Chemical Engineering 378

Science of Materials Engineering

Lecture 36

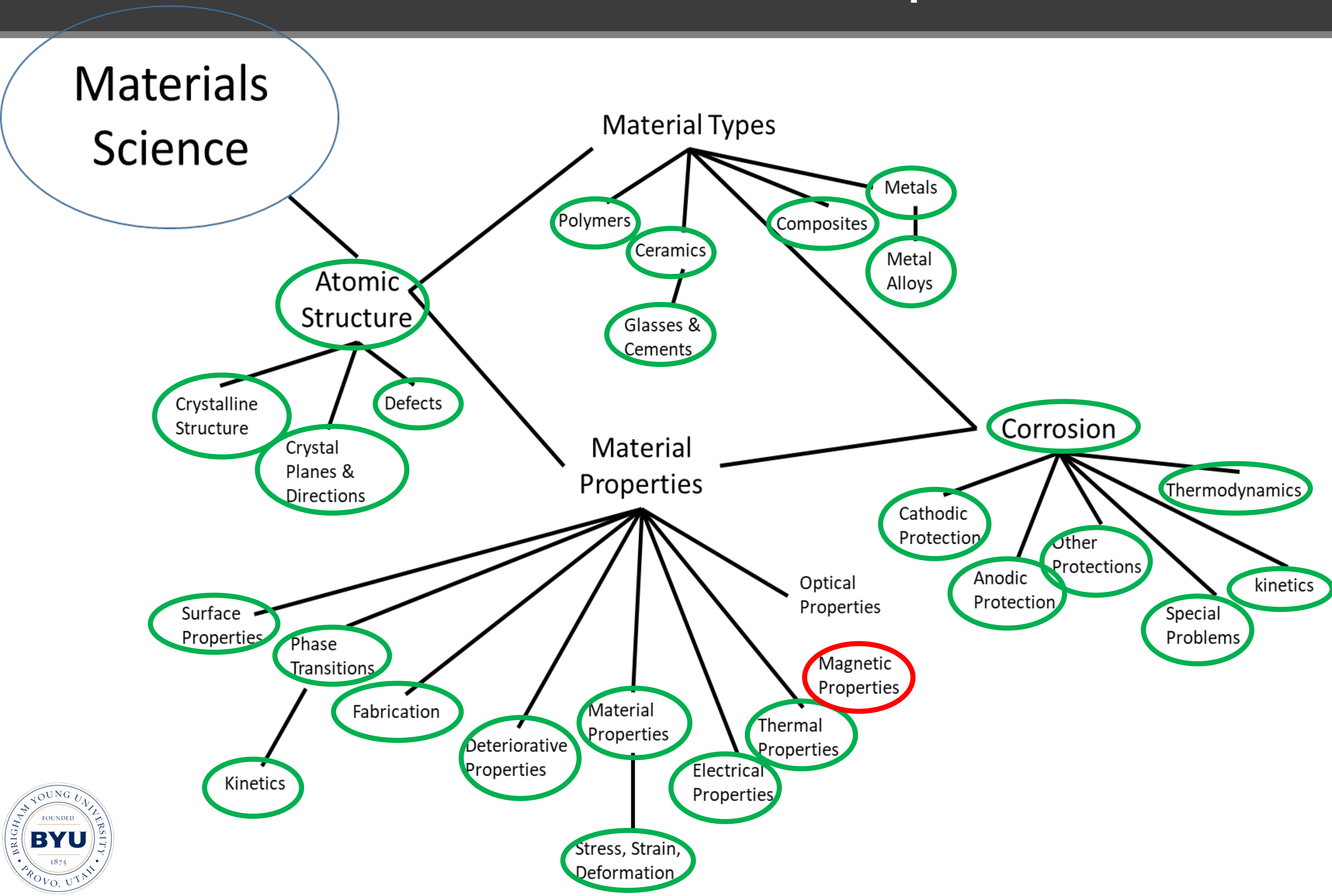
Magnetic Properties

Spiritual Thought

"I urge you to stretch beyond your current spiritual ability to receive personal revelation, for the Lord has promised that 'if thou shalt [seek], thou shalt receive revelation upon revelation, knowledge upon knowledge, that thou mayest know the mysteries and peaceable things—that which bringeth joy, that which bringeth life eternal.'"

- President Russel M. Nelson

Materials Roadmap



OEP Help

Cylinder Hoop Stress Formula

$$\sigma_H = \frac{Pd}{2t}$$

σ_H – cylinder hoop stress in Pa

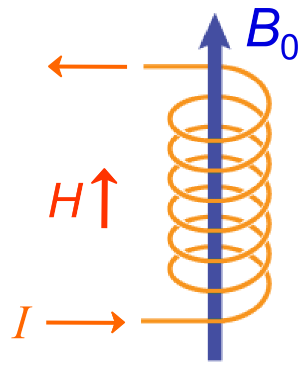
P – internal pressure in Pa

d – cylinder inside diameter in m

t – wall thickness in m

Generation of a Magnetic Field - Vacuum

- Created by current through a coil:



N = total number of turns
ℓ = length of each turn (m)
I = current (ampere)
H = applied magnetic field (ampere-turns/m)
B_0 = magnetic flux density in a vacuum (tesla)

