MANIPAL INSTITUTE OF TECHNOLOGY
MANIPAL
(A constituent institution of MAHE, Manipal)

Basic Electrical Technology

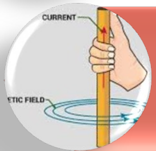
2. Magnetic Circuits & Electromagnetism

LECTURE **

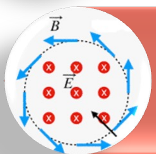
Introduction to Magnetism

Source of Magnetic Field

Permanent Magnet



Electric current



Electric field changing with respect to time

Magnetism

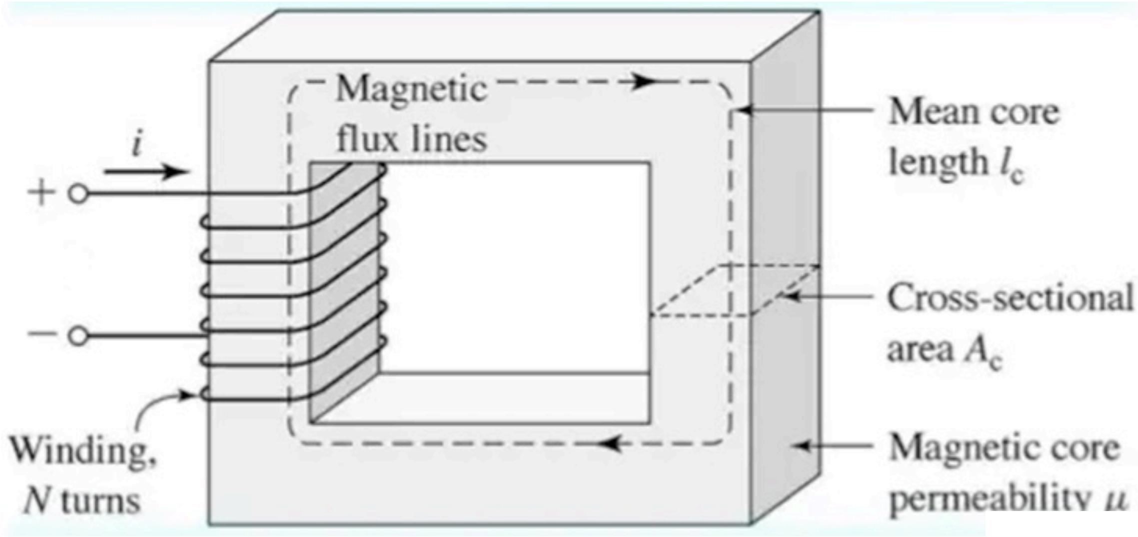
A physical phenomenon by which materials exert an attractive or repulsive force on other materials.

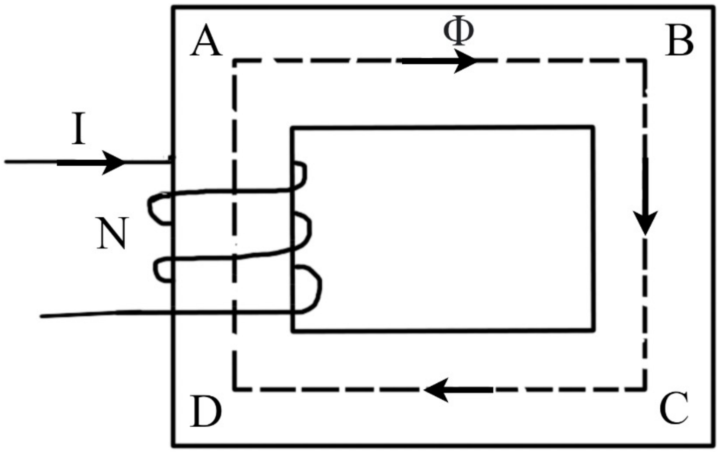
Magnetic Materials

- **Properties:**
  - Points in the direction of magnetic north and south pole when suspended freely and attracts iron filings

- **Classification:**
  - **Natural Magnets:**
    - Occurs naturally in nature
    - All the natural magnets are permanent magnet
  - **Temporary magnets** (exhibits these properties when subjected to external force)
    - Example: Electromagnet – magnetic field is produced by an electric current

Simple Magnetic Circuit

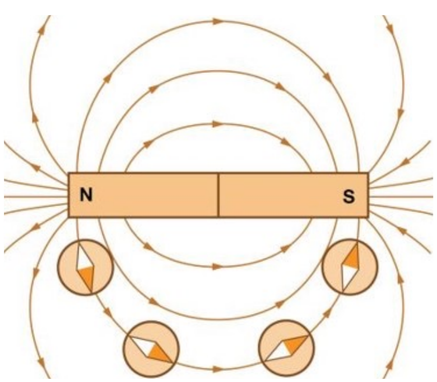




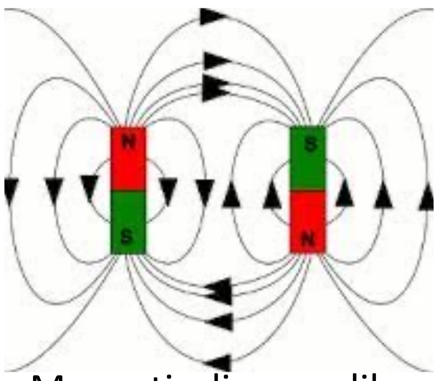
Definitions

- **Magnetic Lines of Force**
  - Magnetic Lines of Force is an imaginary line representing the direction of the magnetic field such that the tangent at any point is the direction of the field vector at that point.
  - Closed path radiating from the north pole, passes through the surrounding, terminates at the south pole, & is from south to north pole within the body of the magnet.

