Chapter 4

Magnetic Materials

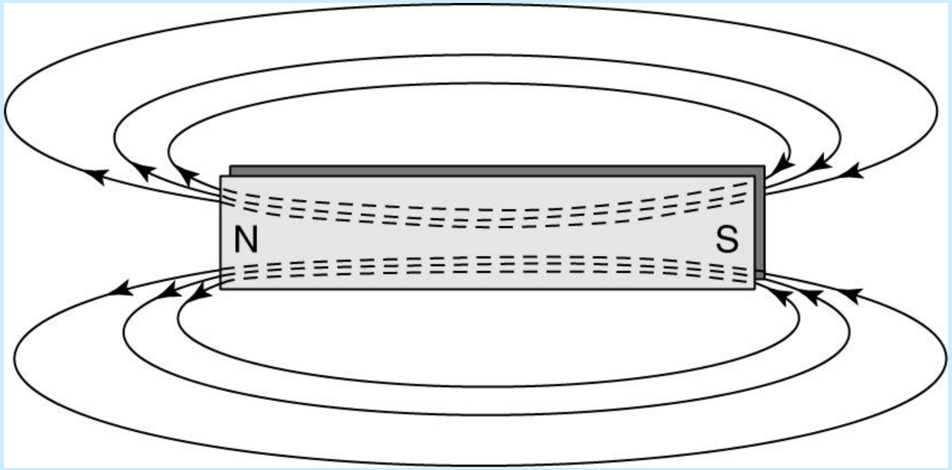
and

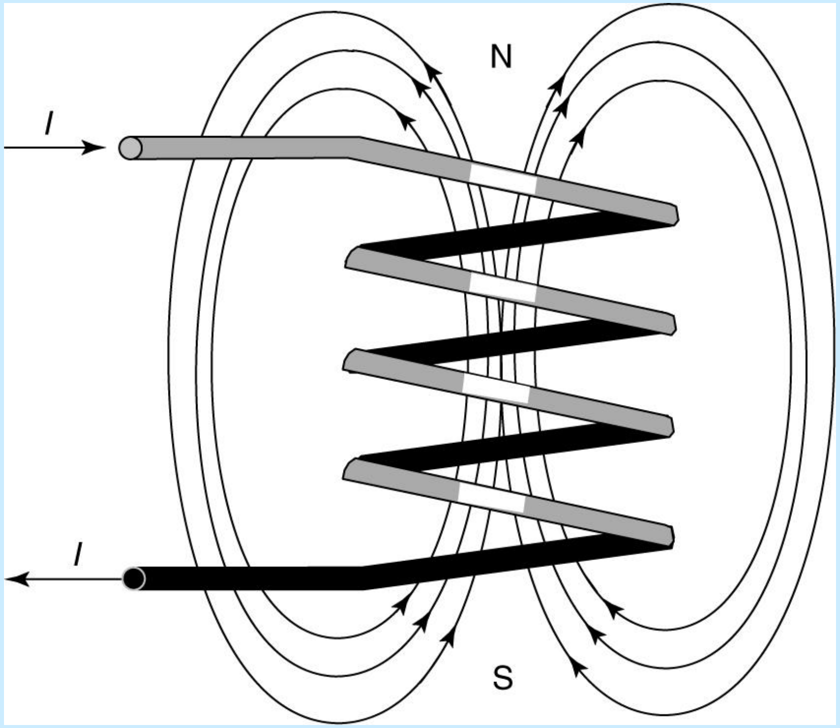
Circuits

Objectives

- List six characteristics of magnetic field.
- Understand the right-hand rule for current and magnetic fluxes.
- Define magnetic flux, flux density, magnetomotive force, magnetic field intensity, permeability, and reluctance.
- Perform basic magnetic circuit calculations.
- Define hysteretisis and eddy current losses.

