MEC 3102 – PRODUCTION ENGINEERING I AND ELECTRICITY & ELECTRONICS II

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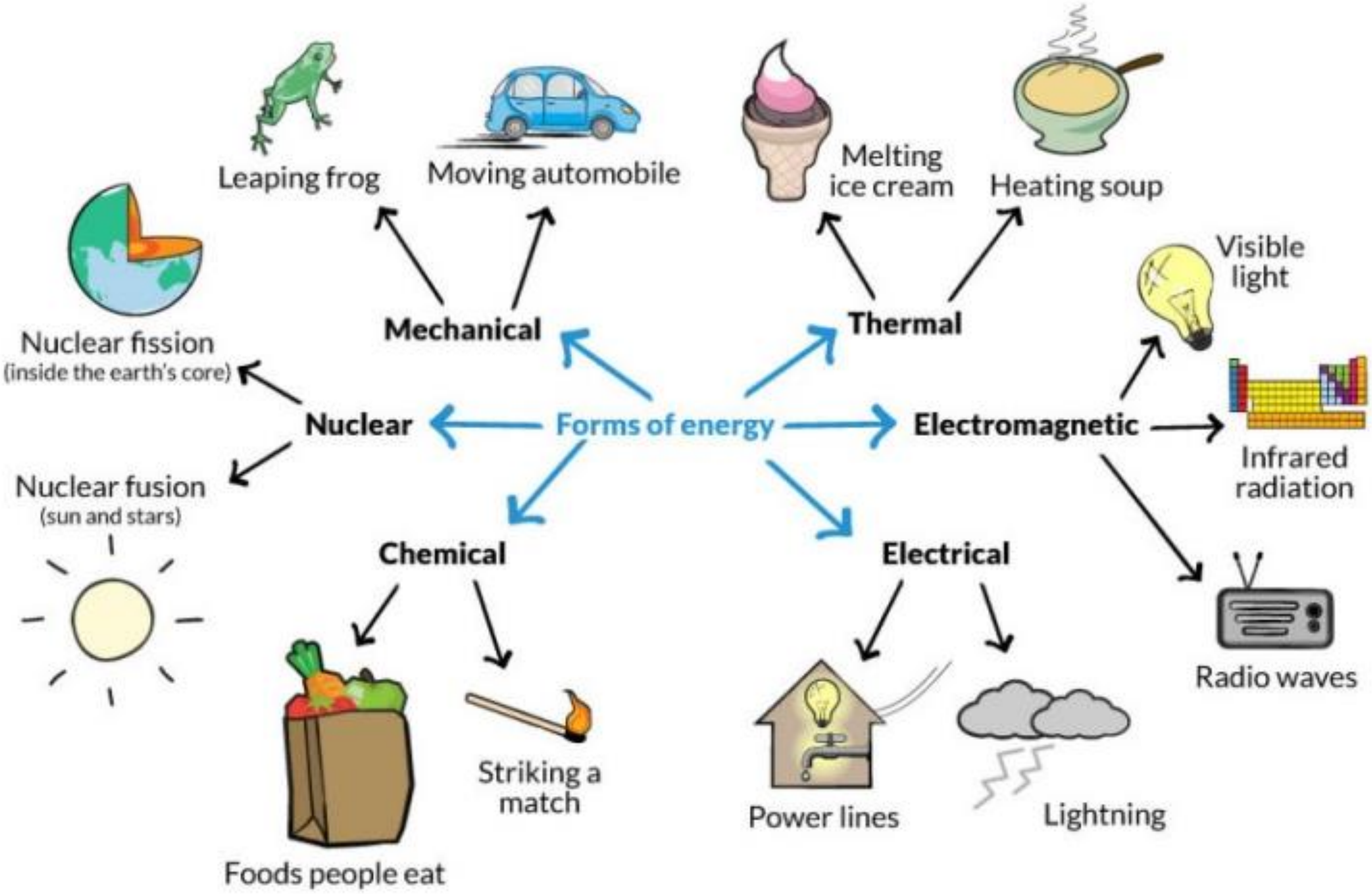
Electrical/Mechanical Energy Conversion

2nd Series Lecture 1 [1]

Types of Energy



INTRODUCTION

- Advantages of using electrical energy
  - ✓It is cheaper
  - ✓Easily transmitted
  - ✓Easy to control and
  - ✓Efficient
- Electrical energy is generated from natural resources
  - ✓Water, coal, diesel, wind, atomic energy, etc.
- Mechanical energy is produced ⟶ Electrical electrical energy using suitable machines.
- For utilization: Electrical energy ⟶ Mechanical, heat, light e.t.c

❖At both ends, energy conversion devices are always required at both ends of a typical electrical system.

❑**Electro/mechanical energy conversion devices**

1. Magnetic Field concepts

- Field concepts are often used to describe forces interact with matter.
  - e.g. Stationary electrical charges: like charges repel and unlike charges attract each other.
- Thus, each charge creates an electric field, and the other charge interacts with the field, resulting into a force.
- Magnetic fields exist in the space around permanent magnets and around wires that carry current.
  - In both cases, the basic source of the magnetic field is electrical charge in motion.
  - In an iron permanent magnet, fields are created by the spin of electrons in atoms.
- These fields aid one another, producing the net external field that we observe.

- We can visualize a magnetic field as lines of magnetic flux that form closed paths. The lines are close together where the magnetic field is strong and farther apart where the field is weaker
- The units of magnetic flux are webers (Wb).
- Hence, **Magnetic field**: The region around a magnet where its poles exhibit a force of attraction or repulsion.

Applications:

- Magnetic fields form the basis of most practical devices for converting energy between electrical and mechanical forms.
- Most electrical equipemts such us *motors, generators, transformers*- which greatly facilitate the distribution of electrical power, *contactors, solenoids, relais, loud speacker, measuring instruments, computer memory systems* etc… depend directely or indirectely upon magnetism.

Distribution of magnetic field

- Place a permanent magnet on a table, cover it over with a sheet of smooth cardboard and sprinkle steel filings uniformly over the sheet.
- Slight tapping of the latter causes the filings to set themselves in curved chains between the poles.
- The shape and density of these chains enable one to form a mental picture of the magnetic condition of the space or ‘field’ around a bar magnet and lead to the earlier idea of lines of magnetic flux.