- Computation of the applied magnetic field, H:

$$H = \frac{N\,I}{\ell}$$

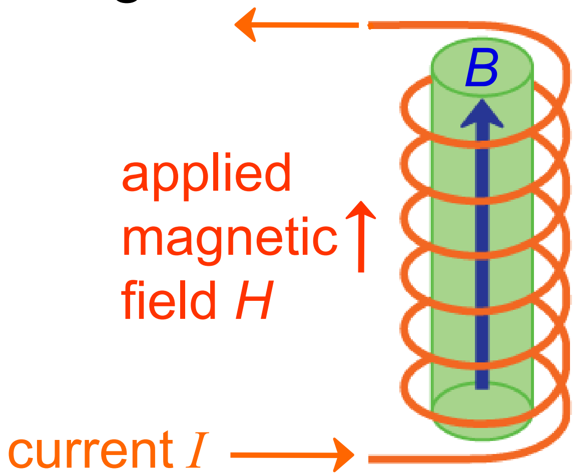
- Computation of the magnetic flux density in a vacuum, B_0:

$$B_0 = \mu_0 H$$

permeability of a vacuum
(1.257×10^{-6} Henry/m)

Generation of a Magnetic Field -- within a Solid Material

- A magnetic field is induced in the material



B = Magnetic Induction (tesla) inside the material

$$B = \mu H$$

permeability of a solid

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

Generation of a Magnetic Field - within a Solid Material (cont.)

- Magnetization $M = \chi_m H$

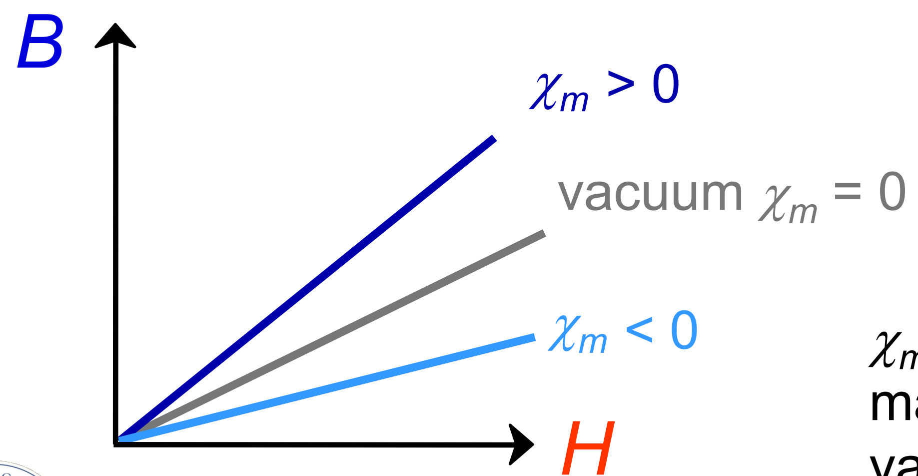
Magnetic susceptibility (dimensionless)

- B in terms of H and M $B = \mu_0 H + \mu_0 M$

- Combining the above two equations:

$$B = \mu_0 H + \mu_0 \chi_m H$$
$$= (1 + \chi_m)\mu_0 H$$

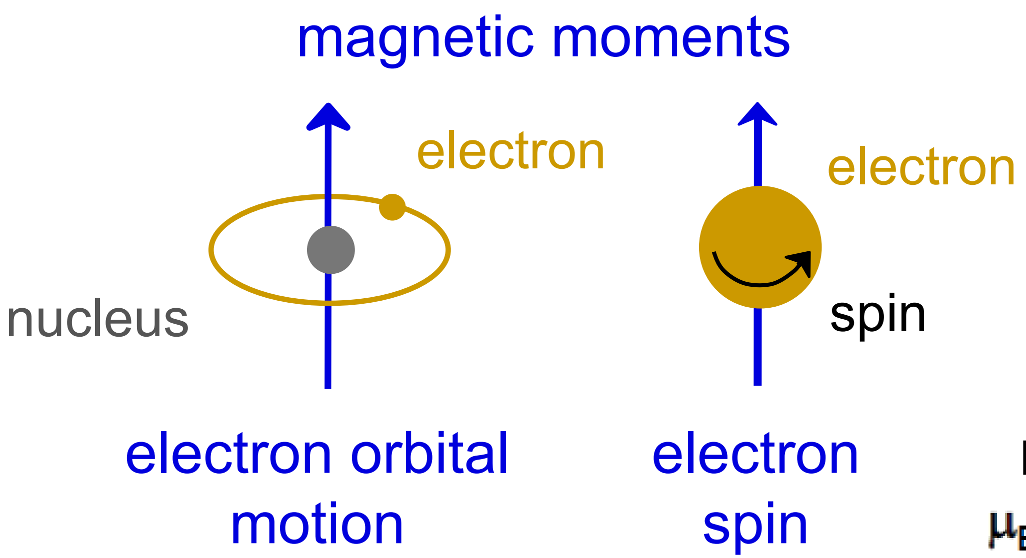
permeability of a vacuum: (1.26×10^{-6} Henry/m)



χ_m is a measure of a material's magnetic response relative to a vacuum

Origins of Magnetic Moments

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



Adapted from Fig. 20.4, *Callister & Rethwisch 10e*.

