convex lenses are relatively thicker across their middle and thinner at their edges as shown in Figure 5.31. At least one side of a convex lens curves outwards. Convex lenses can be further categorized depending on their specific shapes. These include bi-convex lenses, plano-convex lenses and convex meniscus lenses as depicted in Figure 5.31. Task 5.5 demonstrates the action of a convex lens.

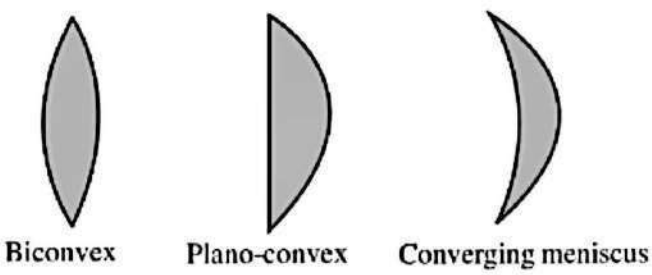


Figure 5.31: *Type of convex lenses*

Task 5.4

On a sunny day, arrange a convex lens and a sheet of paper such that the sunlight is directed through the convex lens and converges to a bright spot on the sheet of paper. Hold the lens at the same position for some minutes. Observe what happens. Discuss with your classmates about your observation.

Caution: Avoid looking at the Sun directly or even into a refracted sunlight.

A concave lens is a lens that diverges rays of light that pass through it. Concave lenses are relatively thinner across their middle and thicker at their edges. At least one side of a concave lens curves inwards. Types of concave lenses include biconcave lens, plano-concave lens and the concave meniscus. Figure 5.32 shows the types of concave lenses.

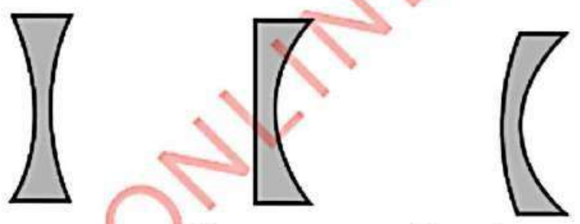


Figure 5.32: *Type of diverging lenses*

Terminologies related to lenses

The discussion of refraction of light rays and the formation of images by lenses requires the use of a variety of terms. If one face of a lens is thought of as being a portion of a spherical surface, then the imaginary line passing through the centre of the sphere and the exact centre of the lens is called the principal axis of the lens. A lens also has an imaginary vertical line that bisects it symmetrically into two halves. This line is the vertical axis of the lens. The point of intersection between the vertical axis and the principal axis is called the optical centre of the lens.

Light rays incident to a lens and travelling parallel to the principal axis will either converge or diverge. In a convex lens, the light rays converge to to a point called the focal point or principal focus. In a concave lens, the light rays diverge, but when traced backwards, they appear to come from a common point, also called a focal point. . In both cases, the focal point is denoted by the letter F. The distance between the focal point and the optical centre is the focal length, denoted by the letter, *f*.

Note that, unlike mirrors, lenses allow light to pass through either face. Therefore, a lens has two focal points on each side of the lens. A lens also has an imaginary point called the centre of curvature, which is the centre of the sphere of which the surface of a lens is a part. The centre of curvature lies on the principal axis and its distance from the optical centre is called the radius of curvature R. The lens has two centres of curvature, on each side of the lens. Note that, the focal point, F is real for a convex lens and virtual for a concave lens.

Other common terms used are; real image, virtual image, image distance, v, object distance, u and magnification, m. All these terms take the same meaning as they were defined in the case of image formation by curved mirrors. Figure 5.33 illustrates the terms used in discussing lenses.

It is important to note that, for thin lenses, the pole and the optical centre merely coincide. Moreover, the plane through the principal focus, which is perpendicular to the principal axis, is called the focal plane.

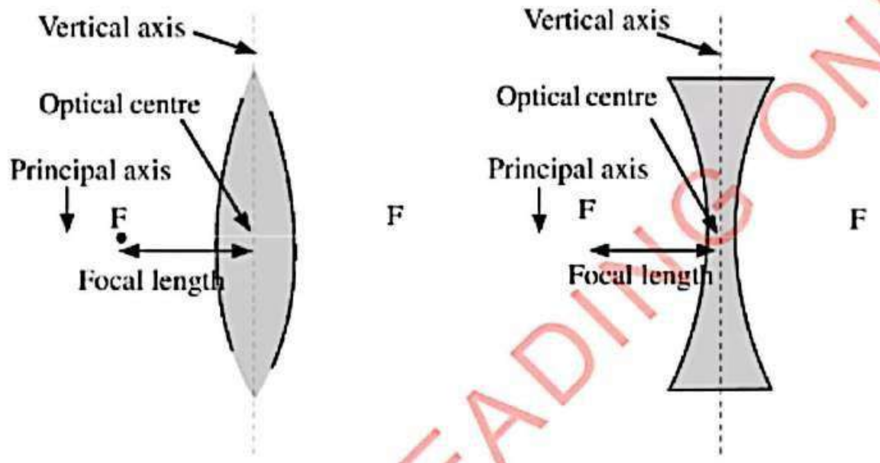


Figure 5.33: *Features of thin lenses*

Images formed by lenses

Image formation by lenses is a result of the refraction of light at both surfaces of the lens. As light enters and exits the lens, it is refracted at each boundary. The net effect of this refraction of light at the two boundaries is a change in direction of the light. Because of the geometric shape of a lens, the refracted light rays either converge to a focal point or appear to diverge from a focal point forming an image as shown in Figure 5.30.

Construction of ray diagrams

How lenses form images of objects can be shown by means of ray diagrams. In ray diagrams, sometimes lenses are represented by vertical lines with an appropriate indication to show whether it is a converging lens or a diverging lens. Figure 5.34 shows the representation of converging lens and diverging lenses in ray diagrams.

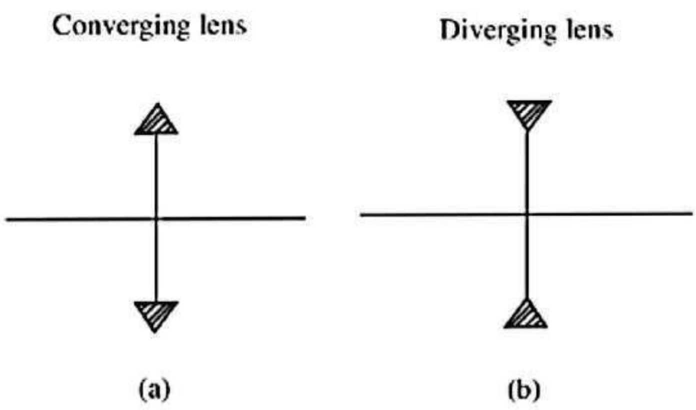
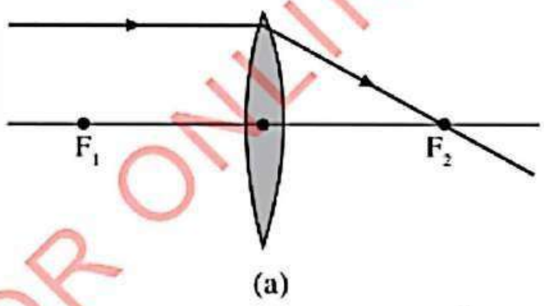


Figure 5.34: *Representation of converging and diverging lenses in ray diagrams*

Some rules are to be followed when one constructs ray diagrams for both convex and concave lenses. These rules originate from the principles of refraction of light. When a ray of light strikes the first face of a lens, it travels from a less dense to a denser medium, thus it bends towards the normal. Upon exiting on the other side of the lens, the ray of light is now travelling from the denser medium to a less dense medium. Therefore, the ray bends away from the normal as it exits the lens. Three important rules are useful in constructing ray diagrams. The rules are:

1. *Convex lens:* A ray of light travelling parallel to the principal axis of a convex lens (Figure 5.35 (a)) is converged to the principal focus.

   Concave lens: A ray of light travelling parallel to the principal axis of a concave lens (Figure 5.35(b)) is diverged in such a way that it appears to be coming from the principal focus.



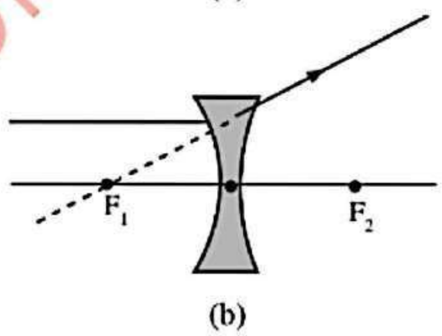
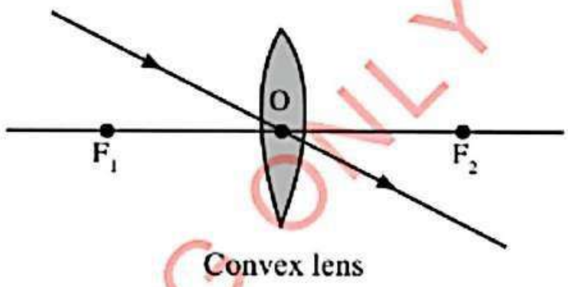


Figure 5.35: *Refraction of incident light rays that are parallel to the principal axis*

2. A ray of light travelling through the optical centre continues to travel along the same path for both convex and concave lenses as seen in Figure 5.36.



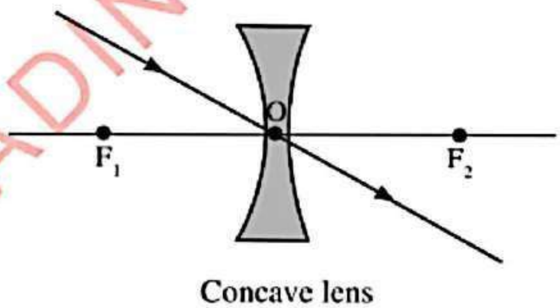
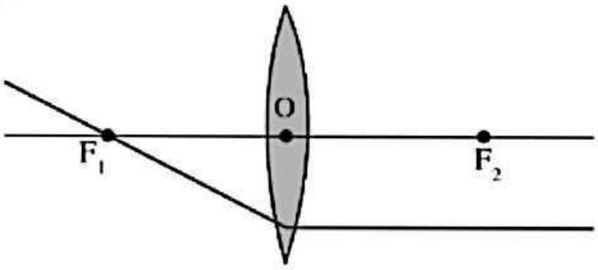


Figure 5.36: *Refraction of light rays incident through the optical centre*

3. *Convex lens:* An incident ray of light travelling through the principal focus of a converging lens is refracted parallel to the principal axis of the convex lens as shown in Figure 5.37 (a).

   Concave lens: An incident ray of light that appears to travel through the principal focus of a diverging lens is refracted parallel to the principal axis. Figure 5.37(b) shows the path of a ray through the principal focus for concave lenses.



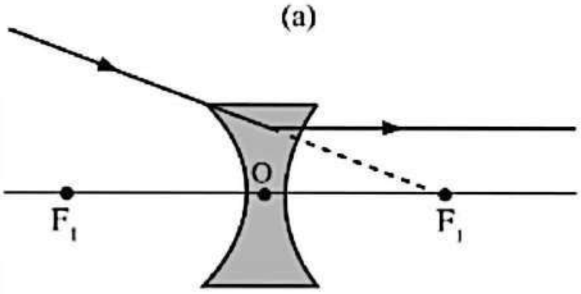


Figure 5.37: *Refraction of light rays incident through the principal focus*

Like in the case of spherical mirrors, any two of the light rays are enough to locate the image formed by a lens. The refraction of light produced by a lens is treated as occurring at a plane through the optical centre, that is, perpendicular to the principal axis of the lens. Whenever rays diverge after passing through the lens, they are extended backwards to locate the virtual images.

Images formed by a convex lens

The location and characteristics of images formed by a convex lens vary depending on the position of the object relative to the optical centre of the lens. One can determine the characteristics of images formed by a convex lens when the object is placed at various locations relative to the optical centre of the lens by performing Activity 5.12.

Note: The image of an object can be obtained by drawing any two of the ray diagrams.

Activity 5.12

Aim: To determine the locations and characteristics of images formed by a convex lens for various object positions

Materials: graph paper, sharp pencil, ruler, computer or tablet with simulation software, spreadsheet software

Procedure

1. Choose an appropriate scale so that the ray diagrams fits on the available space on the graph paper.
2. Draw a convex lens at the centre of the graph paper.
3. Draw a horizontal line passing through the optical centre of the lens. This is the principal axis.
4. Locate the points F_1, $2F_1$, F_2, and $2F_2$ on the principal axis as shown in Figure 5.38. Choose the focal point such that there is a considerable distance between the optical centre, O and the point $2F_1$.
5. Using the chosen scale, draw an upright arrow at a point beyond $2F_1$ point.
6. Choose a point at the head of the object arrow and draw a light ray from this point parallel to the principal axis. Refract this ray according to the rules of refraction.

7. From the same point, draw another ray that passes un-deflected through the optical centre. You may also choose to draw a ray through the focal point and refract it according to the refraction rules.
8. Locate the point at which the refracted rays intersect and draw an arrow from the principal axis to the point of intersection. Figure 5.38 shows the image formation by a convex lens for an object beyond the point $2F_1$.
9. Measure the object distance, the image distance, the object size and the image size. Calculate magnification.
10. Repeat steps 5 to 9 for different positions of the object. That is, the object at the point $2F_1$, object between $2F_1$ and F_1 object at F_1 and object between F_1 and O.
11. Use simulation software to verify your findings by adjusting the object position digitally. Record the image distances and characteristics.
12. Summarise your results using a table and also in spreadsheet software as shown in Table 5.5.

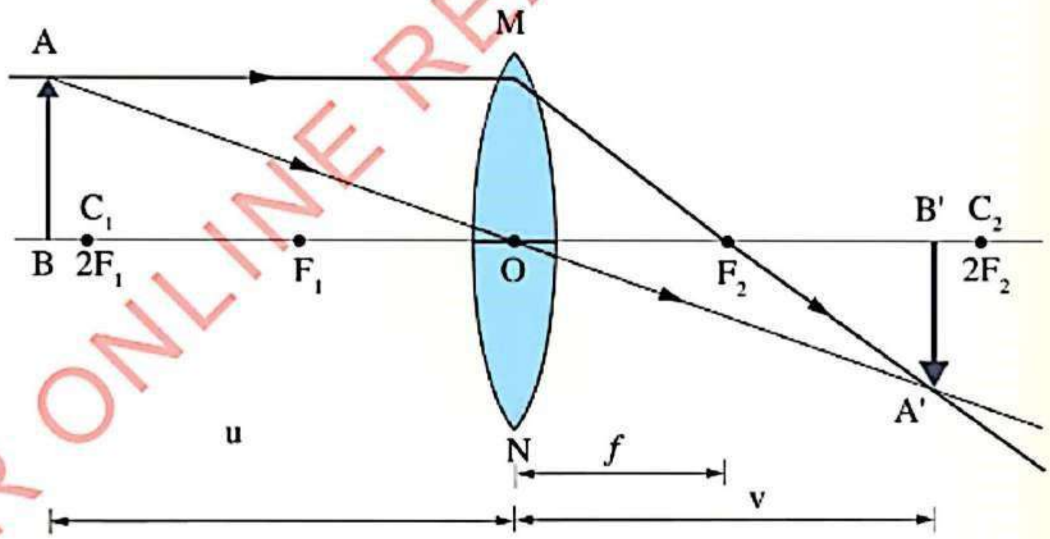


Figure 5.38

Questions

(a) What are the positions (image distance) of the images formed for different object positions?

(b) Describe the nature of the images formed. That is, are the images for various object positions real or virtual?

(c) Are the images for objects at different positions enlarged, the same or diminished?

Table 5.5

Object Position $u\,(cm)$	Image position $v\,(cm)$	Object height $h_0\,(cm)$	Image height $h_1\,(cm)$	Nature of image (real or virtual)	Magnification $(m = h_i/h_0)$
Beyond C					
At C					
Between F and C					
At F					
Between F and O					

The activity focused on the refraction of light and the formation of images by convex lens. It has been observed that an image formed by a convex lens can be virtual or real, upright or inverted and magnified or diminished depending on the object position. By integrating ICT tools, you can enhance your analysis and visualization of these concepts.