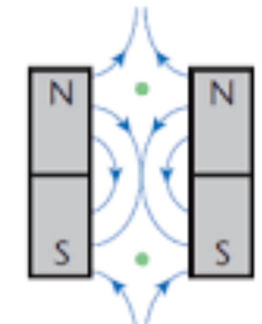
Properties



Magnetic line form a closed path



Magnetic line are like stretched elastic cord always trying to shorten themselves

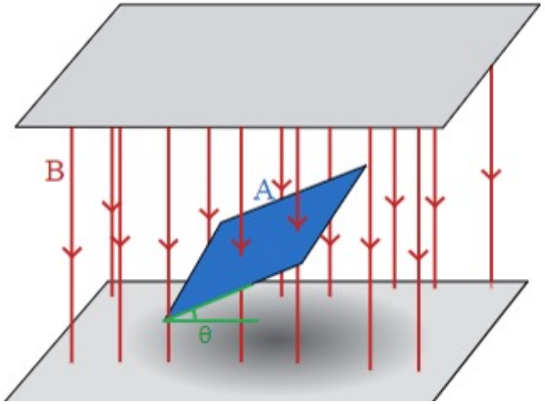


Magnetic line which are parallel in the same direction repeal each other

Definitions

- **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.
  - Magnetic flux is the total number of magnetic field lines penetrating any surface placed perpendicular to the magnetic field
  - $\emptyset = \int \boldsymbol{B.ds}$
  - 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
  - $\mathbf{B} = \boldsymbol{\Phi} / \mathbf{A}$
  - Unit : **Wb/m² (Tesla)**

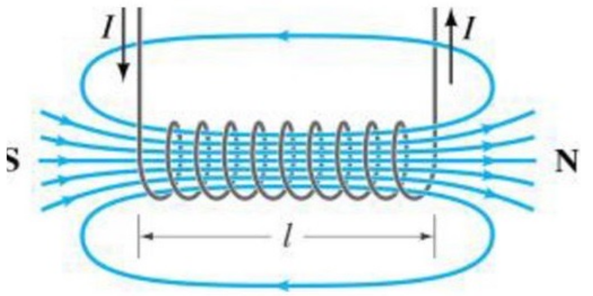
- **Magnetomotive Force (MMF or F)**
  - Analogous to **Electromotive Force (EMF)** of an electric circuit
  - Force which drives the magnetic lines of force through a magnetic circuit
  - $\mathbf{F} = \boldsymbol{\Phi} \times \mathbf{S} = \mathbf{N} \times \mathbf{I}$

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

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

Definitions

- **Magnetic Field Strength (H)**
  - Analogous to **Electric Field Strength**
  - The magnetomotive force (mmf) per meter length of the magnetic circuit
  - $\mathbf{H = (N \times I)/l}$
  - Unit: **A-T/m**



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

Definitions

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

Definitions

- **Reluctance (S)**
  - Analogous to **Resistance**
  - Opposition of a magnetic circuit to the setting up of magnetic flux in it
  - Depends upon: **length** of the magnetic circuit, **area of cross-section** of the circuit, and **nature of material** that makes up the magnetic circuit.
  - Unit: **AT/Wb**

Derivation of an expression for reluctance

$$\mathbf{H} = (\mathbf{N}\times\mathbf{I})/\mathbf{l} \qquad \mu = \mathbf{B}/\mathbf{H} \qquad \mathbf{B} = \Phi/\mathbf{A}$$

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

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

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

Illustration 01

For a solenoid, suppose the **circular core** has a radius of **1 cm** and a length of **20 cm.** Determine the number of turns required for a current of **1 A** to produce a magnetic flux density of **0.1 T** in the core when the core material is a) air, and b) iron having a relative permeability of **1200**.

Ans: (a) 15916 turns, and (b) 14 turns

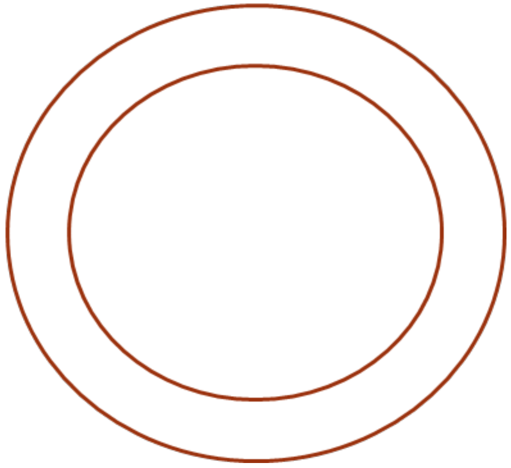
Illustration 02

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

Self-Practice 1

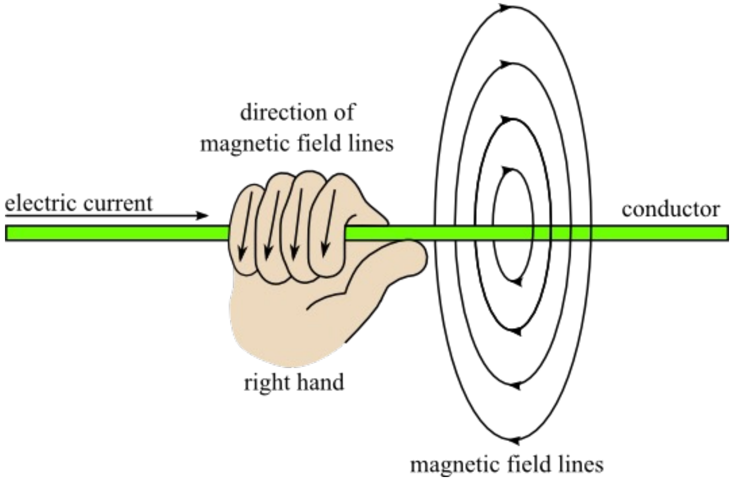
The solenoid core has a radius of **0.01 m** and a length of **0.2 m**. Find the magnetic flux in the core when the current through the coil is **0.1 A** and the core material is (a) air, and (b) iron having a relative permeability of **1500**.