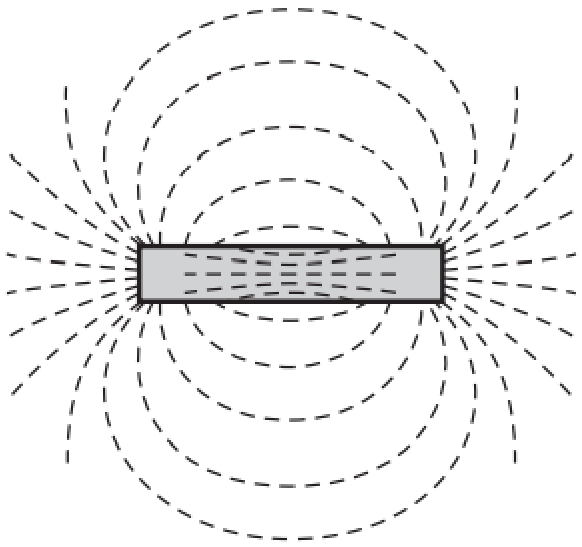


Fig. 1.1: Use of steel filings for determining distribution of magnetic field

Direction of magnetic field

- If a bar magnet rests on a table and four compass needles are placed in positions as indicated
- It is found that the needles take up positions such that their axes coincide with the corresponding chain of filings.
- Their N poles are all pointing along the dotted line from the N pole of the magnet to its S pole
- The lines of magnetic flux are assumed to pass through the magnet, emerge from the N pole and return to the S pole

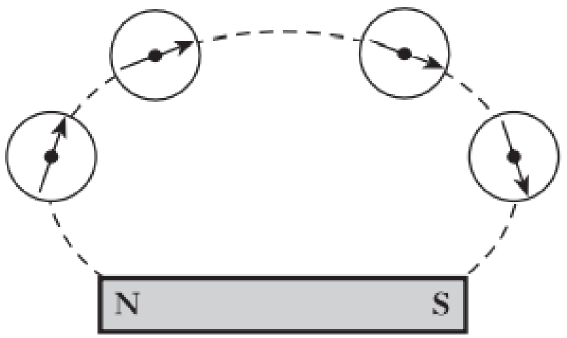


Fig. 1.2: Use of compass needles for determining direction of magnetic field

Characteristics of lines of magnetic flux

1. The direction of magnetic lines of force at any point in a non-magnetic medium, such as air, is from N-pole to the S-pole outside the magnet. But inside the magnet their direction is from S-pole to N-pole.
2. Each line of magnetic flux forms a closed loop.
3. Lines of magnetic flux never intersect.
4. They act like stretched cords, always trying to shorten themselves.

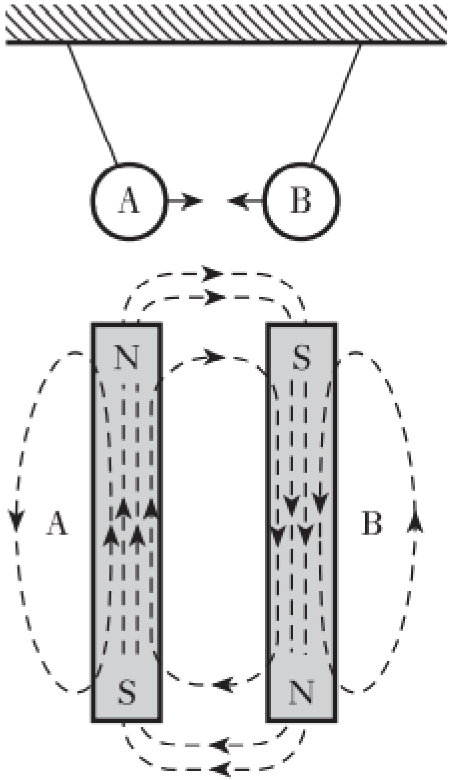


Fig. 1.3: Attraction between magnets

5. Lines of magnetic flux repel each other when they are parallel and are in the same direction.
6. Remain unaffected by non-magnetic materials.
7. Their tendency is to follow the least reluctance path.

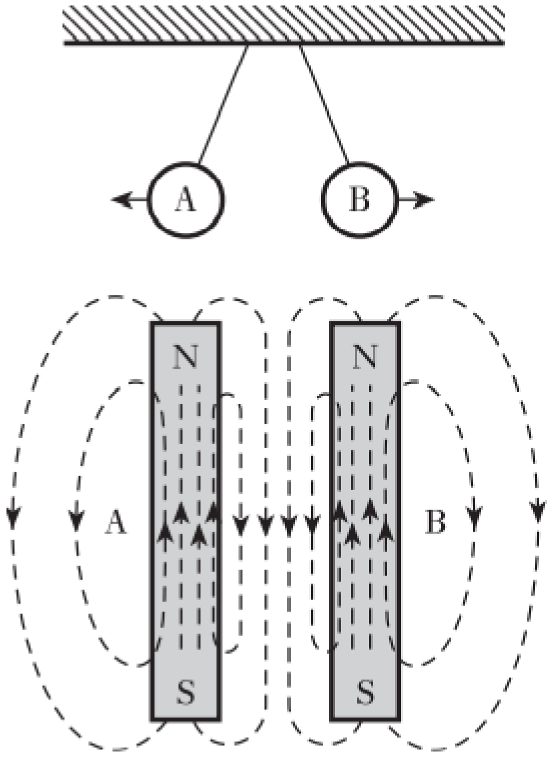


Fig. 1.4: Repulsion between magnets

Magnetic field due to an electric current

- In 1819 a Danish scientist named **Oesterd** discovered the relation between magnetism and electric current.

- By experiment it was found that an electric current **I** flowing through a conductor produces a magnetic field around a conductor.
- The **strength of** the magnetic field depends on current.
  - ✓ A **high current** will produces many lines of forces while **a low current** will produce only few lines close to the wire.