Task 5.5

Use a ray diagram and ICT tools to observe the behavior of light when an object is positioned far beyond the 2F point of a convex lens. Draw the diagram, indicating the focal points and the object's position. Utilize simulation software to replicate the setup, then discuss your findings with classmates, focusing on how the object's distance affects the image's characteristics.

Images formed by a concave lens

To characterize the images formed by a concave lens, perform Activity 5.13.

Activity 5.13

Aim: To determine the images formed by a concave lens

Materials: graph paper, sharp pencil, ruler, computer or tablet with simulation software

Procedure

1. Choose an appropriate scale so that the ray diagram fits on the available space and draw a concave lens at the centre of the graph paper.
2. Draw a horizontal line passing through the centre of the concave lens. This is the principal axis. Locate the points F_1, $2F_1$, F_2, and $2F_2$ on the principal axis as shown in Figure 5.39 such that there is a considerable

distance between point $2F_1$ and the optical centre, O.

3. Using the chosen scale, draw an upright arrow at a point just beyond $2F_1$. The arrow represents an object.
4. From the top of the object arrow, draw a ray toward the focal point on the opposite side of the lens, stopping at the lens.
5. Draw a second ray parallel to the principal axis, and a third ray directed to the optical center of the lens, marking arrowheads to indicate direction.
6. Refract the rays according to the rules for concave lenses: the ray aimed at the focal point will exit parallel to the principal axis, while the parallel ray will diverge as if originating from the focal point on the object's side. Using dashed lines, extend the refracted rays on the opposite side of the lens until they intersect. The point of intersection is the image point of the top of the object. Note that, any two rays are enough to locate the position of an object.
7. Now, choose a point at the bottom of the object and repeat steps 4 to 7. This way you can locate the image of the bottom of the object. Use an arrow to draw the image by joining the top and bottom points of intersection as shown in Figure 5.39.
8. Measure the image distance v, the object distance u, the image height, hi and the object height, h_o. Note that, distances measured behind the lens are considered to be negative.
9. Repeat steps 3 to 9 for different positions of the object.
10. Use simulation software to replicate the setup and explore how varying the object position affects the image. Record your observations.

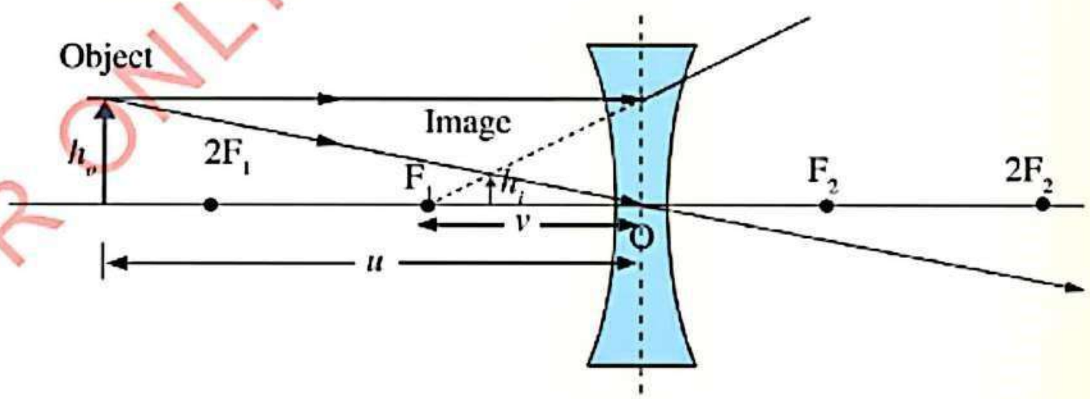


Figure 5.39

Questions

(a) What are the characteristics of the images formed by a concave lens?

(b) Do the characteristics of the images formed by a concave lens vary with the change of object position?

This activity demonstrates that the image positions for an object in front of a concave lens are located between the focal point and the optical centre. For diverging lenses, the images are always erect, diminished, and virtual. By incorporating ICT tools, you can visualise and analyse the behaviour of light more effectively.

Example 5.3

An object 5 cm in length is placed at a distance of 25 cm away from a converging lens of focal length 10 cm. Use a ray diagram to determine the position, size and nature of the formed image.

Solution

Choose a suitable scale for your ray diagram. Take a scale where, 1 cm represents 2.5 cm vertically and 1 cm to represent 5 cm horizontally.

Therefore, the height of the object is represented by 2 cm, the object distance is represented by 5 cm and the focal length is represented by 2 cm.

1. Drawing the ray diagram for the provided information appears as shown in Figure 5.40.

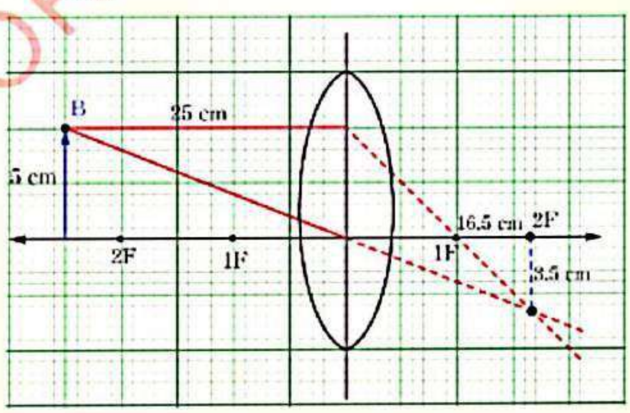


Figure 5.40

2. Thus, measuring the distance of the image, we obtain 3.3 cm on the opposite side of the lens (real image), and the height of the image is 1.4 cm and is inverted.
3. Converting using the scale we have:

   (a) Distance of image

   $$= \frac{3.3 \text{ cm} \times 5 \text{ cm}}{1 \text{ cm}} = 16.5 \text{ cm}$$

   (b) Height of image

   $$= \frac{1.4 \text{ cm} \times 5 \text{ cm}}{1 \text{ cm}} = 3.5 \text{ cm}$$

Thin lens formula

If we represent the object distance by letter u, the image distance by letter v, and the focal length by letter f, then the general formula relating the three quantities is,

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

This equation is called the thin lens formula or lens equation. It is valid for both converging and diverging lenses. The equation is a simpler and more accurate alternative for locating the image formed by either convex or concave lens. The formula can be verified experimentally as demonstrated in Activity 5.14.

Real-is-positive convention

To determine the values of u and v using the formula, a sign convention is adopted. The convention is referred to as the real-is-positive convention. When using this convention, all distances are measured from the optical centre. Distances of real objects and real images are treated as positive whereas distances of virtual objects and images are taken to be negative. Because the principal focus of a concave lens is virtual, concave lenses have negative values of focal length.

Activity 5.14

Aim: To verify the lens equation

Materials: an illuminated object, screen, metre rule, a convex lens of a known focal length, lens holder, computer or tablet with graphing software

Procedure

1. Set up the apparatus as shown in the Figure 5.41.

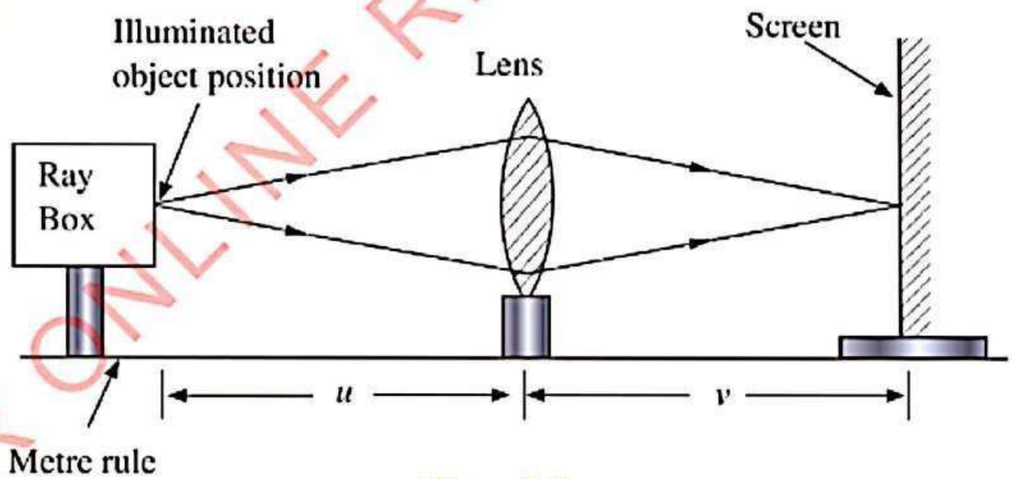


Figure 5.41

2. Place the object and the screen at a reasonable distance apart so that a real image is formed on the screen.
3. Adjust the lens position along the metre rule until a sharp image is formed on the screen.
4. Measure the object and the image distances from the lens. By changing the position of the object, obtain several values of u and the corresponding values of v. Record your results in a table like the one shown in Table 5.6.

Table 5.6

f (cm)	$\frac{1}{f}$ (cm^{-1})	u (cm)	$\frac{1}{u}$ (cm^{-1})	v (cm)	$\frac{1}{v}$ (cm^{-1})	uv (cm^2)	$\frac{uv}{u+v}$ (cm)

Questions

(a) Determine the average value of $\frac{uv}{u+v}$

(b) Compare the value obtained in (a) above with the focal length of the lens.

(c) Plot graphing software to plot a graph of $\frac{1}{v}$ against $\frac{1}{u}$.

(d) Analyse the graph to determine the relationship between object distance and image distance.

(e) Explain how you can obtain the value of the focal length from the graph.

The average value obtained from the formula $\frac{uv}{u+v}$ is the focal length of the lens. This is in agreement with the lens formula. Note that, from the formula,

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

Therefore, $f=\frac{uv}{v+u}$

Alternatively, the value of f may be obtained by plotting a graph of $\frac{1}{v}$ against $\frac{1}{u}$. The graph is a straight line with an intercept on both axes, as shown in Figure 5.42. From the graph, we may use the formula, $\frac{1}{f}=\frac{1}{u}+\frac{1}{v}$ to realize that, at y-intercept, $\frac{1}{u}=0$. So, $\frac{1}{f}=\frac{1}{v}$ or $f=v$.

The focal length may therefore be obtained by using the y-intercept of the graph and finding its reciprocal.

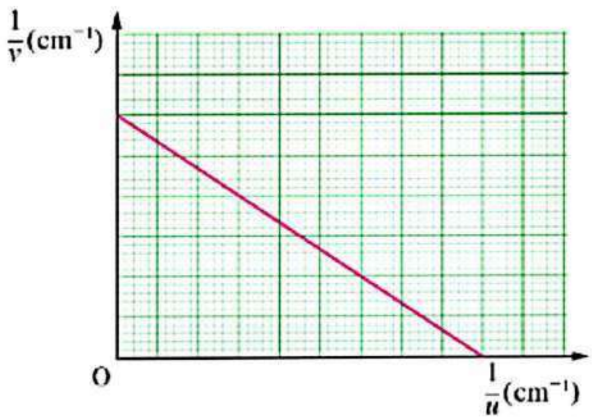


Figure 5.42: *A graph of $\frac{1}{v}$ against $\frac{1}{u}$*

Focal length of a convex lens

The focal length of a converging lens can be determined experimentally using various methods. Activity 5.15 describes one of the methods.

Activity 5.15

Aim: To estimate the focal length of a converging lens

Materials: a converging lens, lens holder, metre rule, plain paper (screen)

Procedure

1. Fix the lens on the holder and the screen on a stand.
2. Place the screen and the lens on a table in such a way that the light from a distant object passes through the lens as shown in Figure 5.43.
3. Move the screen closer or away from the lens until a sharp image of the distant object is focused on the screen.

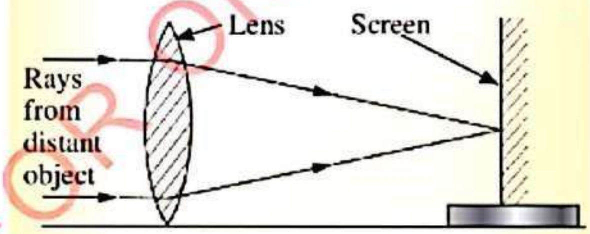


Figure 5.43

4. Measure the distance between the screen and the lens.

Question

What is the distance between the screen and the lens?

The image of a distant object is formed at the focal point of a convex lens. Therefore, the distance between the screen and the lens is the focal length of the lens. Note that, this is not a very accurate method but a quick way of estimating the focal length of a convex lens.

Example 5.4

An object is placed 12 cm from a convex lens of a focal length of 18 cm. Using the lens formula, find the position of the image.

Solution

For a convex lens, the value of focal length is positive. Therefore, $f = +18$ cm and $u = +12$ cm.

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

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

$$= \frac{1}{18} - \frac{1}{12}$$

$$= \frac{2\text{ cm} - 3\text{ cm}}{36\text{ cm}}$$

$$= \frac{-1}{36\text{ cm}}$$

$$v = -36\text{ cm}$$

Because the value of v is negative, the image is virtual (on the same side as the object) and is 36 cm from the lens. Because the image is virtual, it is also erect.

Example 5.5

An object is placed 10 cm from a concave lens of focal length 15 cm. Using the lens formula, determine the nature and the position of the image.

$u = +10 \text{ cm}, \ f = -15 \text{ cm}$

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

$$\frac{1}{-15\,cm} = \frac{1}{10\,cm} + \frac{1}{v}$$

$$\frac{1}{v} = \frac{-1}{15\,cm} - \frac{1}{10\,cm}$$

$$\frac{1}{v} = \frac{-2 \text{ cm} - 3 \text{ cm}}{30 \text{ cm}^2} = \frac{-5 \text{ cm}}{30 \text{ cm}^2}$$

$v = -6 \text{ cm}$

A virtual image is formed 6 cm from the lens, on the same side as the object.

Magnification by a lens

Magnification is a measure of the extent to which an optical system changes the size of an image of an object. The linear or lateral magnification produced by a lens is the ratio of the height of the image to the height of the object. If the image size is bigger than the object size, then the image is said to be enlarged. On the other hand, when the image size is smaller than the object size, the image is said to be diminished. Magnification is usually denoted by the letter m. Thus,

$$m = \frac{image\ height\ (h_i)}{object\ height\ (h_0)}$$

Example 5.6

An object 2 cm high is placed 24 cm from a converging lens. An erect image, which is 6 cm high, is formed. Determine the focal length of the lens.

Solution

Using the lens formula:

$h_0 = 2 \text{ cm}, \ h_i = 6 \text{ cm}, \ u = 24 \text{ cm}$

$$m = -\frac{v}{u} = -\frac{v}{24\text{cm}}$$

Also, $m = \frac{h_i}{h_0}$

$$= \frac{6 \text{ cm}}{2 \text{ cm}} = 3$$

Thus, $m = -\frac{v}{24\text{cm}} = 3$

$v = -72 \text{ cm}$

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

$$= \frac{1}{24\text{cm}} + \frac{1}{-72\text{cm}}$$

$$= \frac{3 \text{ cm} - 1 \text{ cm}}{72 \text{ cm}^2} = \frac{2 \text{ cm}}{72 \text{ cm}^2}$$

$f = 36 \text{ cm}$

Therefore, the focal length of the lens is 36 cm.

Example 5.7

A vertical object, 10 cm high, is placed 30 cm in front of a diverging lens. An image of the object is formed 7.5 cm in front of the lens. Determine the focal length and the magnification of the lens.

Solution

Given

$h_0 = 10$ cm, $v = 7.5$ cm, $u = 30$ cm

Using the lens formula $\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$

$$f = \frac{uv}{v+u} = \frac{30 \text{ cm} \times (-7.5 \text{ cm})}{(-7.5 \text{ cm}) + 30 \text{ cm}} = -10 \text{ cm}$$

$f = -10$ cm (Negative sign indicates that f is measured against the incident ray)

$$m = \frac{v}{u} = \frac{-(-7.5 \text{ cm})}{30 \text{ cm}} = 0.25$$

The positive value of magnification indicates that the image is erect or upright. Therefore, the focal length, f is 10 cm and the magnification, m is 0.25.

