Magnetic Properties of Materials

a) Transmission electron micrograph showing the microstructure of the perpendicular magnetic recording medium used in hard-disk drives.

b) Magnetic storage hard disks used in laptop (left) and desktop (right) computers.

c) Inside of a hard disk drive.

d) Laptop

Magnetism

- The phenomenon by which materials exert an attractive or repulsive force or influence on other materials.

- The underlying principles and mechanisms that explain magnetic phenomena are complex and subtle

- Many modern technological devices rely on magnetism and magnetic materials, including electrical power generators and transformers, electric motors, radio, television, telephones, computers, and components of sound and video reproduction systems.

- Iron, some steels, and the naturally occurring mineral lodestone are well-known examples of materials that exhibit magnetic properties.

- In fact, **all** substances are influenced to one degree or another by the presence of a magnetic field.

Topics included

A brief description of the origin of magnetic fields and magnetic field vectors and magnetic parameters;

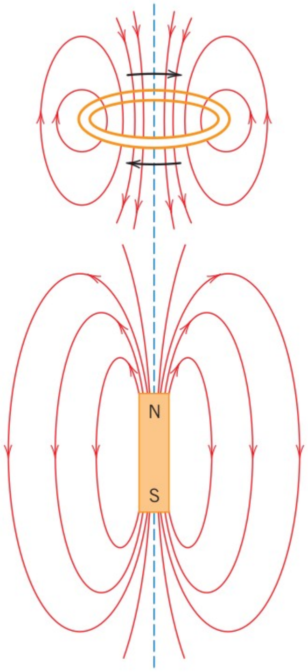
- Diamagnetism,
- paramagnetism,
- ferromagnetism, and
- ferrimagnetism;
- different magnetic materials; and superconductivity.

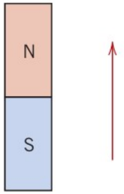
Magnetic dipole and Magnetic Field

- Magnetic forces are generated by moving electrically charged particles;

Let us consider these magnetic forces in terms of a field.

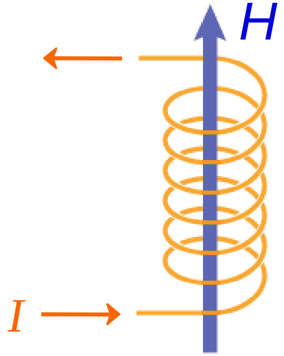
- Imaginary lines of force that may be drawn to indicate the direction of force at positions in the vicinity of the source (bar magnet or moving current).
- The magnetic field distributions as indicated by lines of force.





Generation of a Magnetic Field -- Vacuum

- Created by current through a cylindrical coil:

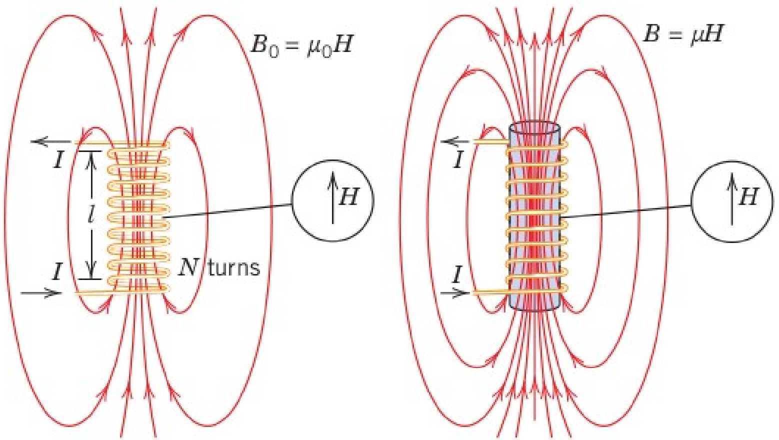


N = total number of turns

l = length of the coil (m)

I = current (ampere)

