Basic Electrical Technology

2. Magnetic Circuits & Electromagnetism

Introduction to Magnetism
Series Magnetic Circuits

Magnetism

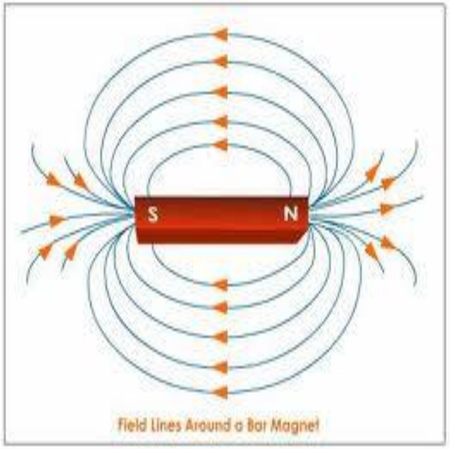
- A physical phenomena by which materials exert attractive or repulsive force on other materials

- **Magnetic Materials**
  - Properties:
    - Points in the direction of magnetic north and south pole when suspended freely and attracts iron fillings
  - Classification:
    - Natural Magnets: Lodestone
    - Temporary magnets (exhibits these properties when subjected to external force)

Definitions

- **Magnetic Line of Force**
  - Closed path radiating from north pole, passes through the surrounding, terminates at south pole and is from south to north pole within the body of the magnet

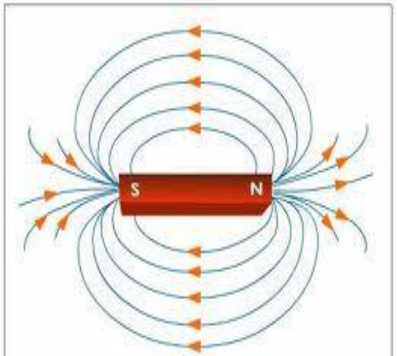
- **Magnetic Field**
  - The space around which magnetic lines of force act
  - Strong near the magnet and weakens at points away from the magnet



- **Magnetic Flux (ϕ)**
  - Analogous to Electric Current
  - Number of magnetic lines of force created in a magnetic circuit.
  - Unit : Weber (Wb)

Definitions

- **Magnetic Flux Density (B)**
  - Analogous to Current Density
  - No. of magnetic lines of force created in a magnetic circuit per unit area normal to the direction of flux lines
  - $\boldsymbol{B} = \boldsymbol{\Phi} / \boldsymbol{A}$
  - Unit : Wb/m^2 (Tesla)



Field Lines Around a Bar Magnet

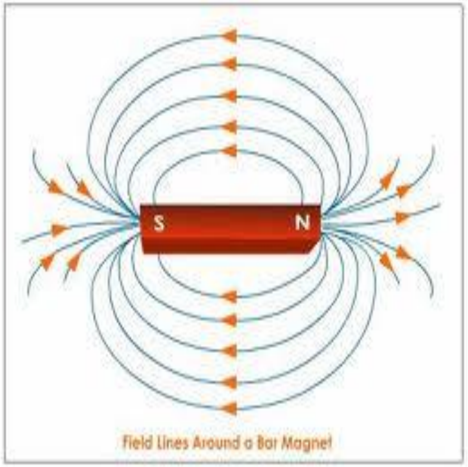
- **Magneto Motive Force (F)**
  - Analogous to EMF
  - Force which drives the magnetic lines of force through a magnetic circuit
  - $\boldsymbol{F} = \boldsymbol{\Phi} \times \boldsymbol{S} = \boldsymbol{N} \times \boldsymbol{I}$

    Where, $\boldsymbol{\Phi}$ = Magnetic flux, $\boldsymbol{S}$ = Reluctance of the magnetic path

    $\boldsymbol{N}$ = No. of turns of the coil, $\boldsymbol{I}$ = Current flowing through the coil
  - Unit: AT (Ampere-Turns)

Definitions

- **Magnetic Field Strength (H)**
  - Analogous to Electric Field Strength
  - The magneto motive force per meter length of the magnetic circuit
  - $\boldsymbol{H = (N \times I)/l}$
  - Unit: AT/m