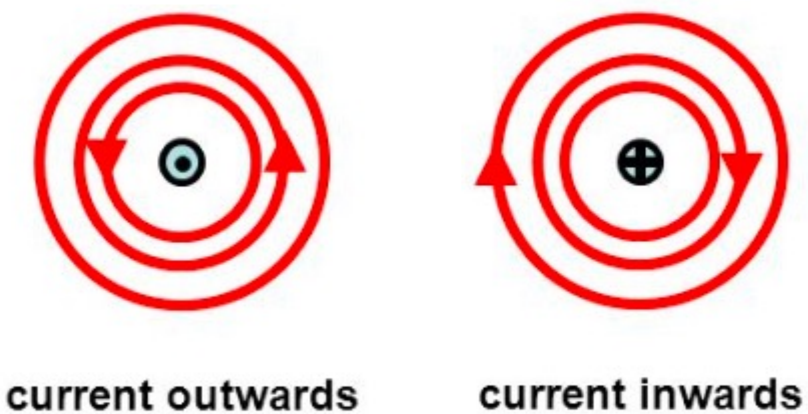
Ans: (a) $1.97 * 10^{-7}$ Wb, and (b) $2.96 * 10^{-4}$ Wb

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

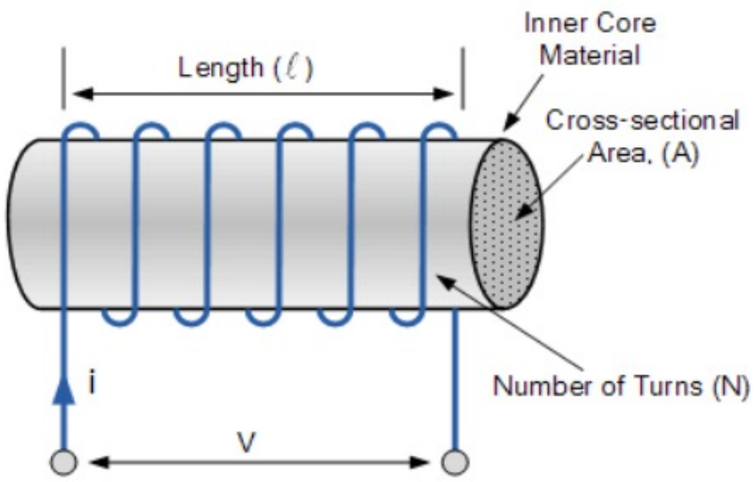


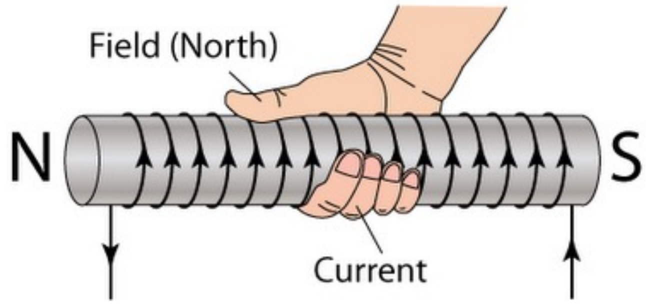


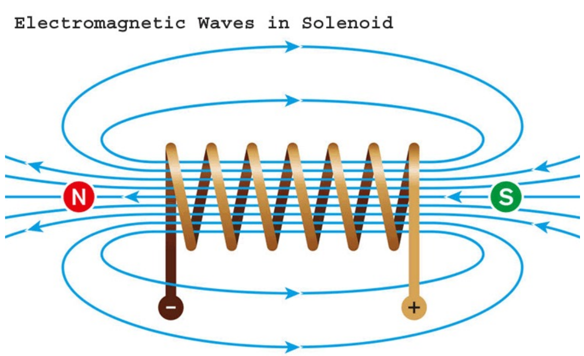
Magnetic Field (in a Solenoid)