Introduction





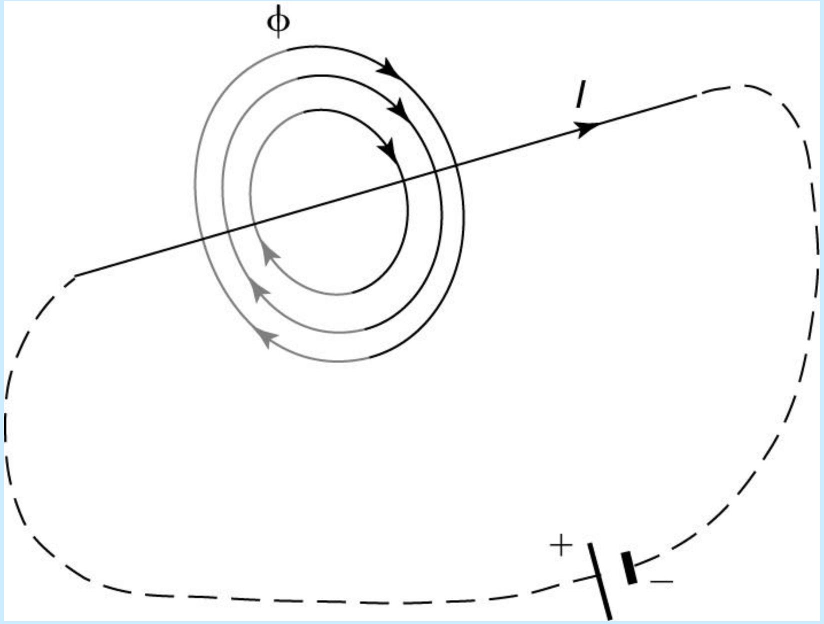
A bar magnet creates magnetic field as lines of flux that can be visualized by sprinkling iron particles near the poles of the magnet.

By convention, we designate the place where magnetic flux leaves the magnet as a NORTH pole and the place where magnetic flux returns to the magnet as the SOUTH pole.

Magnetic flux is continuous and travels from south to north inside the magnet.

Electromagnet can be created by passing a current through a coil.

Magnetic Flux



Magnetic flux and electric current both form closed paths.

If the current is a DC circuit, then magnetic flux is also DC, and if the current is AC, the flux is also AC.

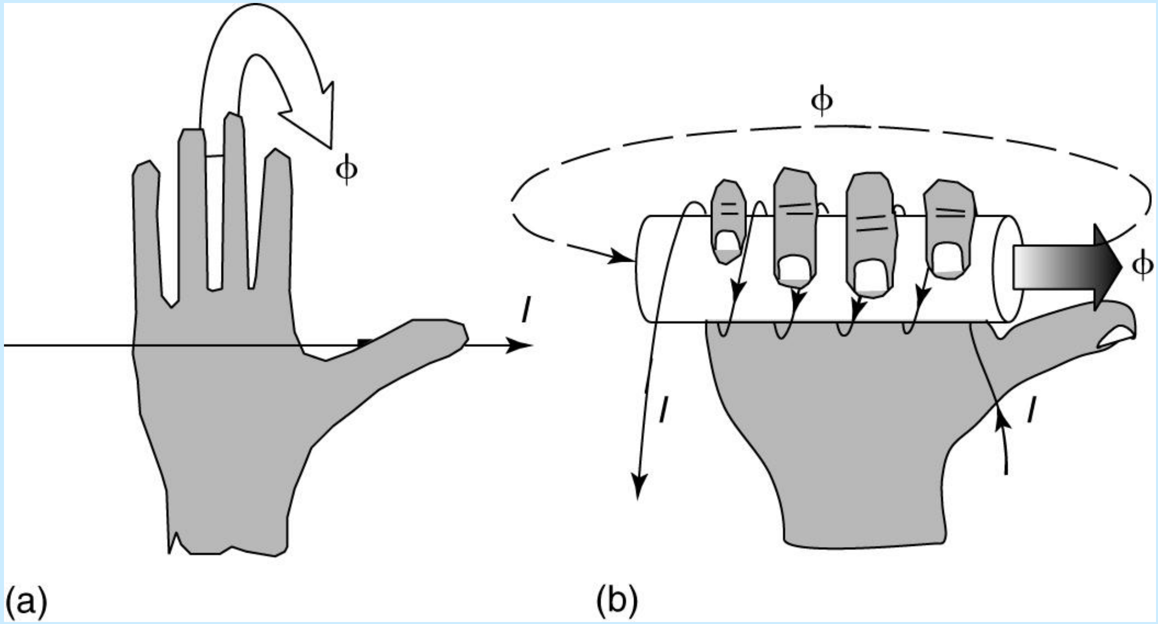
In SI units magnetic flux is in Webbers

Magnetic Flux Density :

$$B = \frac{\phi}{A}\left(\frac{Wb}{m^2}\right)$$

- ***B*** is a vector having magnitude and direction. The direction is determined by the right-hand rule.
- Flux lines form closed paths around the current causes them.
- ***B*** exists inside and outside of the conductor.
- ***B*** is a linear function of current except in ferromagnetic materials.
- ***B*** is greatest near the surface of the conductor.
- Flux always leaves the north pole of the magnet and enters the south pole.

Right-hand rule



A single wire carrying current:

Visualize it lying across your right palm with thumbs indicating the current direction.