Bohr Magnetons

μ_B **= 9.27 x 10^{-24} Am^2**

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

Iron Has 2.22 Bohr Magnetons, so:

$$M_s = 2.22\ \mu_B\ N$$

$$B_s = \mu_o M_s$$

- Four types of response...

Example 1

Given that the net magnetic moment per atom of iron is 2.22 Bohr magnetons, what are the saturation magnetization (M_s) and saturation flux density (B_s) for iron?

$$M_s = 2.22\ \mu_B\ N$$

$$B_s = \mu_o M_s$$

where M_s = the saturation magnetization

μ_o =1.257 x 10^{-6} Henry/m

μ_B = 9.27 x 10^{-24} Am^2

N = number of atoms/m^3

Example 1 Solution

First find N (atoms/m³)

$$N = \frac{\rho\, N_A}{A_{Fe}}$$

$$N = \frac{\left(7.97\ \frac{g}{cm^3}\right)\left(6.022\ x10^{23}\ \frac{atoms}{mol}\right)}{\left(\frac{m}{100\ cm}\right)^3\ \left(55.85\,\frac{g}{mol}\right)}$$

$$N = 8.6\ x\ 10^{28}\,\frac{atoms}{m^3}$$

Example 1 Solution

$$M_s = 2.22\ \mu_B\ N$$

$$M_s = \left(\frac{2.22\ Bohr\ magneton}{atom}\right)\left(\frac{9.27\ x\ 10^{-24}\ A\ m^2}{Bohr\ magneton}\right)\left(\frac{8.6\ x\ 10^{28}\ atoms}{m^3}\right)$$

$$M_s = 1.77\ x\ 10^6\ \frac{A}{m}$$

$$B_s = \mu_o M_s$$

$$B_s = 1.257\ x\ 10^{-6}\ \frac{H}{m}\ (1.77\ x\ 10^6\ \frac{A}{m})$$

$$B_s = 2.22\ \text{Tesla}$$

Unit Conversions

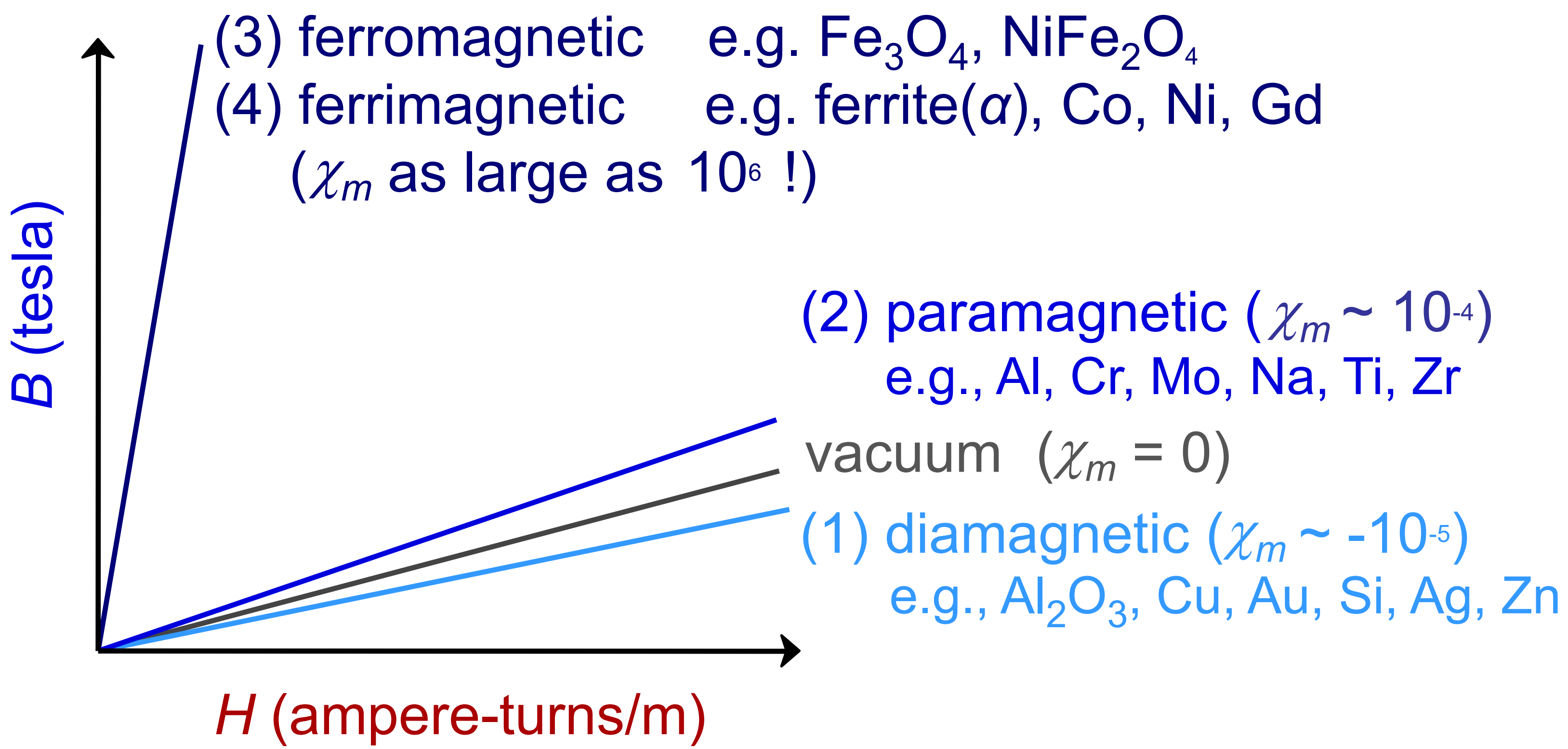
- **Units of the Henry are Webers per Ampere**
- **Units of the Weber are Volt-seconds**
- **Tesla is a Wb/m^2**

