

ELECTROMAGNETISM

Student's learning outcomes (SLOs)

After studying this chapter, students will be able to:

- describe the pattern and direction of the magnetic field due to currents in straight wires and in solenoids.
- state the effect on the magnetic field of changing the magnitude and direction of the current.
- describe how the magnetic effect of a current is used in relays and loudspeakers (including giving examples of their application).
- describe an experiment to show that a force acts on a current-carrying conductor in a magnetic field (including the effect of reversing:
 - (a) the current
 - (b) the direction of the field
- state and use the relative directions of force, magnetic field, and current.
- describe the magnetic field patterns between currents in parallel conductors and relate these to the forces on the conductors (excluding the Earth's field).
- state that a current-carrying coil in a magnetic field may experience a turning effect and that the turning effect is increased by increasing:
 - (a) the number of turns on the coil
 - (b) the current
 - (c) the strength of the magnetic field
- describe the operation of an electric motor, including the action of a split ring commutator and brushes.
- describe and explain the action of relays in switching circuits.
- state that it is theorized that the Earth's magnetic field is generated by the rotation of the Earth and its molten iron core that contains charged particles in motion.

Electromagnetism is the branch of physics that deals with the interactions between electric and magnetic fields. It explains how electric charges produce electric fields, and how moving charges, like an electric current, create magnetic fields. This connection helps us to understand how modern devices work. Electromagnetism is an essential part of everyday life, powering electric circuits, communication systems and generators. Even light is an electromagnetic wave, showing how important this force is in science and technology. Learning about electromagnetism gives us the knowledge to build useful machines and to understand the science behind today's technology.

17.1 Magnetic Effects of Steady Current

The magnetic effects of a steady current can be demonstrated through experiments involving a current-carrying conductor.

Magnetic Field B Due to Current in a Straight Wire

Hans Christian Orsted stated that, a steady electric current in a conductor generates a magnetic field B around it. This can be demonstrated by passing a current-carrying wire through a vertical cardboard sheet and connecting it to a battery. When current flows, magnetic field is produced around it whose

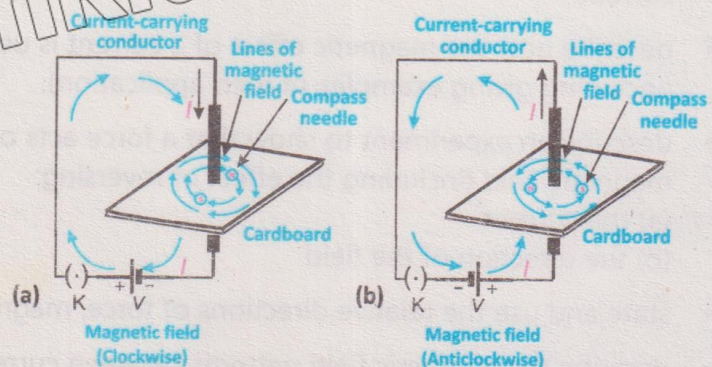


Fig. 17.1: Magnetic effects of a current

direction can be determined using right hand grip rule. Concentric circles are formed by the magnetic field around the conductor. This can be observed by placing small compasses or sprinkling iron filings on the cardboard. The compass needles align themselves along the direction of the magnetic field, pointing tangentially to the circular lines of force (Fig. 17.1-a). If the direction of the current is reversed by switching the battery terminals, the compass needles and iron filings also reverse their alignment, indicating that the magnetic field direction depends on the current flow (Fig. 17.1-b). In the dot and cross convention, a dot (·) represents current flowing out of the paper, while a cross (×) indicates into the paper. The magnetic field is strongest near the conductor and weakens with distance. This concept is essential in electrical engineering, particularly with alternating currents.

Direction of the Magnetic Field of a Current-Carrying Wire

The direction of the magnetic field B around a current-carrying straight wire can be found using the right-hand grip rule, as shown in Fig. 17.2.

