B38EM Introduction to Electricity and Magnetism
Lecture 6

Magnetic materials

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Magnetostatics

- Magnetic Flux Density

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

$\mu = \mu_r \mu_0$

Permeability is the degree of magnetization of a material in response to a magnetic field.

$$\mu_o = 4\pi \times 10^{-7}\ \mathrm{H/m}$$

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 3 \times 10^8 \qquad (m/s)$$

Magnetostatics

- ## Magnetic Dipole - Magnetic Fields in Matter

Just as the electric dipole was helpful to understand the behaviour of dielectric materials

PERMITTIVITY ε: Level of polarizability

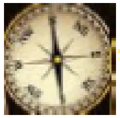
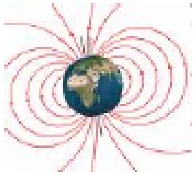
The magnetic dipole is helpful to understand the behaviour of magnetic materials

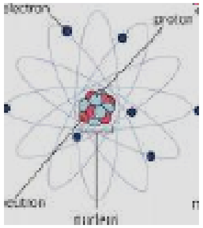
PERMEABILITY μ: Ability to support formation of $\boldsymbol{B}$

Permeability is the degree of magnetization of a material in response to a magnetic field.

Magnetostatics

- ## Magnetic Fields in Matter

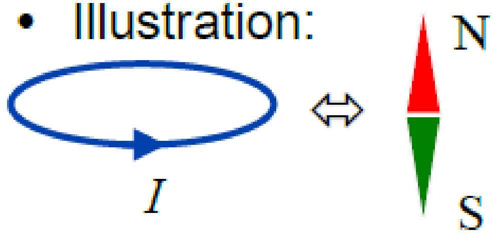
  - All magnetic phenomena are due to electric charges in motion
    - horseshoe magnets  , compass needles , Earth,.. 
  - Examination on atomic level reveals SMALL “CURRENT LOOPS”
    - electrons “orbiting” around nuclei or “spinning” about their axes
  - Macroscopic purposes
    - Treated as magnetic dipoles



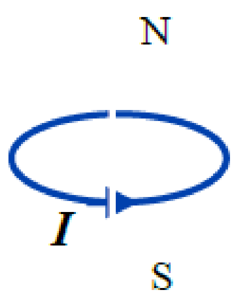
  - If no magnetic field is applied
    - random orientation → dipole fields cancel each other out
  - What happens when we apply a magnetic field?

Magnetostatics

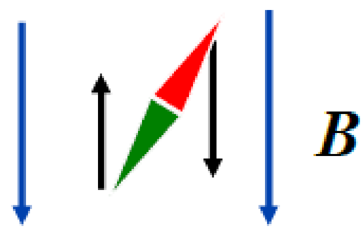
- Magnetic Fields in Matter
  - Illustration:



magnetic dipole can be viewed as pair of magnetic charges (in analogy to electric dipole)



magnetic dipole is the elementary source of the magnetic field

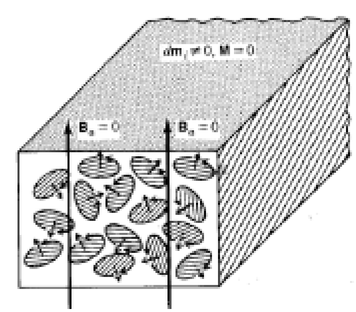


a magnetic field exerts a force (torque) on a magnetic dipole

- dipole moment distribution sets up induced secondary fields:

Field in free space due to sources

Total field ← $\mathbf{B}_{total} = \mathbf{B}_{app} + \mathbf{B}_{ind}$ ← Field due to induced magnetic dipoles



Magnetostatics

- Concept of Permeability

  - For most materials, the **magnetisation** is proportional to the **H** field,

    $$\mathbf{M} = \chi_m \mathbf{H}$$

    magnetic susceptibility (dimensionless)

    (**M** and **H** [A/m])

  - Furthermore, we obtain

    $$\mathbf{B} = \mu_0(\mathbf{H}+\mathbf{M}) = \mu_0(1+\chi_m)\mathbf{H} = \mu\mathbf{H}$$

    where μ is the **permeability** of the material

    * **M** shows how the applied **H**-field affects the **H**-field inside the material

Material	Susceptibility	Material	Susceptibility
Diamagnetic:		*Paramagnetic:*	
Bismuth	-1.6×10^{-4}	Oxygen	1.9×10^{-6}
Gold	-3.4×10^{-5}	Sodium	8.5×10^{-6}
Silver	-2.4×10^{-5}	Aluminum	2.1×10^{-5}
Copper	-9.7×10^{-6}	Tungsten	7.8×10^{-5}
Water	-9.0×10^{-6}	Platinum	2.8×10^{-4}
Carbon Dioxide	-1.2×10^{-8}	Liquid Oxygen (−200° C)	3.9×10^{-3}
Hydrogen	-2.2×10^{-9}	Gadolinium	4.8×10^{-1}

Magnetostatics

- Concept of Permeability

  - Knowing the permeability of a magnetic material tells us all we need to know from the point of view of macroscopic electromagnetics

  - The **relative permeability** of a magnetic material is the ratio of the permeability of the magnetic material to the permeability of free space

$$\mu_r = \frac{\mu}{\mu_0}$$

Magnetostatics

- Concept of Permeability

  - **What happens when we apply a magnetic field?**
    - Medium becomes magnetically polarised (***magnetised***)
    - The induced magnetic dipole modifies the magnetic field.. ..both inside and outside the magnetized material
  - **Electric fields → electric polarisation** has always direction of **E**
  - **Magnetic fields →** materials acquire different **magnetisations**

MAGNETISATION	Aligned as B	Aligned opposite to B	Magnetisation remains after external field is removed
TYPE OF MATERIAL	PARAMAGNETIC	DIAMAGNETIC	FERROMAGNETIC

  - ***Permanent magnet*** (Material remains magnetised in the absence of an applied magnetic field)

Magnetostatics

- Magnetic Properties of Solids

All materials react to an applied external magnetic field.
Magnetic materials can be placed in 3 categories:

Diamagnetic: $\mu_r < 1$ (e.g. $\mu_{r\_copper} = 0.999994$)
materials that get magnetized in **opposition** of an externally applied magnetic field. (**Most materials**)
They repel **B** lines (both poles).
Silver, Lead, Copper, Water, superconductors (levitation)

Paramagnetic: $\mu_r > 1$
materials that get magnetized in the direction of, and **proportional** to, the applied magnetic field.
They weakly attract **B** lines (either pole).
Platinum, aluminum, oxygen

Ferromagnetic: μ_r very large iron: 200 - 300,000 nickel=100 - 600,
materials that produce magnetization often orders of magnitude greater than the applied **B** field.
Permanent Magnets

Magnetostatics

- Magnetic Properties of Solids

Material	Relative Permeability
Copper	0.9999906
Silver	0.9999736
Lead	0.9999831
Air	1.00000037
Oxygen	1.000002
Aluminum	1.000021
Titanium 6-4 (Grade 5)	1.00005
Palladium	1.0008
Platinum	1.0003
Manganese	1.001
Cobalt	250
Nickel	600
Iron	280,000

Diamagnetic

Paramagnetic

Ferromagnetic