$$\text{Tesla} = \frac{\text{H}}{\text{m}}\frac{\text{A}}{\text{m}} = \frac{\text{Wb}}{\text{A m}}\frac{\text{A}}{\text{m}} = \frac{\text{Wb}}{\text{m}^2}$$

$$\text{Tesla} = \frac{\text{Wb}}{\text{m}^2}\frac{\text{Vs}}{\text{Wb}} = \frac{\text{Vs}}{\text{m}^2} = \frac{\text{Js}}{\text{C m}^2} = \frac{\text{J}}{\text{A m}^2}$$

$$= \frac{\text{Nm}}{\text{Am}^2} = \frac{\text{N}}{\text{Am}} = \frac{\text{kgm}}{s^2\,\text{Am}} = \frac{\text{kgms}}{s^2\,\text{C m}} = \frac{\text{kg}}{\text{Cs}}$$

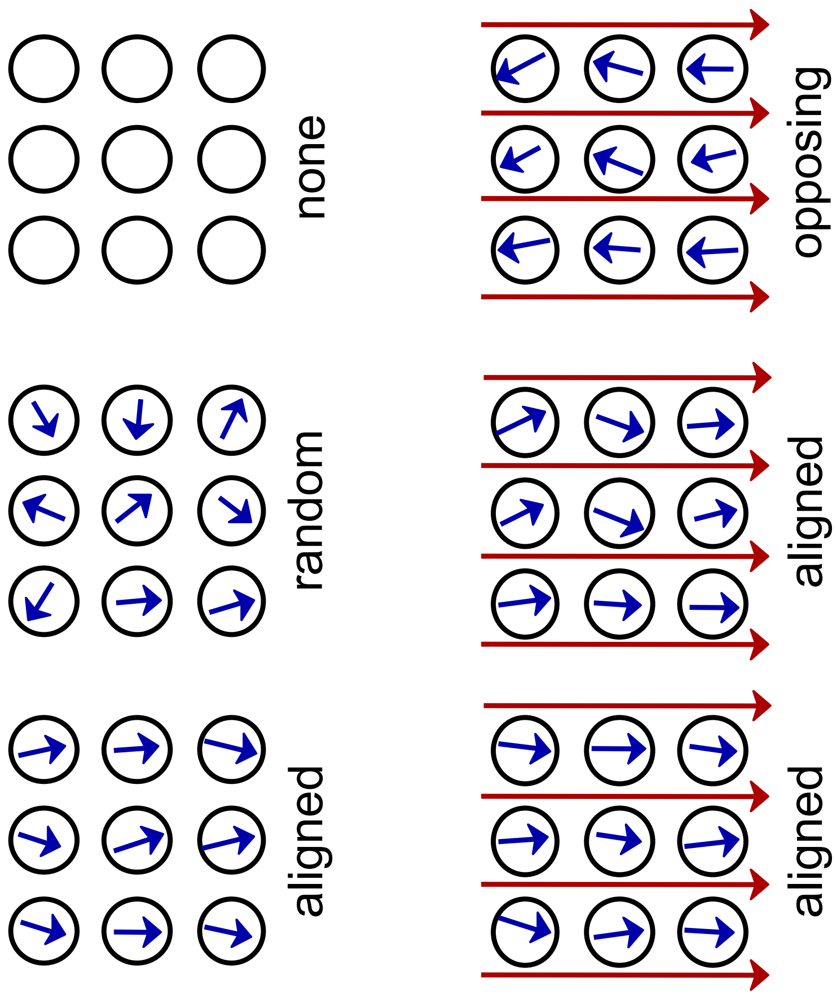
Types of Magnetism



Plot adapted from Fig. 20.6, *Callister & Rethwisch 10e*.
Values and materials from Table 20.2, *Callister & Rethwisch 10e*.

Magnetic Responses for 4 Types

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



(1) diamagnetic

Adapted from Fig. 20.5(a), *Callister & Rethwisch 10e*.