The fingers of your right hand will then indicate the direction of the magnetic flux is wrapped around the wire.

A coil:

Visualize the coil in your right hand with your fingers wrapped in the direction of the coil current.

Your thumb then indicates the direction of flux through the middle of the coil, that is curved around to form a closed path.

Magnetomotive Force (MMF)

Current causes magnetic flux. The more current is provided, the more magnetic flux is formed. Flux can also be increased by wrapping the wire into a coil.
The product of number of turns and the current is called the magnetomotive force.

$$MMF = N \times I(A \cdot t)$$

Magnetic Field Intensity (MFI)

MFI gives a measure of how much MMF per unit length is required to establish the magnetic flux.

$$H = \frac{NI}{l}\left(\frac{A \cdot t}{m}\right)$$

length of the flux path in meters

Permeability

$$B = \mu H$$

Magnetic field intensity is related to flux density by the permeability of the material.
Permeability is a measure of how easy it is to establish magnetic flux in the material

Permeability of free space

$$\mu_0 = 4\pi \times 10^{-7}\left(\frac{Wb}{A \cdot t \cdot m}\right)$$

Relative permeability

$$\mu = \mu_r \mu_0$$

Reluctance

In an electrical circuits, current and voltage are related by the resistance.

Magnetic flux flows through the circuit as a function of MMF. The MMF and flux are related by the reluctance of the circuit.

$$F = \phi \mathcal{R}$$

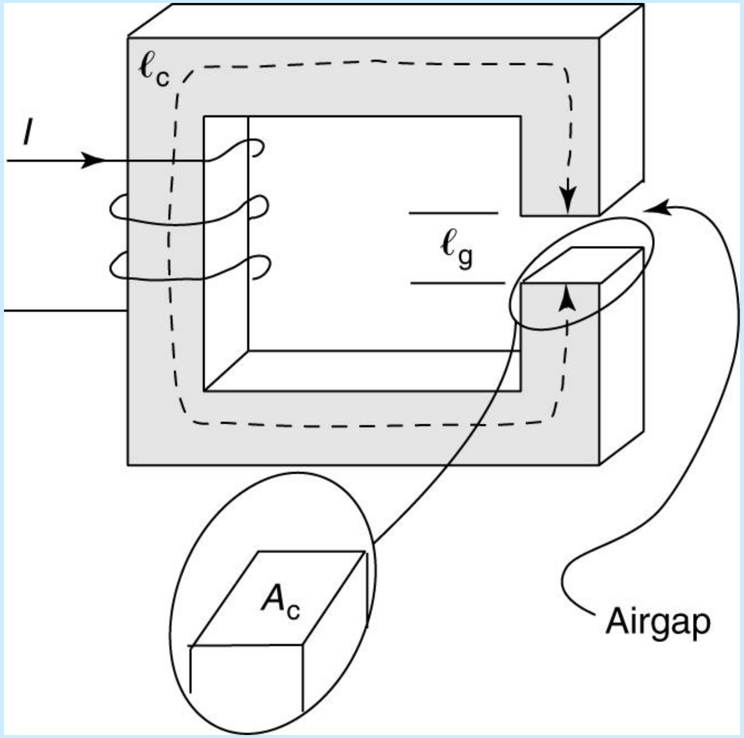
Reluctance is the function of circuit dimensions and material properties.

$$\mathcal{R} = \frac{l}{\mu A}\left(\frac{A \cdot t}{Wb}\right)$$

examples

Calculation Procedures

A coil wrapped around on an iron core with an air gap.



Goal: To calculate the flux density as a function of the current

In a real magnetic circuit, most, but not all, of the flux is confined to the iron core. The flux that escapes the core and passes through the air is called leakage flux.

Neglecting leakage flux, the flux in the air gap is the same as in the core:

$$\phi_g = \phi_c = \phi$$

If the gap is small, the flux is not distorted, but in case of a large air gap fringing effect, that reduces the flux density may occur.