H = magnetic field strength



(a) (b)

$$H = \frac{NI}{l}$$

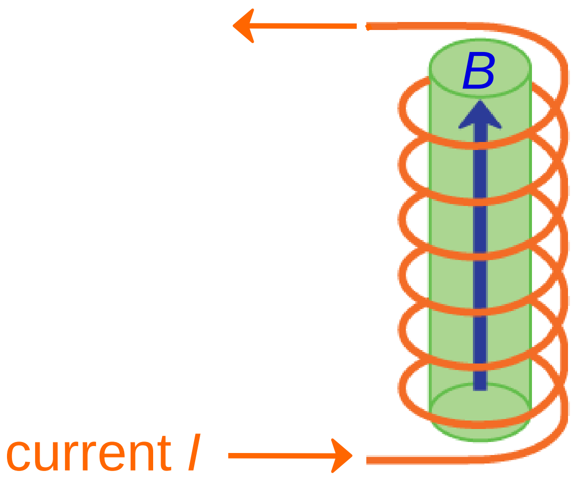
Magnetic flux density, B - magnitude of the internal field strength within a substance that is subjected to an H field
Units: webers per square meter (Wb/m^2)

The magnetic field strength and flux density are related as:

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

The parameter is called the permeability, which is a property of the specific medium through which the H field passes and in which B is measured

Units: webers per ampere-meter ($Wb/A \cdot m$) or henries per meter.



B = Magnetic field (tesla) induced in the material

In a vacuum,

$$B_0 = \mu_0 H$$

where $_0$ is the permeability of a vacuum, a universal constant, which has a value of 4×10^{-7} (1.257×10^{-6}) H/m.

$$B = \mu \frac{NI}{l}$$

- Relative permeability (dimensionless) $\mu_r = \dfrac{\mu}{\mu_0}$

a measure of the degree to which the material can be magnetized, or the ease with which a B field can be induced in the presence of an external H field.

Magnetization of the solid

In the presence of an H field, the magnetic moments within a material tend to become aligned with the field.
The measure of this contribution is:

$$B = \mu_0 H + \mu_0 M$$

Recall:

Analogous expression for the dielectric case

$$D = \varepsilon_0 \mathscr{E} + P$$

- D is also called the dielectric displacement, and P is the polarization, or the increase in charge density above that for a vacuum because of the presence of the dielectric.

The magnitude of M is proportional to the applied field as follows

$$M = \chi_m H$$

What is the relation between χ_m and μ_r?

Magnetization of the solid

In the presence of an H field, the magnetic moments within a material tend to become aligned with the field.
The measure of this contribution is:

$$\boxed{B = \mu_0 H + \mu_0 M}$$

Recall:

Analogous expression for the dielectric case

$$D = \varepsilon_0 \mathscr{E} + P$$

- D is also called the dielectric displacement, and P is the polarization, or the increase in charge density above that for a vacuum because of the presence of the dielectric.

The magnitude of M is proportional to the applied field as follows

$$M = \chi_m H$$

χ_m and μ_r are related as:

$$\boxed{\chi_m = \mu_r - 1}$$

Magnetic field distributions is typically indicated by lines of force are shown for a current loop and a bar magnet

- Within a magnetic field, the force of the field exerts a torque that tends to orient the dipoles with the field.

A familiar example is the way in which a magnetic compass needle lines up with the Earth’s magnetic field.

Let’s learn how things work:

- Compass in your smartphone
- Compass in the aircraft

https://www.youtube.com/watch?v=f2oMZdRuVBY

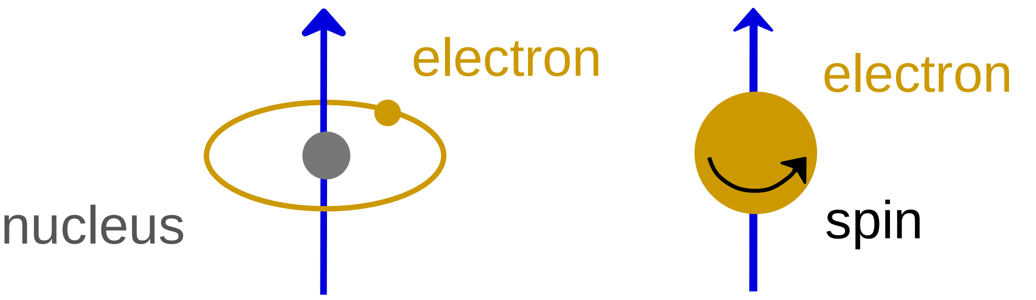
Magnetic quantities and their units

		SI Units	
Quantity	***Symbol***	***Derived***	***Primary***
Magnetic induction (flux density)	B	Tesla (Wb/m^2)[a]	kg/s·C
Magnetic field strength	H	Amp·turn/m	C/m·s
Magnetization	M (SI) I (cgs–emu)	Amp·turn/m	C/m·s
Permeability of a vacuum	μ_0	Henry/m[b]	kg·m/C^2
Relative permeability	μ_r (SI) μ' (cgs–emu)	Unitless	Unitless
Susceptibility	χ_m (SI) χ'_m (cgs–emu)	Unitless	Unitless

Origins of Magnetic Moments

- Magnetic moments arise from electron motions and the spins on electrons.

magnetic moments



electron orbital motion

electron spin-
up or down direction

Bohr magneton $_B$
Magnitude = 9.27×10^{-24} $A \cdot m^2$

For each electron in an atom, the spin magnetic moment is $\pm_B$

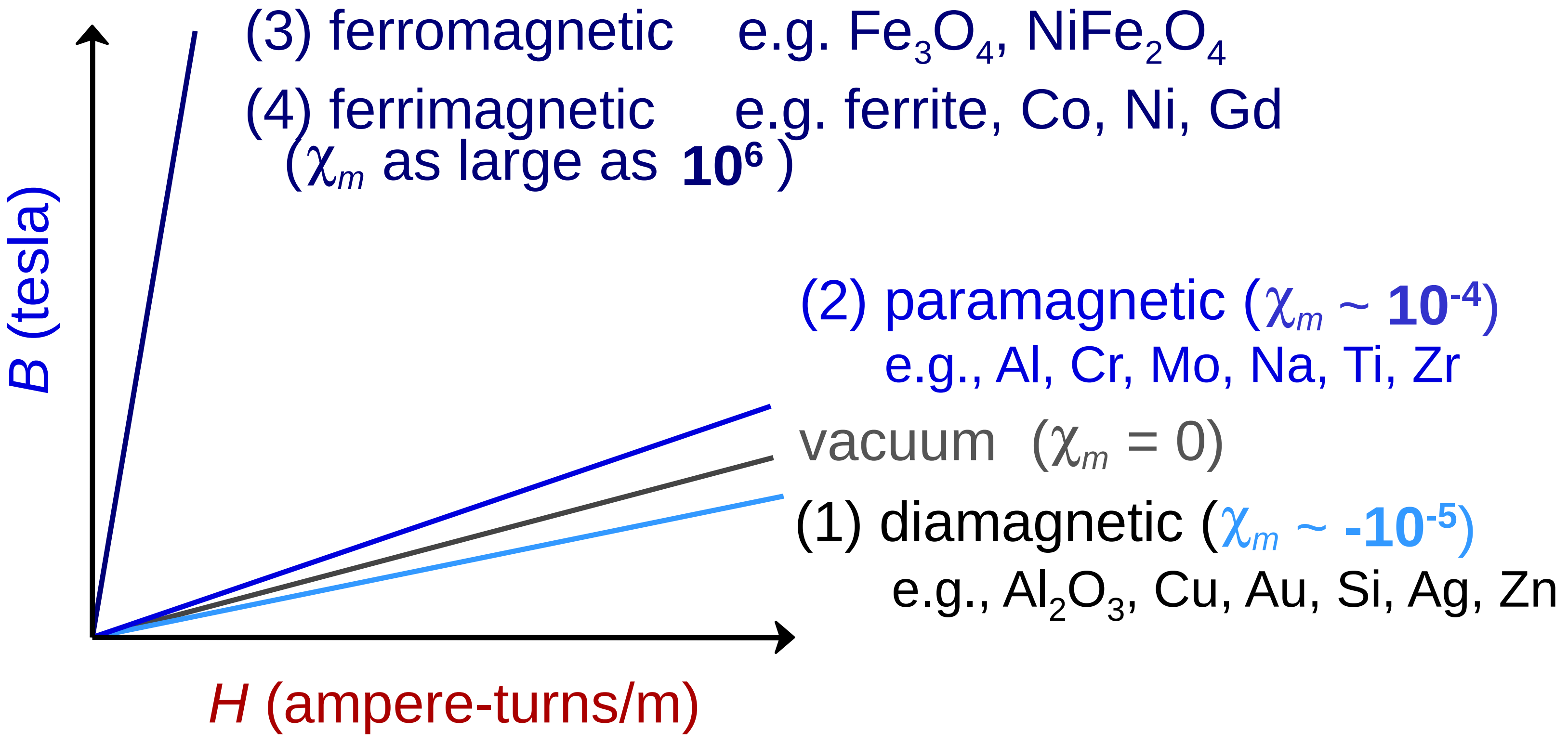
- Net atomic magnetic moment:
  -- sum of moments from all electrons.