According to the right-hand grip rule:

If you hold the wire in your right hand with your thumb pointing in the direction of the current, then your fingers curl around the wire in the direction of the magnetic field.

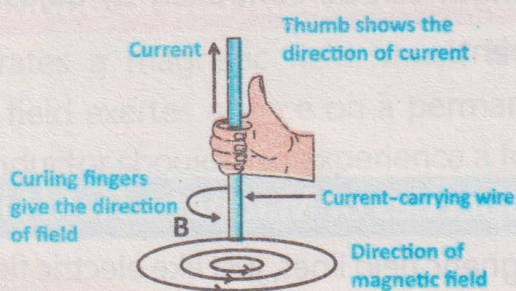


Fig. 17.2: Current-carrying conductor

This simple method helps us to quickly find the magnetic field direction around any straight current-carrying wire. The magnetic field forms circular loops around the wire, and its direction depends on the direction of the current. If the current changes direction, the direction of magnetic field also changes.

Magnetic Field Due to Current in a Solenoid

A solenoid is a coil of wire wound in the shape of a cylinder that generates a magnetic field when current flows through it. The combined effect of all loops of the wire of solenoid makes the field strong and uniform, like a bar magnet with north and south poles. A solenoid acts as a magnet and can attract or repel a bar magnet.

This temporary magnet, powered by electricity,

is called an electromagnet (Fig. 17.3). The right-hand rule helps to find out the direction of the magnetic field produced by the solenoid (Fig. 17.4). According to this rule:

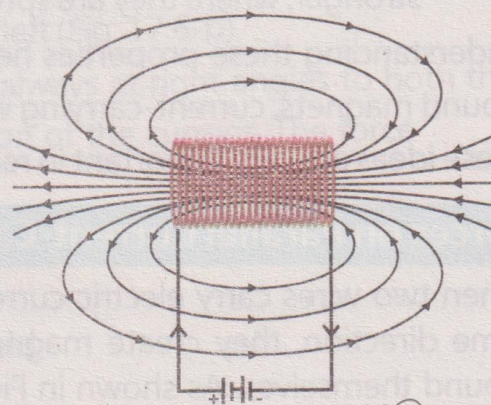


Fig. 17.3: Magnetic field due to solenoid

If you grip the solenoid with your right hand such that the curled fingers point in the direction of the conventional current, then the thumb will point towards the north pole of the solenoid.

Electromagnets are useful in motors, relays and magnetic locks because their magnetic strength can be controlled by adjusting the current.

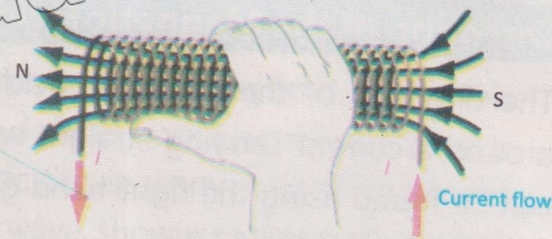


Fig. 17.4: Right hand rule for a solenoid

Properties of Magnetic Field Lines

Magnetic field lines, just like electric field lines, are imaginary. They do not physically exist but are a way to visualize the magnetic field. These lines have important properties:

1. Magnetic field lines always start from the north pole and end at the south pole.
2. Magnetic field lines always form closed loops.
3. At any point, the tangent to a magnetic field line shows the direction of the magnetic field.
4. Magnetic field lines never cross (intersect) each other.
5. Where magnetic field lines are closer together, the magnetic field is stronger; where they are spread apart, the magnetic field is weaker.

Understanding these properties helps us to visualize how magnetic fields behave around magnets, current-carrying wires, and in devices like motors and generators. These ideas are very important in real-world technologies.

Forces on Parallel Current-Carrying Conductors

When two wires carry electric current in the same direction, they create magnetic fields around themselves. As shown in Fig. 17.5(a), the magnetic fields between the two wires interact in such a way that the opposite poles are near each other, and the two wires attract each other. This happens because the magnetic fields support each other between the wires and pull them together.