(2) paramagnetic

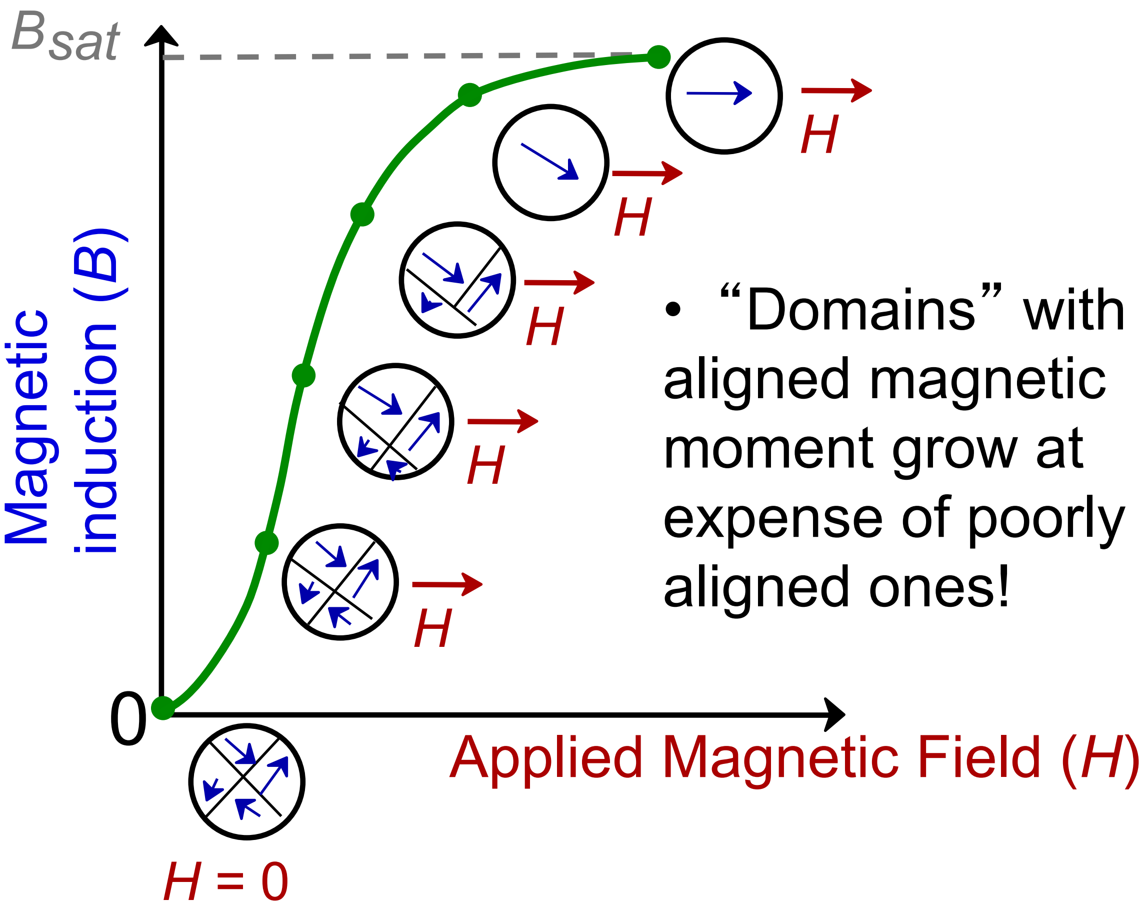
Adapted from Fig. 20.5(b), *Callister & Rethwisch 10e*.

(3) ferromagnetic
(4) ferrimagnetic

Adapted from Fig. 20.7, *Callister & Rethwisch 10e*.

Domains in Ferromagnetic & Ferrimagnetic Materials

- As the applied field (*H*) increases the magnetic domains change shape and size by movement of domain boundaries.

