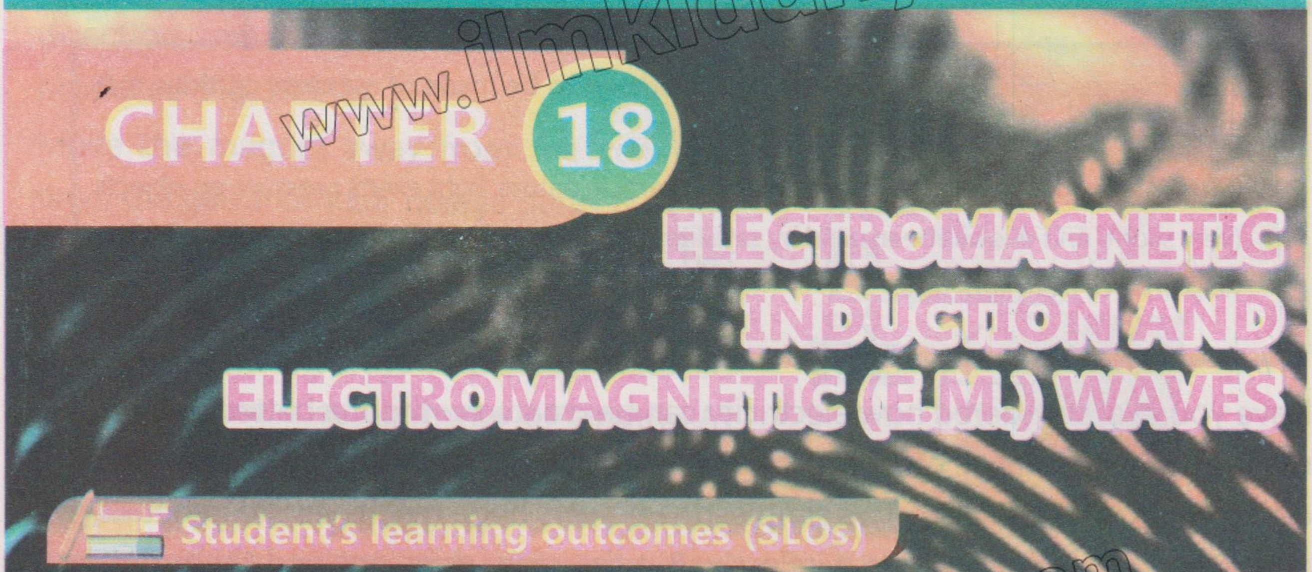

CHAPTER 18

ELECTROMAGNETIC INDUCTION AND ELECTROMAGNETIC (E.M.) WAVES

Student's learning outcomes (SLOs)

After studying this chapter, student will be able to:

- describe an experiment to demonstrate electromagnetic induction.
- use the fact that the magnitude of an induced e.m.f. is affected by the rate of change of the magnetic field or the rate of cutting of magnetic field lines, and the number of turns in a coil, to solve simple electromagnetic problems.
- use the fact that the effect of the current produced by an induced e.m.f. is to oppose the change producing it (Lenz's law).
- describe how a.c. generators work (rotating coil or rotating magnet setup) and the use of slip rings and brushes where needed.
- sketch and interpret graphs of e.m.f. against time for simple A.C. generators (including relating the position of the generator coil to the peaks, troughs and zeros of the e.m.f.).
- explain the principle of operation of a simple iron-cored transformer.
- use the terms primary, secondary coils and step-up and step-down transformer.
- use the equation $V_P / V_S = N_P / N_S$ (where P and S refer to primary and secondary) to solve problems.
- describe the deflection of an electron beam by electric fields and magnetic fields.
- interpret wave forms on oscilloscopes.
- state that the speed of all electromagnetic waves in: vacuum is 3.0×10^8 m s^{-1}, air is approximately the same as in a vacuum.
- explain qualitatively, how scattering of light by molecules in the air give the sky its blue colour during the day and its shades of red during sunset (use of the terms Rayleigh and Mei scattering are not required).

- state that theoretically light can also be considered to be made of massless particles that carry energy and momentum called 'photons'.
  (Students should know as an example of this particle nature, light exerts pressure on objects (very slight) and this has been used by satellites that have 'solar sails' that accelerate with the help of force from light rays.)

Have you ever wondered how electricity can be created without a battery? When a magnet moves near a wire, it produces electricity, a fascinating process called electromagnetic induction. This simple idea powers huge machines like generators and even charges our phone wirelessly. But the story does not end there. These changing electric and magnetic fields can travel through space as electromagnetic (E.M) waves bringing us light, radio signals, Wi-Fi, and even microwaves that heat our food. From lighting up cities to connecting people across the world, electromagnetic induction and E.M waves are the hidden forces shaping our everyday lives. Let us dive into the science behind these amazing wonders.