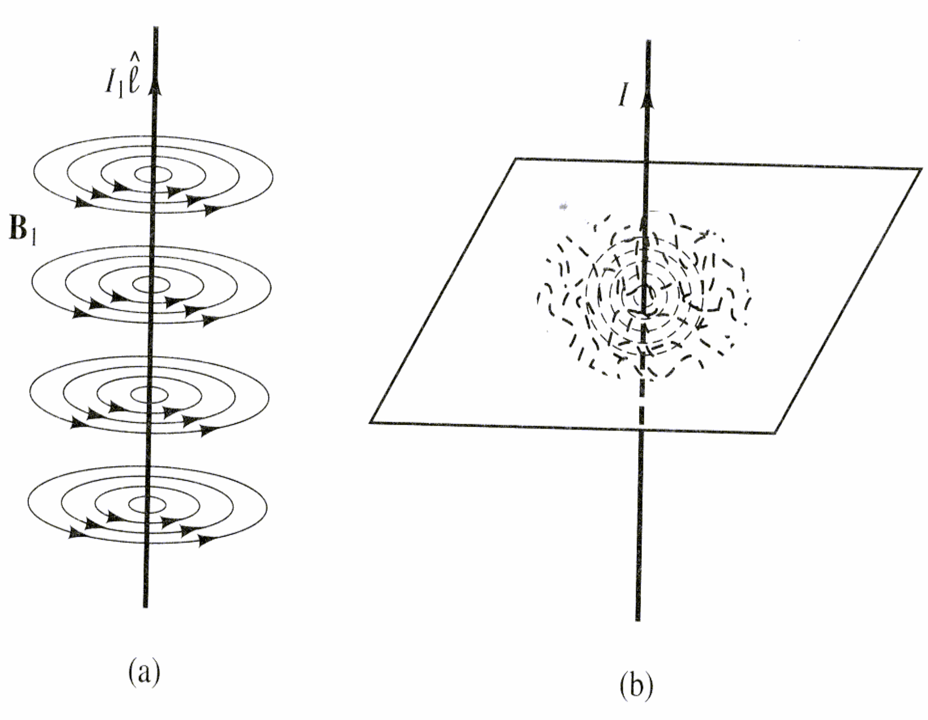
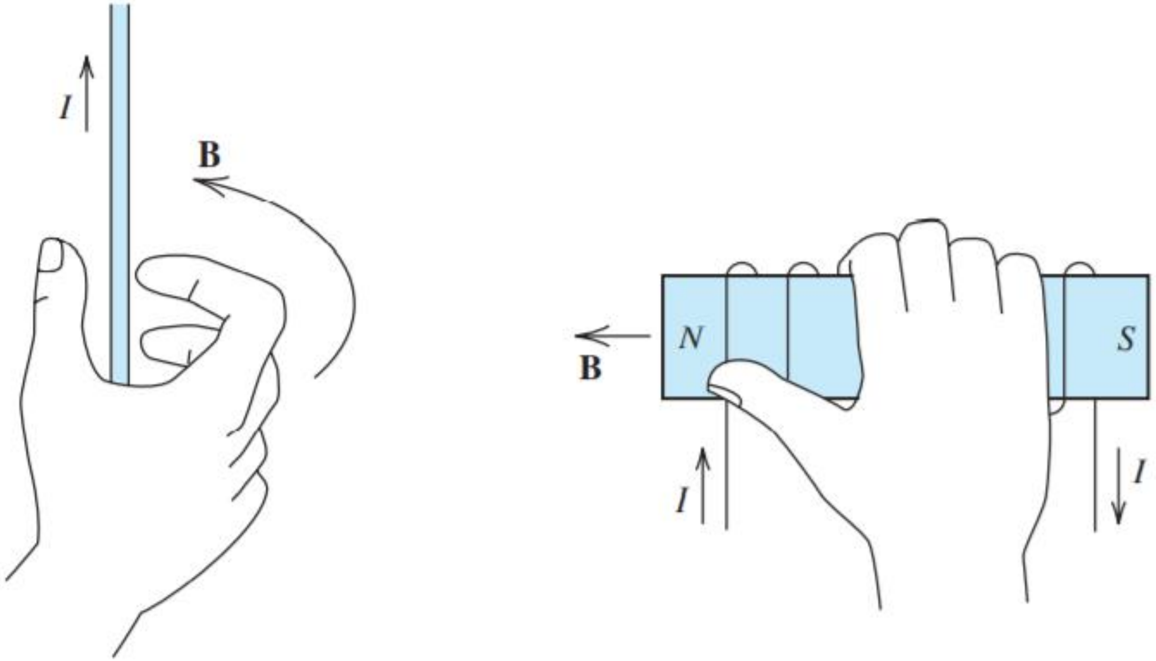


Fig.1.5: Oersted’s experiment

The direction of current and its magnetic field

Right-Hand Rule

- The direction of the magnetic field produced by a current can be determined by the right-hand rule.



(a) If a wire is grasped with the thumb pointing in the current direction, the fingers encircle the wire in the direction of the magnetic field

(b) If a coil is grasped with the fingers pointing in the current direction, the thumb points in the direction of the magnetic field inside the coil

Fig. 1.6: Illustrations of the Right-Hand Rule

Magnetic fields adding or cancelling

- If two wires carrying currents in the same direction, they will both produces a magnetic field and the magnetic interaction is of attractive nature.

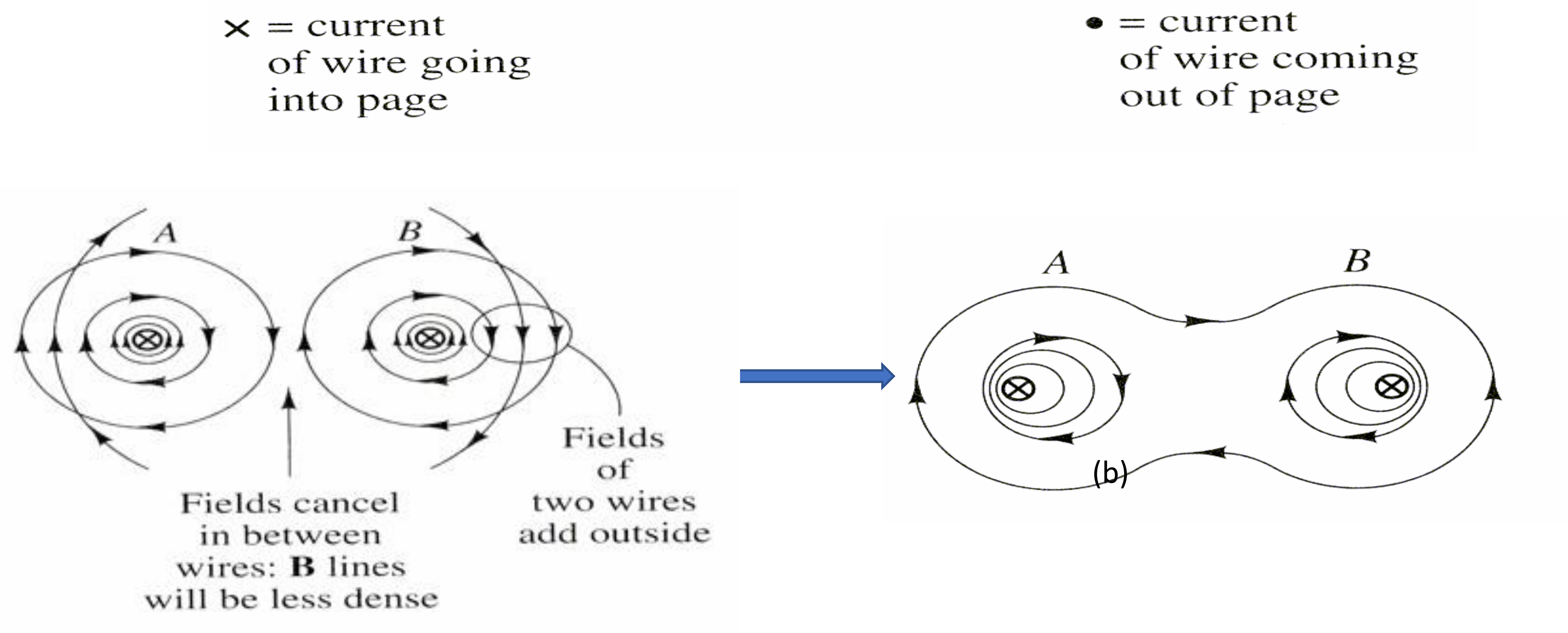


Fig. 1.7: convention of current direction in a wire and Magnetic fields cancelling between two conducors **(=> attraction force)**