- **Permeability (μ)**
  - Analogous to Conductivity
  - A property of a magnetic material which indicates the ability of magnetic circuit to carry magnetic flux.
  - $\boldsymbol{\mu = B \,/\, H}$
  - $\mu_0 = 4\pi \times 10^{-7} \Longrightarrow$ Permeability of free space or air or non magnetic material
  - Unit: H/m

- **Relative Permeability (μ_r)**
  - Permeability of the material with reference to air / vacuum
  - $\boldsymbol{\mu_r = \mu/\mu_0}$

Definitions

- **Reluctance (S)**
  - Analogous to Resistance
  - Opposition of a magnetic circuit to the setting up of magnetic flux in it
  - Unit: AT/Wb

- **Derivation of an expression for reluctance**

$$H = (N \times I)/l$$

$$\mu = B \;/\; H$$

$$B \; = \Phi / \; A$$

$$F \; = N \; \times \; I = H \; \times l = (B/\mu) \times l = ((\Phi / \; A \;)/\mu) \times l = \frac{\Phi}{\mu A} \times l$$

$$F = \frac{\Phi}{\mu_0 \mu_r A} \times l = \Phi \times S$$

$$S = \frac{l}{\mu_0 \mu_r A}$$

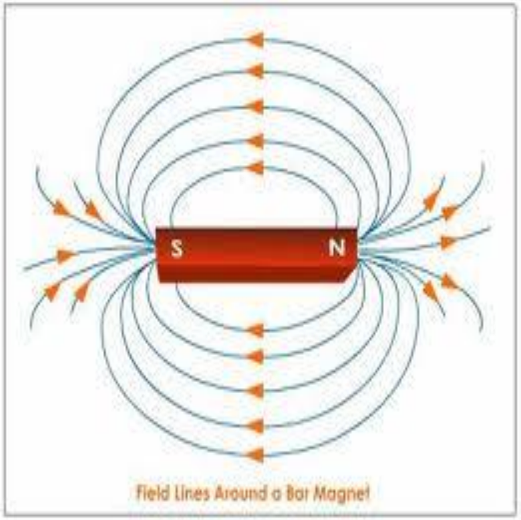


Illustration 01

A ring made of ferromagnetic material has 500 mm^2 as cross-sectional area and 400 mm as mean circumference. A coil of 600 turns is wound uniformly around it. Calculate:

a) The reluctance of the ring

b) The current required to produce a flux density of 1.6 T in the ring

Take μ_r of the ferromagnetic material as 800 for flux density of 1.6 T

Ans:

a) 795774.72 AT/Wb

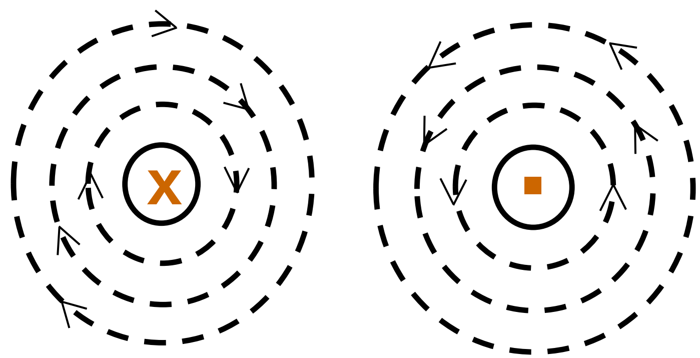
b) 1.06 A

Magnetic Field (in a Current-Carrying Conductor)

- An electric current flowing in a conductor creates a magnetic field around it

- **Direction of magnetic field**
  - **By Maxwell’s Right Hand Grip Rule:**

    Assume that the current carrying conductor is held in right hand so that the fingers wrap around the conductor and the thumb is stretched along the direction of current. Wrapped fingers will show the direction of circular magnetic field lines