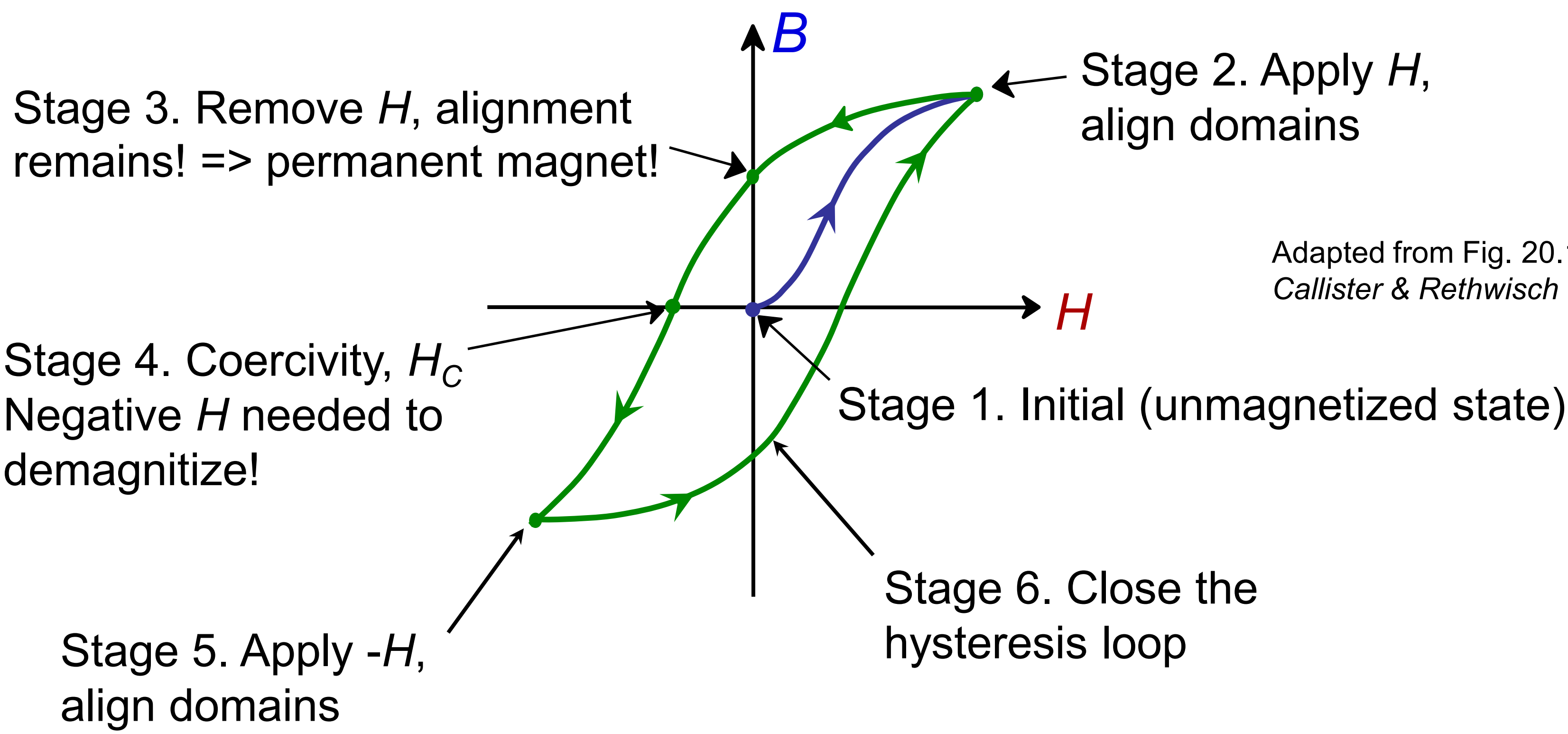


- "Domains" with aligned magnetic moment grow at expense of poorly aligned ones!

Fig. 20.13, *Callister & Rethwisch 10e*.

Hysteresis and Permanent Magnetization

- The magnetic hysteresis phenomenon



Adapted from Fig. 20.14, *Callister & Rethwisch 10e*.

Hard and Soft Magnetic Materials

Hard magnetic materials:

-- large coercivities
-- used for permanent magnets
-- add particles/voids to
   inhibit domain wall motion
-- example: tungsten steel --
   H_c = 5900 amp-turn/m)

Soft magnetic materials:

-- small coercivities
-- used for electric motors
-- example: commercial iron 99.95 Fe

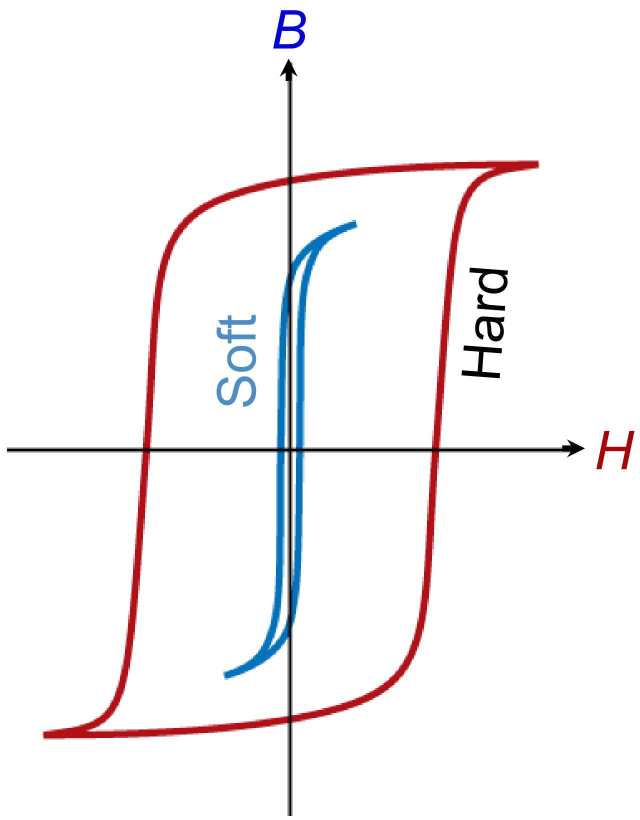


Fig. 20.19, *Callister & Rethwisch 10e*. (From K. M. Ralls, T. H. Courtney, and J. Wulff, *Introduction to Materials Science and Engineering*. Copyright © 1976 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

Magnetic Storage

- Digitized data in the form of electrical signals are transferred to and recorded digitally on a magnetic medium (tape or disk)
- This transference is accomplished by a recording system that consists of a read/write head

-- "write" or record data by applying a magnetic field that aligns domains in small regions of the recording medium