- If you have two parallel wires with current traveling in **opposite directions**, as you do in the series circuit, then the magnetic fields of the **two wires** will be traveling in the **same direction** at the point of intersection, and therefore **repel each other.**

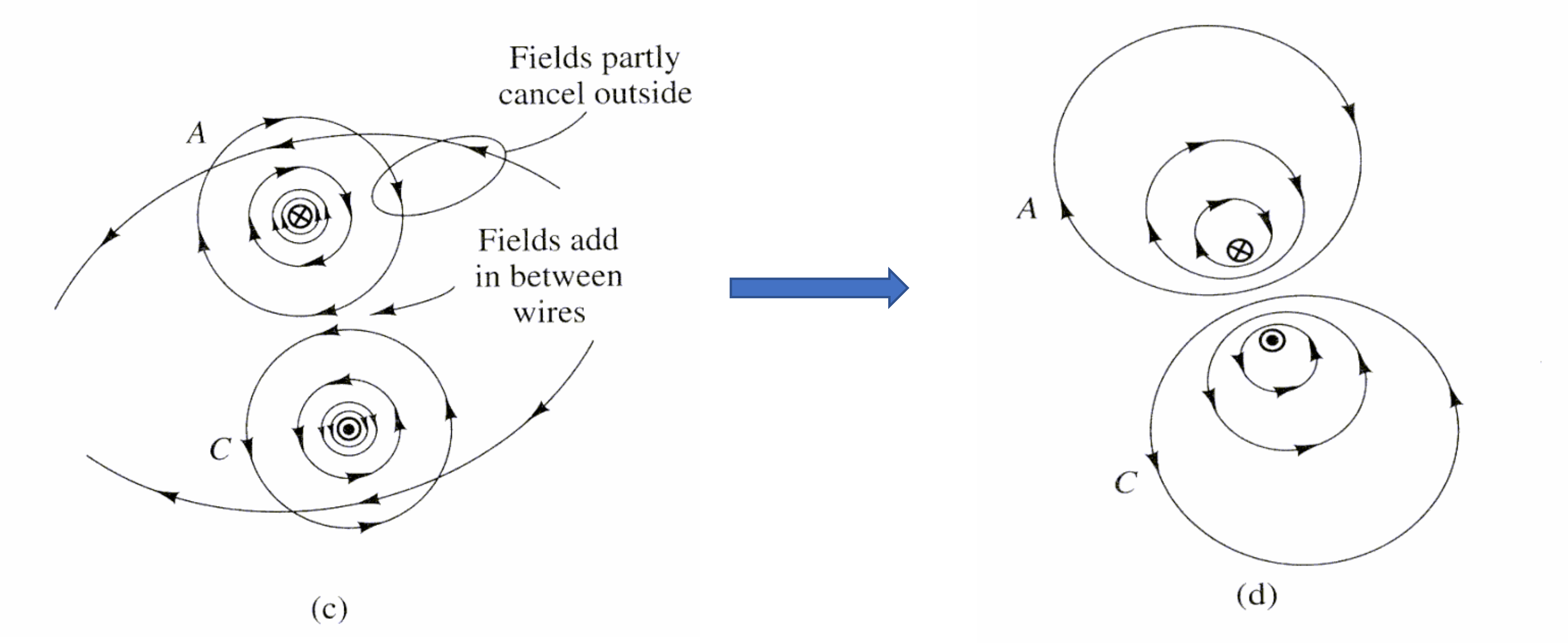


Fig. 1.8: Magnetic fields adding between two wires (=> repulsion force force) and inside a coil of wire.

Magnetic Field Strenght/Intensity (H)

- By experiment **, B** around a current-carrying wire is found to be:

$$B \propto \frac{\mu I}{r} \Rightarrow B = k_m \frac{\mu I}{r}$$

Where is the permeability of the material given by $\mu = \mu_r \mu_0$

$$\begin{cases} \mu_{vacuum} = \mu_0 = 4\pi \times 10^{-7} \, H/m \\ \mu_r = 1 \ \text{for air} \end{cases}$$

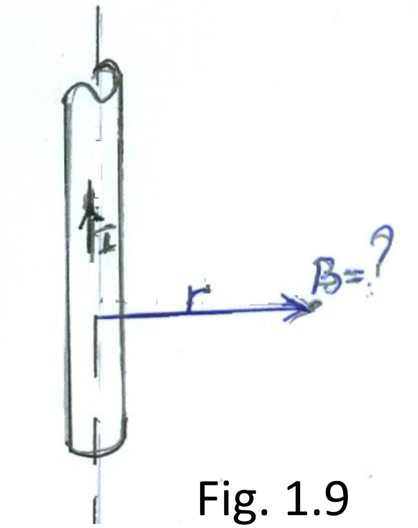


Fig. 1.9

➢Using those values the constant of proportionality is found to be: $k_m = 1/2\pi$

=> $\mathbf{B} = \mu \frac{I}{2\pi r}$ =>> $\mathbf{H} \triangleq \frac{I}{2\pi r}$, independent of the medium

➢ **H** is called magnetic strenght, intensity or magnetizing force or magnetic stress; that drives a resultant flux density **B.**

➢ In general, magnetic fields are set up by charges in motion.

In most of the applications that we consider, the magnetic fields are established by currents flowing in coils.

- We will see that **H** is determined by the currents and the configuration of the coils**.**
- Furthermore, we will see that the resulting flux density **B** depends on **H**, as well as the properties of the material filling the space around the coils.
- The **magnetic field intensity** **H** and **magnetic flux density** **B** are related by :

$$\mathbf{B} = \mu\mathbf{H} = \mu_0\mu_r\mathbf{H} \qquad (1.1)$$

- The units of **H** are amperes/meter (**A/m**), and the units of **μ** are webers/ampere-meter (Wb/Am).
- The value of μ_r ranges from several hundred **- 1** million for various iron and rare-earth alloys.
- The iron used in typical transformers, motors, and generators has a relative permeability of several thousand.

Ampere’s Circuital Law

- **Ampere’s Law:** States that the line integral of magnetic field intensity around a closed path is equal to the sum of the currents flowing through the surface bounded by the path.

- In equation form we have: The **force vector** is given by:

$$\Im = \oint \mathbf{H} \cdot \mathbf{dl} = \sum \mathrm{i}_{\mathrm{enclosed}}$$

✓ For which **dl** is a vector element of length having its direction tangent to the path of integration.