Uses of lenses in life

Lenses have different applications in our daily life. Convex or concave lenses are used in medical eyeglasses for correcting long-sightedness and short-sightedness respectively. Convex lenses are also used in binoculars, cameras, telescopes, microscopes and other optical instruments. On the other hand, concave lenses are used in flashlights to magnify the light produced by a bulb. These lenses are also used in pinholes.

Exercise 5.4

1. (a) Draw ray diagrams to show the nature and position of images formed by a convex lens with focal legth of 30 cm for the following object distances:
   (i) 15 cm
   (ii) 30 cm
   (iii) 45 cm.

   (b) Use the lens formula to determine the nature and position of the image formed by the objects in (a).
2. A vertical object 10 cm high, is placed 30 cm in front of a diverging lens. An image of an object is formed 7.5 cm in front of the lens. Determine the focal length of the lens by using a ray diagram.
3. An object 2 cm high is placed 9 cm from a convex lens of focal length 6 cm. Determine the magnification, position and nature of the formed image.
4. A converging lens forms an upright image that is four times the size of the object. Given that the focal length of the lens is 20 cm, determine the object distance.
5. An object is placed 36 cm from a converging lens of focal length 24 cm. If a real image which is 4 cm high is formed, calculate the height of the object.
6. A lens of focal length 15 cm forms an upright image four times the size

of the object. Calculate the distance of the image from the lens.

7. An object is placed at a distance of 25 cm from a convex lens of focal length 20 cm. Find magnification of the image formed.

Chapter summary

1. When light encounters the boundary between two different optical media, a portion of the light is reflected and the remainder is transmitted into the second medium. The transmitted light undergoes a change in speed that causes a change in its direction. This phenomenon is called refraction.
2. The change in speed and direction of light depends on the refractive indices of the two media.
3. Light travelling from a medium of low refractive index to a medium of high refractive index is bent toward the normal.
4. When light passes through a medium of high refractive index to one of lower refractive index, total internal reflection occurs if the angle of incidence is greater than the critical angle
5. The use of prisms in binoculars relies on their ability to totally reflect the incident light internally.
6. Refraction of light through a glass prism obeys Snell's law.
7. The angle formed by the intersection of the incident ray and the emergent ray directions is called the angle of deviation.
8. The minimum angle of deviation by a triangular prism occurs when the angle of incidence produces a refracted ray that travels parallel to the base of the prism.
9. Dispersion of light is the splitting of white light into its component colours. The split light forms a spectrum of colours.
10. The spectrum colours of white light are red, orange, yellow, green, blue, indigo, and violet.
11. A rainbow is formed as a result of the refraction and reflection of the colours of light in raindrops.
12. Colours of objects result from the reflection and absorption of certain colours by objects.
13. The mixing of pigments is called subtractive mixing of colours. Subtractive complementary colours combine to produce black.
14. The mixing of coloured lights is called additive mixing of colours.

Revision Exercise 5

1. Choose the letter of the correct answer from the given alternatives:

   (a) A pin at the bottom of a basin full of water appears to be 6 cm from the surface. Given that the refractive index of the water is 4/3, what is the actual distance of the pin from the surface?

   (i) 1.33 cm (ii) 4.85 cm
   (iii) 7.33 cm (iv) 8.0 cm

(b) Figure 5.44 shows a ray of light travelling from air to water.

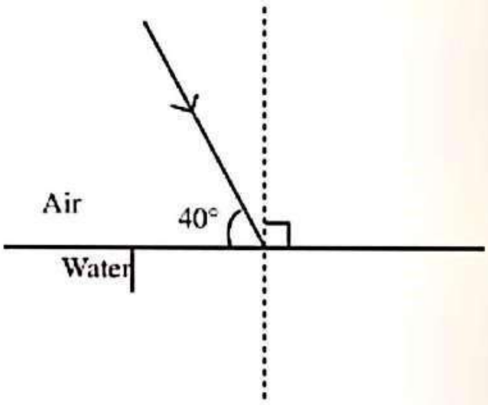


Figure 5.44

Given that the refractive index of water is 4/3, what is the angle of refraction of the ray of light?

(i) $\sin^{-1}\left(\frac{4}{3}\sin(40°)\right)$

(ii) $\sin^{-1}\left(\frac{3}{4}\sin(50°)\right)$

(iii) $\sin^{-1}\left(\frac{4}{3}\sin(50°)\right)$

(iv) $\sin^{-1}\left(\frac{3}{4}\sin(40°)\right)$

(c) Figure 5.45 shows a ray of light travelling through three different media.

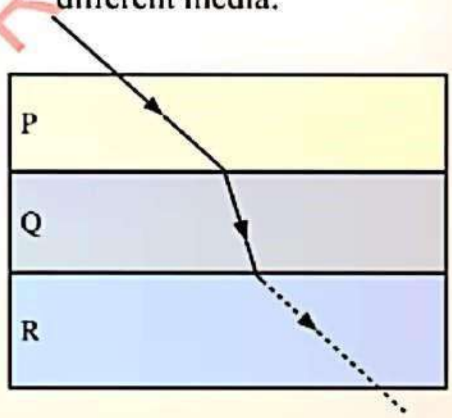


Figure 5.45

Given that the three media are air, glass, and water (not in order), which medium is represented by letters P, Q, and R, respectively?

(i) Air, glass, water.

(ii) Air, water, glass.

(iii) Glass, air, water.

(iv) Glass, water, air.

(d) The radius of curvature of the curved surface of a thin plano-convex lens is 10 cm and the refractive index is 1.5. If the plane surface is silvered, then the focal length will be:

(i) 5 cm (ii) 10 cm

(iii) 15 cm (iv) 20 cm

(e) A ray of light travelling in a transparent medium of refractive index η, falls on a surface separating the medium from the air at an angle of incidence of 45°. The ray can undergo total internal reflection for the following:

(i) $\eta = 1.25$ (ii) $\eta = 1.33$

(iii) $\eta = 1.4$ (iv) $\eta = 1.5$

(f) An air bubble in a glass slab of refractive index 1.5 (near normal incidence) is 5 cm deep when viewed from one surface and 3 cm deep from the opposite face. The thickness of the slab is,

(i) 8 cm (ii) 10 cm

(iii) 12 cm (iv) 16 cm

2. A rectangular glass block 5 cm thick is placed on top of the page of a book. If the refractive index of the glass block is 1.53, calculate the apparent depth of the letters on the book.
3. A ray of light is incident at an angle of 60° on a block of glass of refractive index 1.5. Determine the angle of refraction of the ray.
4. A small coin was placed at the bottom of a tall glass containing some water and viewed from above. The real and apparent depths of the coin were then measured. By varying the depth of the water in the jar, the following readings were obtained:

Table 5.7

Real depth (cm)	8.1	12.0	16.0	20.0
Apparent depth (cm)	5.9	9.0	12.0	15.1

By plotting an appropriate graph from the results, determine the refractive index of the water.
5. State whether it is possible or not to obtain a critical angle when light travels from:
   (a) air to glass.
   (b) water to air.
   (c) glass to air.
   (d) air to water.
6. The refractive index of water is 1.33 and that of glass is 1.5. Calculate the critical angle for:
   (a) a glass-air interface (b) a water-air interface (c) a glass–water interface
7. Figure 5.46 shows some objects placed in front of or behind lenses.

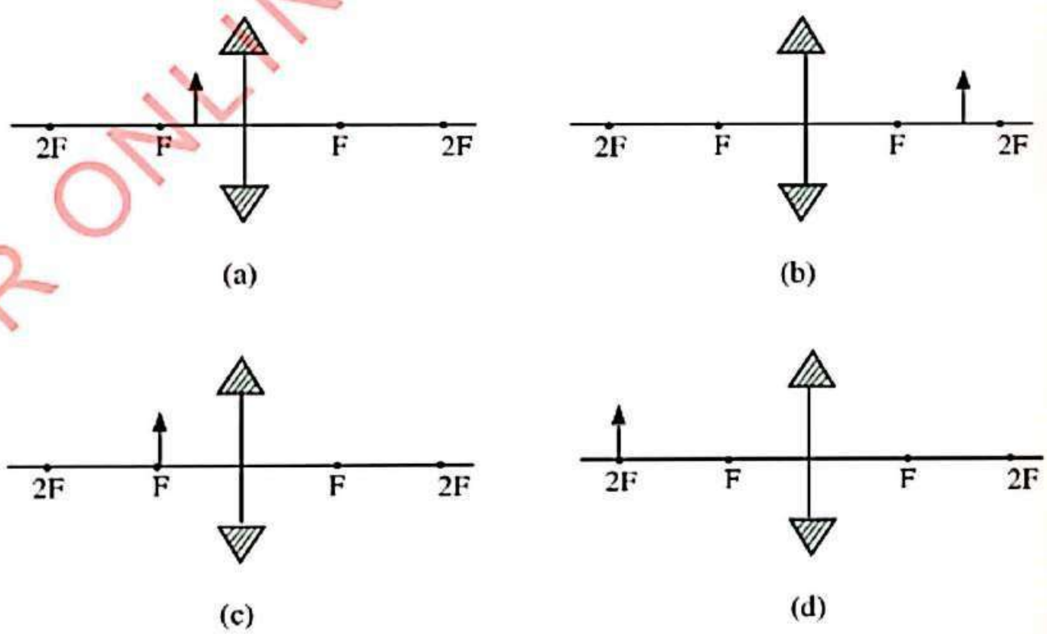


Figure 5.46

By construction, find the nature and position of the image formed by each object.

8. An object 5 cm high is placed 25 cm from a convex lens with a focal length of 20 cm. Using the lens formula, determine the position, size, and nature of the formed image.
9. When an object is placed 30 cm from a lens, a virtual and erect image, which is half the size of the object is formed.
   (a) Explain whether the lens is a concave or a convex lens.
   (b) What is the focal length of the lens?
10. When an object is placed 25 cm from a convex lens, an inverted image, which is twice as large as the object, is formed. How far from the lens must the object be placed to obtain an image four times the size of the object?
11. A beam of light consisting of red, green, and blue is incident on a right-angled prism as shown in Figure 5.47. The refractive indices of the material of the prism for red, green, and blue colours are 1.39, 1.44, and 1.47, respectively. Which colour suffers from total internal reflection? Explain.

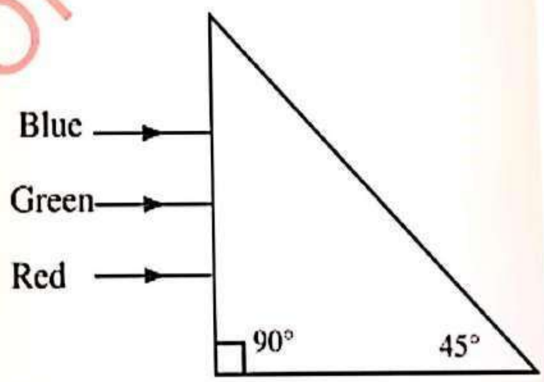


Figure 5.47

12. Rays of light from luminous objects are brought to focus at point Q. A convex lens of 24 cm focal length is then placed 12 cm from Q to intercept the rays before they meet at Q. If now they meet at P, find the distance QP.
13. A glass block whose refractive index is 1.564 for sodium light is to be used to construct a prism such that the angle of minimum deviation for such light shall be equal to the angle of the prism. What is the angle of the prism?
14. Form Two students went to the picnic. The weather was pleasant. They played various games and then had snacks. Suddenly, Gebu, one of them, noticed seven colours extended like a bow in the sky. He said, "Wow, what is rainbow!?" The Ramso, one of them, asked him, "What is a rainbow?" He then explained its formation to all students. After that, everyone in the group thanked him for the knowledge he had given to them.
    (a) If you were in the place of Gebu, how would you have explained such a natural phenomenon?
    (b) Which device can be used to obtain such a phenomenon?
    (c) If Gebu facing the rainbow, then where was the sun?
    (d) What does Gebu show the moral values?

Chapter Six

Optical Instruments

Introduction

Optical instruments enhance the human eye's ability to see distant and tiny objects, making it possible to observe stars and microorganisms that are otherwise invisible. These devices use light, along with lenses, mirrors, and prisms, to form clearer images. In this chapter, you will learn how various optical instruments work, including microscopes, telescopes, and cameras. The competencies developed will enable you to choose, use, and even construct simple optical instruments for different applications.

Think

Life without optical instruments

Simple microscope

The size of an object as viewed by the eye is determined by the size of its image formed on the retina. The size of the image depends on the distance from the object to the observer's eye and the angle subtended by the object at the eye, called angular size (θ). If you want to look closely at a small object, such as an insect, you bring the object close to your eye. By doing so, you increase the angular size and hence make the image on the retina as large as possible. However, your eyes cannot focus sharply on objects that are closer than a point at about 25 cm from the eye. This point is known as the near point of the eye. Moving an object closer to the near point of the eye increases the size of the image on your retina. But if you still move the object closer than the near point, the image will be fuzzy or blurred because the lens of the eye will no longer focus an image on the retina. Therefore, the closest comfortable distance for viewing an image is when an object is at this point. Thus, an object cannot be brought closer to the eye beyond the near point. To overcome this limitation, a converging lens can be used to enlarge the image of an object. The object can then be moved even closer to the eye, resulting in a large image formed on the retina. A lens used in this way forms a device known as a simple microscope.

Structure of a simple microscope

A simple microscope is made of a biconvex lens normally held by a round-shaped frame with a handle. It can therefore be hand-held and moved according to the user's needs. A simple microscope is sometimes called a magnifying glass or simply a magnifier. Figure 6.1 shows a simple microscope.

Figure 6.1: *A simple microscope*

Mode of action of a simple microscope

When using a simple microscope, you can simply put it over the object to be viewed. For the comfort of the observer's eye, the position of the magnifying glass with respect to the object is adjusted so that the object is at the focal point of the lens. This produces a virtual, upright, and magnified image of the object. Note that the largest image can be formed on the retina of the naked eye when the object is at the near point (D ≈ 25 cm). Therefore, for the clear and maximum size of the image to be formed on the retina, the magnifier must have a focal length of approximately 25 cm. The image is formed at infinity when the position of the magnifying glass or the object itself is adjusted so that the object is at the focal point of the magnifying glass. In this way, the eyes see a magnified image such that smaller features can be observed. Figure 6.2 illustrates the action of a simple microscope.