- **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

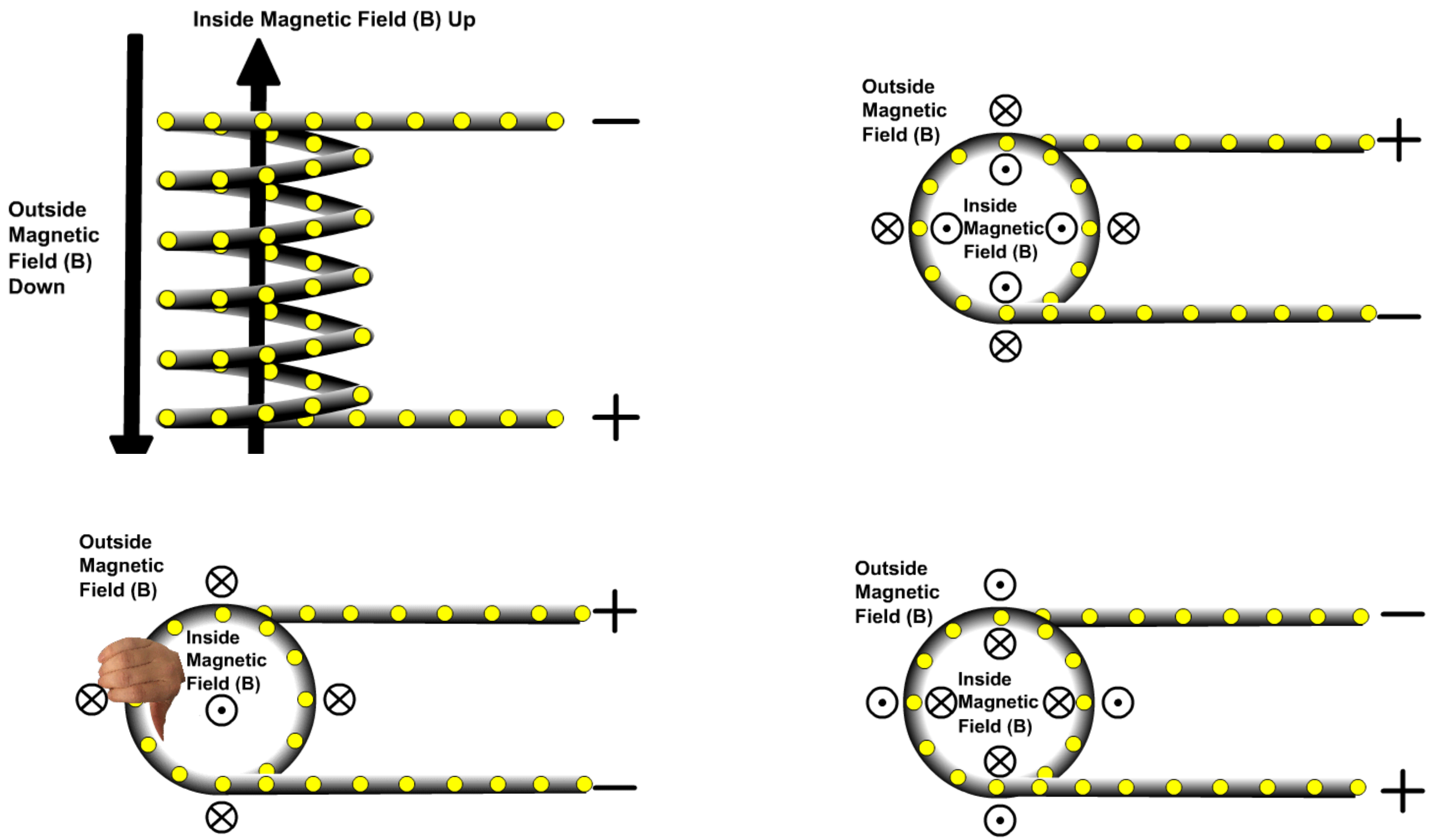




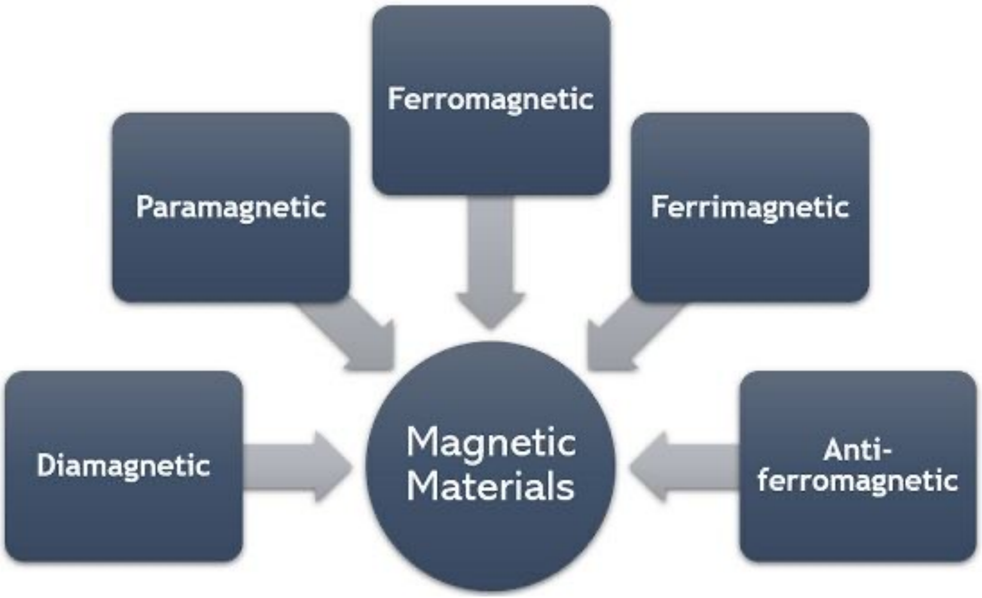


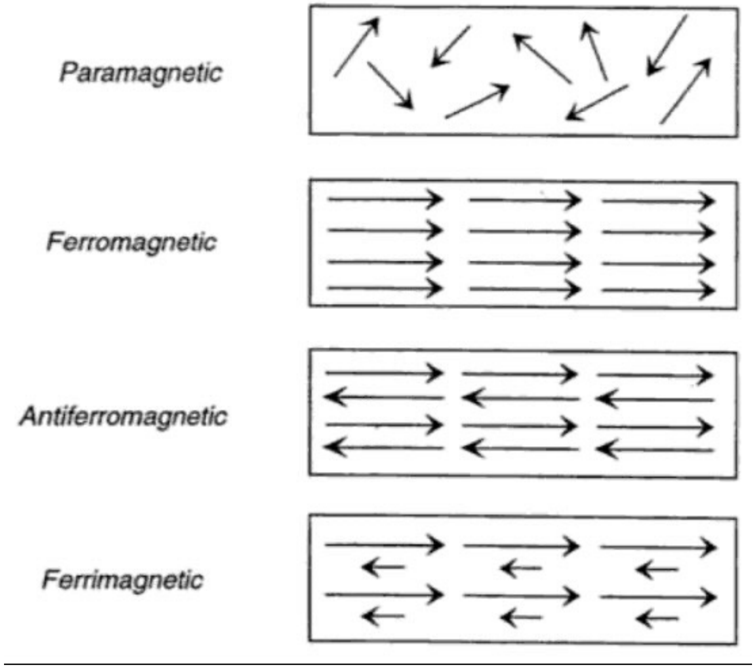
$$B = \frac{\mu_0 N I}{L}$$

Magnetic Field (in a Solenoid)



Classification of Magnetic Materials





Classification of Magnetic Materials

Diamagnetic

$\chi_m < 0$ and $\mu_r \lesssim 1$

Example: Copper, Lead, Bismuth, Water, etc.