18.1 Electromagnetic Induction

Electromagnetic induction is the process by which a changing magnetic field produces an electric current in a conductor.

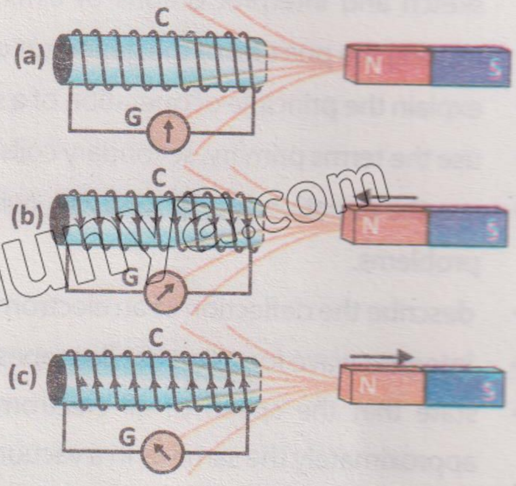

Fig. 18.1: Induced current in a coil by moving a magnet

This principle, first discovered by Michael Faraday and at the same time Joseph Henry in 1831, is fundamental to the operation of many devices such as generators, transformers, and inductors. To understand the phenomena of electromagnetic induction let us perform experiments.

Take a coil of conducting wire, labelled C, and connect it to a galvanometer G, as shown in Fig. 18.1. First, keep the magnet still near the coil. We will notice that the galvanometer needle does not move, no electricity is produced because there is no change happening in the magnetic field (Fig 18.1-a) Now, move the magnet towards the coil. The galvanometer needle deflects in one direction, meaning that current is being produced (Fig. 18.1-b).

Move the magnet away from the coil. This time, the galvanometer needle deflects in the opposite direction, showing the current has reversed (Fig.18.1-c).

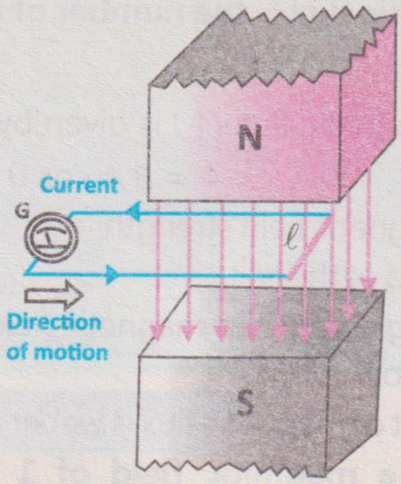

Fig. 18.2: Induction of current by moving a wire through a magnetic field

There are different ways to produce induced e.m.f. Imagine a straight wire of length (ℓ) placed in the magnetic field of a permanent magnet as shown in Fig. 18.2. This wire is connected to a sensitive galvanometer, forming a closed circuit or loop without using any battery. When the loop is still in the magnetic field, no current flows, and the galvanometer shows no deflection. But when the loop is moved from left to right, the wire cuts through the magnetic field lines, and current starts to flow through the loop. The galvanometer shows this current. When the motion stops, the current also stops. If the loop is moved in the opposite direction, the current also changes direction, which is shown by the galvanometer deflecting in the opposite direction. The amount of the induced current depends on how fast the wire is moved and the resistance in the loop. If we change the resistance of the loop by connecting different resistors and move the loop at the same speed each time, we notice that the product of the current I and resistance R always remains constant.

$$\text{i.e;} \qquad I \times R = \text{constant}$$

This constant value is the induced e.m.f. When the circuit is complete, this induced e.m.f. causes a current to flow. The induced current can be increased in the following ways:

(i) using a stronger magnetic field

(ii) moving the loop more quickly

(iii) using a coil with many turns instead of a single loop

We can also do the experiment in another way: instead of moving the loop through the magnetic field, we can keep the loop still and move the magnet. The result is the same in both cases. This shows that it is the relative motion between the loop and the magnet that creates the induced e.m.f. In simple terms, this movement changes the magnetic flux through the loop.

Magnetic flux is the number of magnetic field lines passing through a certain area.

The magnetic flux (ϕ) is given by

$$\phi = B\,A\cos\theta \quad \text{.........} \quad (18.1)$$

B = Magnetic field strength

A = Area of the coil

θ = Angle between magnetic field and normal to the coil

The unit of magnetic flux is weber (Wb).