However, if the current in the two wires flows in opposite directions, their magnetic fields

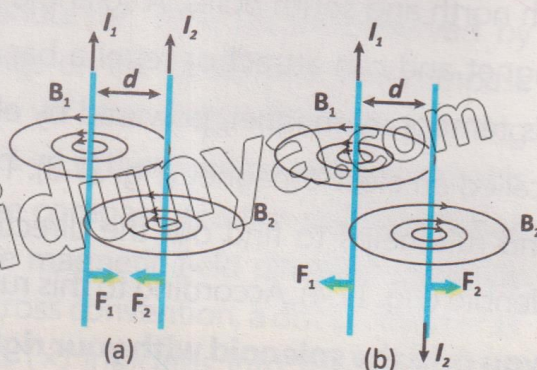


Fig. 17.5: Forces between parallel wires

oppose each other, and the wires will repel each other (Fig. 17.5-b). This important behaviour is the basic idea behind electromagnetic devices and technologies like electric motors and electromagnets.

17.2 Force on a Current-Carrying Conductor in a Magnetic Field

It is known that an electric current generates a magnetic field, much like a permanent magnet does. Since a magnetic field exerts a force on a permanent magnet, it follows that a current-carrying conductor should also experience a force when placed in a magnetic field.

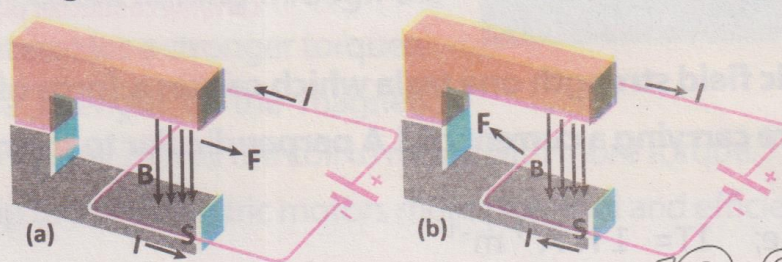


Fig. 17.6: Force on a current-carrying wire in magnetic field

The effect of a magnetic field on a wire carrying current can be illustrated using the setup in Fig. 17.6. A battery creates an electric current in the wire positioned inside the magnetic field of a permanent magnet. This wire then generates its own magnetic field, which interacts with the magnetic field of the magnet. As a result, a force acts on the wire. Based on the direction of the current, the wire is either pushed to the right (Fig. 17.6-a) or pulled to the left (Fig. 17.6-b).

Michael Faraday found that this force is always at right angles to both the direction of the magnetic field and the direction of the current. The force becomes stronger if:

1. The electric current (I) in the wire increases
2. The magnetic field (B) becomes stronger
3. Length (L) of the wire inside the magnetic field

The magnitude of this force is given as:

$$F = ILB\sin\theta$$

The direction of this force can be determined using **Fleming's left-hand rule**, which states:

Extend the thumb, forefinger, and middle finger of the left hand so that they are at right angles to one another. If the forefinger represents the magnetic field direction and the middle finger shows the current direction, then the thumb will point in the direction of the force acting on the conductor.

As illustrated in Fig. 17.7, the force on the conductor is perpendicular to both the current and the magnetic field, in accordance with Fleming's left-hand rule.

The SI unit of magnetic field (also called magnetic flux density) is the tesla (T).