-- "read" or retrieve data from medium by sensing changes in magnetization

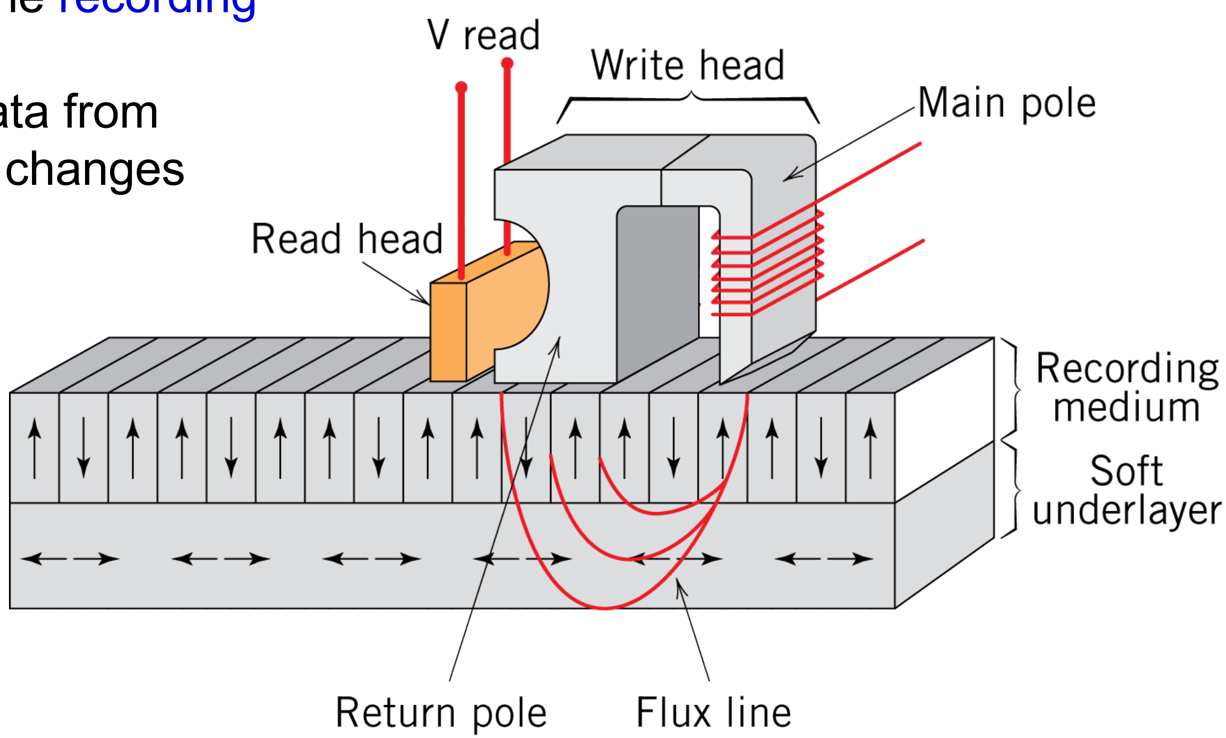


Fig. 20.23, *Callister & Rethwisch 10e*.
(Courtesy of HGST, a Western Digital Company.)

Magnetic Storage Media Types

- Hard disk drives (granular/perpendicular media):
  - -- CoCr alloy grains (darker regions) separated by oxide grain boundary segregant layer (lighter regions)
  - -- Magnetization direction of each grain is perpendicular to plane of disk

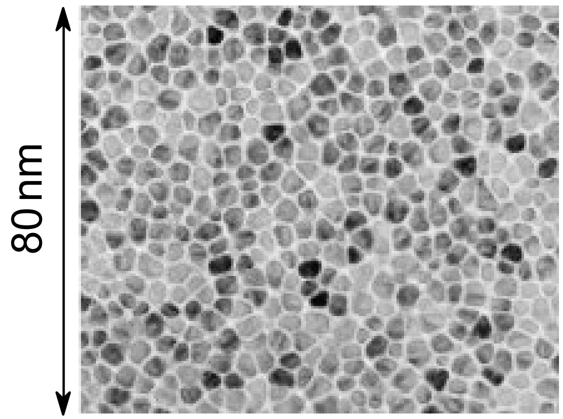
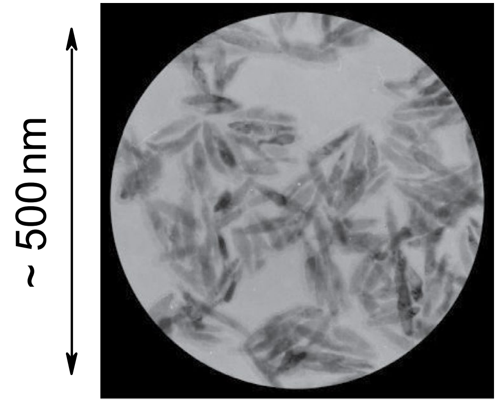
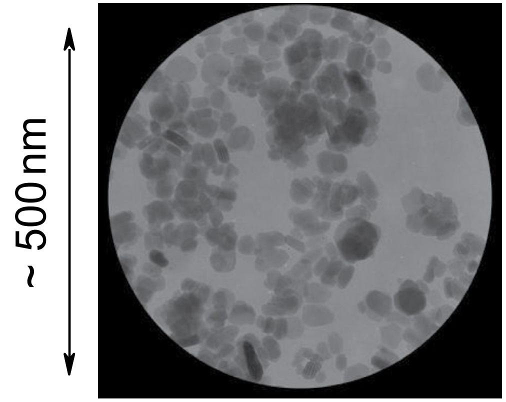


Fig. 20.24, *Callister & Rethwisch 10e*. (Courtesy of Seagate Recording Media)

- Recording tape (particulate media):



-- Acicular (needle-shaped) ferromagnetic metal alloy particles



-- Tabular (plate-shaped) ferrimagnetic barium-ferrite particles

Fig. 20.25, *Callister & Rethwisch 10e*. (Courtesy of Fuji Film Inc., Recording Media Division)