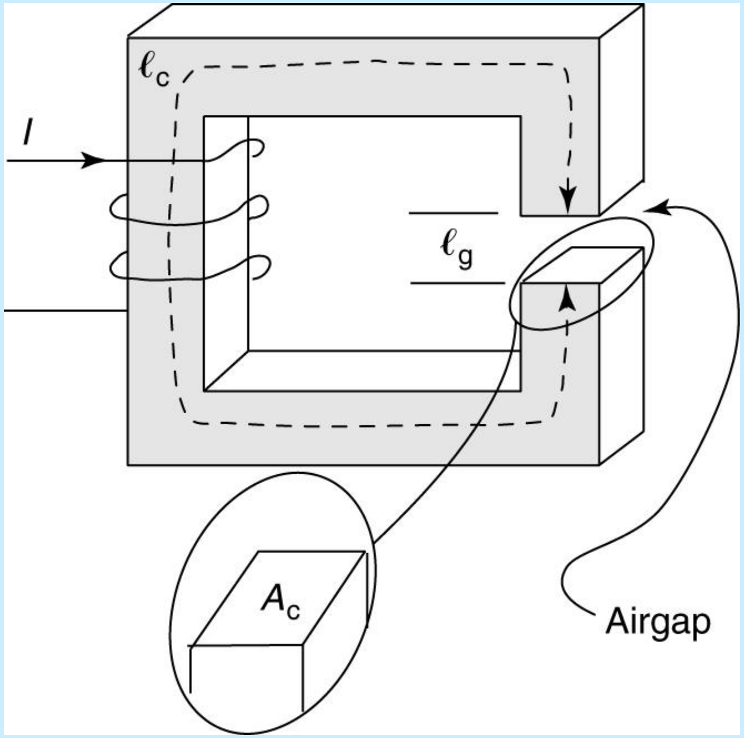
The flux density of the core and the gap are the same:

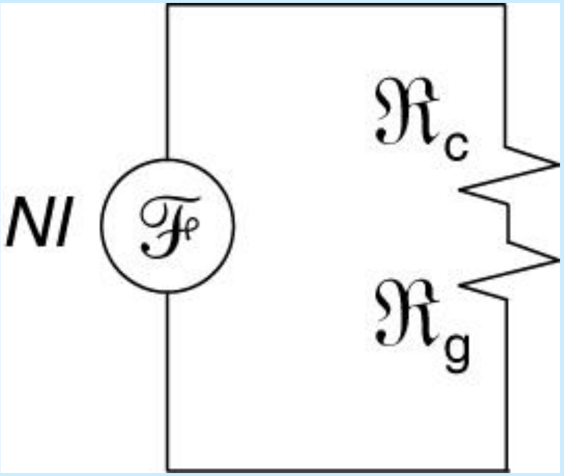
$$B_g = \frac{\phi}{A_g} = B_c = \frac{\phi}{A_c}$$

$$A_c = A_g$$

$$MMF = NI$$

We have two elements in the circuit (iron core and air) and each will have and MMF drop:





Magnetic equivalent circuit

We have two elements in the circuit (iron core and air) and each will have and MMF drop:

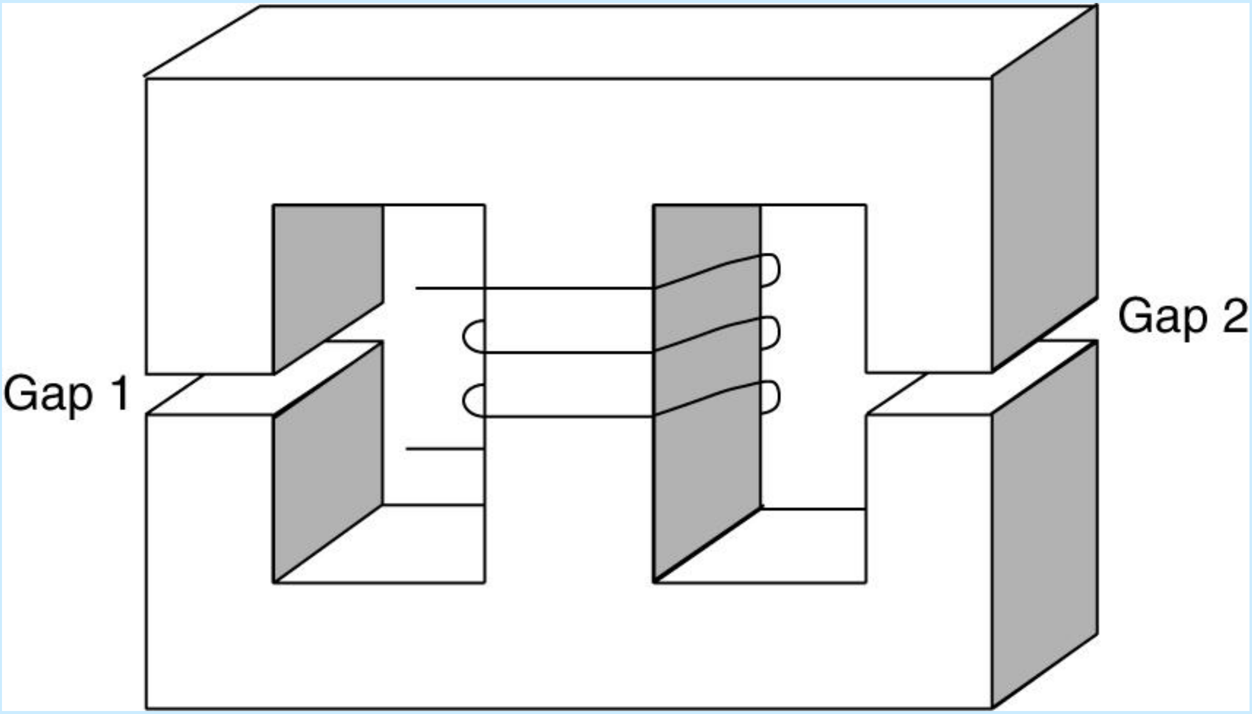
$$MMF = H_c l_c + H_g l_g$$

$$H = \frac{B}{\mu}$$

$$MMF = \frac{B l_c}{\mu_r \mu 0} + \frac{B l_g}{\mu 0} = \phi(\frac{l_c}{\mu_r \mu 0 A}) + \phi(\frac{l_g}{\mu 0 A})$$

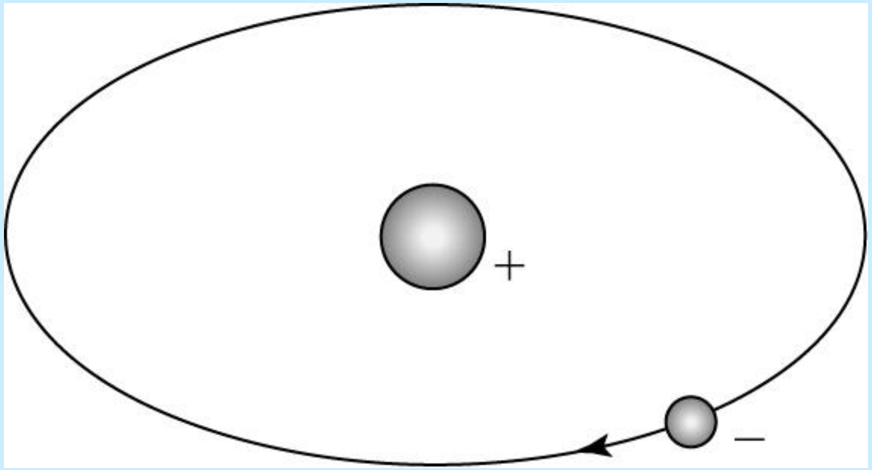
It can be also viewed as Ohm's law for magnetic circuits with consideration of reluctances of the core and the gap:

$$MMF = \phi R_{core} + \phi R_{gap}$$



example

Properties of Magnetic Materials



Electron moves around the nuclear in the atom

↓

This motion is a small electric current

↓

Magnetic field (moment) is generated

Electron spins around its axis

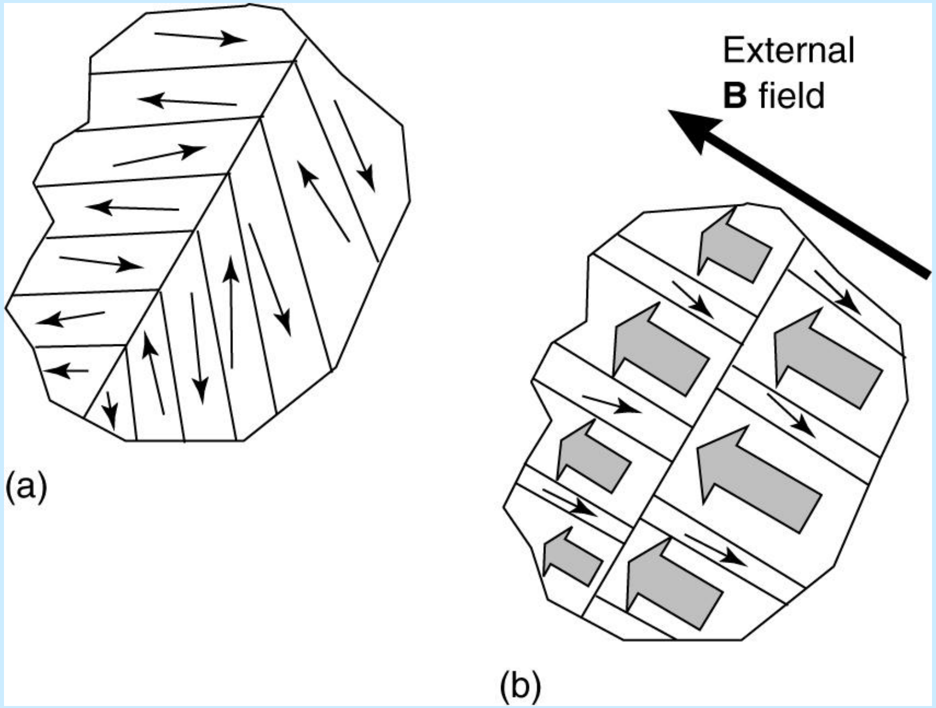
↓

Additional magnetic (moment) field

For about two-thirds of the elements, the orbital and spin moments cancel, so that atom has no net moment.

There are few elements that have a net magnetic moment – they are called ferromagnetic

Ferromagnetic Materials



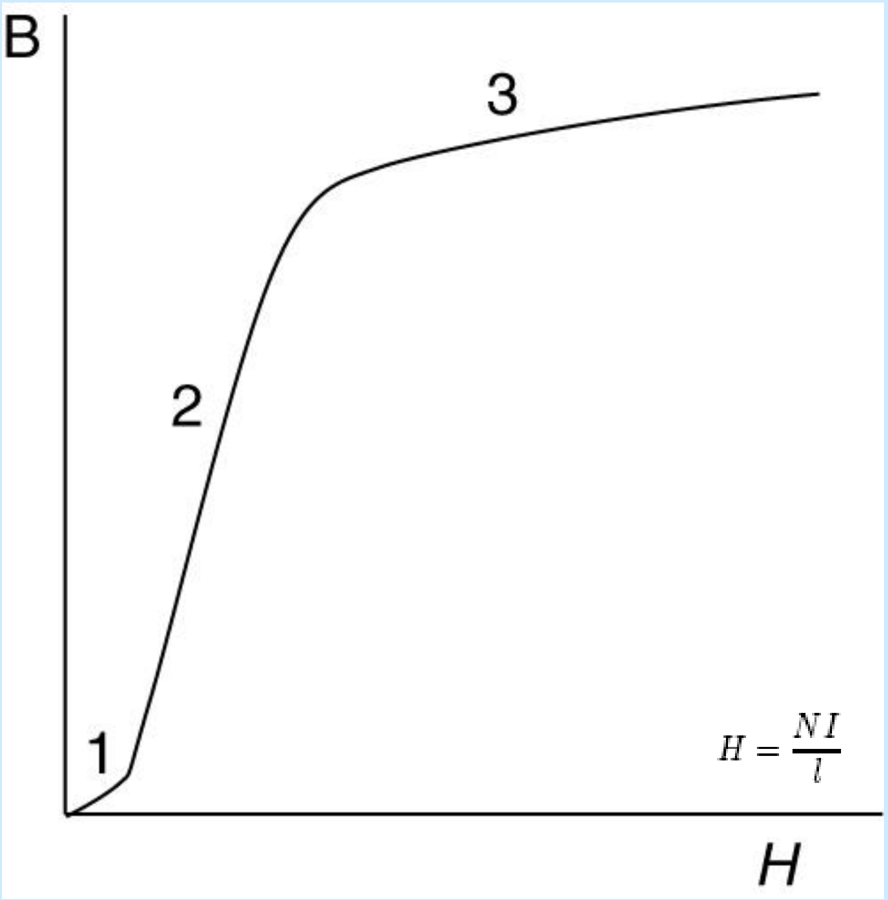
Metals have a crystalline structure.

The metallic crystals contain microscopic magnetic domains.

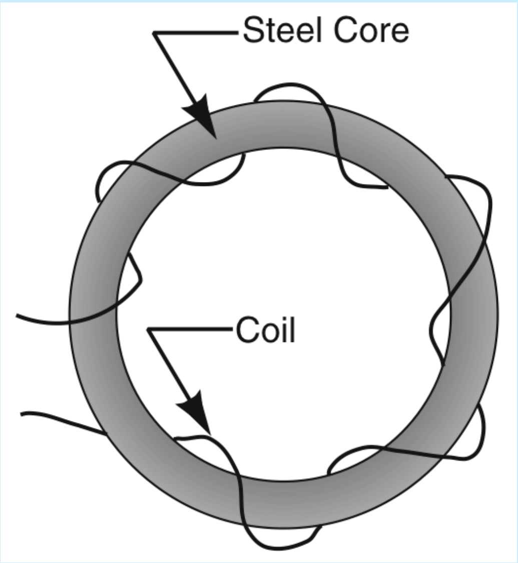
In the absence of the external field domains are randomly oriented and there is no net moment.