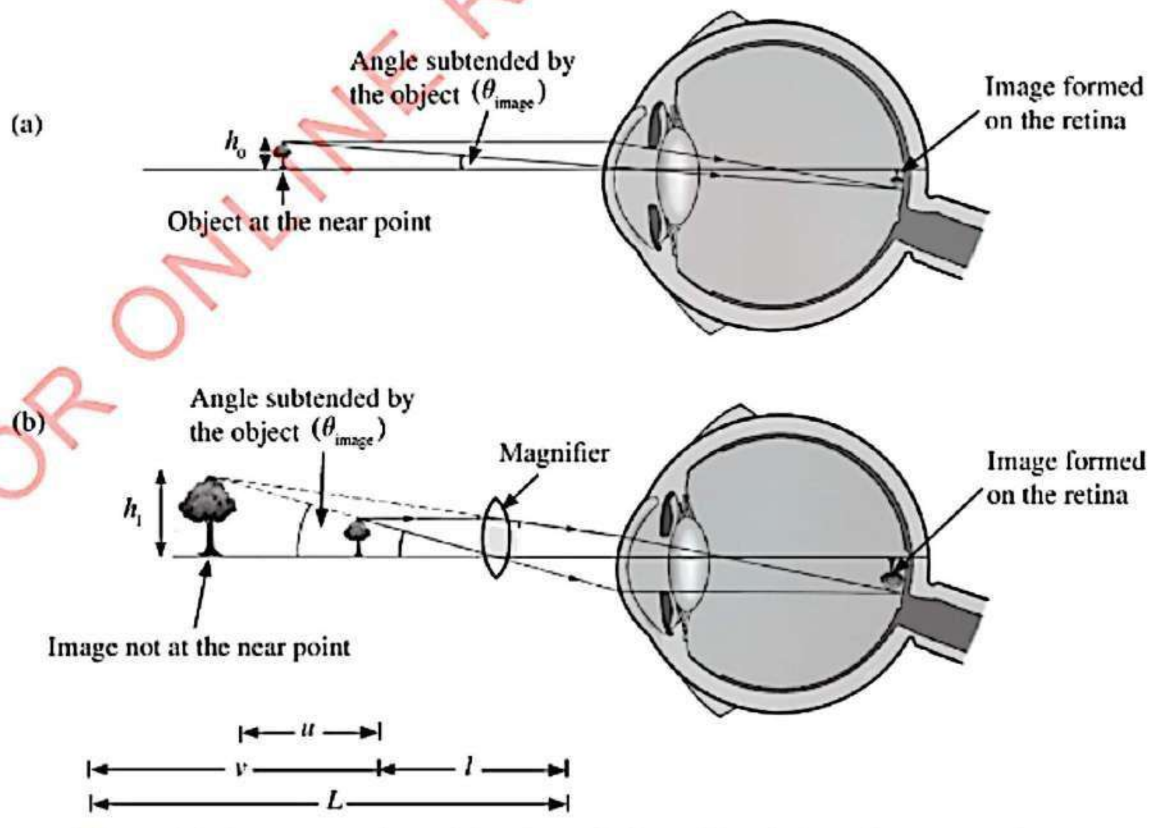


Figure 6.2: *Viewing an object (a) with a naked eye (b) with the aid of a magnifier*

Magnification of a simple microscope

A simple microscope magnifies an object by increasing its angular size. The magnification produced by the simple microscope depends on the focal length of the lens. Lenses of short focal length give larger magnification than those with long focal length. In Figure 6.2(a), the object is at the near point, where it subtends an angle θ_{object} to the eye. On the other hand, in Figure 6.2(b), the magnifier in front of the eye forms an image far away from the lens; the image subtends an angle θ_{image} at the magnifier. The usefulness of the magnifier is given by the ratio of the angle subtended by the image (θ_{image}) to the angle subtended by the object (θ_{object}). This ratio is called the angular magnification, M, and is given by, $M = \frac{\theta_{image}}{\theta_{object}}$

The angular magnification should not be confused with the linear or lateral magnification, m, of a simple lens, which is the ratio of the image height, hi, to the object height, ho, given by, $m = \frac{h_i}{h_o}$

Linear magnification is also given by the ratio of the image distance, v, to the object distance, u. That is: $m = \frac{v}{u}$

It follows that, $\frac{v}{u} = \frac{h_i}{h_o}$ and thus, $v = u \times \frac{h_i}{h_o}$.

To find the value of angular magnification, let the angles subtended by the object and the image be very small, such that, $\sin\theta_{object} = \tan\theta_{object} \approx \theta_{object}$ and $\sin\theta_{image} = \tan\theta_{image} \approx \theta_{image}$.

Suppose the object in Figure 6.2 has a height, h_o, and it is placed at the focal point, $f = D = 25$ cm, where it subtends an angle θ_{object}. If the angle θ_{object} is very small, then,

$$\tan\theta_{object} \approx \theta_{object} = \frac{h_o}{D}.$$

The virtual image formed by the lens subtends a small angle θ_{image} such that,

$$\tan\theta_{image} \approx \theta_{image} = \frac{h_i}{v}. \text{ But } v = \frac{uh_i}{h_o}$$

Therefore, $\tan\theta_{image} \approx \theta_{image} = h_i \times \frac{h_o}{uh_i} = \frac{h_o}{u}$.

Now, $M = \frac{\theta_{image}}{\theta_{object}} = \frac{h_o}{u} \div \frac{h_o}{D} = \frac{h_o}{u} \times \frac{D}{h_o} = \frac{D}{u}$

Hence, angular magnification, $M = \frac{D}{u}$.

Using the lens formula, $\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$

The angular magnification is maximum when the image is at the near point of the eye.

Then, $\frac{1}{f}=\frac{1}{u}+\frac{1}{25}$

Using real is positive, $\frac{1}{f}=\frac{1}{u}-\frac{1}{25}$

This implies that, $u=\frac{25f}{25+f}$

Since $M=\frac{D}{u}$, and $D=v$,

Then, $M=\frac{25}{\frac{25f}{25+f}}=1+\frac{25}{f}$

$$M=1+\frac{25}{f}$$

This is the expression for the angular magnification of the simple microscope. The eye is most relaxed when the image is at infinity. In this case, the object has to be at the focal point of the lens. Thus,

$$\theta_{object}\approx\frac{h_o}{25} \text{ and } \theta_{image}\approx\frac{h_i}{f}$$

Here, the magnification is said to be minimum, given by,

$$M=\frac{\theta_{\text{object}}}{\theta_{\text{image}}}=\frac{h_i}{f}\div\frac{h_o}{25}=\frac{25\text{cm}}{f}$$

Angular magnification is also known as the magnifying power of the microscope. The angular magnification of a simple microscope may be made as large as possible by decreasing its focal length f. However, decreasing the focal length is limited by the imperfection of the lens. The limitation of the simple microscope can be overcome by using a compound microscope.

Example 6.1

A simple microscope with a focal length of 5 cm is used to read the division of scale 1.5 mm in size. How large will the size of the divisions be as seen through the simple microscope?

Solution

$f=5\ cm,\ h_o=1.5\ mm$

$M=\frac{25}{f}+1=\frac{25\ cm}{5\ cm}+1=6$

$M=\frac{h_i}{h_o}$

$h_i=h_oM$

$h_i=1.5\ mm\times6=9\ mm$

Therefore, each division will appear to have a size of 9 mm when viewed through the simple microscope.

Construction of a simple microscope

One can construct a simple microscope for various simple uses. Materials that are important in constructing a simple microscope include a biconvex lens and a hard box.

Task 6.1

Construct a simple microscope

Task 6.2

1. Fill a transparent plastic bottle with water and seal it.
2. Place the bottle filled with water on a page with text. Observe what happens to the letters on the page.

Uses of a simple microscope

A simple microscope has a range of applications. The following are some of the uses of a simple microscope:

1. It is used to view specimens in a laboratory.
2. It is used by watchmakers to view small components of a watch.
3. It is used to read small prints.
4. It is used to concentrate light rays.

Exercise 6.1

1. A small object is placed 3 cm from the lens of a simple microscope. The focal length of the lens is 5 cm.
   (a) Find the linear magnification produced by the simple microscope.
   (b) How far from the lens should you place the object to obtain maximum magnification of the image?
2. A magnifying glass of focal length 5 cm is used to magnify a small object held 4 cm from the optical centre of the lens. Determine the position and magnification of the formed image.
3. The magnifying power of a simple microscope is 8. What will be the focal length?
4. A student with a near-normal point (25 cm) reads a story book with small fonts using a thin convex lens of focal length 5 cm.
   (a) What are the closest and the farthest distances the student can read when viewing through the magnifying glass?
   (b) What are the maximum and minimum angular magnification (magnifying power) possible using the above simple microscope?

Compound microscope

The magnification of a simple microscope is limited to $M \leq 9$ for realistic focal lengths. This means that the object will appear 9 times larger when viewed using a simple microscope of maximum magnification. For example, an object whose size is 1 mm will be seen to be 9 mm when viewed through a magnifier. However, the size of bacteria, for example, is much smaller than 1 mm. Thus, to see a bacterium, a magnification larger than 9 is required. To achieve this, a new microscope that uses two lenses in such a way that one lens compounds the effect of the other lens is normally used. Such a microscope is called a compound microscope.

Structure of a compound microscope

A compound microscope is composed of a lens system, a lighting system and a focusing system. The lens system is made up of two convex lenses. A lens that is placed nearer the object is called the objective lens. This lens forms a real, inverted and magnified image of the object. The image formed by the objective lens serves as the object for the second lens, which is known as the eyepiece. The eyepiece functions as a simple microscope to produce the final image, which is enlarged and virtual.

A compound microscope has a revolving nose piece that allows the user to change the objective lens according to needs. The compound microscope also consists of the lighting system, which may be called the illumination system. It consists of a light source, which can be an electric bulb, a light-emitting diode (LED) or sometimes natural sunlight. There is also a mirror and a condenser which help to transmit light through an object for viewing. On the other hand, the compound microscope has a focusing system.

This system is made of coarse and fine adjustment knobs, which are essential for moving the objective lens away or towards the object in searching for a clear image. The system also has the inclination joint, which helps in tilting the microscope for a comfortable view. Other parts of a compound microscope include the body tube, which separates the objective and the eyepiece and assures continuous alignment of the optics. A stage is used for holding the object to be viewed, and the base supports the whole structure of the microscope. Figure 6.3 shows important parts of a compound microscope.

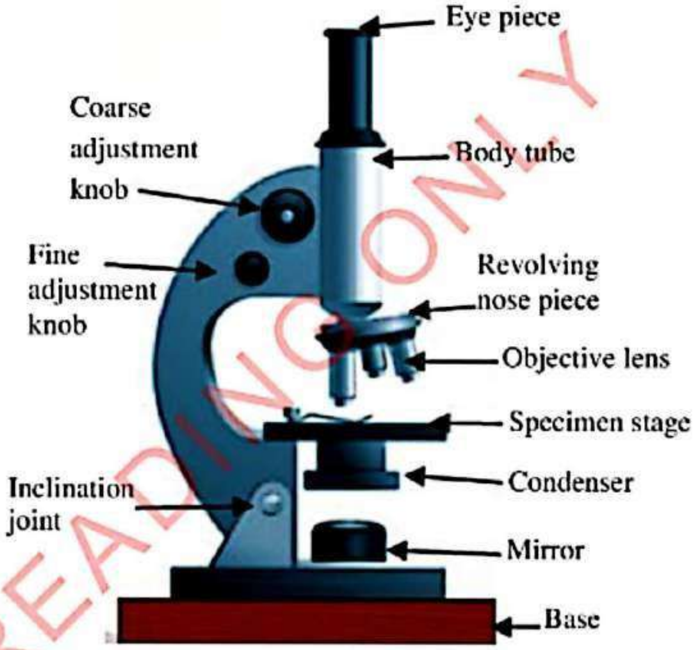


Figure 6.3: *A compound microscope*

Mode of action of a compound microscope

A compound microscope works by using the principle that an image formed by one optical element can serve as the object for the second optical element. That is, an image formed by the objective lens is used as the object for the eyepiece. The object to be viewed is placed just beyond the first focal point F_o of the objective lens, which forms a real and enlarged image I_1 as illustrated by Figure 6.4.

In a properly designed compound microscope, the image formed by the objective lens lies just inside the focal point F_e of the eyepiece. The eyepiece (or ocular) acts as a simple magnifier and forms a final virtual image I_2. The position of I_2 may be anywhere between the near and far points of the eye.

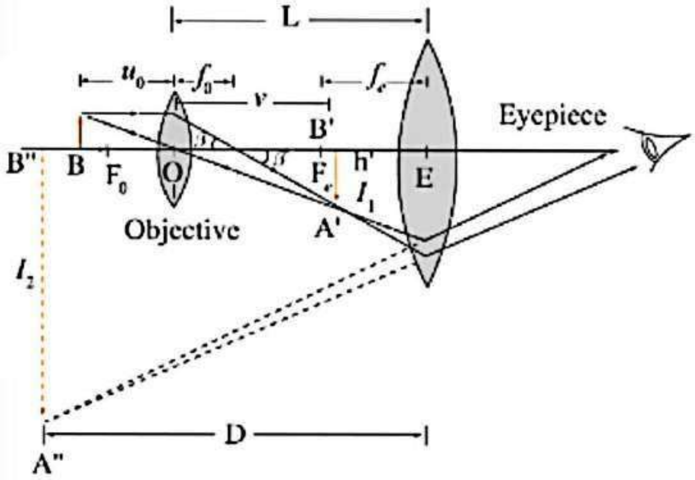


Figure 6.4: *Image formation by a compound microscope*

Magnification of a compound microscope

As for a simple magnifier, what matters when viewing through a microscope is the angular magnification M. The overall angular magnification of the compound microscope is the product of two factors.

The first factor is the lateral magnification m_o of the objective lens, which determines the linear size of the real image I_1. The second factor is the angular magnification M_e of the eyepiece, which relates the angular size of the virtual image seen through the eyepiece to the angular size that the real image I_1 would have if you view it without the eyepiece. The first factor is given by the ratio of distance of the image formed by the objective lens to the distance between the object and the objective lens. According to Figure 6.4, the lateral magnification is,

$$m_o = \frac{v}{u_o}$$

The object is normally placed at a point very close to the focal point F_o of the objective lens, that is, $u_o \approx f_o$. Therefore, the lateral magnification of the objective lens is approximately taken as,

$$m_o = \frac{v}{f_o} \text{ but } v \approx L - f_e$$

$$m_o = \frac{L - f_e}{f_o}$$

The real image I_1, formed by the objective lens, is close to the focal point F_e of the eyepiece, that is, $u_e \approx f_e$. As a result, the image formed by the eyepiece appears at infinity. Although the eye can focus on an image formed anywhere between the near point and infinity, it is most relaxed when the image is at infinity. From the relation,

$$M_e = \frac{D}{u_e}$$

then, angular magnification is,

$$M_e = \frac{D}{f_e}$$

where f_e is the focal length of the eyepiece.

Since D is approximately 25 cm, then,

$$M_e = \frac{25 \text{ cm}}{f_e}$$

The overall angular magnification M of a compound microscope is the product of the two magnifications: the lateral magnification of the objective lens and the angular magnification of the eyepiece.

That is;

$$M = m_o M_e$$

$$M = m_o M_e = \frac{L - f_e}{f_o} \times \frac{25\text{ cm}}{f_e}$$

To produce large magnification, f_e and f_o must be very small compared to L.

Therefore,

$$L - f_e \approx L.$$

$$M = m_o M_e = \frac{L - f_e}{f_o} \times \frac{25\text{ cm}}{f_e}$$

Hence, $M = \frac{25L}{f_o f_e}$

Note that; f_o, f_e and L are measured in centimetres (cm). This expression is used to determine the magnification produced by a compound microscope.

Task 6.3

Observe the image formed by a compound microscope, then state the nature of the formed image.

Example 6.2

A compound microscope consists of the objective lens and the eyepiece lens of focal length 12 cm and 4 cm, respectively. The two lenses are separated by a distance of 30 cm. The microscope is focused so that the image is formed at infinity. Determine the position of the object.

Solution

The final image is at infinity and two lenses are separated by the distance of 30 cm as shown in Figure 6.5.

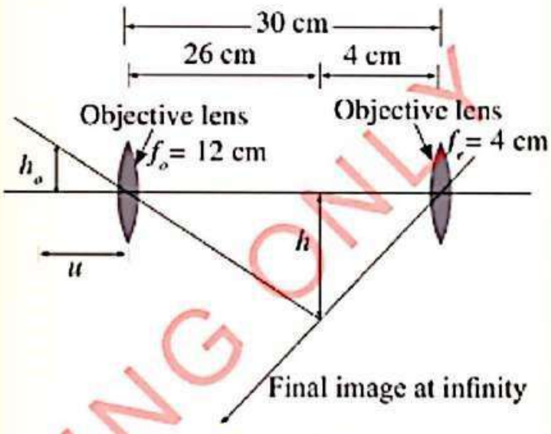


Figure 6.5

From

$$v = L - f_e;$$

$$v = 30\text{ cm} - 4\text{ cm}$$

$$= 26\text{ cm}$$

Using lens formula,

$$\frac{1}{f} = \frac{1}{u} + \frac{1}{v}; \quad \frac{1}{12} = \frac{1}{u} + \frac{1}{26}$$

$$\frac{1}{u} = \frac{1}{12\text{ cm}} - \frac{1}{26\text{ cm}};$$

$$\frac{1}{u} = \frac{26\text{ cm} - 12\text{ cm}}{312\text{ cm}^2}$$

$$\frac{1}{u} = \frac{14\text{ cm}}{312\text{ cm}^2}$$

$$u = 22.3\text{ cm}$$

Therefore, the object distance is 22.3 cm from the objective lens.