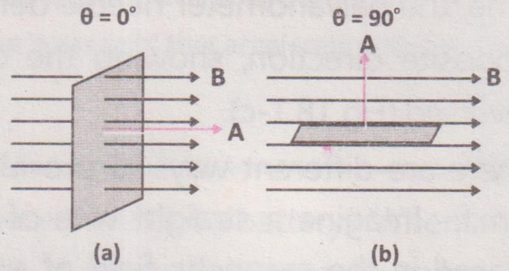

Fig. 18.3: Magnetic flux through a surface (a) Maximum (b) Zero

When a magnetic field of 1 tesla passes perpendicularly through an area of one square metre, the magnetic flux is equal to one weber.

Mathematically; $1\text{ Wb} = 1\text{T m}^2$

The magnetic flux is maximum when the angle between **B** and **A** is 0° (Fig. 18.3-a). However, when the angle between **B** and **A** is 90°, flux will be zero (Fig. 18.3-b).

Faraday's Law of Electromagnetic Induction

The average e.m.f. induced in a conducting coil of *N* loops is equal to the negative of the rate at which the magnetic flux is changing with time.

Mathematically; it is expressed as:

$$\varepsilon = -N\,\frac{\Delta\phi}{\Delta t} \quad \text{.........} \quad (18.2)$$

Where:

ε = induced e.m.f. (in volts, V)

N = number of turns in the coil

$\frac{\Delta\phi}{\Delta t}$ = rate of change of magnetic flux

Negative sign indicates that the induced emf opposes the change of magnetic flux that produce it.

Example 18.1: A coil with 25 turns experiences an induced emf of 2.5 V for 0.20 s. Assuming the e.m.f. is constant during this interval, calculate the total change in magnetic flux ($\Delta\phi$) through the coil.

Solution:

Given that;

Number of turns $N = 25$

Induced emf $\varepsilon = 2.5\text{ V}$

Time interval $\Delta t = 0.20\ \text{s}$

To find; Change in flux $\Delta\phi = ?$

Using the formula: $\varepsilon = (N \times \Delta\phi) / \Delta t$

Rearranging to solve for $\Delta\phi$:

$$\Delta\phi = (\varepsilon \times \Delta t) / N$$

Substituting the values $\Delta\phi = (2.5\ \text{V} \times 0.20\ \text{s}) / 25$

$$\Delta\phi = 0.5 / 25 = 0.02\ \text{Wb}$$

Magnitude and Direction of Induced e.m.f (Lenz's Law)

Lenz's Law is a fundamental principle in electromagnetism that describes the direction of the induced current resulting from a changing magnetic flux. It states that:

The direction of induced current is always such that it opposes the cause which produces it.

This law is a direct consequence of the conservation of energy. If the induced current were to reinforce the change instead of opposing it, it would lead to a perpetual increase in energy, which is impossible.

When a magnetic field near a conductor changes whether due to a moving magnet, a varying current, or a changing coil orientation an electromotive force (e.m.f.) is induced, driving a current. The direction of this current is not arbitrary; it must generate its own magnetic field that counteracts the original change in flux. For example, if a magnet is pushed toward a coil, the coil's induced current will produce a magnetic field that repels the magnet, resisting its motion (Fig. 18.4-a). Conversely, if the magnet is pulled away, the induced current will create a field that attracts the magnet, again opposing the movement (Fig.18.4-b).

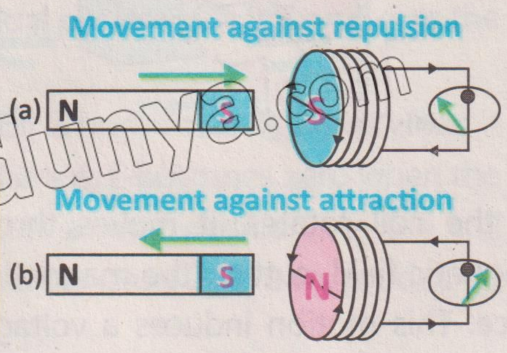

Fig. 18.4: Lenz's law

Do You Know?

- Simply moving a magnet through a coil can generate current. This is the same principle used in wind turbines and bicycle dynamos.
- The faster you change the magnetic field in a coil, the greater the current it produces, this is why fast-rotating generators make strong current.

Brain Teaser

If we stop moving a magnet near a coil, what happens to the induced current?

Tidbit

The faster we move a magnet through a coil, the greater the voltage (e.m.f.) is induced.

18.2 A.C. Generator

An alternating current (A.C) generator is a device that converts mechanical energy into electrical energy using electromagnetic induction. The most basic type includes a rectangular coil placed between the poles of a permanent magnet, as shown in Fig. 18.5(a). The coil is connected to two slip rings, which rotate along with the coil, while carbon brushes remain fixed and maintain contact with the slip rings to transfer the generated current.