When external field is applied domains in the direction of the applied magnetic field tend to expand and some may rotate creating net moment.

As more of domains align with the external field, they effectively magnify the field.



The cast steel toroid with a coil



Applied current results in the magnetic field in the core with the magnetic flux density:

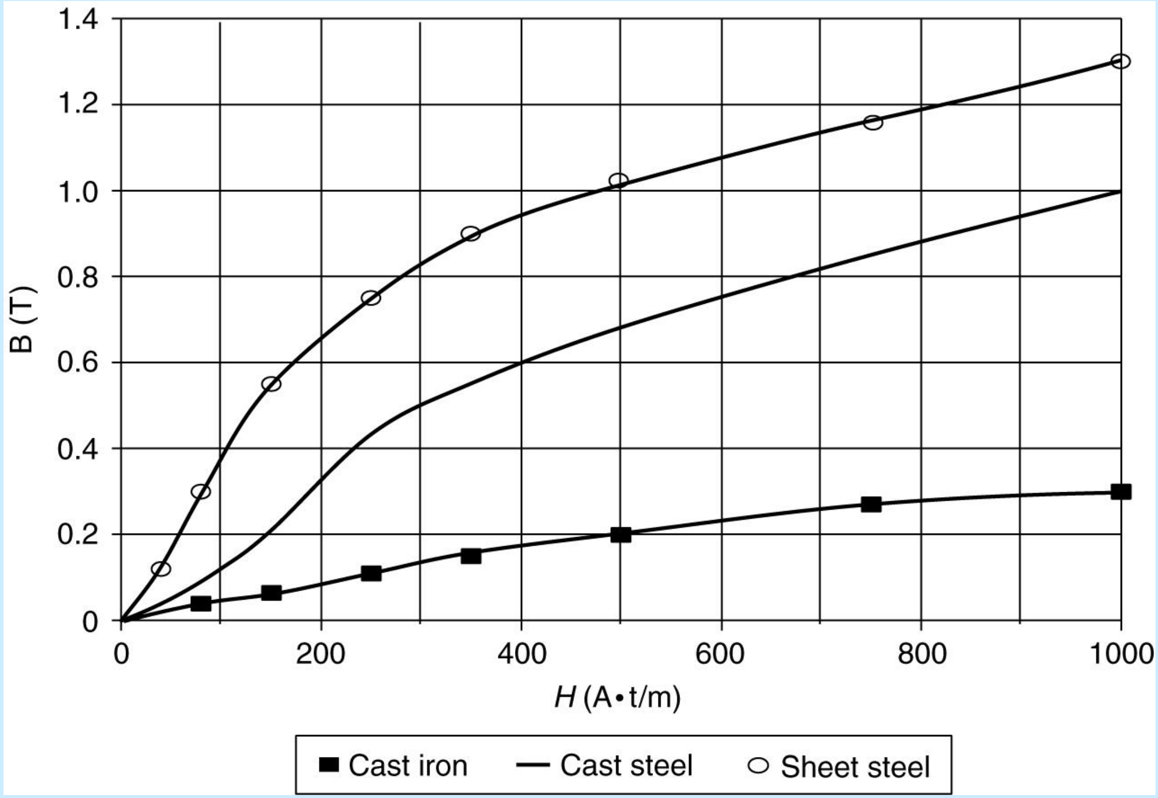
$$B = B_0 + M$$

B_0 is the flux density that would exist without a core, and M is the contribution of the core

Region 1 : the applied field intensity is not strong enough to change the domains and they do not contribute much to the flux density. Thus relative permeability is low.

Region 2 : the applied field intensity is capable of making domains expand and rotate quickly. Relative permeability may be very high.