Uses of a compound microscope

Compound microscopes have a wide range of applications in different aspects of life. Some of the applications of compound microscopes include:

(a) Viewing laboratory small samples such as tissues and body fluids to check for infections caused by microorganisms;

(b) Studying micro-organisms and cells in Biology experiments; and

(c) Observing the Brownian motion of fluid particles. Figure 6.6 shows a student observing something using a compound microscope.

Figure 6.6: *Using a compound microscope*

Construction of a simple compound microscope

One can easily construct a simple optical compound microscope. Activity 6.1 illustrates the steps for constructing a simple compound microscope using local materials.

Activity 6.1

Aim: To construct a simple compound microscope

Materials: two convex lenses, hard manila sheets (coloured black), scissors, cutter, rubber disc, drill, a film canister or a small plastic container, plywood, a wooden stick

Procedure

1. Use the black manila sheets to construct two tubes with slightly different diameters such that the smaller tube can slide into the larger tube. Make sure each tube is longer than the focal length of your lens.
2. Fix a lens to one end of each tube.
3. Slide the small tube inside the larger tube such that you have one tube with a lens on both sides of the tube.
4. Cover each side of the tube with a rubber disc to protect the lenses.
5. Drill a hole at the bottom of a canister.
6. Insert the smaller tube into the open end of the canister to about half the length of the canister. Ensure that the lens coincides with the hole drilled on the canister.
7. Use a square piece of plywood or plastic to set your base. The square should have 10 cm sides. Attach a white sheet at the middle of the base to act as the stage.
8. Use a wooden stick to create a vertical stand. Make the stand 2 cm tall.

9. Attach your microscope to the stand and try to observe different small objects using your own microscope.

Question

What is the nature of images of different objects when viewed through your microscope?

The intermediate image formed by a compound microscope is real, inverted and magnified.

Exercise 6.2

1. (a) Draw a labelled ray diagram showing the formation of a final image by a compound microscope at the least distance of distinct vision.
   (b) A compound microscope has an objective lens of focal length 2 cm and eye piece of focal length 6 cm. An object is placed 2.4 cm from the objective lens. If the distance between the objective lens and eyepiece is 17 cm, find the distance of the final image from the eye piece.
2. The total magnification produced by a compound microscope is 20. The magnification produced by the eyepiece is 5. The microscope is focused on a certain object. The distance between the objective and eyepiece lens is 14 cm. If the least distance of distinct vision is 20 cm, calculate the focal length of the objective and the eyepiece lens.
3. Suppose you have lenses A and B having focal lengths 100 cm and 4 cm, respectively. If asked to choose one as an eyepiece, which one would you opt for, and why?
4. (a) Draw a labelled ray diagram of a compound microscope. Explain briefly its working principle.
   (b) In a compound microscope, why should the objective lens form an image at a point around the focal point of the eyepiece?

Astronomical telescope

The human eye has limitations when viewing objects that are very far from the observer. When the object is at a distance far from the point 2F of the eye lens, its image is formed at the focal point of the eye lens. However, this image is extremely small and sometimes cannot be decoded by the brain. How can this limitation be overcome? Astronomers use a device named an astronomical telescope to observe the universe and its components, which are extremely far from our eyes.

Structure of an astronomical telescope

Just like the compound microscope, an astronomical telescope uses two convex lenses: the objective lens and the eyepiece. It also consists of a focusing system for adjusting the sharpness and clarity of the image. However, unlike the compound microscope, the objective lens of a telescope has a large focal length while the eyepiece has a much shorter focal length.

Since the astronomical telescope uses a lens as its objective glass, it is also called a refracting telescope. Figure 6.7 shows some parts of the astronomical telescope.

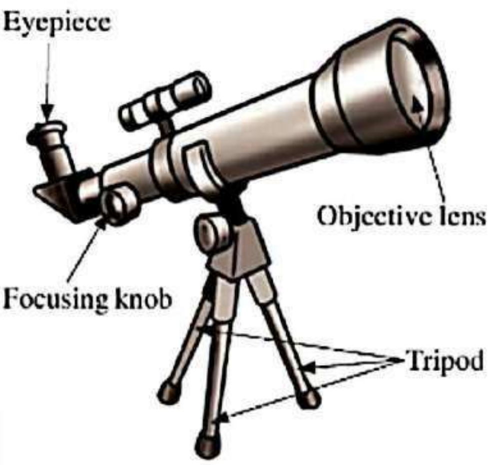


Figure 6.7: *Parts of an astronomical telescope*

Mode of action of an astronomical telescope

A telescope is used to provide angular magnification of distant objects. Light from a distant object enters the objective lens and a real image is formed in the tube at the second focal point of the objective lens. This image becomes the object for the eyepiece. The position of the eyepiece lens is adjusted until the image from the objective lens falls at the focal point of the eyepiece. The image of the eyepiece is inverted and magnified as illustrated in Figure 6.8. Note that the main considerations with an astronomical telescope are its light-gathering power and its resolution or resolving power. The light-gathering power depends on the area of the objective lens. The larger the diameter of the objective lens, the brighter the image observed. The resolving power, which is the ability to observe two close objects distinctly, also depends on the diameter of the objective lens. So, the desire is to make astronomical telescopes with an objective lens of larger diameter. Nevertheless, lenses with big diameters tend to be very heavy and therefore, difficult to make and to be supported by their edges. Further, it is rather difficult and expensive to make such large-sized lenses that may form images that are free from any kind of distortions.

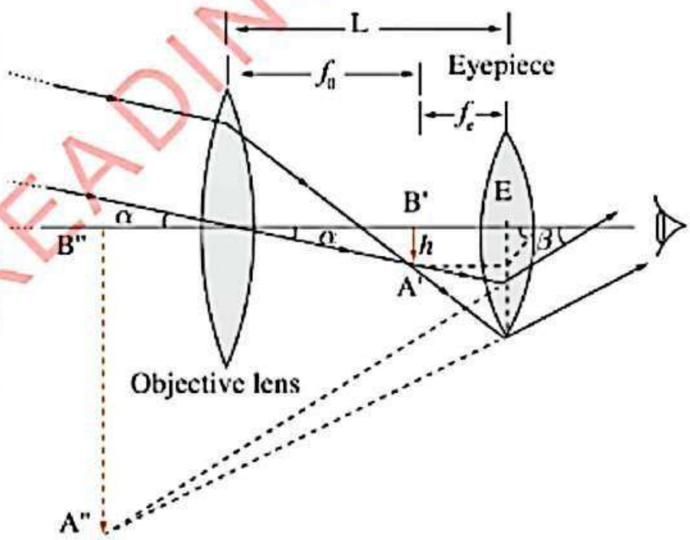


Figure 6.8: *Image formation by an astronomical telescope*

Magnification of an astronomical telescope

The magnifying power, m, of the astronomical telescope is given by the ratio of the angle β subtended by the final image at the eye and the angle α subtended by the object at the objective lens. That is; $m = \frac{\beta}{\alpha}$

Assuming that the angles are very small, we have,

$$\tan\alpha \approx \alpha \text{ and } \tan\beta \approx \beta$$

The angle subtended by the object at the objective lens is the same as the angle subtended by the first image at the objective lens. Thus, $\tan\beta \approx \beta = \frac{h}{f_e}$

Similarly, the angle subtended by the final image at the eye is the same as the angle that a ray coming from the head of first image and travelling parallel to the principal axis makes with the principal axis after it passes through the lens. Then,

$$\tan\beta \approx \beta = \frac{h}{f_e}.$$

Thus,

$$m = \frac{h}{f_e} \times \frac{f_o}{h} = \frac{f_o}{f_e}.$$

Therefore, the magnification produced by an astronomical telescope is the ratio of the focal length of the objective lens to that of the eyepiece lens. Note that the distance between the two lenses,

$$L = f_e + f_o$$

Example 6.3

Find the magnification of a telescope with an objective lens whose focal length is 100 cm and an eyepiece lens whose focal length is 2 cm.

Solution

$$m = \frac{f_o}{f_e}$$

$$m = \frac{100\text{ cm}}{2\text{ cm}} = 50$$

Uses of an astronomical telescope

A telescope is used to view distant objects such as stars and planets. It is one of the primary tools in the fields of astronomy and astrophysics.

Construction of a simple astronomical telescope

One can easily construct a simple astronomical telescope using locally available materials.

Activity 6.2

Aim: Construct a simple astronomical telescope using materials that are available in your surroundings

Materials: two convex lenses of different focal lengths, hard manila sheets, scissors, tape or glue

Procedure

1. Measure the focal length of each lens by focusing sunlight onto a paper and measuring the distance to the sharpest point.
2. Use the black manila sheets to construct two tubes with slightly different diameters such that the smaller tube can slide into the larger tube. Make sure each tube is longer than the focal length of your lens.
3. Paint the inside of both tubes black or line them with black paper to reduce internal reflections of light.
4. Fix the objective lens securely at one end of the larger tube using tape or glue.

5. Fix the eyepiece lens securely at one end of the smaller tube using tape or glue.
6. Insert the smaller tube with the eyepiece into the larger tube with the objective lens as in Figure 6.9.

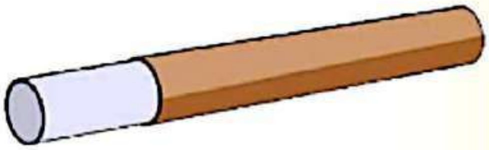


Figure 6.9

7. Adjust the length between the lenses to about the sum of their focal lengths ($f_1 + f_2$) to focus the image.
8. Use your telescope to observe distant objects like the moon or buildings, and record your observations.

Questions

1. What did you observe when looking through your telescope? Was the image upside down?
2. How did adjusting the distance between the lenses affect the focus and clarity of the image?
3. What challenges did you face during the construction of the telescope, and how did you solve them?
4. How could you improve your telescope to increase magnification or image clarity?

Exercise 6.3

1. An astronomical telescope in normal adjustment has a total length of 78 cm and produces an angular magnification of 15. What is the focal length of the objective and eyepiece lens?
2. An astronomical telescope has its two lenses 78.0 cm apart. If the objective lens of the telescope has a focal length of 75.5 cm, what is the magnification produced by the telescope?
3. A homemade telescope has an objective lens of focal length 140 cm and an eyepiece of focal length 4 cm. What is the magnifying power of this telescope? Determine the separation distance between the objective lens and the eyepiece.
4. How would the magnification of an astronomical telescope be affected if the focal length of the eyepiece and the objective lens are increased?
5. An observatory telescope has an objective lens of focal length 14 m. Suppose an eyepiece of focal length 2 cm is used,
   (a) What is the angular magnification of the telescope?
   (b) If this telescope is used to view the moon, what is the diameter of the moon's image formed by the objective lens? The diameter of the moon is 3.48×10^6 m and the radius of the lunar orbit is 3.8×10^8 m.

Binoculars

When you visit a national park, you cannot get very close to dangerous animals, such as lions and leopards, for safety reasons. To closely watch such animals, one needs to use a device that can help the eye see distant objects closely. An optical device used in such a situation is called binoculars.

Structure of binoculars

Binoculars can be considered as having two telescopes that are exactly the same and placed beside each other, such that they accurately point in the same direction. This allows the observer to use both eyes when looking at distant objects. The main components of binoculars are the eyepiece, the objective lens and prisms. The objective lens focuses a distant object to a point near the focal point of the eyepiece, which magnifies that image. A pair of prisms inverts the image so that it can be seen properly upright by the eyes. Other parts are the focusing system, which allows the lenses to be moved back and forth. Figure 6.10 shows some parts of binoculars.

Figure 6.10: *Parts of binoculars*

Mode of action of binoculars

Two objective lenses are situated at the ends of both telescopes making the binoculars. The purpose of the objective lens is to collect light from the object that the user is looking at and form the image of the object at or near the focal point of the eyepiece. The eyepiece can be thought of as a magnifying glass. It picks up the small image formed by the objective lens and magnifies it so that the observer can clearly see the object. However, when light is refracted through the objective, the light rays cross over, resulting in an upside-down image. The eyepiece simply magnifies this image so that the viewer sees the object upside down. This problem can be solved by deploying a pair of prisms. These prisms are essentially used to rotate and reflect the image using the principle of total internal reflection. To rotate the image 180 degrees, prisms are arranged in a way that each prism effectively rotates the image 90 degrees. Normally, two types of prisms are used in binoculars: roof prisms and porro prisms. Figure 6.11 shows how image inversion is achieved in binoculars.

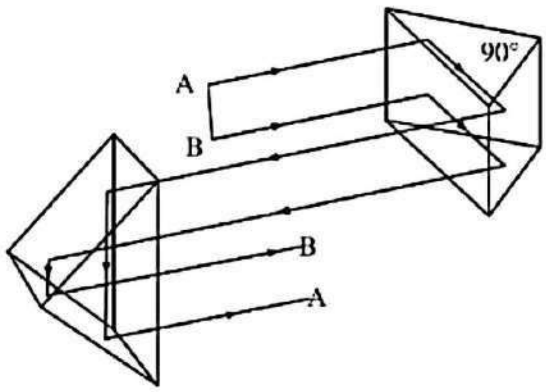


Figure 6.11: *Image inversion by prisms*

Magnification of binoculars

Since binoculars are made of two identical refracting telescopes, the magnifying power of the binoculars can be calculated as in the case of the astronomical telescope.

That is; $m = \frac{f_o}{f_e}$

where, f_o is the focal length of the objective lens and f_e is the focal length of the eyepiece. The quality of images formed by binoculars is determined by the magnification power and the size of the objective lens. While the magnifying power affects the size of the image, the size of the objective lens affects the clarity and details of the image. Commercial binoculars are normally imprinted with information about the objective lens size and the magnification power.

Example 6.4

A pair of binoculars, acting as a telescope, produces an angular magnification of 7.5. What is the eyepiece's focal length if the binoculars have an objective lens of a focal length of 75.0 cm?

Solution

$$m = \frac{f_o}{f_e}$$

$$f_e = \frac{75.0 \text{ cm}}{7.5} = 10 \text{ cm}$$

Uses of binoculars

Being able to focus on distant objects, binoculars are used in various activities that require the observer to view distant objects in detail. For example, binoculars are commonly used by tourists to view animals. Also, soldiers use binoculars to view the enemy camp from a far point. Likewise, surveyors use binoculars to survey and observe the landscape and other features.

Construction of a simple pair of *binoculars*

A simple pair of binoculars can be constructed using locally available materials.

Task 6.4

Use the locally available materials to design and construct a simple pair of binoculars and use them to view various distant objects. Discuss with your class members, factors which may affect the performance of your binoculars.

Lens camera

The camera is one of the optical instruments that have been used since the discovery of lenses. The word camera is a Latin word that means "a room or enclosure". Thus, the primary component of a camera is the light-tight enclosure or box. A camera is made up of different components contained inside the light tight box. Depending on the components, cameras may take many forms, including film cameras, digital cameras and video cameras. In this section, we discuss the simplest form of a camera, which is known as a lens camera.

Structure of a lens camera

Major components of a lens camera include a biconvex lens, a film, a diaphragm, a shutter and a mounting base. Figure 6.12 shows some parts of a lens camera.

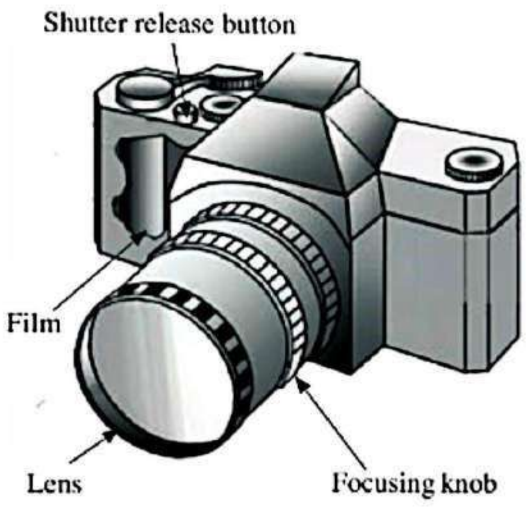


Figure 6.12: *Parts of a lens camera*

The lens is the image-forming device in a camera. The focal length of a lens determines the size of the image that will be formed on the film. Therefore, four basic categories of lenses exist.