1 tesla (T) is defined as:

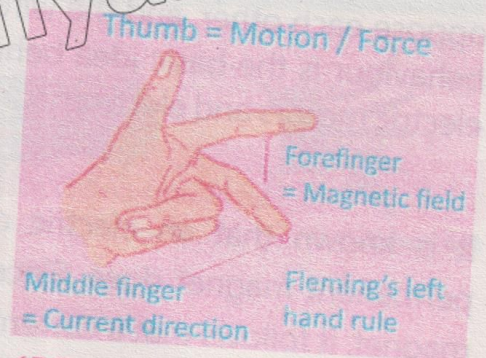


Fig 17.7: Direction of force on a current-carrying conductor placed in a magnetic field

The magnetic field strength one tesla which causes a force of 1 N on a 1 metre length of wire carrying a current of 1 A perpendicular to the magnetic field.

$$\text{i.e; } 1\text{T} = 1 \text{ N A}^{-1} \text{ m}^{-1}$$

17.3 Turning Effect on a Current-Carrying Coil in a Magnetic Field

Let us imagine a rectangular coil PQRS that is carrying a current and is placed in a magnetic field, as shown in Fig. 17.8. The coil is positioned in such a way that it is perpendicular to the magnetic field of a permanent magnet. Now, if we connect the ends of the coil to a battery, electric current starts flowing through the coil. When this happens, we can apply Fleming's Left Hand Rule to understand what force acts on the different parts of the coil. According to the rule:

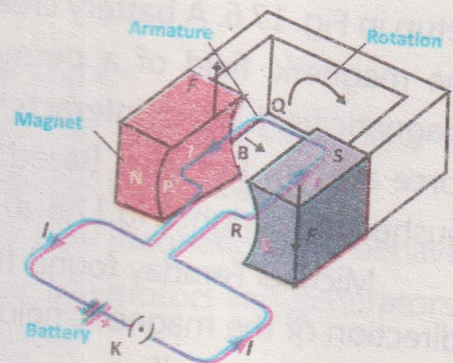


Fig. 17.8: A current-carrying coil in a magnetic field

On the side PQ of the coil, the force acts outward. On the side RS, the force acts inward. This happens because the current flows in opposite directions on the two sides of the coil. As a result, two forces are produced that are equal in magnitude but opposite in direction. These opposite forces form a couple. A couple produces a rotational effect or torque, which causes the coil to start rotating.

Thus, we can say that:

When a current-carrying coil is placed in a magnetic field, it experiences a couple of forces that makes the coil rotate, as shown in Fig.17.8. This is the working principle

of electric motors, which are used everywhere around us from fans to cars.

The turning effect on the coil can be made stronger by

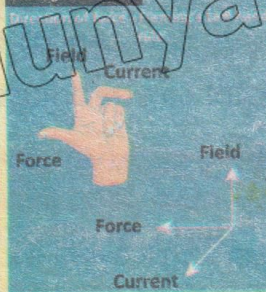
1. increasing the number of turns of the coil. More loops mean a stronger turning effect of force.
2. increasing the current flowing through the coil. More current creates a stronger torque.
3. increasing the strength of the magnetic field. A stronger magnet makes the coil to rotate with more torque.

These factors help to make electric motors more powerful and efficient.

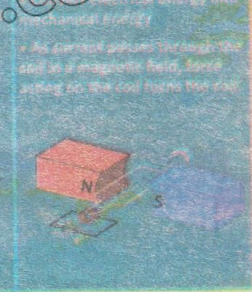


Do You Know?

Force on current-carrying conductor in Magnetic field



Electric Motor converts electrical energy into mechanical energy



17.4 Electric Motor

An electric motor is a device that converts electrical energy into mechanical energy. There are two types of electric motors, one is Alternating Current (A.C) motor and the other is Direct Current (D.C) motor. A D.C motor operates using the interaction between a current-carrying coil (armature) and a magnetic field. When a coil is placed in a magnetic field, it experiences forces that cause it to rotate (Fig. 17.9).