Paramagnetic

$X_m > 0$ and $\mu_r \gtrsim 1$

Example: Platinum, Tungsten, Aluminum, etc.

Ferromagnetic

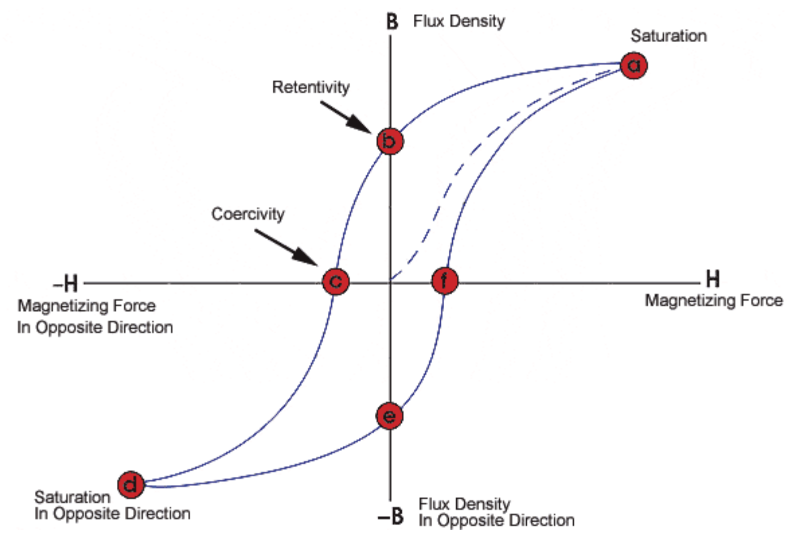
$X_m \gg 0$ and $\mu_r \gg 1$

Example: Iron, Cobalt, Nickel, etc.

X_m = Magnetic susceptibility

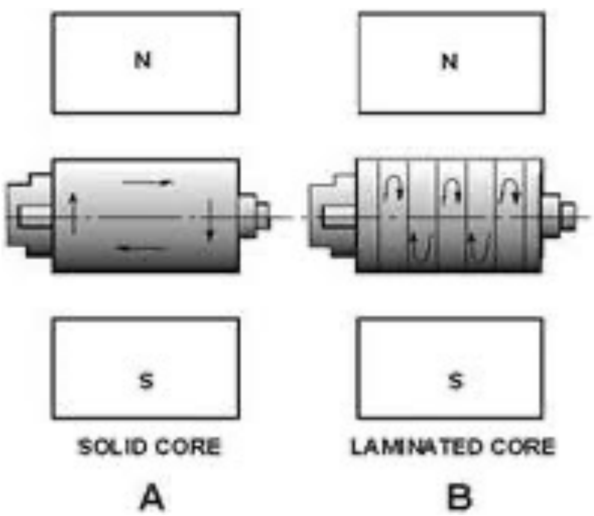
Losses in Magnetic Circuit

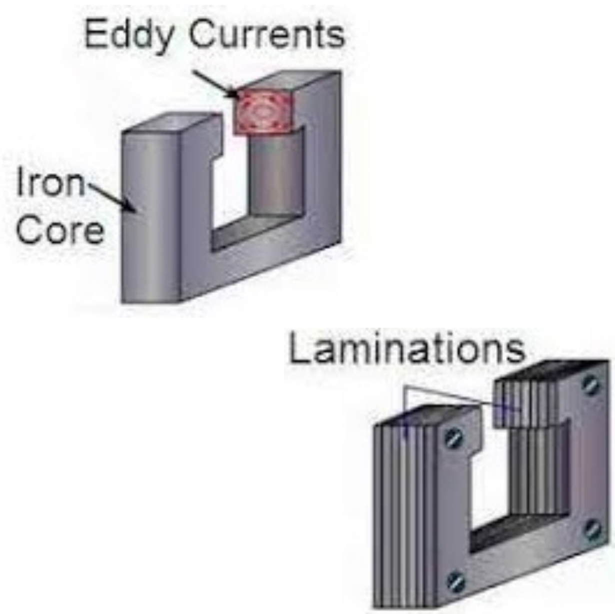
- **Hysteresis Loss**
  - Lagging of magnetization or flux density behind the magnetizing force is called **Magnetic Hysteresis**
  - The energy dissipated as heat in the process of magnetization and demagnetization which is proportional to the area of the hysteresis loop is the **Hysteresis Loss.** It is caused due to molecular friction in a ferromagnetic material under an alternating magnetic field.