These are:

(a) Normal lens which allows the viewing field of approximately 50 degrees, giving a picture that is normal in size relative to the background and which looks natural to the viewer.

(b) Wide angle lens which enables a view of 90 degrees and is used when smaller objects are to be photographed.

(c) Telephoto lens or long-focus lens which has a wider field of view than the normal lens. It shows enlarged detail of the image over the same film area. The telephoto lens has a long reach, allowing you to capture an object that is far away. You have probably seen a photograph where an object is in focus but the background is blurred; this is often done with a telephoto lens.

(d) Interchangeable lens which offers the photographer the opportunity to select a focal length that is best for a given situation. In recent years, variable focal length or "zoom" lenses have become very popular.

The diaphragm determines the amount of light that passes through the lens by changing the size of the aperture. The aperture is an opening whose diameter is adjustable. The size of the aperture is measured in f-number; the larger the number the smaller the aperture. Most cameras use an iris-type diaphragm, which consists of a number of very thin metal blades. They are mounted so that the size of the lens opening can be changed by a rotating ring or a moving lever.

The shutter is a mechanical device that acts as a gate, controlling the duration of time that light is allowed to pass through the lens and fall on the film.

A film is a light-sensitive surface of the camera. It is normally rolled to the back of the camera. In most cameras, the film is wound up on a spool with an interleaving light-tight backing paper. However, in a digital camera, an electronic detector called a charge-coupled device (CCD) array is used instead of a film. The digital information is stored on a memory chip for play back on the screen of the camera.

Mode of action of a lens camera

To take a photograph of an object, the image of the object must be sharply focused on the film. This is done by adjusting the distance of the lens from the film. After focusing and correctly setting the aperture size and shutter time, the shutter release button is pressed. The shutter opens to allow light to enter and expose the film to form an image of the object being photographed. The film is then developed to produce a photograph of the object. Figure 6.13 illustrates the image formation by a lens camera.

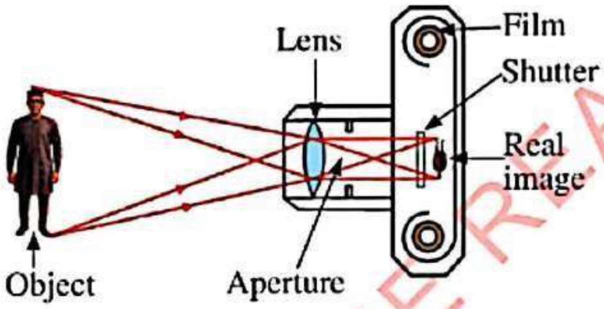


Figure 6.13: *Image formation by a lens camera*

Magnification of a lens camera

The magnification produced by a lens camera is given as;

$$m = \frac{\textit{image height } (h_i)}{\textit{object height } (h_o)} = \frac{\text{image distance } (v)}{\text{object distance } (u)}$$

Recalling the lens formula,

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

This can also be written as,

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

and so,

$$v = \frac{uf}{u-f}$$

then,

$$m = \frac{v}{u} = \frac{uf}{u-f} \times \frac{1}{u} = \frac{f}{u-f}$$

Hence, $m = \frac{f}{u-f}$.

Therefore, magnification produced by the lens camera depends on the focal length f of the convex lens used and the object distance u.

Example 6.5

A lens camera of focal length 10 cm is used to take a picture of a girl 1.5 m tall. Determine the magnification of the image if the girl is 11 m from the camera.

Solution

$f = 10 \text{ cm} = 0.1 \text{ m}, \; u = 11 \text{ m}$

but

$$m = \frac{f}{u-f}$$

$$m = \frac{0.1 \text{ m}}{11 \text{ m} - 0.1 \text{ m}}$$

$$= 0.009$$

Therefore, the image is reduced by a factor of 0.009.

Construction of a simple lens camera

A simple lens camera can easily be constructed using local materials, including the lens from unused optical instruments. Perform task 6.5 to construct your lens camera.

Task 6.5

Using locally available materials, design and construct and test a simple lens camera.

Uses of cameras

The main function of a camera is to take photographs. However, specialised cameras have other additional functions as follows:

(a) Video cameras are used to take motion pictures. Figure 6.14 shows a video camera.

Figure 6.14: *A video camera*

(b) Closed-circuit television (CCTV) cameras are used for surveillance in high-security installations, banks, shopping malls, offices and residences. Figure 6.15 shows an example of a CCTV security camera.

Figure 6.15: *Closed-circuit television (CCTV) camera*

(c) Digital cameras are used to capture images that can be fed into computers. An example of a digital camera is shown in Figure 6.16.

Figure 6.16: *A digital camera*

Exercise 6.4

1. A photographer used a camera fitted with a lens having a focal length of 50 mm to take a photograph of a flower that is 5 cm in diameter. Suppose the flower is placed 20 cm in front of the camera lens.
   (a) At what distance from the film should the lens be adjusted to obtain a sharp image?
   (b) What would the diameter of the image of the flower on the film be?
   (c) What is the nature of the lens of this camera?
2. You are standing at a point 1.2 m in front of a plane mirror while

holding a camera. If you wish to take a picture of your own image, at what distance should you focus your camera?

3. A lens camera is used to photograph a person who is 2.8 m tall and standing 2.7 m in front of the camera. If the film is placed 10 cm behind the lens, calculate the height of the produced image.

The human eye

The human eye is a natural optical instrument that is exceptionally important for human life. It belongs to a general group of eyes found in nature called "camera-type eyes" since the optical behaviour of the eye is similar to that of a lens camera. The human eye can respond to a range of light frequencies. The human eye looks whitish with a central black spot as seen in Figure 6.17.

Figure 6.17: *The human eye*

Structure of the human eye

The eye is nearly spherical and is about 2.5 cm in diameter. The front portion is somehow more sharply curved and is covered by a tough, transparent membrane called the cornea. The region behind the cornea contains a liquid called aqueous humour. Next to the aqueous humour, there is a crystalline lens, which is a capsule containing a fibrous jelly, hard at the centre and progressively softer at the outer portions. The crystalline lens is held in place by ligaments that attach it to the ciliary muscles which encircle the lens. In front of the lens, there is an aperture with a variable diameter known as the pupil.

The pupil's size is controlled by the iris, which is attached to the ciliary muscles. The iris is responsible for the colour of the eye. It acts as the diaphragm in a lens camera. Behind the lens, the eye is filled with a thin watery jelly called the vitreous humour. This jelly helps to focus the rays of light and also maintains the shape of the eye. After the vitreous humor, there is a lining on the rear inner surface of the eye called the retina. The retina hosts some photosensitive cells known as cones and rods which respond to the light falling on them. Cones and rods are connected to millions of nerves which are later joined together to form the optic nerve. The eye is protected by a tough whitish skin known as the sclera. Figure 6.18 shows parts of the human eye.

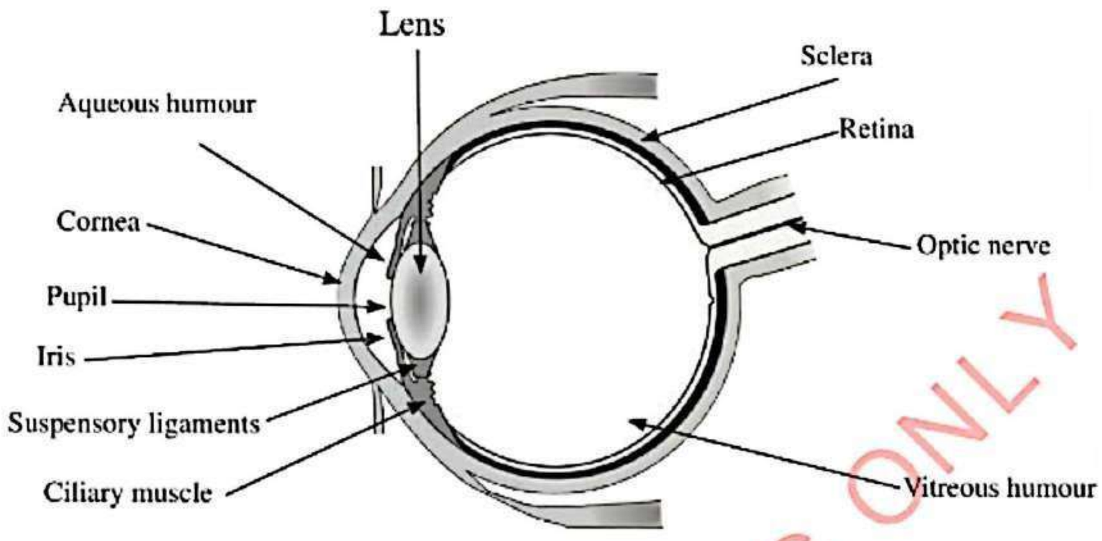


Figure 6.18: *Parts of a human eye*

Images formed by the human eye

When light strikes the eye, it passes through the cornea. The cornea is shaped like a dome, so it bends the light to help the eye focus. The light through the cornea and the aqueous humour enters the eye through the pupil. The iris controls the size of the pupil, which in turn determines the amount of light that enters the eye. Next, light passes through the lens. The lens works together with the cornea to focus light correctly on the retina. Light from the lens travels through the vitreous humor towards the retina. The image is formed on the retina as illustrated in Figure 6.19. When light hits the retina to form the image, the photoreceptors on the retina turn the light into electrical signals, which travel to the brain through the optic nerve.

The indices of refraction of both the aqueous humour and the vitreous humour are about 1.336, which is nearly equal to that of water. The crystalline lens, while not homogeneous, has an average index of refraction of 1.437. This is not very different from the indices of the aqueous and vitreous humour. As a result, most of the refraction of light entering the eye occurs at the outer surface of the cornea, as shown in Figure 6.19.

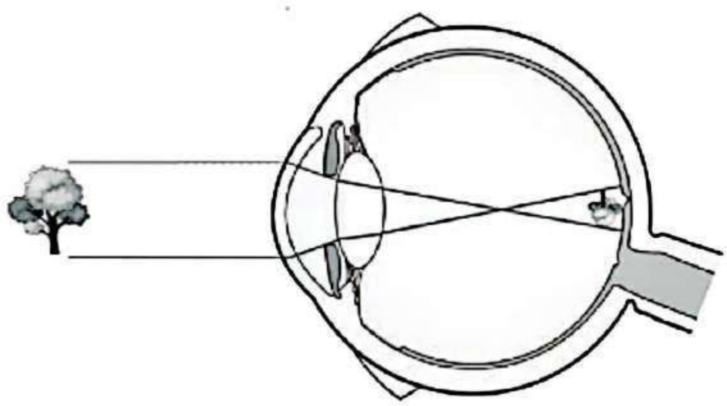
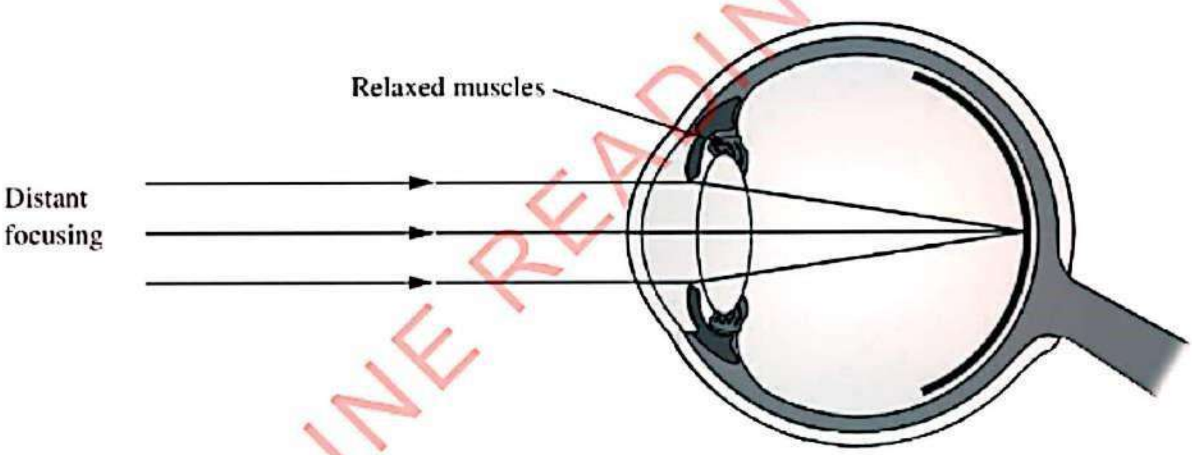


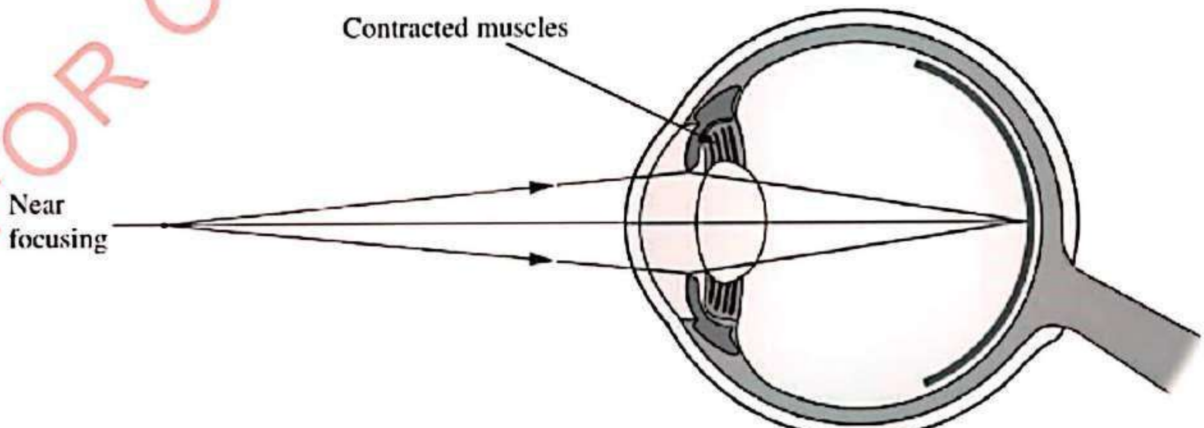
Figure 6.19: *Image formation by the human eye*

Accommodation of the human eye

For an object to be seen sharply, the image must be formed exactly at the location of the retina. The eye adjusts to different object distances *u* by changing the focal length *f* of its lens. This is because the lens-to-retina distance, corresponding to *v*, does not change. However, this is different from the lens camera in which the focal length is fixed and the lens-to-sensor distance is changed. For the normal eye, a distant object is sharply focused when the ciliary muscles are relaxed. This causes the curvature of the lens to decrease, thereby increasing its focal length (Figure 6.20(a)). To focus sharply on a closer object, the tension in the ciliary muscle increases, causing the ciliary muscle to contract. This causes the lens to bulge, resulting in the increase of its curvature and decrease of its focal length (Figure 6.20(b)). The process by which the eye focuses on objects at different distances by varying the focal length of the lens is called accommodation.



(a)



(b)

Figure 6.20: *Focusing distant and near objects*

The extremes of the range over which distinct vision is possible are known as the far point and the near point of the eye. The far point of a normal eye is the maximum distance at which the light from the object can still be focused onto the retina. The near point is the shortest distance from the eye at which the light from the object can be focused onto the retina. The eye tends to be blind when the object is closer to the eye than the near point. The position of the near point depends on the amount by which the ciliary muscle can increase or decrease the curvature of the crystalline lens. The range of accommodation gradually diminishes with age because the crystalline lens grows throughout a person's life, and the ciliary muscles become less capable of distorting a larger lens. For this reason, the near point gradually recedes as one grows older. The recession of the near point is a condition called presbyopia.