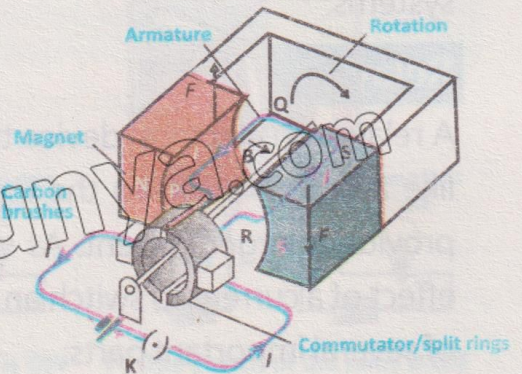


Fig. 17.9: Working principle of D.C motor

However, without any external help, the coil would stop rotating after 90° , as the forces acting on its sides (such as PQ and RS) push it into a vertical position, making the coil perpendicular to the magnetic field. At this point, the net force becomes zero, preventing further rotation. To keep the coil rotating, the current direction must be reversed just as the coil reaches the vertical position. This is achieved using a split ring commutator, which is a metal ring divided into two halves, each connected to one end of the coil. Carbon brushes maintain contact with the commutator, allowing current to flow. As the coil rotates, the commutator also rotates, and when the coil reaches the vertical position, each half of the commutator

switches brushes, reversing the current direction. As a result, direction of the current changes the direction of the forces which allows continuous rotation of the coil. The

speed of the motor can be adjusted by controlling the current flowing through it.

Tidbit

What is the special role of a split ring commutator in D.C motor?

17.5 Use of Magnetic Effects of Current

The magnetic effects of electric current are used in modern technology. The principle of creation of magnetic field due to current flow in a wire is utilized in relays and loudspeakers which rely on the interaction between electric currents and magnetic fields to perform their functions. These applications demonstrate how the magnetic effects of current enable the conversion of electrical energy into mechanical energy or sound, making them essential in electrical and electronic systems.

Relay

A relay is an electrical device that uses magnetism to control another circuit. It acts like a bridge between the input and output circuits, allowing a small current to provide a larger current. As shown in figure 17.10 (a), a relay uses the magnetic effect of a current to switch an output circuit ON or OFF. A mechanical relay consists of several important parts:

(a) Coil and Core

The relay has a coil made of wire wound around a magnetic core. When an electrical current passes through the coil, it creates a magnetic field. This magnetic field is the key that makes the relay work.

(b) Armature

The armature is a small movable piece inside the relay. When the coil becomes magnetised and demagnetised, it pulls the armature towards itself. This movement helps to open or close the switch connected to the relay.

(c) Return Spring

The return spring is connected to the armature. It brings the armature back to its original position when the current stops. In simple words, it acts like a reset button that resets the relay when electricity is cut off.

(d) Moving Contact

The moving contact is attached to the armature. When the armature moves due to magnetism, the moving contact also moves. This contact either joins or breaks the circuit, allowing or stopping the flow of current to the device (like a lamp). Similarly, it helps to open door lock, starting of motor car and heavy machines.

How a Relay Works?

A relay helps to turn ON and OFF a lamp easily:

When the switch is OFF

No current flows through the coil. The armature stays in its normal position. As a result, the lamp's circuit remains open, and the lamp does not glow, as shown in Fig. 17.10 (b).

When the switch is ON

Current starts flowing through the coil. The coil becomes magnetised and pulls the armature towards it. This action closes the lamp's circuit and the lamp glows, as shown in Fig. 17.10 (c).