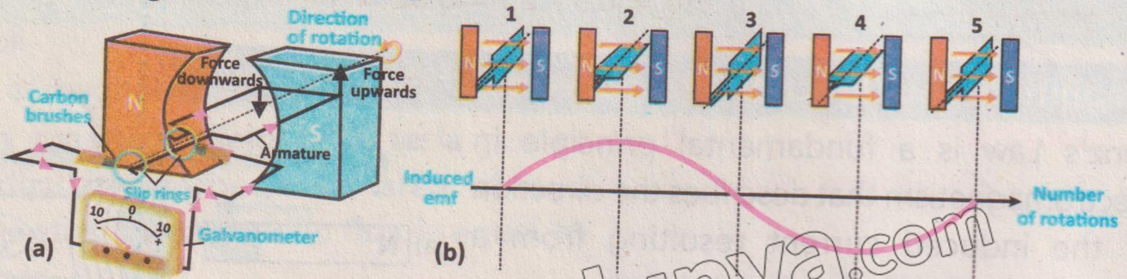

Fig. 18.5: An A.C generator and graph of current

As the coil rotates, it moves through the magnetic field, cutting the magnetic lines of force. This motion induces a voltage across the ends of the coil. The faster the coil rotates, the faster it cuts the magnetic field, resulting in a larger induced voltage. The induced voltage (or e.m.f.) changes throughout the rotation, as shown in Fig. 18.5(b).

Tidbit

A generator works by spinning a coil in a magnetic field, creating electricity powering cities.

When the coil is vertical, it moves along the field lines, and no magnetic flux is cut. So, the induced voltage is zero. As the coil rotates and becomes horizontal, it cuts the magnetic field lines at the maximum rate, producing the maximum voltage. After a half-turn, the direction of the coil's movement through the field reverses, causing the polarity of the voltage to switch, resulting in an alternating voltage. This continuous change in direction creates an alternating current (A.C), which flows back and forth in the external circuit. The shape of the voltage graph is a sine wave, completing one full cycle in each full rotation of the coil. The number of such cycles per second is called the frequency, measured in hertz (Hz).

Do You Know?

In an A.C. generator, the voltage reverses direction with every half-turn of the coil that is why it is called alternating current. Slip rings in an A.C. generator help to maintain continuous electrical contact with the rotating coil while allowing current to alternate naturally.

For example; if the coil rotates once per second, the frequency is 1 Hz, and if it

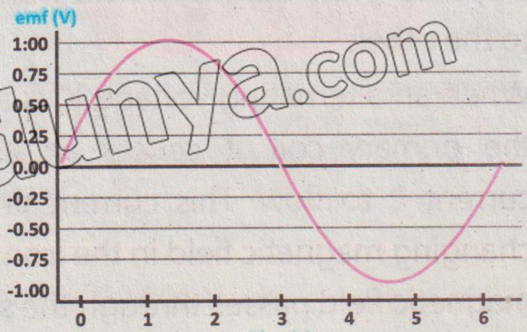

Fig. 18.6: Graph of e.m.f. against time for simple A.C generator

rotates 50 times per second, the frequency is 50 Hz (which is the frequency of A.C mains in many countries like Pakistan). According to Faraday's law of electromagnetic induction, an e.m.f. is produced in a coil when there is a change in magnetic flux through it. The amount of e.m.f. generated depends on how fast the magnetic field is being cut by the coil.

Figure 18.6 shows how the e.m.f. varies with time during the rotation of a coil in a simple A.C generator. The graph clearly displays a sinusoidal pattern, which represents the alternating nature of the generated voltage.

The e.m.f. reaches its maximum value when the coil is horizontal, as this is when it cuts the magnetic field lines at the highest rate. The e.m.f. becomes zero when the coil is vertical, since no magnetic flux is being cut at that position. As the coil continues to rotate, the direction of the e.m.f. reverses every half-turn, producing alternating current.

- At 0 and π radians (or 0° and 180°), the coil is vertical, and the e.m.f. is zero.
- At π/2 and 3π/2 radians (or 90° and 270°), the coil is horizontal.
- At π/2, the e.m.f. is positive maximum.
- At 3π/2, it reaches the negative maximum due to the reversal in direction of motion.

This repeating cycle creates the familiar A.C waveform, which alternates between positive and negative values over time.