Activity 6.3

Aim: To determine far and near points of the eye

Materials: manila paper, sellotape

Procedure

1. Draw a vertical line about 50 cm long on a sheet of manila paper.
2. Stick the paper on the wall.
3. Stand about 2 m from the wall and cover one of your eyes with your hand.
4. Cover the line by bringing the index finger of your other hand close to your face.
5. Without moving your finger, switch to the other eye.
6. Now move to about 4 m from the wall and repeat the process.
7. Move as far as possible from the wall and repeat steps 3-5. Record all your observations.

Question

Explain the appearance of the line at each of the distances.

Defects of the human eye

For an object to be seen by the human eye, light from the object must be focused on the retina. However, there are cases when light from the object cannot be focused on the retina. This arises mainly from incorrect distance relationships in the eye. A normal eye can form an image on the retina for an object at infinity when the ciliary muscles are relaxed, and for a nearby object when the ciliary muscles are contracted, as illustrated in Figure 6.20. In some cases, the size of the eyeball is defective, leading to conditions known as short-sightedness (myopia) and far-sightedness (hyperopia).

Short-sightedness (myopia)

In the myopic (short-sightedness or near-sightedness) eye, the eyeball is too long from front to back in comparison with the radius of curvature of the cornea (or the cornea is too sharply curved). This causes the rays of light from an object at infinity to be focused in front of the retina. The most distant object for which an image can be formed on the retina is then nearer than infinity. Therefore, a person suffering from short-sightedness can see nearby objects clearly but not distant objects. Figure 6.21 illustrates a myopic eye.

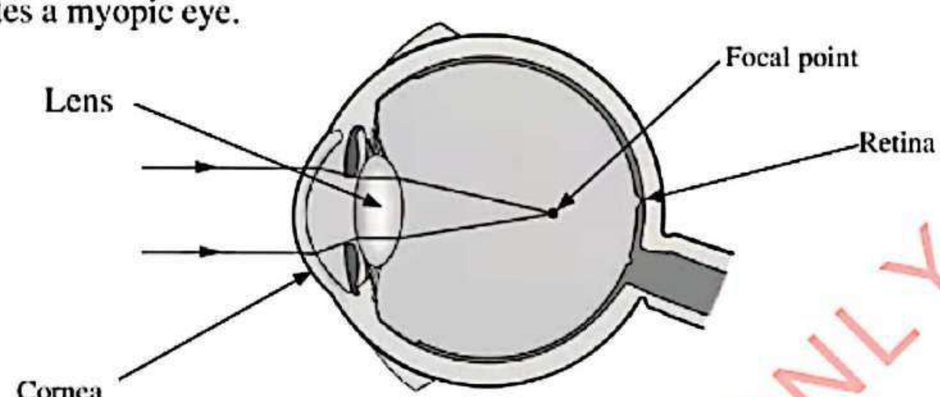


Figure 6.21: *Myopia*

Correction of myopia

To correct myopia, rays of light from a distant object should be diverged before entering the eye. Therefore, correcting the myopic eye involves the use of a concave (diverging) lens, which forms the image of a distant object close to the eye lens. The image formed by the glass lens is then focused onto the retina by the eye lens. Figure 6.22 illustrates the correction of a myopic eye.

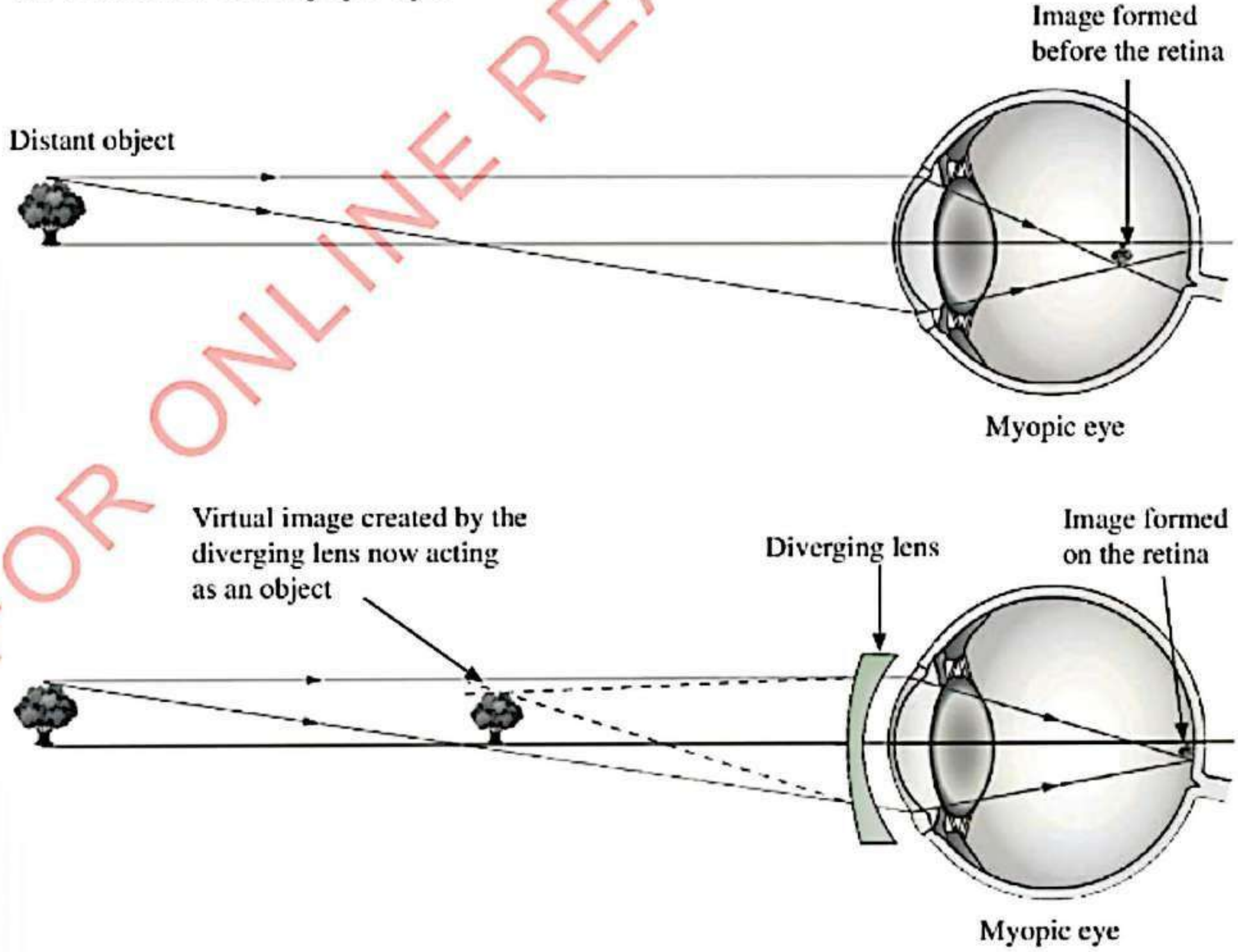


Figure 6.22: *Correcting a myopic eye*

Note that lenses used for vision correction are usually described in terms of lens power, P, which is given by the reciprocal focal length expressed in metres. Hence,

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

The unit of lens power is the dioptre, D. Thus, a lens with $f = 0.50$ m has a power of 2.0 D, $f = 0.250$ m corresponds to 4.0 D, and so on. The numbers used for the prescription of the glass lenses are usually powers expressed in diopters.

Long-sightedness (hyperopia)

In the hyperopic (long-sightedness or far-sightedness) eye, the eyeball is too short or the cornea is not curved enough. This causes the rays of light from a near object to be focused behind the retina. A person suffering from long sightedness can see distant objects clearly, but cannot see nearby objects clearly. The near point of the eye may be more than a metre away, making ordinary reading difficult. Figure 6.23 illustrates the hyperopic eyes.

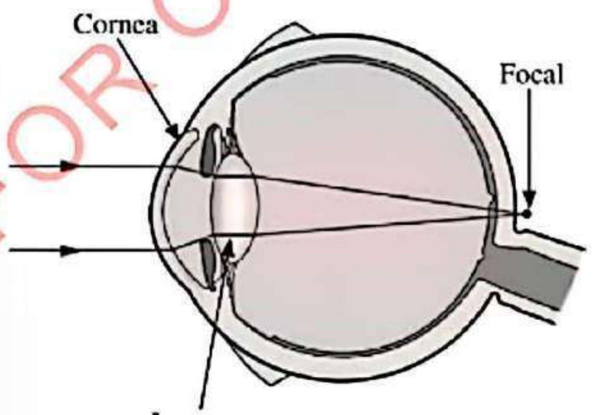


Figure 6.23: *Hyperopia*

Note that the myopic eye produces too much convergence of light rays from a distant object, while a hyperopic eye produces insufficient convergence of rays of light from a near object.

Presbyopia

Presbyopia is the gradual loss of the eye's ability to focus on nearby objects because of old age. The term "presbyopia" comes from a Greek word that means "old eye." This defect is normally observed after the age of 40 years. Presbyopia is caused by loss of eye lens flexibility, which is necessary to change its focal length in order to focus on objects. This results in insufficient accommodation, leading to image formation behind the retina, as shown in Figure 6.24.

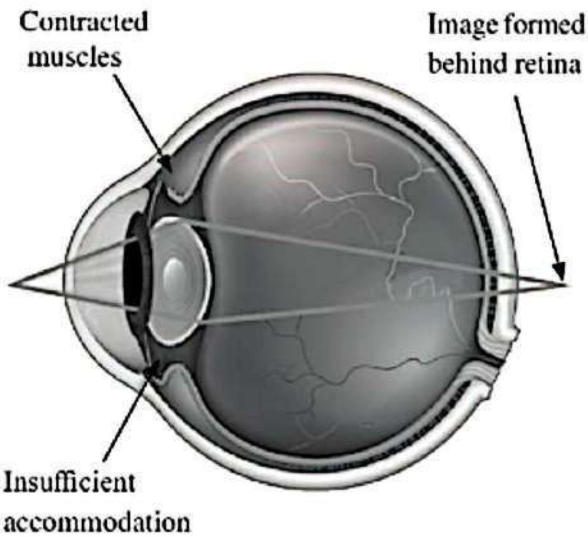


Figure 6.24: *Presbyopic eye*

Correction of hyperopia and presbyopia

In the case of either a presbyopic or a hyperopic eye, the near point is farther from the eye than normal. Therefore, to see clearly an object at a normal reading distance, which is about 25 cm, a convex lens is required to form a virtual image at or beyond the near point. The lens converges the rays of light from a near object to form the image at or beyond the near point. The eye lens then focuses the image of the glass lens onto the retina. Figure 6.25 shows the correction of the hyperopic or presbyopic eye.

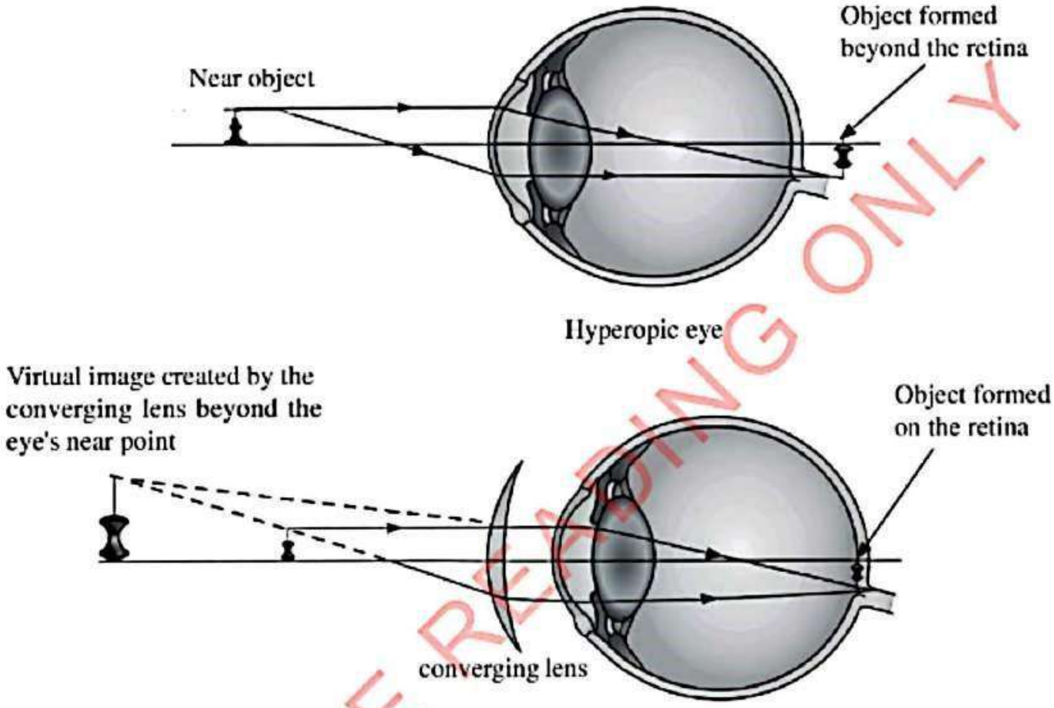


Figure 6.25: *Correction of the hyperopic eye*

Astigmatism

Astigmatism is the imperfection in the curvature of the eye that causes the formation of blurred images on the retina. It occurs when either the cornea or the lens has mismatched curves. That is, instead of having a curve like a ground ball, the surface is egg-shaped. This causes the lens to have different focal points when looking at the same object. Consequently, rays of light from the object are focused at different points, leading to image formation at different positions on the retina. The result is blurred vision. Figure 6.26 illustrates astigmatism. Astigmatism is often present at birth and may occur in combination with near-sightedness or far-sightedness.

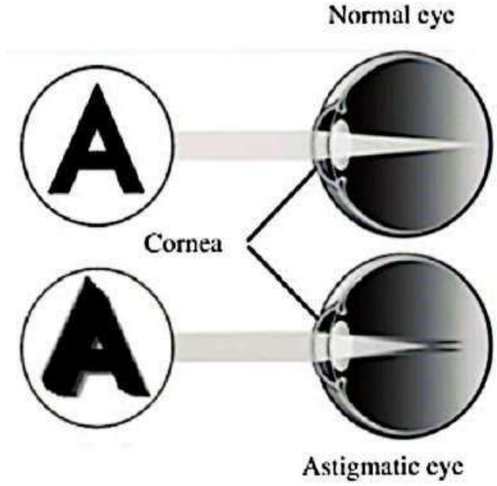


Figure 6.26: *Astigmatism*

Astigmatism can be corrected by either using corrective lenses or performing eye surgery.

Example 6.6

The far point of a myopic eye person is 50 cm in front of the eye. What is the nature and power of the lens required to correct the problem?

Solution

The nature of the lens should be a concave lens (diverging lens). A concave lens makes the objects at infinity appear at the far point.

For the object at infinity, $u = \infty$, the far point of the defective eye, $v = -50$ cm.

By the lens formula:

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

$$= \frac{1}{-50 \text{ cm}} + \frac{1}{\infty} = \frac{1}{-50 \text{ cm}}$$

$$f = -50 \text{ cm} = -0.5 \text{ m}$$

Therefore, power

$$= \frac{1}{f} = \frac{1}{-0.5 \text{ m}} = -2.0 \text{ D}.$$

Comparison between the lens camera and the human eye

The lens camera has many similarities with the human eye. Table 6.1 shows the differences and similarities between the lens camera and the human eye.