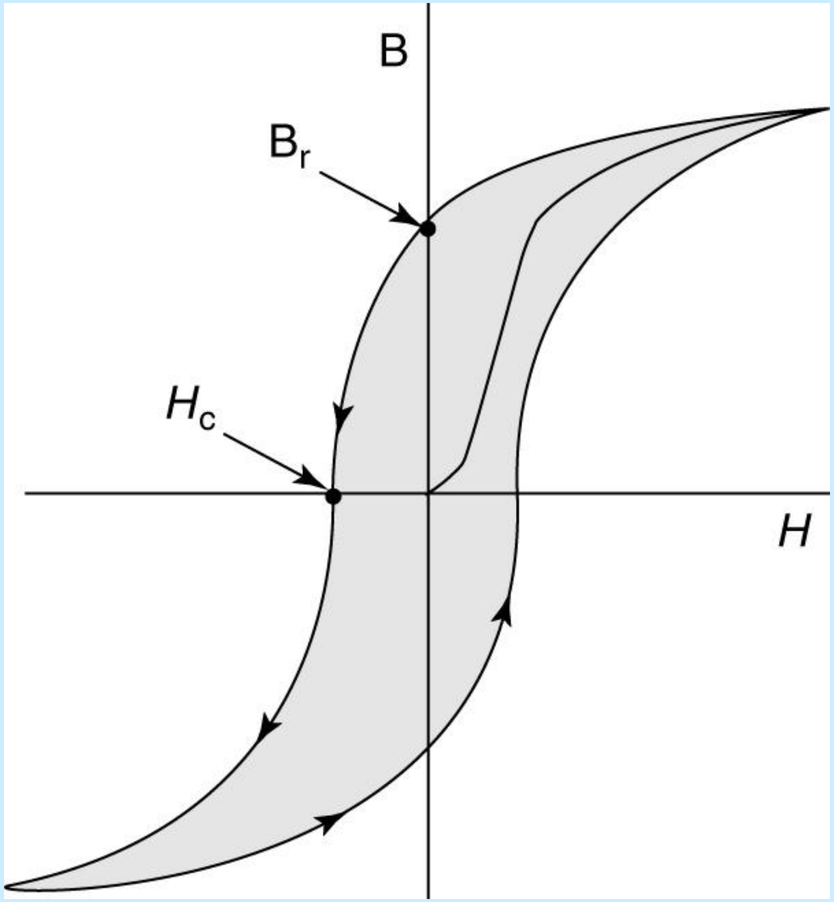
Region 3 : Saturation (all the easy domains are aligned)



Some ferromagnetic materials have higher relative permeability than other materials and are easier to magnetize.

example

Hysteresis



In the **initial state** material is **magnetized**.

<u>What if we reduce MMF?</u>

The flux density in the core does not decrease along the same curve. The expanded and rotated domains do not automatically return to their previous state.

As H is reduced, the ferromagnetic material remains partially magnetized. Even when MMF completely removed and H=0, there is still **residual magnetism (B_r)** in the material.

To completely remove the residual magnetism the field intensity has to be reversed to the negative value – **coercive force (H_c).**

Completing the cycle yields the complete B-H **hysteresis loop.**

Magnetic Core Losses

The area enclosed by the hysteresis loop represents energy that is converted to heat as material cycles around the loop.

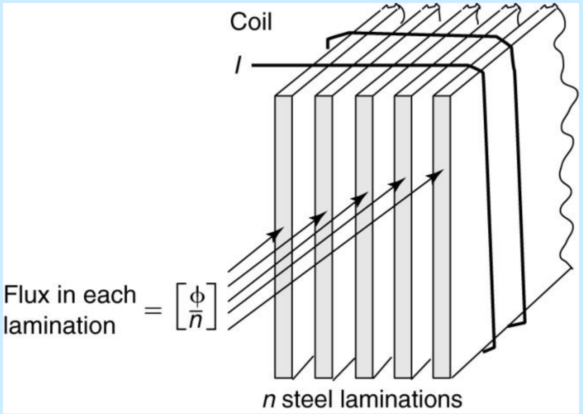
Core Losses

Hysteresis Loss

Due to the expansion, contraction, and realignment of magnetic domains, which produces microscopic friction.
Hysteresis loss is minimized by using a soft magnetic material which has a narrow hysteresis loop.

Eddy Current Loss

Due to currents induced in the core that oppose the changing magnetic flux.
This effect can be reduced using lamination technique.



IMPORTANT NUMBERED EQUATIONS FROM THIS CHAPTER

$$B = \frac{\phi}{A} \tag{4–1}$$

$$\mathcal{F} = N \times I \tag{4–2}$$

$$H = \frac{NI}{\ell} \tag{4–3}$$

$$B = \mu H \tag{4–4}$$

$$\mu_o = 4\pi \times 10^{-7} \frac{\text{Wb}}{(\text{A}\cdot\text{t}\cdot\text{m})} \tag{4–5}$$

$$\mu = \mu_r \mu_o \tag{4–6}$$

$$\mathcal{F} = \phi \mathfrak{R}$$

$$\mathfrak{R} = \frac{\ell}{\mu A}$$

$$\mu_r = \frac{B}{\mu_o H}$$

$$P_h = k_h f B_{max}^n$$

$$P_e = k_e (B_{max} t f)^2$$