18.3 Transformer

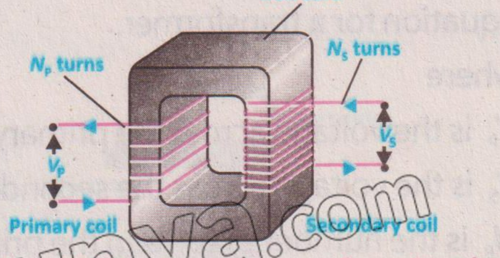

Fig. 18.7: Structure of a simple transformer showing primary and secondary coils wound around an iron core

A transformer is a device used to increase or decrease the voltage in an alternating current (A.C) circuit. It works without any electrical connection between its input and output coils. Figure 18.7 shows a simple transformer. It has two coils of wire: the primary coil with N_p turns and the secondary coil with N_s turns. Both coils are wound on a soft iron core, which helps carry the magnetic field from one coil to the other.

When an alternating voltage V_P is applied to the primary coil, it causes an alternating current I_P to flow. This current produces a changing magnetic field in the iron core. The magnetic field passes through the secondary coil, where it induces an alternating voltage V_S. This causes an alternating current I_S to flow in the secondary circuit. There is no direct electrical connection between the two coils. Energy is transferred from the primary coil to the secondary coil through the magnetic field in the core.

Do You Know?

The buzzing sound in transformers is due to the iron core vibrating at 50 or 60 Hz This vibration is caused by varying magnetic field and not by the current directly.

Step-up and Step-down Transformers

Transformers are used to either increase or decrease voltage in A.C circuits. When the secondary coil has more turns than the primary coil, the transformer increases the output voltage, it is called a step-up transformer (Fig. 18.8-a). Conversely, when the secondary coil has fewer turns than the primary, the output voltage is reduced, and it is known as a step-down transformer (Fig. 18.8-b).

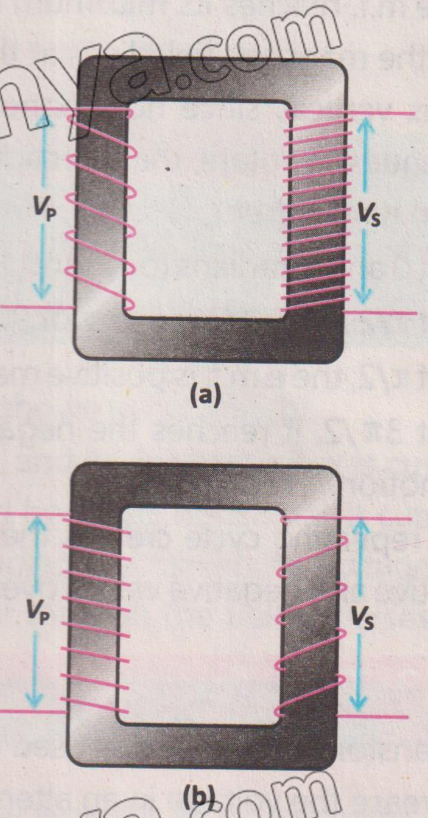

Fig. 18.8: (a) Step-up transformer
(b) Step-down transformer

This relationship between coil turns and voltages is described by the equation:

$$\frac{V_S}{V_P} = \frac{N_S}{N_P} \quad .... \quad (18.3)$$

This equation is known as the turns-ratio equation for a transformer.

where

V_P is the voltage across the primary coil

V_S is the voltage across the secondary coil

N_P is the number of turns in the primary coil

N_S is the number of turns in the secondary coil

This equation shows that the voltage ratio is directly proportional to the number of turns in the coils. For example, if the primary has 5 turns and the secondary has 10 turns, the output voltage will be twice the input voltage.

Tidbit

Step-up transformers increase voltage for long-distance transmission, while step-down transformers reduce it to safe levels in our home.

Example 18.2: Electricity is transmitted at a voltage of 20,000 V with a current of 5 A through power cables that have a resistance of 10 Ω. Calculate the power loss in the cables?

Solution:

Given that;

$$\text{Voltage } V = 20{,}000\ \text{V}$$
$$\text{Current } I = 5\ A$$
$$\text{Resistance } R = 10\ \Omega$$

To find;

$$\text{Power loss } P = ?$$

We know that;

$$\text{Power loss } P = I^2 R$$

Substituting the values

$$P = (5)^2 \times 10$$
$$P = 25 \times 10$$
$$P = 250\ \text{W}$$

The power loss in the cables is 250 W.

18.4 Deflection of Electron Beam in Electric and Magnetic Fields

The direction of electron beam or cathode rays can be changed by electric and magnetic field.

Deflection by Electric Field

The cathode rays generated from an electron gun are negatively charged electrons moving with high speed. Each negatively charged electron in cathode ray beam is attracted by the positive electrode and is repelled by the negative electrode. Thus, we can say that

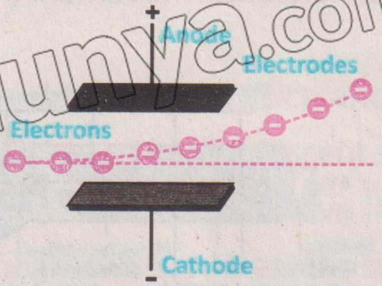

Fig. 18.9: Deflection of electron beam in an electric field

cathode rays are deflected toward positive electrode in the presence of electric field, as shown in Fig. 18.9.