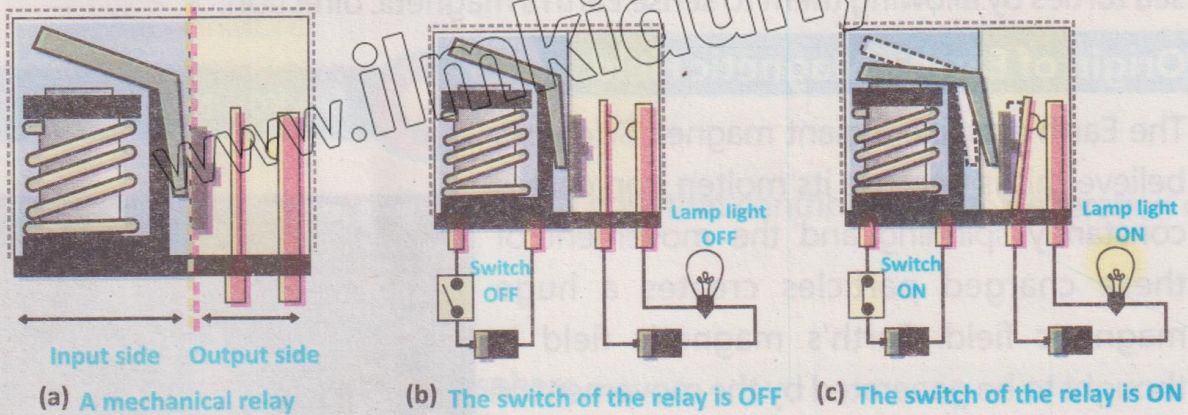


Fig. 17.10: Relay

Loudspeaker

A loudspeaker also uses the magnetic effects of current to convert an electrical signals into sound. It consists of a coil (attached to a diaphragm) which is placed in a permanent magnetic field as shown in Fig. 17.11. When an alternating current (audio signal) flows through the coil, it generates a varying magnetic field that interacts with the permanent magnetic field. This interaction generates a force on the coil, causing it to move back and forth. The movement of the coil vibrates the diaphragm, producing sound waves that correspond to the

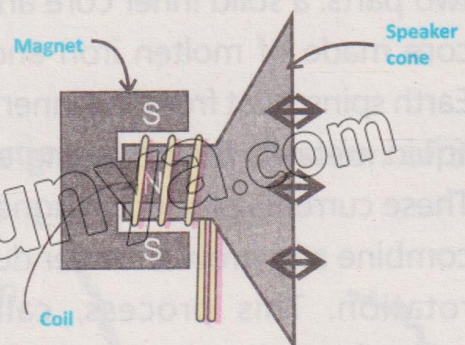


Fig. 17.11: Magnetic effects in loudspeakers

electrical signal. Loudspeakers are used in audio systems, public address systems, and televisions etc.

17.6 Earth's Magnetic Field

Earth's magnetic field acts like an invisible shield that surrounds the planet and stretches into space (Fig. 17.12). It is similar to the field of a bar magnet, with a north and south pole, but unlike a regular magnet, it constantly shifts and can even flip over time. This magnetic field is essential because it protects the Earth from dangerous solar winds and cosmic radiations by pushing away harmful charged particles and radiations. It also helps with navigation, guiding both humans and animals like migratory birds and sea turtles by allowing them to sense Earth's magnetic direction.

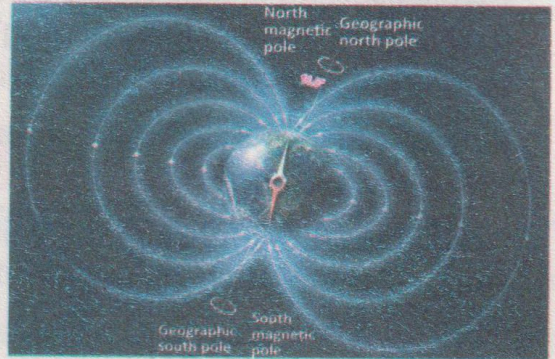


Fig. 17.12: Earth's magnetic field

Origin of Earth's Magnetic Field

The Earth acts like a giant magnet. Scientists believe this is because its molten iron core is constantly spinning and the movement of these charged particles creates a huge magnetic field. Earth's magnetic field is thought to be generated by the movement of liquid metal in its core, a process known as the dynamo effect (Fig. 17.13). The core has two parts: a solid inner core and a liquid outer core made of molten iron and nickel. As the Earth spins, heat from the inner core causes the liquid metal to flow, creating electric currents. These currents produce magnetic fields, which combine and grow stronger due to the Earth's rotation. This process, called magneto-hydrodynamics, keeps the magnetic field active and forms the magnetosphere, a protective barrier that shields Earth from harmful solar wind and space radiation.