Losses in Magnetic Circuit

- **Eddy Current Loss**
  - The varying flux in the magnetic core induces emf and hence eddy current within the material
  - Flow in closed loops in planes perpendicular to the magnetic field
  - Results in loss of power and heating of the material
  - Cores of electric machines are laminated to reduce eddy current loss





Comparison of Electric and Magnetic Circuits

Analogy

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

Electric Circuits	Magnetic Circuits
Conductance	Permeance
Electric Field Intensity	Magnetic Field Intensity
Voltage Drop	MMF Drop

Differences

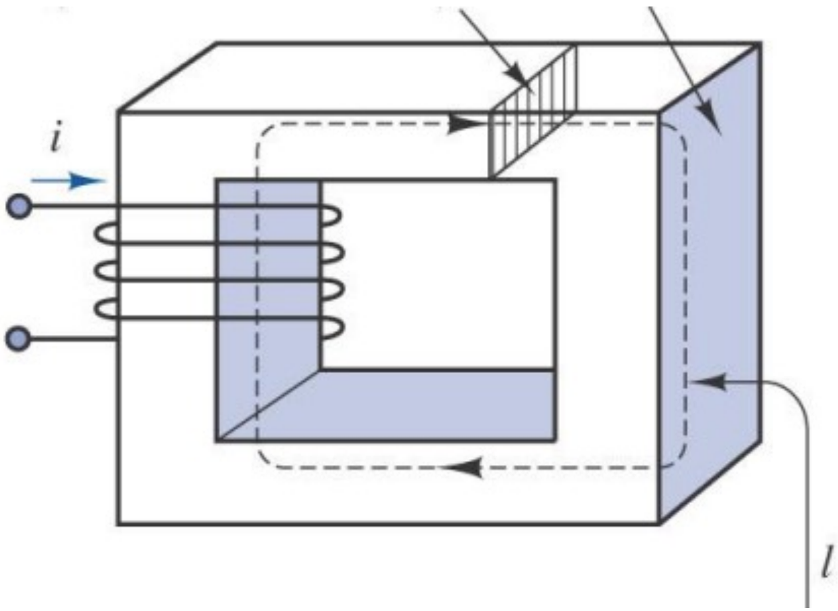
Electric Circuits	Magnetic Circuits
Current actually flows	Flux does not flow, it seems to flow
Current can not flow in air / vacuum	Flux can be created in air / vacuum
Resistivity (P) varies very slightly with temperature	μ_r is not constant for a given magnetic material
Energy is expended and dissipated as heat as long as the current flows	No energy is expended in a magnetic circuit (practically)

Magnetic Circuits

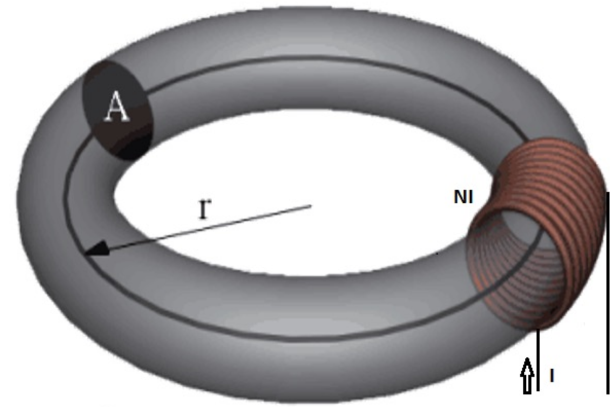
The complete closed path followed by any group of magnetic lines of flux

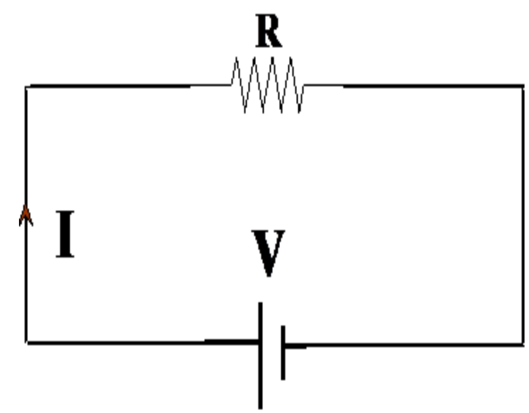
Cross-sectional area

Ferro-magnetic material



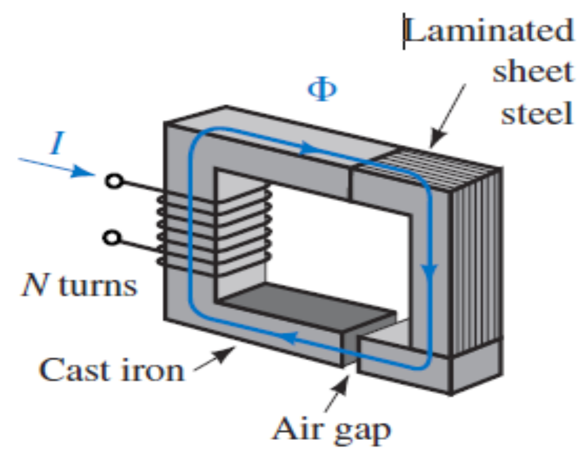
Mean path of magnetic flux lines

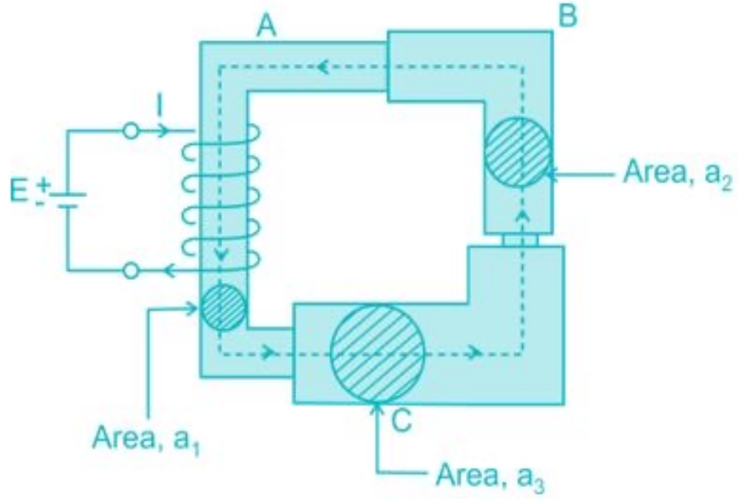




Series Magnetic Circuit

- 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





Series Magnetic Circuit

$$S_1 = \frac{l_1}{\mu_0\,\mu_{r1}\,a_1},\quad S_2 = \frac{l_2}{\mu_0\,\mu_{r2}\,a_2}$$