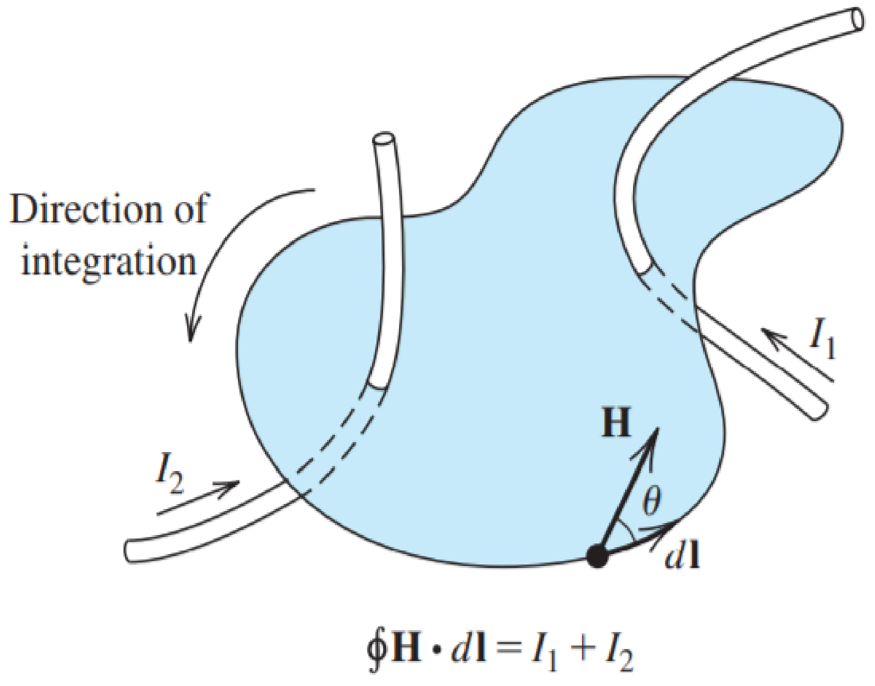


Fig. 1.10

Recalling that the vector dot product is given **by :**

$$\mathbf{H} \cdot \mathbf{dl} = \mathrm{Hdl}\cos\theta, \quad \text{where } \theta \text{ is the angle between } \mathbf{H} \text{ and } \mathbf{dl}$$

- For **N** conductors :

$$\Im = \oint \mathbf{H} \bullet d\mathbf{l} = NI$$

Note that : $\Im = \int_a^b \mathbf{H} \bullet d\mathbf{l}$ is called magnetomotive force (m.m.f.)

- If the magnetic intensity has constant magnitude and points in the same direction as the incremental length **dl** everywhere along the path, Ampère's law reduces to :

$$HL = \sum I_{linked}$$

- In some cases, we can use Ampère's law to **find formulas for the magnetic field in** the **space around a current-carrying wire** or **coil**.

Force on current carrying wire: <u>Lorentz force</u>

- A current-carrying wire in a magnetic field will experiance a Lorentz force in a direction given by Fleming's left hand rule.

Left-hand rule:

i. Hold the thumb, first finger and second finger of the left hand in the manner indicated, whereby they are mutually at right angles as shown in fig.1.11.
ii. Point the **F**irst finger in the **F**ield direction.
iii. Point the se**c**ond (middle) finger in the **C**urrent direction.
iv. The thu**M**b then indicates the direction of the **M**echanical force exerted by the conductor.

- The mechanical force exerted by the conductor always acts in a direction perpendicular to the plane of the conductor and the magnetic field direction.

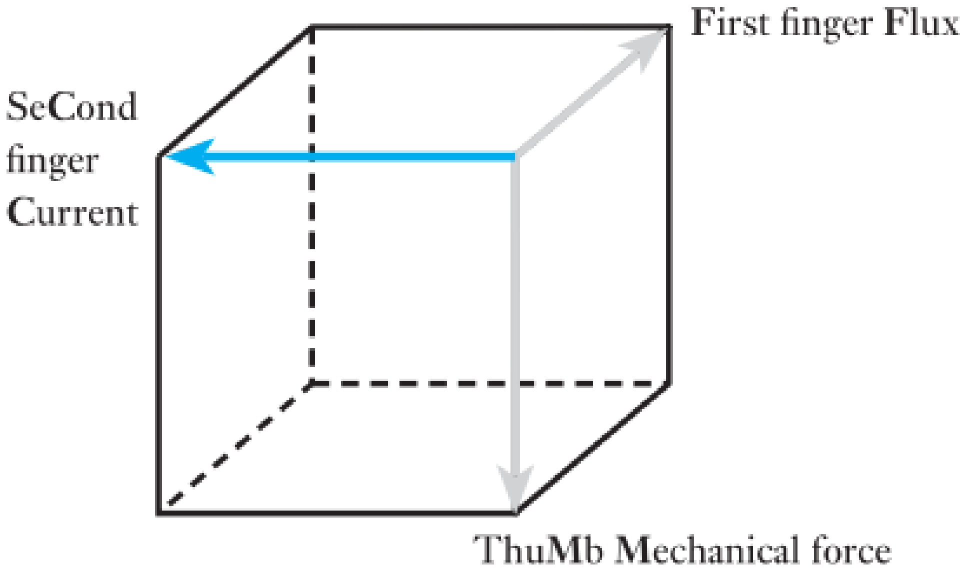


Fig. 1.11: Left-Hand Rule demonstration

Force determination

- For a straight wire of length and a constant magnetic field, the force on the wire will be given by:

F [newtons] ∝ flux density [tesla] × L [metres] × I [amperes]

For a flux density of B teslas,

$$F = BlIsin(\theta) \quad [\text{Newtons}] \qquad (1.2)$$

✓θ is the angle between the wire and the field. Note that, the force is maximized if the direction of the field is perpendicular to the wire.

- For a magnetic field having a cross-sectional area of **A** square metres and a uniform flux density of **B** teslas [T], the total flux in webers (Wb) is represented by the Greek capital letter Φ (phi).

It follows that,

$$\Phi[\mathrm{Wb}] = \mathrm{B}\ [\mathrm{T}] \times \mathrm{A}\ [\mathrm{m}^2]$$

Therefore,

$$\Phi = \mathrm{BA} \tag{1.3}$$

- We say that the flux passing through the surface bounded by a coil **links** the coil. If the coil has N turns, then the total flux linkages are given by:

$$\lambda = \mathrm{N}\Phi$$

and

$$B = \frac{\Phi}{A} \tag{1.4}$$

Example 1:

A conductor carries a current of 800 A at right angles to a magnetic field having a density of 0.5 T. Calculate the force on the conductor in newtons per metre length.