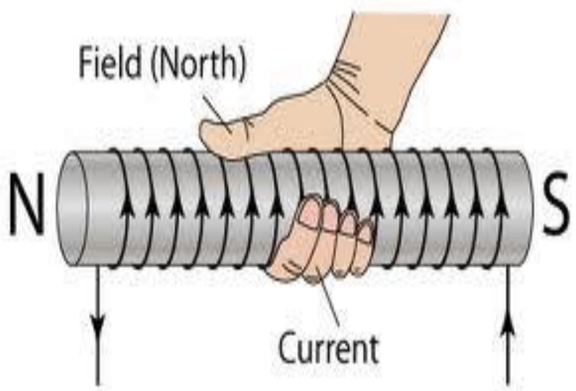


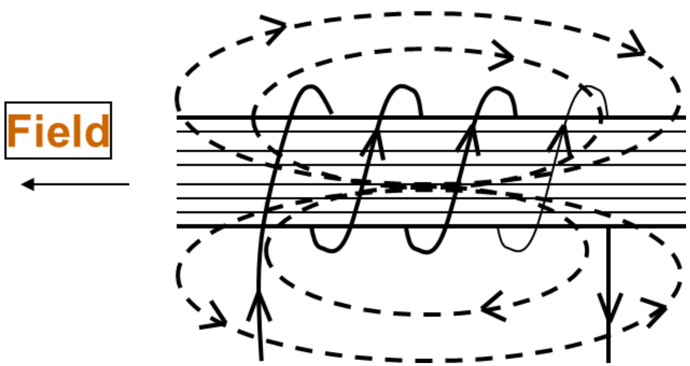
Current inwards   Current outwards

Magnetic Field (in a Solenoid)

- **Direction of magnetic field**
  - **By Right Hand Grip Rule:**

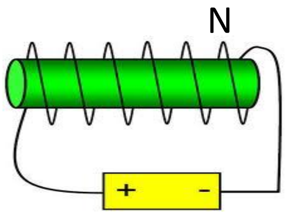
    If the coil is gripped with the right hand, with the fingers pointing in the direction of the current, then the thumb, outstretched parallel to the axis of the solenoid, points in the direction of the magnetic field inside the solenoid

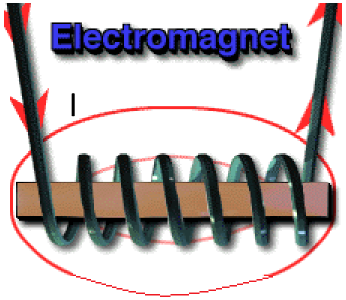




Electromagnets

- **Principle:** An electric current flowing in a conductor creates a magnetic field around it
- Strength of the field is proportional to the amount of current in the coil
- The field disappears when the current is turned off
- A simple electromagnet consists of a coil of insulated wire wrapped around an iron core
- Widely used as components of motors, generators, relays etc.





Comparison of Electric and Magnetic Circuits

Analogy:

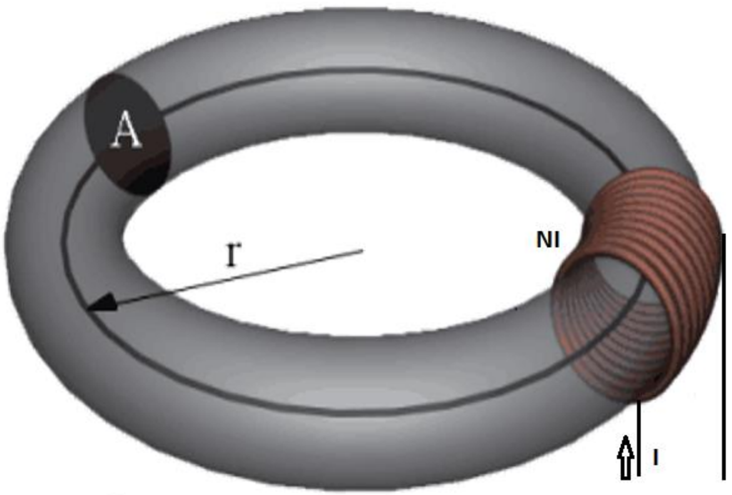
Electric Circuits	Magnetic Circuits
Current	Flux
Current Density	Flux Density
EMF	MMF
Conductivity	Permeability
Resistance	Reluctance