$$S_3 = \frac{l_3}{\mu_0\,\mu_{r3}\,a_3},\quad S_g = \frac{l_g}{\mu_0\,a_g}$$

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

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

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

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

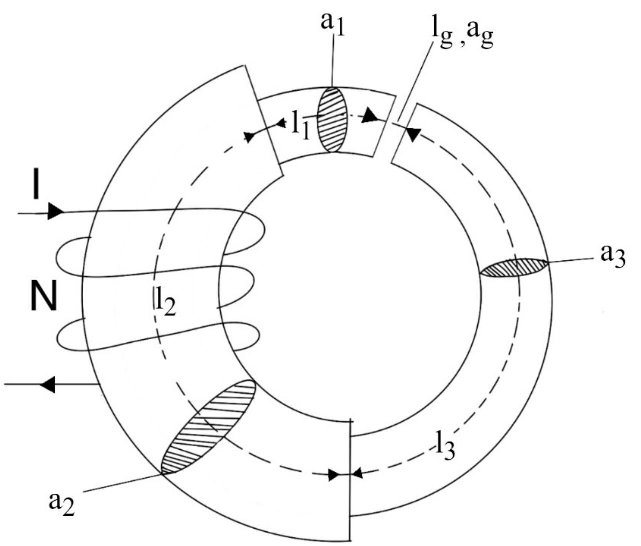
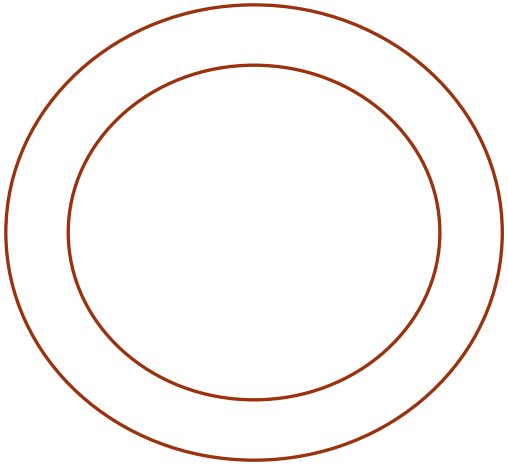


Illustration 3

An iron ring has a circular cross-sectional area of **5 cm²** and a mean circumference of **100 cm.** The ring is uniformly wound with a coil of **1000** turns. The 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 the 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**.



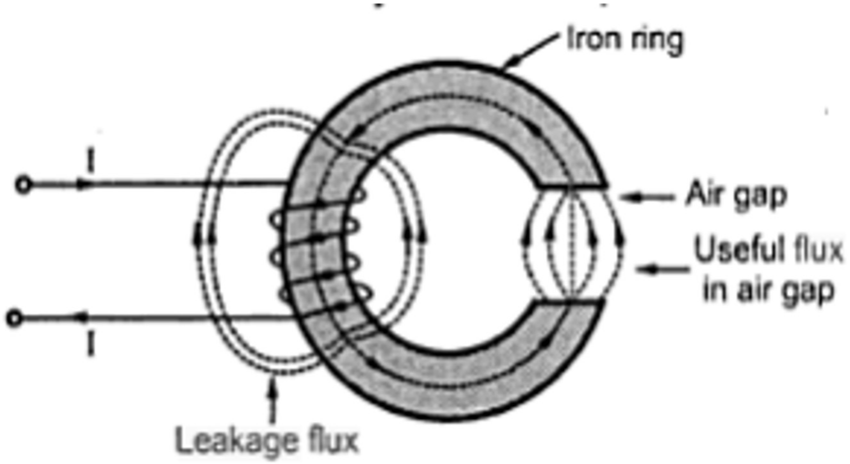
Ans:
a) 1.99 A
b) 0.385 mWb
c) 5.17 A

Useful & Leakage Flux

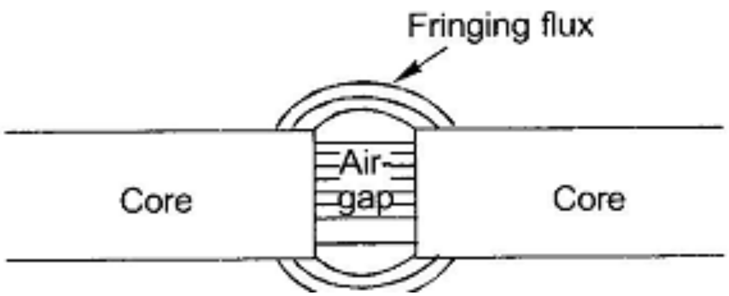
Magnetic leakage

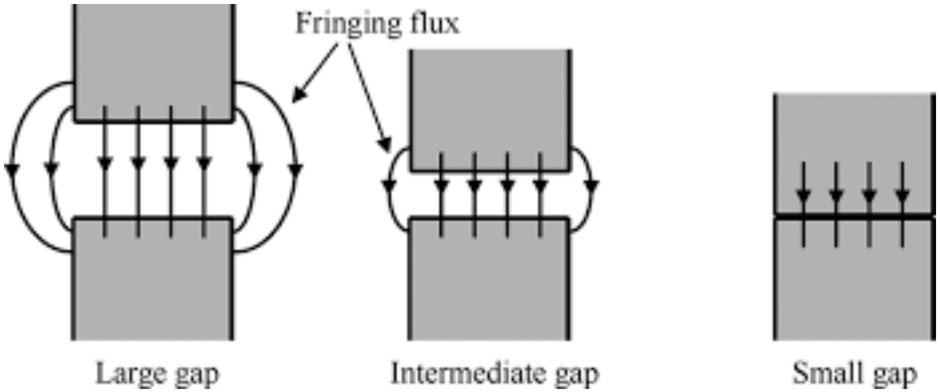
- The passage of magnetic flux outside the path along which it can do useful work
- Total flux of coil = Useful flux + Leakage flux
- **Leakage Coefficient**