Deflection by Magnetic Field

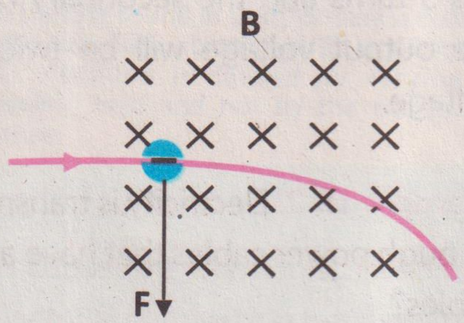

Fig. 18.10: Deflection of electron passing through uniform magnetic field

A magnetic field exerts force on electrically charged particles that are in motion. Cathode rays generated from an electron gun are a stream of negatively charged electrons. Electrons, while passing through the magnetic field, are deflected as shown in Fig. 18.10. To determine the direction of force and thus the deflection of the electron beam, the Fleming's left-hand rule can be used.

18.5 Waveform on Oscilloscope

A Cathode Ray Oscilloscope (CRO) is a widely used electronic instrument designed to display, observe, and measure how electrical signals change with time. The main component of the CRO is a cathode ray tube (CRT), as illustrated in Fig. 18.11(a), which includes an electron gun, deflecting system, and a fluorescent screen.

Brain Teaser

Which travels faster radiowaves or gamma rays? Why?

The electron gun generates a focused beam of electrons. It contains a heated filament F that heats the cathode C, causing it to emit electrons. These electrons are then accelerated and focused by three anodes placed at high positive potential. A control grid G, kept at a negative potential, controls how many electrons reach the screen and thus adjust the brightness of the spot formed. Once accelerated, the electron beam enters the deflecting system. The deflection system consists of two pairs of plates: the Y-plates, which control vertical movement (up and down) based on the input signal, and the X-plates, which control horizontal movement (left to right).

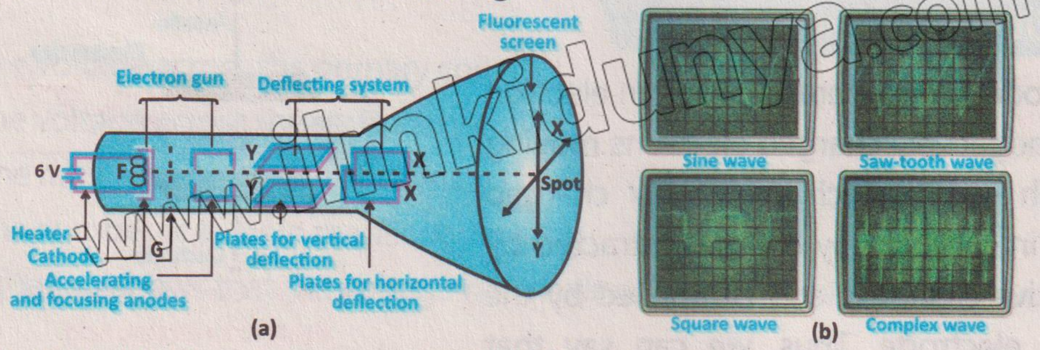

Fig. 18.11: (a) Schematic diagram of CRO (b) Different waveforms displayed on a CRO screen

The fluorescent screen is coated with a material that glows when the electron beam strikes it. As the beam strikes different points on the screen, it leaves a visible trace, allowing the waveform of the signal to be seen. To move the spot horizontally across the screen in a regular time-based manner, the CRO uses a saw-tooth waveform, which is applied to the X-plates. This waveform (Fig. 18.12) increases steadily over time and then rapidly drops to its starting value, repeating this cycle continuously. This pattern of voltage, called a saw-tooth wave, causes the electron beam to sweep from left to right and then drops to zero. This motion creates a time axis on the screen, enabling the CRO to display how the signal changes over time.

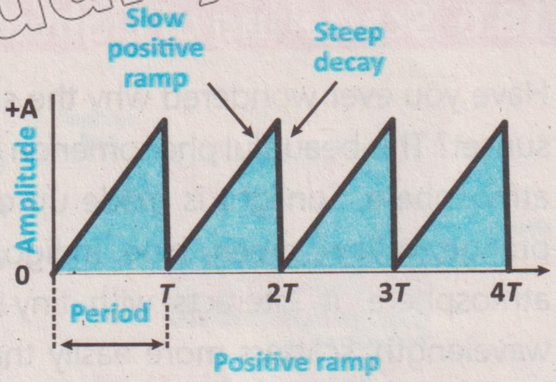

Fig. 18.12: Schematic diagram of a saw-tooth wave

When a sine wave is applied to the Y-plates and a saw-tooth voltage to the X-plates, the beam moves both up and down and side to side, tracing the waveform of the signal on the screen. The result is a clear, real-time display of the signal's shape. The display appears stable only when the frequency of the sawtooth wave (time base) is equal to or a multiple of the input signal's frequency. This synchronization can be adjusted using controls on the CRO.