Solution:

$$F = BlI = 0.5[\mathrm{T}] \times 1[\mathrm{m}] \times 800[\mathrm{A}] = \mathbf{400N}$$

Example 2:

A rectangular coil measuring 200 mm by 100 mm is mounted such that it can be rotated about the midpoints of the 100 mm sides. The axis of rotation is at right angles to a magnetic field of uniform flux density 0.05 T. Calculate the flux in the coil for the following conditions: **(a)** the maximum flux through the coil and the position at which it occurs; **(b)** the flux through the coil when the 100 mm sides are inclined at 45° to the direction of the flux (Fig. 1.12).

Fig. 1.12

Solution:

a) The maximum flux will pass through the coil when the plane of the coil is at right angles to the direction of the flux.

$$\Phi = BA = 0.05 \times 200 \times 10^{-3} \times 100 \times 10^{-3} = 1\ \mathbf{mWb}$$

b)

$$\Phi = BA\sin\theta = 1 \times 10^{-3} \times \sin 45^{0} = \mathbf{0.71\ mWb}$$

The Magnetic Force between Two Current-carrying Conductors:

- The **Force exerted on** the conductor C_2 -of length L-due to B_1 (flux density produced by the current I_1) is:

$$F_2 = B_1 I_2 L = \mu_0 H_1 L I_2$$

$$= \mu_0 \frac{I_1}{2\pi d} L I_2 \qquad (1.5)$$

$$\Rightarrow F_2 = \mu_0 \frac{I_1 I_2}{2\pi} \frac{L}{d}$$

$$\because F_1 = -F_2$$

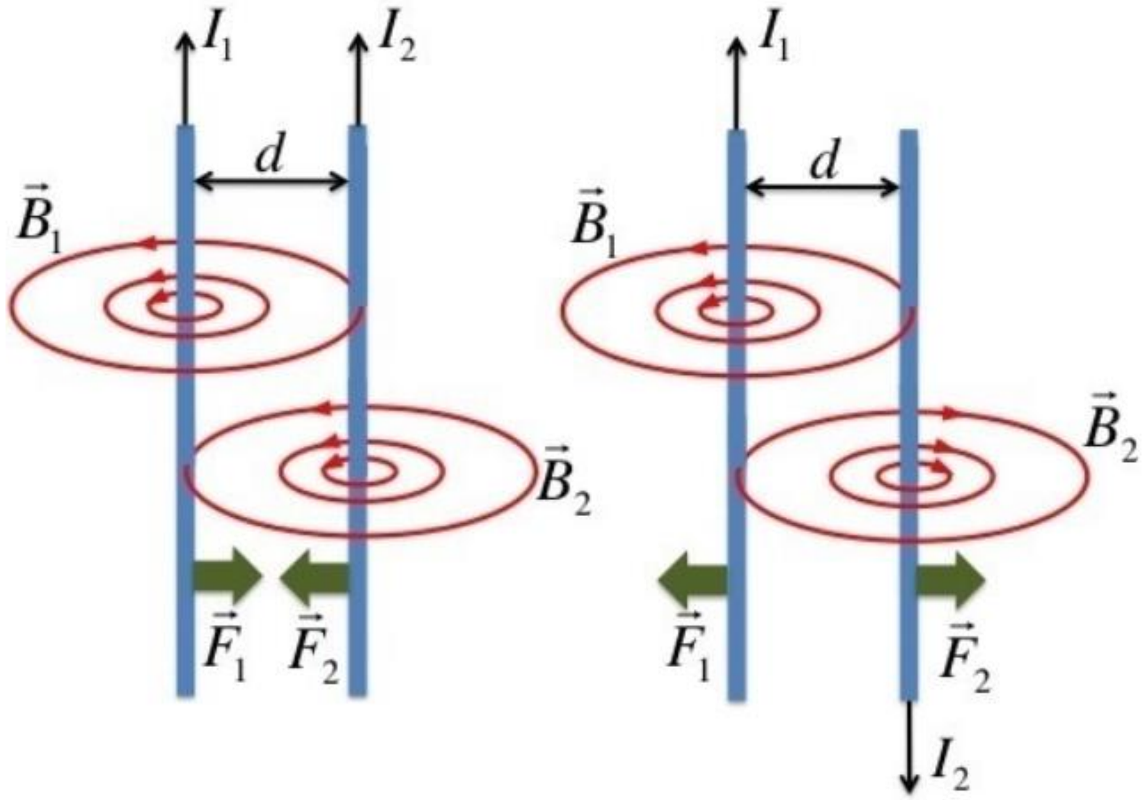


Fig. 1.13: Two current-carrying conductors

2. Electromagnetic induction

- The phenomenon by which an emf is induced in a circuit (and hence current flows when the circuit is closed) when magnetic flux linking with it changes is called **electro-magnetic induction.**

- In 1831, Michael Faraday made the great discovery of **electromagnetic induction**, a method of obtaining an electric current with the aid of magnetic flux.
- When switch S was closed, a deflection was obtained on galvanometer G,
- When S was opened, G deflected in the reverse direction.

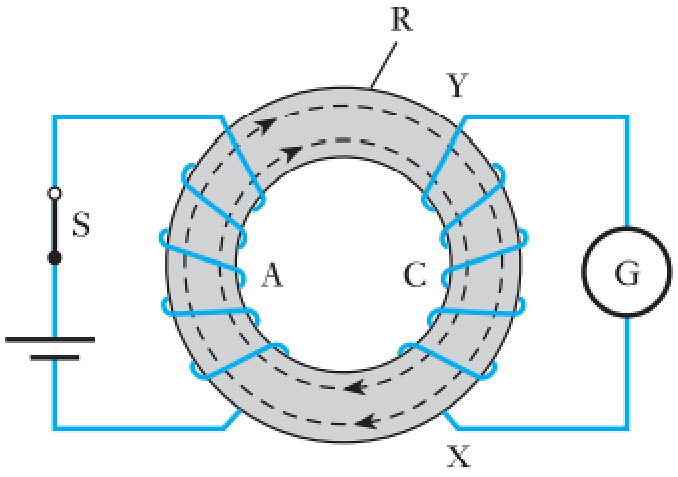


Fig. 2.1

Illustration of Electromagnetic Induction

- When a permanent bar magnet is taken nearer to the coil or away from the coil, as shown in Fig. 2.2:
  - ✓A deflection occurs in the needle of the galvanometer.
- Although, the deflection in the needle is opposite is two cases.