Table 6.1: Similarities and differences between the lens camera and the human eye

Criteria	Lens camera	Human eye
Lens	Uses convex lens	Uses convex lens
Image	The image is real, reduced and inverted	The image is real, reduced and inverted
Light control	The amount of light entering the camera is controlled by the diaphragm	The amount of light entering the eye is controlled by the pupil
Image point	The image is formed on a special film	The image is formed on the retina
Focusing	Focusing is done by altering the distance between the lens and the film	Focusing is done by altering the shape of the lens which alters its focal length
Image processing	The image is processed chemically in a process called "Developing"	The image is converted to electrical signals that travel through the optic nerve to the brain for processing

Exercise 6.5

1. The distance from the cornea to the retina of someone's eye is 2.1 cm. Determine the effective focal length of this eye if an object is,
   (a) At infinity.
   (b) Located 1 m away.
   (c) Located 25 cm away.
2. A far-sighted eye can only focus on objects beyond 100 cm. What focal length and power of the contact lens are needed to correct this problem?
3. A near-sighted eye can only focus on objects closer than 50.0 cm. What sort of contact lens will correct this problem? Determine its power.
4. (a) Differentiate between magnifying power and magnification of a lens.
   (b) A near point of a long-sighted patient is 90 cm. Determine:
      (i) the focal length of a lens that can be used to enable the patient to see an object which is at a distance of 25 cm from the patient's eye
      (ii) the power of the patient's eye
      (iii) the magnification of the patient's eye lens
5. A student finds the writing on the blackboard to be blurred and unclear when seated at the back desk of the classroom. However, he sees clearly when sitting at the front desk, approximately 2 metres from the blackboard.
   (a) Draw the ray diagram to illustrate how the image of the blackboard writing is formed by his eye lens when he is seated at the:
      (i) last desk
      (ii) front desk
   (b) Name the defect of vision the student is suffering from. Also, list two causes of this defect.
   (c) Name the kind of lens that would enable him to see clearly when he is seated at the last desk. Draw the ray diagram to illustrate how this lens helps him to see clearly.

Chapter summary

1. Optical instruments use refraction or reflection of light to form different types of images.
2. Microscopes make it possible to see very small objects by producing an enlarged image of an object.
3. Telescopes and binoculars allow us to see objects that are far away.
4. Cameras provide us with a recorded image of an object. The image can be a still image or a moving image (video).
5. The human eye can discern colour, judge distance and see great detail from both near and far positions by adjusting the focal length of its lens.
6. Myopia is a condition in which close objects appear clearly, but far ones

do not. This is because the image is formed in front of the retina.

7. Hyperopia is a condition in which images of nearby objects are blurry, whereby the image is formed behind the retina.
8. Presbyopia is the gradual loss of the eye's ability to focus on nearby objects, and it occurs because of old age.
9. Astigmatism is the imperfection in the curvature of the eye that causes the formation of blurred images. It occurs when either the cornea or the lens has mismatched curves.

Revision Exercise 6

1. Choose the correct answer from the given alternatives.
   (i) The part of the human eye that corresponds to the film in a camera is the ________.
   (a) iris (c) retina
   (b) pupil (d) cornea
   (ii) In the astronomical telescope, f_o is the focal length of the objective lens and f_e is the focal length of the eyepiece lens. For greater magnification, f_o should be ____.
   (a) much larger than f_e
   (b) equal to f_e
   (c) slightly smaller than f_e
   (d) much smaller than f_e
   (iii) Which of the following statements is not the reason why a microscope has an objective lens of short focal length?
   (a) It allows more light to be collected.
   (b) It keeps the distance between the objective lens and the eyepiece lens small.
   (c) It gives the microscope more magnifying power.
   (d) It makes the image formed to be inverted.
   (iv) Which of the following combinations of lenses can be used on a compound microscope?

	Objective lens	Eyepiece lens
(a)	Long-focus converging lens	Short-focus converging lens
(b)	Long-focus converging lens	Short-focus diverging lens
(c)	Long-focus converging lens	Long-focus converging lens
(d)	Short-focus converging lens	Long-focus converging

2. (a) A student sitting at the back of the classroom cannot read the letters written on the blackboard clearly. What advice will a doctor give him? Draw a ray diagram for the correction of this defect

(b) A person needs a lens of power – 4.5 D for the correction of his vision.
   (i) What kind of defect in vision is he suffering?
   (ii) What is the focal length of the collective lens?
   (iii) What is the nature of the corrective lens?

3. Read the passage carefully and answer the following questions given below.

   The diameter of the eyeball is about 2.3 cm, and a normal eye can adjust the focal length of its eye lens to see objects situated anywhere from 25 cm to an infinite distance away from it.

   (a) What is the power of the (normal) eye lens when the ciliary muscles are fully relaxed?
   (b) What is the power of the (normal) eye lens when the ciliary muscles are in their maximum contract position?
   (c) What is the maximum variation in the power of the lens when it adjusts itself from the normal relaxed position to the position where one can see the nearby object clearly?

4. An astronomer wants to order a large concave mirror for a telescope that will produce high-quality images. Explain and advise whether the astronomer should order a spherical mirror or a parabolic mirror.

5. An astronomical telescope is used to view an object at infinity and has an objective lens with a focal length of 15.0 cm. Where must the eyepiece of focal length 0.5 cm be placed to form an image at infinity? What is the total angular magnification?

6. In a particular compound microscope, the objective lens and eyepiece lens are 15 cm apart. The focal length of the objective lens is 2.0 cm, while that of the eyepiece lens is 6.25 cm.
   (a) How far from the objective lens should an object be placed in order to obtain the final image of a distant vision?
   (b) What is the total magnifying power of the microscope?

7. Explain the meaning of the following terms as used in optical instruments.
   (i) Magnifying power
   (j) Accommodation

8. Why are prism binoculars preferred over traditional ones?

9. (a) Explain how the image of an object is formed in the human eye.
   (b) Give two defects of the human eye and explain how they can be corrected.
   (c) Describe two ways in which a lens camera and the human eye are similar.
   (d) Describe two ways in which a lens camera and the human eye are different.

10. The objective and eyepiece of a compound microscope are 24 cm apart. Suppose the focal lengths of the objective and the eyepiece are 3 cm and 9 cm, respectively.
   (i) Where must a specimen be located to produce a final virtual image at infinity?

(ii) What could be the total magnification of this microscope? (Assume a microscope is used by a person whose nearest distance for a distinct vision is 25 cm).

11. The far point of a certain myopic eye is 50 cm in front of the eye. An eyeglass lens is to be worn to correct this myopic eye. If the glass lens is worn 2 cm in front of the eye, find:
    (a) The focal length of the lens will help the wearer clearly see an object at infinity.
    (b) The power of the lens.

12. (a) A 1.8 m tall student stands 2.5 m in front of a digital camera with a converging lens whose focal length is 0.05 m.
    (b) Find the image distance and state whether the image is real or virtual.
    (c) Determine the magnification and height of the image.

13. Two students complain that they cannot see objects that are closer than 1 m from their eyes.
    (a) What problem do they have? Describe it using a neat ray diagram.
    (b) How can their problem be solved?
    (c) Determine the power of the device that can be used to solve their problem

Answers to numerical questions

Chapter One

Exercise 1.2

1. 1.5×10^{-9}C

3. 12 V

4. 60 F

Exercise 1.3

1. 2.5×10^{-2}C
2. 2.5 mC
3. 2.73μF
4. (a) 1 μF (b) 11 μF

Revision Exercise 1

13. (a) 2.7×10^{-10} C or 0.27 nC
(b) 4.32 nC

15. (a) 0.9 μF (b) 2.7×10^{-6} C

Chapter Two

Exercise 2.1

3. (b) 28Ω (c) 8Ω

4 (b) 3Ω (c) 2Ω

Exercise 2.2

1. 6.4 Ω
2. 5.5×10^{-7} Ωm
3. (a) 5.5 Ω (b) 2.18 A
4. (c) 8.73 V
5. (a) 2.0 Ω, (b) 1.5 V
6. 3.64 V
7. 40 Ω

Exercise 2.3

1. 6.0 Ω
2. (a) 3.33 A, 4.17 A
(b) 3.6Ω, 2.88Ω
3. (a) 757.58 A
(b) 8.64×10^{12} J, 2.4×10^{6} kWh
4. (a) 1 200 W,
(b) 2.16×10^{7} J, 6 kWh
5. 1.05 kWh
6. (a) 0.25 A (b) 960 Ω
7. (b) 3Ω
(c) (i) 0.099Ω (ii) 121.2 A
(d) 5.94 V

Exercise 2.4

2. (a) 1.6 A

Exercise 2.5

5. 1.67 A
6. 0.543 A

Revision Exercise 2

1.

a	b	c	d
(iv)	(iii)	(iii)	(iv)

3. $6 \times 10^{-7}\ \Omega m$

4. 15Ω

5. 1.44×10^{-18} J

6. (a) 1.6 A (b) 46.08 kJ

7. (b) (i) 4 V (ii) 8 V (c) 2 A

8. (a) (i) 12 V (ii) 12 V
   (b) (i) 6 A (ii) 3 A (c) 9 A

10. (a) $8.87\times10^{-3}\Omega$

11. (a) 32Ω (b) 4.5 W
    (c) 1.41 W (d) 0.28 W

13. (a) 10Ω (b) 2.4 A
    (c) 1.2 A (d) 1.2 A
    (e) 12 V

14. (a) 4.62Ω (b) 3.25 A
    (c) 1.5 A, 1.0 A, 0.75 A
    (d) 49 W
    (e) 22.5 W, 15 W, 11.25 W

Chapter Three

Revision Exercise 3

14. (a) No
    (b) Yes, 0.75 m from P

Chapter Four

Exercise 4.2

3. 0.25 m/s, 0.5 m/s
4. 70°, 140°
5. 120 cm
6. 7

Exercise 4.3

2. $v = 15$ cm, $h_i = 3$ cm
3. $f = 30$ cm
4. $f = 6$ cm, $v = -15$, $h_i = -6$ cm
5. $v = 30$ cm, $m = -1$,

Revision Exercise 4

3. (a) concave mirror
   (b) 100 cm (c) 25 cm
4. (a) concave mirror
   (b) 4 (c) 60 cm
8. (a) 36 cm (b) 3 cm

Chapter Five

Exercise 5.1

1. 47.8 cm
2. 28.9°
3. 2.3 m
4. (a) 1.1 (b) 27.8°
5. 1.95 m
6. (a) 1.24×10^{8} m/s (b) 24.4°

Exercise 5.2

2. 1.20
3. 45°
4. 1.5
5. 1.5
6. (a) 14.17 cm, 62.7°

Exercise 5.4

1. (a) (i) -30 cm (virtual, erect, and enlarged), (ii) at infinity, (iii) 90 cm, real, inverted, and enlarged.
2. -10 cm
3. $m = 2$, 18 cm, real, inverted, and enlarged
4. 60 cm
5. 2 cm
6. 75 cm
7. 4

Revision Exercise 5

2. 3.27 cm
3. 35.3°
4. 1.34
6. (a) 41.8° (b) 48.8° (c) 62.5°
8. 100 cm, 20 cm
9. (b) -30 cm
10. 20.83 cm
12. 4 cm
13. 77.1°

Chapter Six

Exercise 6.1

1. (a) 6 (b) 25 cm
2. 20 cm, 5
3. 3.6 cm
4. (a) 4.2 cm, 5 cm
   (b) 6, 5

Exercise 6.2

1. (b) 30 cm
2. 3.3 cm, 5 cm

Exercise 6.3

1. 73.1 cm, 4.9 cm
2. 30.2
3. 35, 144 cm
5. (a) 700 (b) 12.82 cm

Exercise 6.4

1. (a) 6.7 cm (b) 1.7 cm
2. 2.4 m
3. 10.4 cm

Exercise 6.5

1. (a) 2.1 cm (b) 2.06 cm
   (c) 1.94 cm
2. 33.33 cm, 3 D
3. 2 D
4. (b) (i) 34.62 cm
   (ii) 2.89 D
   (iii) 3.6

Revision Exercise 6

2. (b) (ii) 22.2cm
3. (a) 43.48 D
   (b) 47.39 D
   (c) 3.91 D
5. 15.5 cm, 30
6. (a) 2.6 cm (b) 30
10. (a) 3.75 cm (b) 11.12
11. (a) -48 cm (b) 2.08 D
12. (a) 4.9 cm real
    (b) 0.0196, 3.53 cm

Glossary

Accommodation (of the eye)	is the adjustment of the focusing power of the eye to see objects clearly over a range of distances. Accommodation is achieved by changing the shape of the crystalline lens.
Angle of deviation	is the angle through which the direction of a ray of light is changed by a refracting surface of a prism. It is the angle between the incident and refracted (or emergent) ray.
Apical angle	is an angle included between refracting surfaces and which is contained in a principal section of a prism.
Ammeter	a device for measuring electric current in a circuit. It is calibrated in amperes (A).
Alnico	is a family of iron alloys that, in addition to iron, are composed primarily of aluminium, nickel, or cobalt.
Ampere	is the SI unit of electric current and indicates the rate at which charge flows in a circuit.
Battery	is several electric cells connected to produce electric current through converting chemical energy to electrical energy.
Critical angle	is the angle of incidence in the denser medium for which the angle of refraction in the less dense medium is 90°. It is the smallest angle of incidence at which total internal reflection occurs.
Conduction electrons	free electrons that can move from one atom to another within a material.
Contact charging	is the process of transferring electric charges from one body to another by making the bodies touch each other or by rubbing.
Coulomb	is a quantity of electric charge that passes through a given point in a circuit in one second when a steady current of 1 ampere flows. It is the SI unit of electric charge.
Dispersion (of white light)	is the splitting of visible white light into its component colours by a dispersive medium. This occurs because each colour has its own frequency of dispersion.

Dip needle	is an instrument used to measure the angle of inclination of a magnetic field.
Demagnetisation	is the process of destroying the magnetic property or magnetism of an object.
Electrostatic	is the study of stationary electric charges.
Electrophorus	is a simple manual electric generator used to produce electrostatic charges by electrostatic induction.
Electrostatic force	is the push or pull of electric charges at rest.
Electric circuit	a closed path for electric charge to flow through. It consists of a voltage source, connecting wires and devices such as resistors and switches.
Electrical conductor	material that permits current to flow freely through it under an applied voltage. Metals are good conductors.
Electric current	is the rate of flow of electrons, or the sustained movement of electrical charge.
Electrification	is the process of introducing electric charges to a body so that it is electrically charged.
Electromagnet	is a type of magnet whose magnetic property is produced by an electric current.
Focal plane	is an area in a camera where light is focused.
Farad	is the SI unit for capacitance.
Ferromagnetic	magnetic materials that can be permanently magnetised.
Magnification	is the apparent enlargement of an object by an optical instrument.
Magnetic poles	are the two ends of a magnet or magnetised body where the lines of force are most concentrated. The strength of a magnet is strongest at the poles.
Magnetic shielding	process of limiting the passage of magnetic field lines through a region by diverging them.
Magnetisation	involves aligning the dipoles in a material to produce a net effect of attraction or repulsion. It is the process of making magnets.
Magnetism	is a physical phenomenon arising from the force caused by magnets.

Magnetic field	region around a magnet in which magnetic materials are affected by the magnet. Lines of action of magnetic force represent it.
Magnetic lines	are imaginary lines of action of magnetic force that run from the force from the north pole to the south pole of a magnet and through a magnet to form closed loops.
Magnetic meridian	is a vertical plane in which the magnet rests with its axis lying in the magnetic north-south direction.
Optical density	is a measure of the extent to which a substance transmits light or electromagnetic radiation.
Polarization (in a cell)	is a chemical reaction that occurs while a current flows. The reaction causes hydrogen bubbles to form on the surface of the electrode. The bubbles form a barrier that increases internal resistance, resulting in poor cell performance.
Polychromatic light	consists of multiple wavelengths, which appear as different colours.
Prism	is a 3-dimensional transparent body, usually made of optical glass, with at least two polished plane faces inclined towards each other from which light is reflected or through which light is refracted.
Rainbow	is an arc of coloured light in the sky, produced by reflection, refraction and dispersion of light within droplets of rain in the air. This results in splitting up the white light of the sun into its component colours.
Real image	is produced in an optical instrument, such as a lens or mirror, and can be projected onto a screen. The actual intersection of light rays forms real images.
Regelation	is the phenomenon of melting under pressure and freezing again when the pressure is reduced.

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