CROs are extremely useful for measuring and analyzing electrical signals. They can show the waveform of a signal, measure its amplitude, determine its time period and frequency, and even allow comparison of two signals to measure their phase difference. For instance, if two waveforms are displayed together and one rises while the other falls, they may be out of phase by 180°, which can be easily observed on the screen.

A cathode ray oscilloscope is an essential tool in electronics, physics, and medical diagnostics. It uses electron beams, deflecting plates, and a fluorescent screen to visually represent electrical signals. The inclusion of a saw-tooth wave in its time base is important, as it ensures that the electron beam sweeps across the screen at a constant rate, making accurate and stable signal display possible.

18.6 Scattering of Light in the Atmosphere

Have you ever wondered why the sky is blue during the day and turns reddish at sunset? This beautiful phenomenon is caused by scattering of sunlight in the Earth's atmosphere. Sunlight is made up of all the colours of the visible spectrum; red, orange, yellow, green, blue, indigo, and violet. As this light passes through the atmosphere, it interacts with tiny gas molecules. Blue light, having a shorter wavelength, scatters more easily than red or green light. As shown in Fig. 18.13, during daytime, this scattered blue light reaches us from all directions, making the sky appear blue.

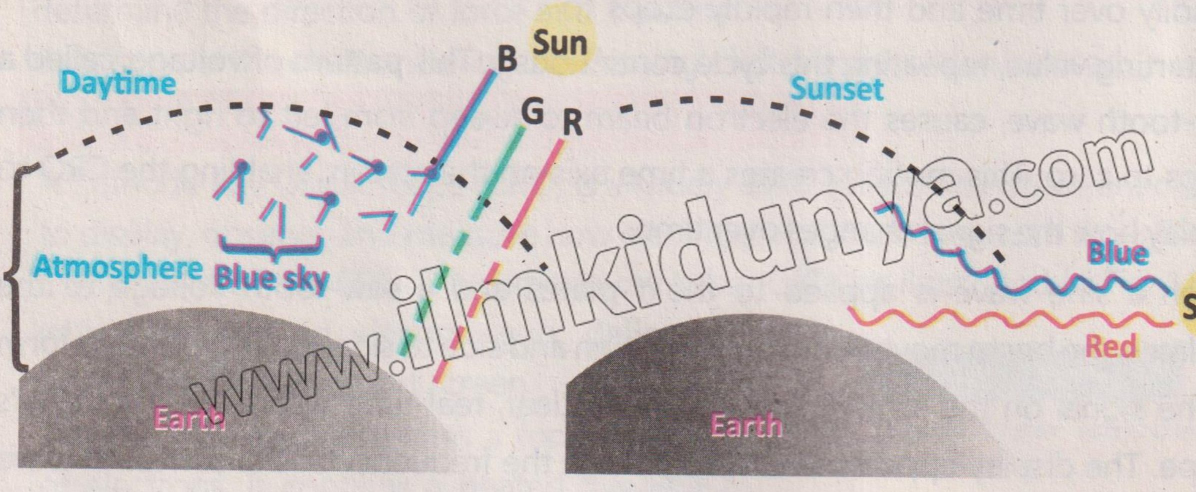

Fig. 18.13: Scattering of sunlight during daytime and sunset

During sunrise or sunset, the sunlight has to pass through a longer path in the atmosphere. By the time the light reaches us, much of the blue light has already been scattered out of the path. What remains are the longer wavelengths like red and orange, which scatter less. These colours dominate the sky near the horizon, giving it the warm, reddish hues we often see in the evening.

Tidbit

The sky is not blue, it is violet. But our eyes perceive scattered violet + blue as blue. Sunsets are red because blue light gets scattered away over long distances.

Brain Teaser

Why does the sky appear blue during the day but red at sunset?

Factors such as dust, pollution, and water droplets in the atmosphere can make the sunset even more dramatic by enhancing the scattering of certain colours, leading to deep reds and purples.