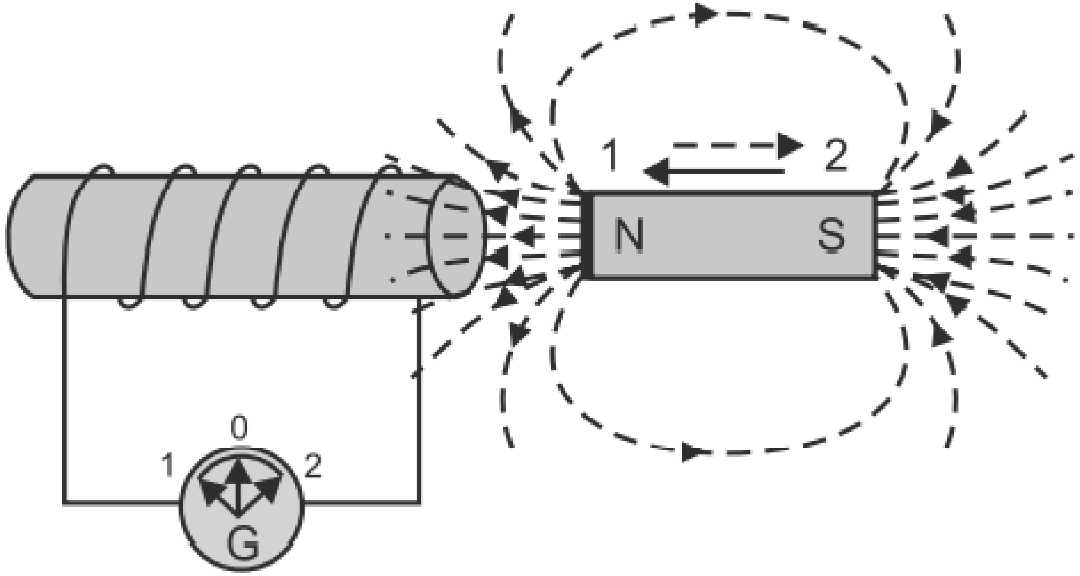


Fig. 2.2: Bar magnet in motion

- On the other hand, if the bar magnet is kept stationary and the coil is brought nearer to the magnet or away from the magnet, as shown in Fig. 2.3:
    - ✓ Again a deflection occurs in the needle of the galvanometer.
- Still, deflection in the needle is opposite in the two cases.
- However, if the magnet and the coil both are kept stationary, no matter how much flux is linking with the coil, there is no deflection in the galvanometer needle.

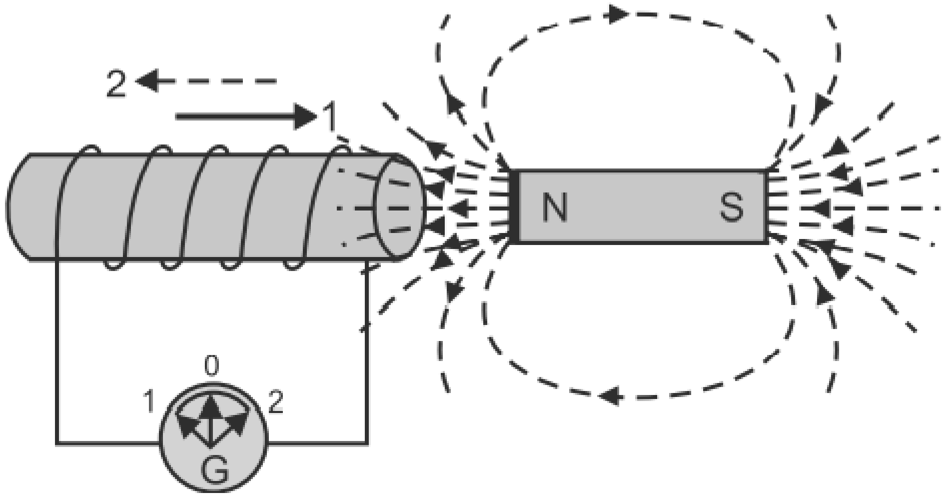


Fig. 2.3 Coil in motion

Factors that lead to an increased current in the coil:

i. By using a stonger magnet
ii. Increasing the motion of the magnet
iii. Increasing the Area or the Number of Turnsof the Coil

The following points are worth noting:

i. The deflection in the galvanometer needle shows that emf is induced in the coil. This condition occurs only when flux linking with the circuit changes i.e., either magnet or coil is in motion.

ii. The direction of induced emf in the coil depends upon the direction of magnetic field and the direction of motion of coil.

Faraday's Laws

First law: This law states that "Whenever a conductor cuts across the magnetic field, an emf is induced in the conductor." or "Whenever the magnetic flux linking with any circuit (or coil) changes, an emf is induced in the circuit."

Second Law: This law states that "The magnitude of induced emf in a coil is directly proportional to the rate of change of flux linkages."

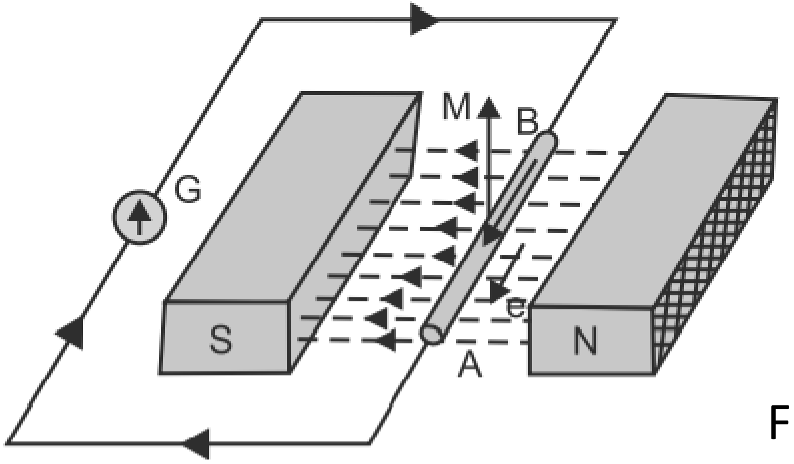
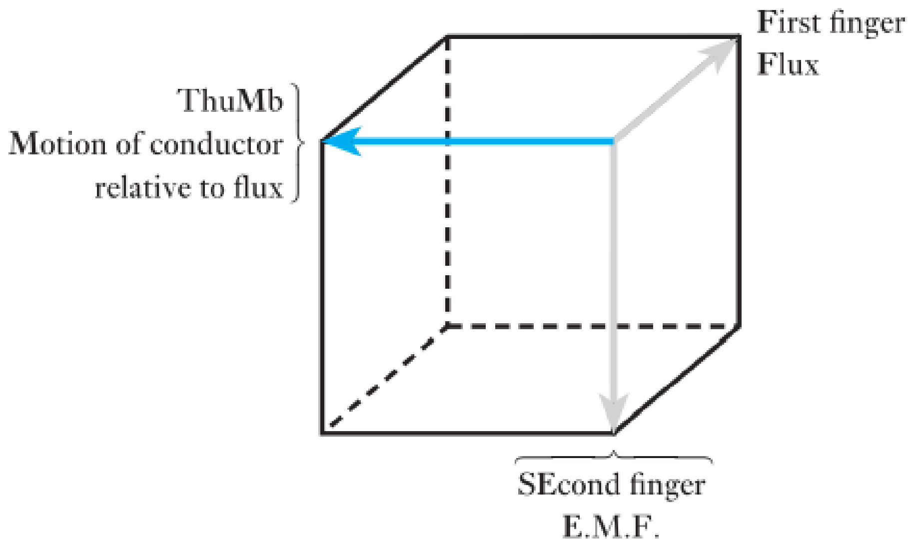


Fig. 2.4

Direction of induced e.m.f.