- Four types of response...

Magnetic moments of atoms

- The net magnetic moment for an atom is the sum of the magnetic moments of each of the constituent electrons, including both orbital and spin contributions.
- In each atom, orbital moments and/or spin moments of some electron pairs cancel each other.
- For an atom having completely filled electron shells or subshells, when all electrons are considered, there is total cancellation of both orbital and spin moments.
- Hence, the inert gases (He, Ne, Ar, etc.) as well as some ionic materials are not capable of being permanently magnetized.
- The type of magnetic response includes diamagnetism, paramagnetism, ferromagnetism, antiferromagnetism and ferrimagnetism.

Types of Magnetism



Magnetic Responses of 4 Types

(1) diamagnetic

Weak and non-Permanent, change in orbital motion of electrons to H.

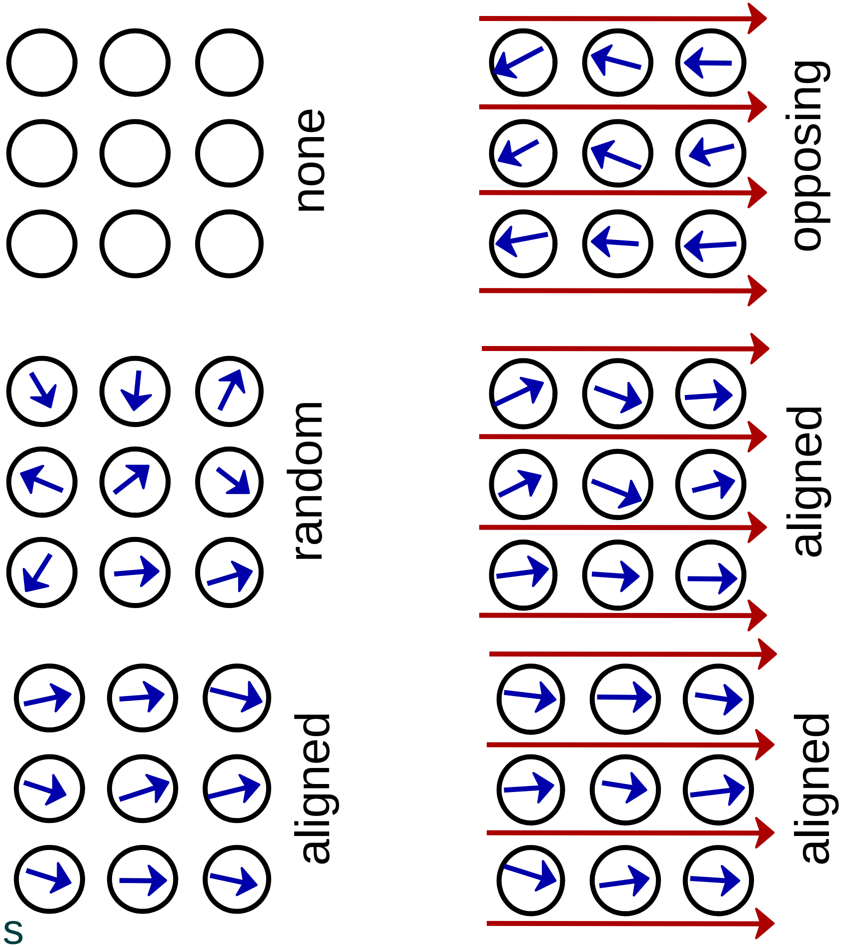
(2) paramagnetic

Each atom has a permanent dipole Moment: incomplete cancellation of electron spin and/or orbital magnetic moments.