18.7 Particle Nature of Light

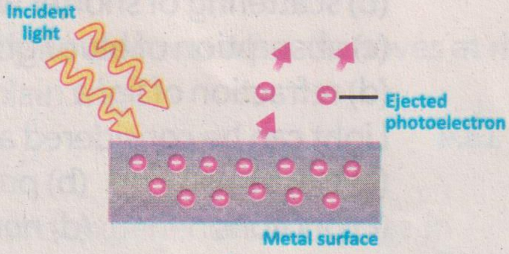

Fig. 18.14: Particle nature of light

Light is commonly known to behave as a wave, but it also has a particle-like nature. According to modern physics, light can be viewed as a stream of massless particles known as photons. These photons carry energy and momentum, even though they have no rest mass. This idea helps explain how light interacts with matter in situations where wave theory falls short.

One important piece of evidence for the particle nature of light is the photoelectric effect, shown in Fig. 18.14. When light shines on a metal surface, it can transfer energy to electrons. If the energy is high enough, electrons are ejected from the surface, these are called photoelectrons. This effect proves that light energy comes in packets (photons), and not as a continuous wave. Another example is radiation pressure light can exert a tiny force when it hits an object. Though the force is very small, it has real-world applications. For instance, solar sails on some spacecrafts are designed to reflect sunlight. The momentum of the photons gradually pushes the sail forward, allowing the spacecraft to move through space without using any fuel.

This concept demonstrates the dual nature of light it behaves like both a wave and a particle, depending on how it interacts with materials. It is one of the most fascinating ideas in modern physics.

EXERCISE

A. Multiple Choice Questions

Tick (✓) the correct answer.

18.1 What happens to the induced e.m.f. in a coil if the rate of change of the magnetic field increases?

(a) Decreases
(b) Remains the same
(c) Increases
(d) Becomes zero

18.2 In an A.C generator, slip rings are used to:

(a) reverse current direction periodically
(b) convert A.C to D.C
(c) prevent induced current
(d) increase magnetic flux

18.3 The sky appears blue during the day due to:
(a) reflection of light
(b) scattering of shorter wavelengths
(c) absorption of blue light
(d) refraction of light

18.4 Light can be considered as massless particles called:
(a) electrons (b) protons
(c) photons (d) neutrons

18.5 In a transformer, energy is transferred from the primary coil to the secondary coil through:
(a) direct electrical connection (b) a magnetic field in the iron core
(c) electrons flowing through the core (d) heat conduction

B. Short Answer Questions

18.1 What is the direction of induced current in Lenz's law?

18.2 Why are slip rings used in an A.C generator?

18.3 When is induced e.m.f. zero in an A.C generator?

18.4 Why is the sky red at sunset?

18.5 What is a transformer and on what principle does it work?

C. Constructed Response questions

18.1 If a magnet is moved quickly into a coil, a larger e.m.f. is induced. Why does speed affect the magnitude of the induced current?

18.2 Why is an iron core used in transformers instead of wood or plastic? Explain briefly.

18.3 How does the concept of photons help explain the working of solar sails in space?

18.4 Why can a transformer work only on alternating current and not on direct current ?

D. Comprehensive Questions

18.1 Describe how Lenz's Law supports the law of conservation of energy. Give one real-life example to support your explanation.

18.2 Compare step-up and step-down transformers. Include the difference in number of turns, voltage output, and where is each used.

18.3 How does the scattering of sunlight cause the sky to appear blue during the day and red at sunset? Explain.

18.4 What is an oscilloscope, and how does it help in analyzing electrical signals? Describe its main components.

18.5 What is the shape of the path followed by an electron when it moves at right angles to a uniform magnetic field? Explain why.

D. Numerical Problems

18.1 A coil consisting of 50 tightly wound turns experiences a change in magnetic flux from 0.3 Wb to 0.8 Wb over a time interval of 0.4 s. Determine the average induced electromotive force (e.m.f.) generated in the coil during this time. **[Ans: -62.5 V]**

18.2 A circular loop of radius 0.2 m and resistance 5 Ω is placed perpendicular to a magnetic field of 0.5 T. If the field drops to zero in 0.1 s, calculate:
(a) the induced emf
(b) the induced current and its direction (assuming the field points into the page) **[Ans: 0.63 V, 0.126 A]**

18.3 A transformer has 500 primary turns and 100 secondary turns. If the primary voltage is 220 V, find: (a) secondary voltage (b) is this a step-up or step-down transformer? **[Ans: 44 V, Step-down ($V_s < V_p$)]**

18.4 A step-up transformer has a turns ratio of 2:100. If an alternating voltage of 25 V is applied to the primary coil, what will be the secondary voltage? **[Ans: 1250 V]**

18.5 A step-down transformer has a turns ratio of 100:5. If an A.C voltage of 190 V is applied to the primary coil, what is the voltage across the secondary coil? **[Ans: 9.5 V]**