$$\lambda = \frac{\textbf{Total Flux of the Coil}}{\textbf{Useful Flux}} = \frac{\phi_{\text{iron}}}{\phi_{\text{air-gap}}} \approx \mathbf{1.10\ to\ 1.25}$$



Fringing





When **air gap is small:** $\mathbf{A_i = A_g}$ and $\mathbf{B_i = B_g}$

When **air gap is more:** $\mathbf{A_g > A_i}$ and $\mathbf{B_g < B_i}$

Illustration 4

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

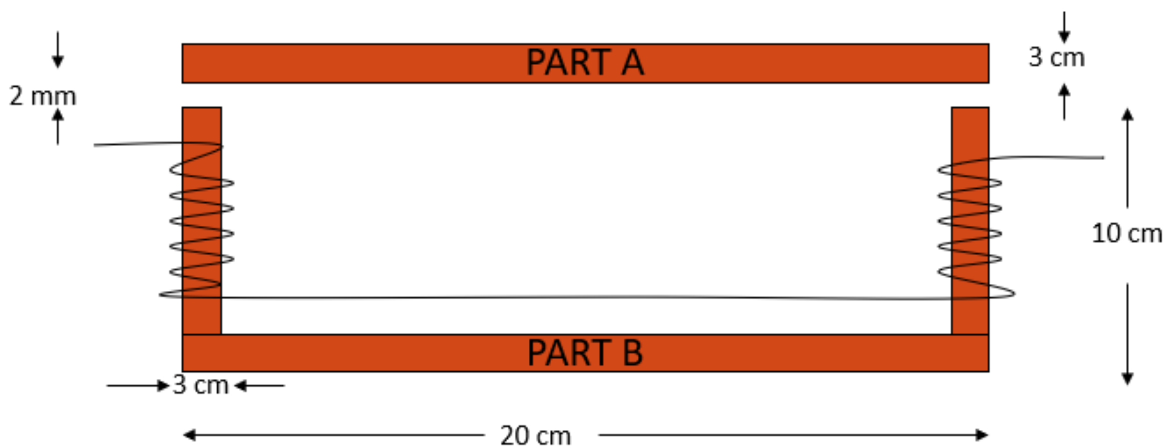
c) the mmf, and

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

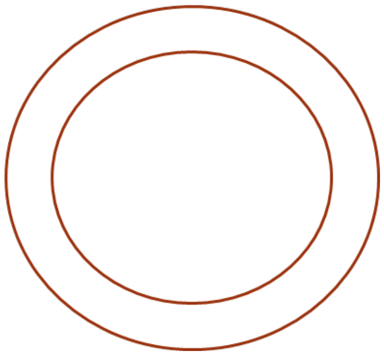
Φ = 0.63 mWb, B = 0.7 T

Illustration 5

A ring of cross-sectional area **12 cm²** 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	---

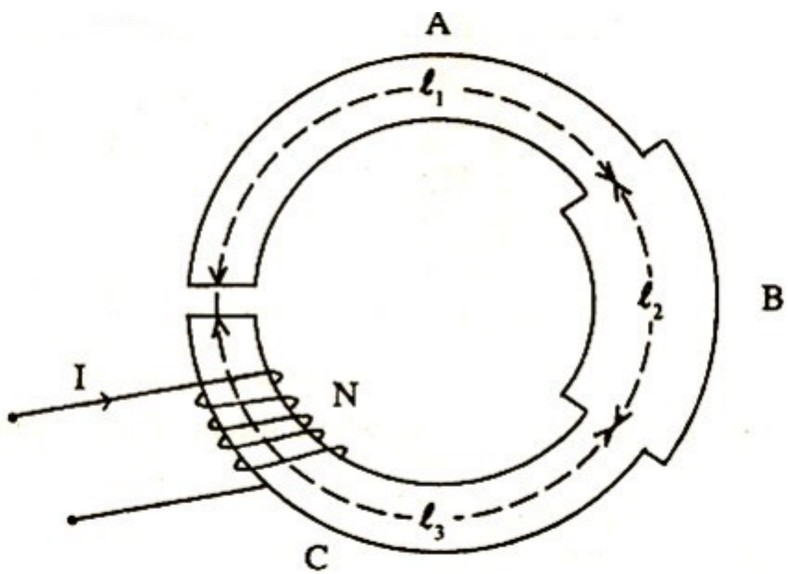
A coil of **660 turns** carrying a current of **2.1 A** is wound uniformly on the ring. Determine the flux density in the air gap. Assume no leakage and fringing effect.



Ans: 0.703 Wb/m²

Self-Practice 2

The iron ring shown in Figure is made up of a material having a relative permeability of **1000** and has a flux density of **2 T** in the air gap. For the given dimensions of **l_1 = 0.15 m**, **l_2 = 0.1 m**, **l_3 = 0.2 m**, **l_{ag} = 1 cm**, **$A_1 = A_3 = A_{ag} = 2*10^{-4}$ m^2**, **$A_2 = 3*10^{-4}$ m^2**, if the current through the coil is **1.5 A**, compute the number of turns required.



Ans: 11027 turns