Do You Know?

The solar wind and the Earth's magnetic field

At the centre of the Earth is the solid inner core. The outer iron-nickel core is solid due to the extremely high pressure rather than a drop in temperature. The inner core is in fact hotter than the outer core.

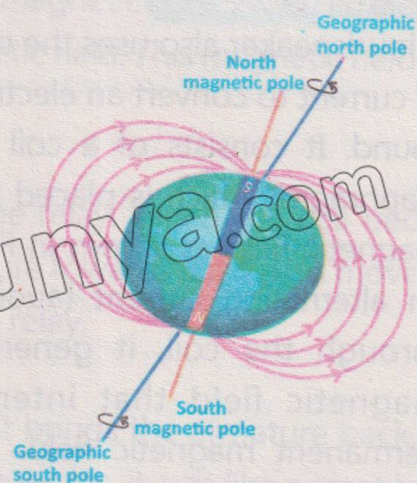


Fig. 17.13: Origin of Earth's magnetic field

EXERCISE

A. Multiple Choice Questions

Tick (✓) the correct answer.

- 17.1 Which statement is true about the magnetic poles?
- (a) Unlike poles repel
 - (b) Like poles attract
 - (c) Magnetic poles do not affect each other
 - (d) A single magnetic pole does not exist
- 17.2 A D.C motor converts:
- (a) mechanical energy into electrical energy
 - (b) mechanical energy into chemical energy
 - (c) electrical energy into mechanical energy
 - (d) electrical energy into chemical energy
- 17.3 The part of a D.C motor that reverses the direction of current through the coil every half-cycle:
- (a) the armature
 - (b) the commutator
 - (c) the brushes
 - (d) the split rings
- 17.4 The two main layers of the Earth's core that contribute to the generation of the magnetic field are:
- (a) crust and mantle
 - (b) inner core and outer core
 - (c) lithosphere and asthenosphere
 - (d) troposphere and stratosphere
- 17.5 What does a steady electric current in a conductor generate around it?
- (a) Electric field
 - (b) Light
 - (c) Magnetic field
 - (d) Sound waves
- 17.6 What happens to the magnetic field direction when the direction of the current is reversed?
- (a) The magnetic field remains unchanged
 - (b) The magnetic field also reverses direction
 - (c) The magnetic field becomes stronger
 - (d) The magnetic field disappears

B. Short Answer Questions

- 17.1 What is the direction of the magnetic field around a straight current carrying wire?
- 17.2 What happens to the magnetic field if the magnitude of the current in a wire is increased?
- 17.3 How can you identify the north and south poles of an unmarked magnetized steel bar?
- 17.4 What rule determines the direction of force on a current-carrying conductor placed in a magnetic field? Explain briefly.
- 17.5 What role does the commutator play in a D.C motor?
- 17.6 What is the source of the Earth's magnetic field according to the theory?

C. Constructed Response Questions

- 17.1 Why does a magnetic field form around a conductor when current flows through it, but not when the current is OFF? What does this reveal about the nature of electricity and magnetism?
- 17.2 In a D.C motor, why does the coil stop turning after 90° if the direction of the current is not reversed? What mechanical feature solves this issue?
- 17.3 How does placing a wire at different angles to a magnetic field affect the magnetic force it experiences, and why is this important in designing motors?

D. Comprehensive Questions

- 17.1 How is a magnetic field created around a current-carrying wire, and what factors affect its strength?
- 17.2 Explain the concept of the right-hand grip rule and how it helps determine the direction of the magnetic field around a current-carrying conductor.
- 17.3 Describe an experiment that demonstrates the magnetic field produced by a current-carrying conductor using a compass or iron filings.
- 17.4 Discuss the theory behind the Earth's magnetic field and the role of the Earth's molten core in generating it.