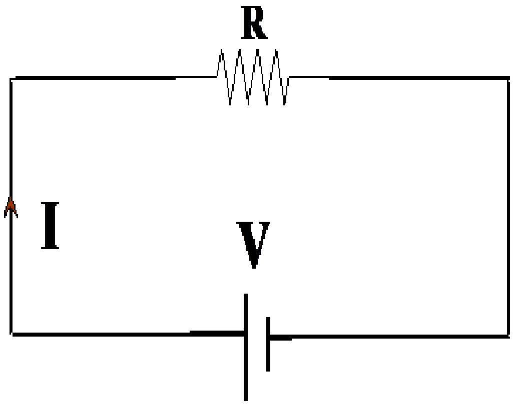
Differences:

Electric Circuits	Magnetic Circuits
Current actually flows	Flux does not flow
Current can not flow in air / vacuum	Flux can be created in air / vacuum

Magnetic Circuits

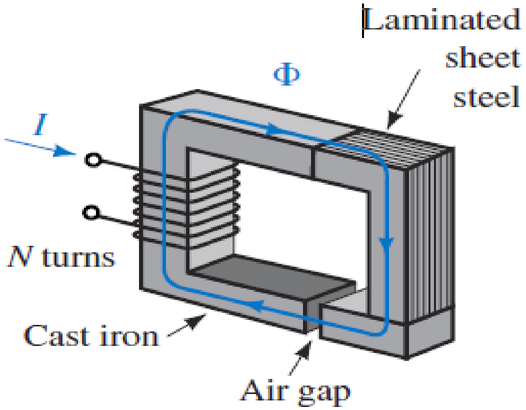
The complete closed path followed by any group of magnetic lines of flux





Series Magnetic Circuit

- Flux ϕ is the same in all sections if leakage flux is neglected.
- Flux density and reluctance in each section may vary, depending on its effective cross-sectional area and material.
- Equivalent reluctance is the sum of reluctance of different parts/elements.
- The resultant MMF is the sum of MMFs in each individual parts/elements



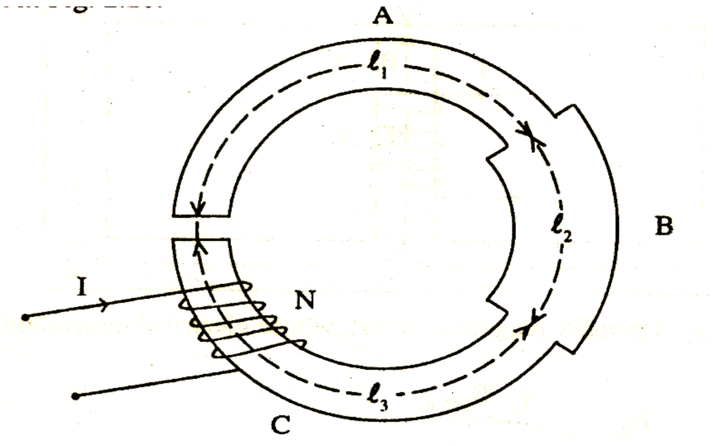
Rectangular shaped series magnetic circuit with air gap.

Series Magnetic Circuit

$$S_1 = \frac{l_1}{\mu_0\, \mu_{r1}\, A_1},\ S_2 = \frac{l_2}{\mu_0\, \mu_{r2}\, A_2}$$

$$S_3 = \frac{l_3}{\mu_0\, \mu_{r3}\, A_1}, S_g = \frac{l_g}{\mu_0\, A_1}$$

$$S_T = S_1 + S_2 + S_3 + S_g$$



$$Total\ mmf = \phi_1 S_1 + \phi_2 S_2 + \phi_3 S_3 + \phi_g S_g$$

$$= H_1 l_1 + H_2 l_2 + H_3 l_3 + H_g l_g$$

$$= \left(\frac{B_1 l_1}{\mu_0 \mu_{r1}} + \frac{B_2 l_2}{\mu_0 \mu_{r2}} + \frac{B_3 l_3}{\mu_0 \mu_{r3}} + \frac{B_g l_g}{\mu_0}\right)$$

Useful & Leakage Flux

- **Magnetic leakage:**
  - The passage of magnetic flux outside the path along which it can do useful work