(3) ferromagnetic
(4) ferrimagnetic

possess a permanent magnetic moment in the absence of an external field and manifest very large and permanent magnetizations

No Applied Magnetic Field ($H = 0$) | Applied Magnetic Field (H)



Ferromagnetic materials

- The maximum possible magnetization, or saturation magnetization, M_s of a ferromagnetic material represents the magnetization that results when all the magnetic dipoles in a solid piece are mutually aligned with the external field; there is also a corresponding saturation flux density, B_s.

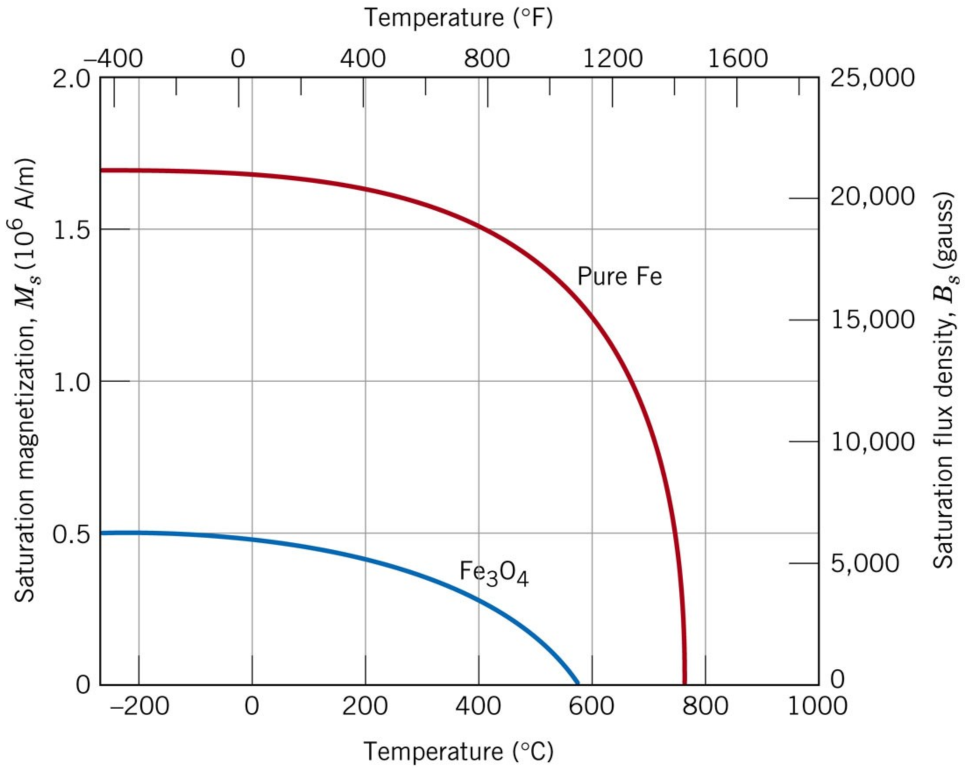
- The saturation magnetization is equal to the product of the net magnetic moment for each atom and the number of atoms present.

- For each of iron, cobalt, and nickel, the net magnetic moments per atom are 2.22, 1.72, and 0.60 Bohr magnetons, respectively.

- Magnetic susceptibilities χ_m is as high as 10^6 for ferromagnetic materials. Hence, H << M. Therefore, we can obtain the magnetic flux density as:

$$B \cong \mu_0 M$$

Influence of Temperature on Magnetic Behavior



With increasing temperature, the saturation magnetization diminishes gradually and then abruptly drops to zero at Curie Temperature, Tc.

Numerical:

Calculate (a) the saturation magnetization and (b) the saturation flux density for nickel, which has a density of 8.90 g/cm^3.

Magnetic moment per atom for Ni: 0.60 Bohr magneton

A_{Ni} = 58.71 g/mol

Solution:

The saturation magnetization is the product of the number of Bohr magnetons per atom (0.60, as given), the magnitude of the Bohr magneton $_B$, and the number N of atoms per cubic meter.

The number of atoms per cubic meter can be obtained from density as:

$$N = \frac{\rho N_A}{A_{Ni}}$$