Fleming's right-hand rule

- ❖If the first finger of the right hand is pointed in the direction of the magnetic flux, as in Fig. 2.5,
- ❖The thumb is pointed in the direction of motion of the conductor relative to the magnetic field, then
- ❖The second finger, held at right angles to both the thumb and the first finger, represents the direction of the e.m.f.



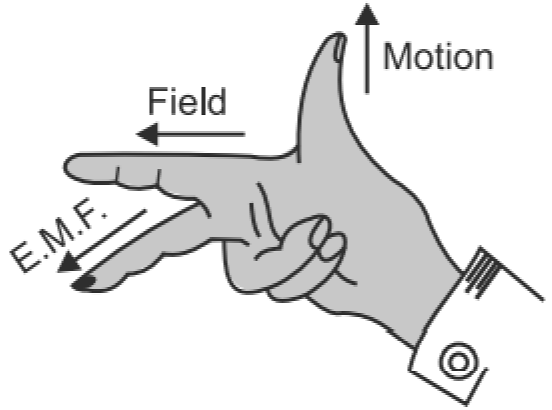


Fig. 2.5

Lenz's law

- The direction of an induced e.m.f. is always such that it tends to set up a current opposing the motion or the change of flux responsible for inducing that e.m.f

Or

- The direction of the current that is induced is such that it produces its own magnetic field in a manner that opposes the original magnetic field.

Magnitude of the generated or induced e.m.f.

- The work done in moving conductor AA through a distance d metres to position BB is $(BlI \times d)$ joules.
    - ➢If this movement of AA takes place at a uniform velocity in t seconds, the e.m.f. induced in the conductor is constant at, say, E volts. Hence the electrical power generated in AA is IE watts and the electrical energy is IEt watt seconds or joules.

➢Since the mechanical energy expended in moving the conductor horizontally across the gap is all converted into electrical energy, then

$$IEt = BlId$$

Therefore,

$$E = \frac{Bld}{t}$$

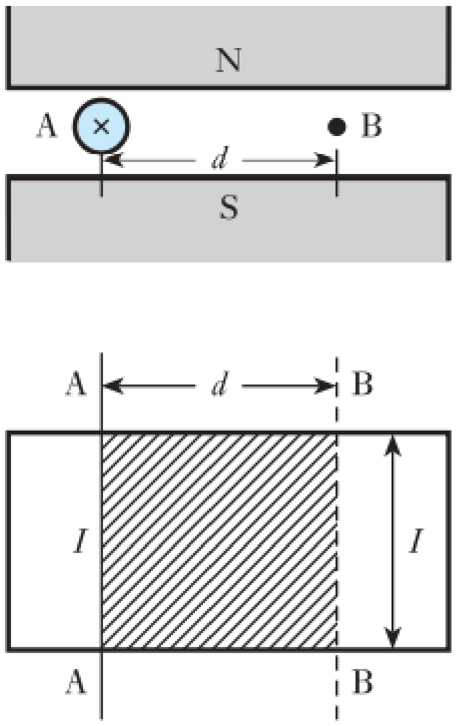


Fig.2.6

and

$$E = Blu \tag{2.1}$$

where u is the velocity in metres per second. But Bld is the total flux, Φ [Wb], in the shaded region of Fig. 2.6. This flux is cut by the conductor when the latter is moved from AA to BB. Hence,

$$E = \frac{\Phi[Wb]}{t[s]}$$

In general, if a conductor cuts or is cut by a flux of $d\Phi$ webers in dt seconds, e.m.f. generated in conductor $= d\Phi/dt$ volts.

$$e = \frac{d\Phi}{dt} \tag{2.2}$$

Example 3

Calculate the e.m.f. generated in the axle of a car travelling at 80 km/h, assuming the length of the axle to be 2 m and the vertical component of the earth's magnetic field to be 40 µT (microteslas).

Solution:

$$u = 80\ [km]/h = \frac{(80 \times 100)\ [\mathrm{m}]}{3600\ [s]} = 22.2\ m/s$$

Vertical component of earth's field is $40 \times 10^{-6}\ \mathrm{T}$

$$\text{Flux cut by axle} \quad \begin{aligned} &= 40 \times 10^{-6}\ [\mathrm{T}] \times 2\ [\mathrm{m}] \times 22.5\ [\mathrm{m/s}] \\ &= 1776 \times 10^{-6}\ \mathrm{Wb/s} \end{aligned}$$

and e.m.f. generated in axle is

$$e = \mathbf{1780}\ \boldsymbol{\mu}\mathbf{V}$$

Magnitude of e.m.f. induced in a coil

The average e.m.f. induced in one turn is

$$\frac{\Phi}{t} \text{ volts}$$

The average e.m.f. induced in a coil is

$$\frac{N\Phi}{t} \text{ volts} \qquad (2.3)$$

Flux linkage (λ)

$$\lambda = N\Phi \text{ (Wb)}$$

$$e = \frac{N(\phi_2 - \phi_1)}{t}$$

In differential form,

$$e = \frac{d}{dt}(N\Phi) \text{ volts} \qquad (2.4)$$

and

$$e = \frac{d\lambda}{dt} \qquad (2.5)$$

In general,

$$e = N\frac{d\Phi}{dt} \qquad (2.6)$$

Example 4

A magnetic flux of 400 μWb passing through a coil of 1200 turns is reversed in 0.1 s. Calculate the average value of the e.m.f. induced in the coil.

Solution:

$$e = \frac{N(\phi_2 - \phi_1)}{\Delta t} = \frac{1200 \times (400 - (-400)) \times 10^{-6}}{0.1} = \mathbf{9.6\ V}$$

Induced e.m.f

When flux linking a conductor (or coil) changes, an emf is induced in it. This change in flux linkages can be obtained in the following two ways:

i. Dynamically induced emf

Moving the conductor and keeping the magnetic field system stationary or vice-versa (as in case of DC and AC generators).

ii. statically induced emf

Changing the flux linking with the coil (or conductor) without moving either coil or field system.

- ✓ obtained by changing the magnitude of the current in the field system (solenoid), as in transformers.