- Total flux of coil = Useful flux + Leakage flux

- **Leakage Coefficient**:

$$\lambda = \frac{\text{Total Flux of the Coil}}{\text{Useful Flux}}$$

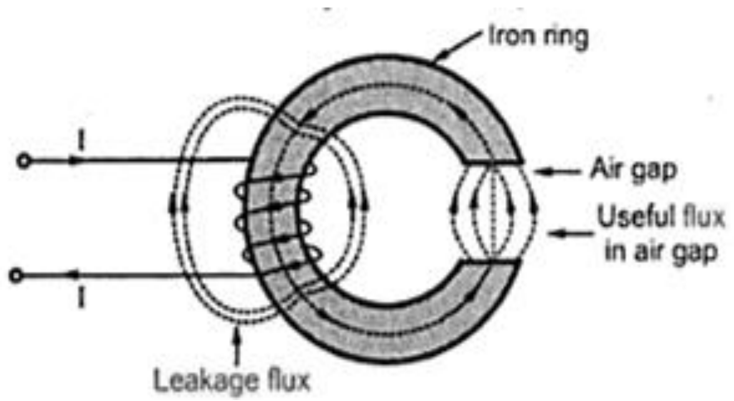


Illustration 2

An iron ring has a circular cross- sectional area of 5 cm^2 and a mean circumference of 100 cm. The ring is uniformly wound with a coil of 1000 turns. Relative permeability of iron is 800.

a) Find the current required to produce a flux of 1 mWb in the ring.
b) If a saw cut of 2 mm wide is made in the ring, find the flux produced, if the current is same as that found in **part a**.
c) Find the current required to produce the same flux as in **part a** for the cut made in the ring in **part b**.

Ans:
a) 1.99 A
b) 0.385 mWb
c) 5.17 A

Illustration 3

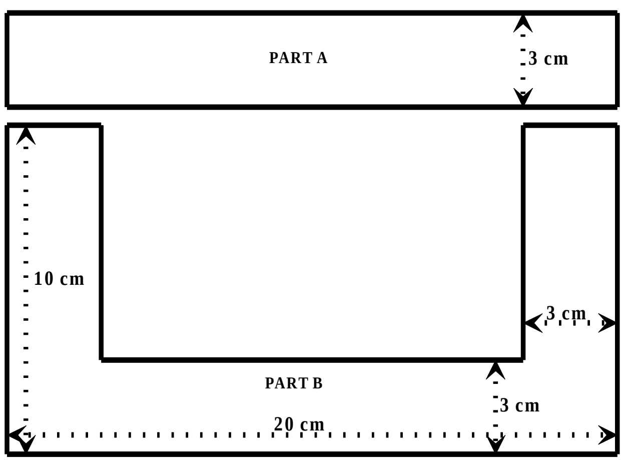
The magnetic circuit shown in the figure is made of iron having a square cross-section of 3 cm side. It has two parts A and B, with relative permeabilities of 1000 and 1200 respectively, separated by two air gaps, each 2 mm wide. The part B is wound with a total of 1000 turns of wire on the two side limbs carrying a current of 2.5 A. Calculate

a) The reluctances of Part-A, Part-B & air gaps

b) the total reluctance

c) the mmf

d) the flux and the flux density



Hint:

Length of Part A = 1.5 + (20-1.5-1.5)+1.5 = 20cm

Length of Part B = (10-1.5)+(20-1.5-1.5)+(10-1.5) = 34 cm

Ans:

S_A = 176838.83AT/Wb,

S_B = 250521.67AT/Wb

S_g = 3536776.51AT/Wb

S_T = 3964137AT/Wb

mmf = 2500 AT

Φ = 0.63 mWb, B = 0.7 T

Illustration 4

A ring of cross sectional area 12 cm^2 has 3 parts made of following materials:

Part	Material	Length	Relative Permeability
A	Iron	25 cm	800
B	Steel	18 cm	1100
C	Air	2 mm	---

A coil of 660 turns carrying a current of 2.1 A is wound uniformly on the ring. Determine the flux density in the air gap. Assume no leakage and fringing effect.

Ans: 0.703 Wb/m^2