Superconductivity

Found in 26 metals and hundreds of alloys & compounds

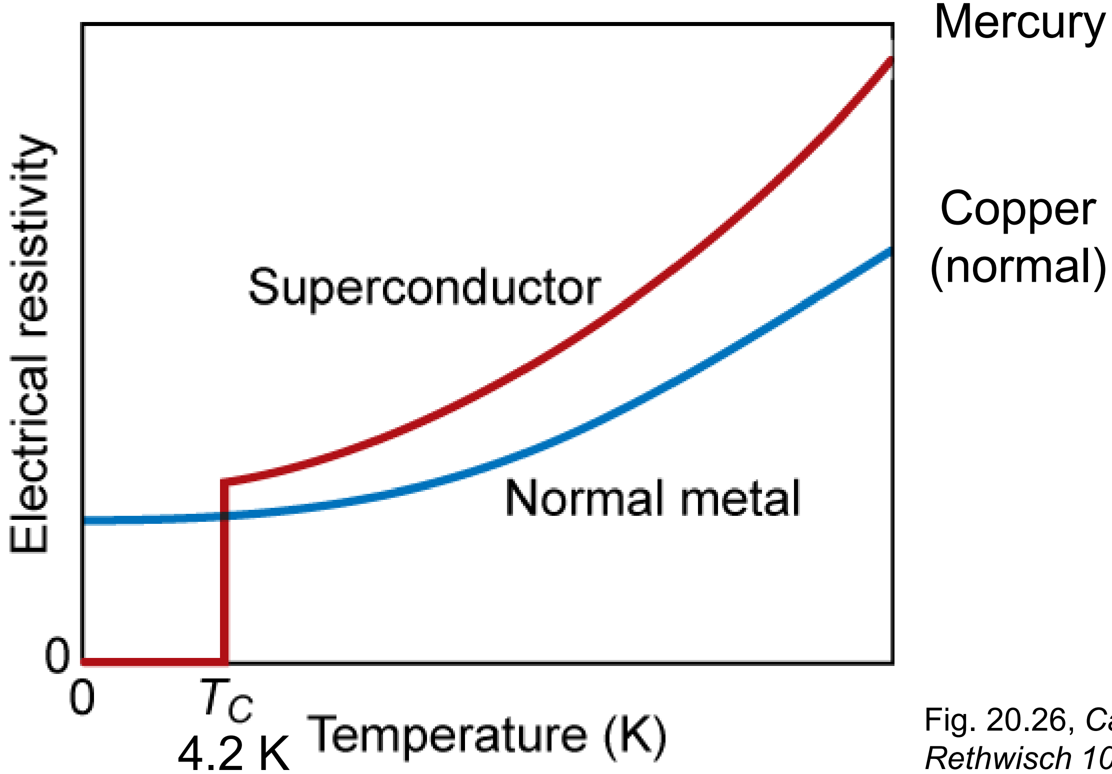


Fig. 20.26, *Callister & Rethwisch 10e*.

- T_C = critical temperature
  = temperature below which material is superconductive

Critical Properties of Superconductive Materials

T_C = critical temperature - if $T > T_C$ not superconducting
J_C = critical current density - if $J > J_C$ not superconducting
H_C = critical magnetic field - if $H > H_C$ not superconducting

$$H_C(T) = H_C(0)\left(1 - \frac{T^2}{T_C^2}\right)$$

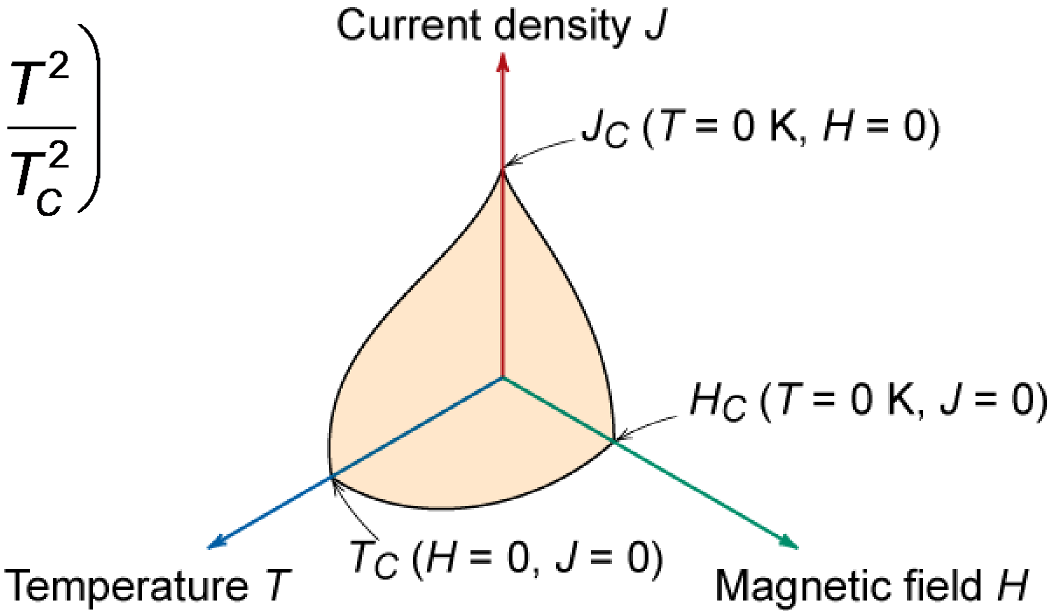


Fig. 20.27, *Callister & Rethwisch 10e*.

Meissner Effect

- Superconductors expel magnetic fields

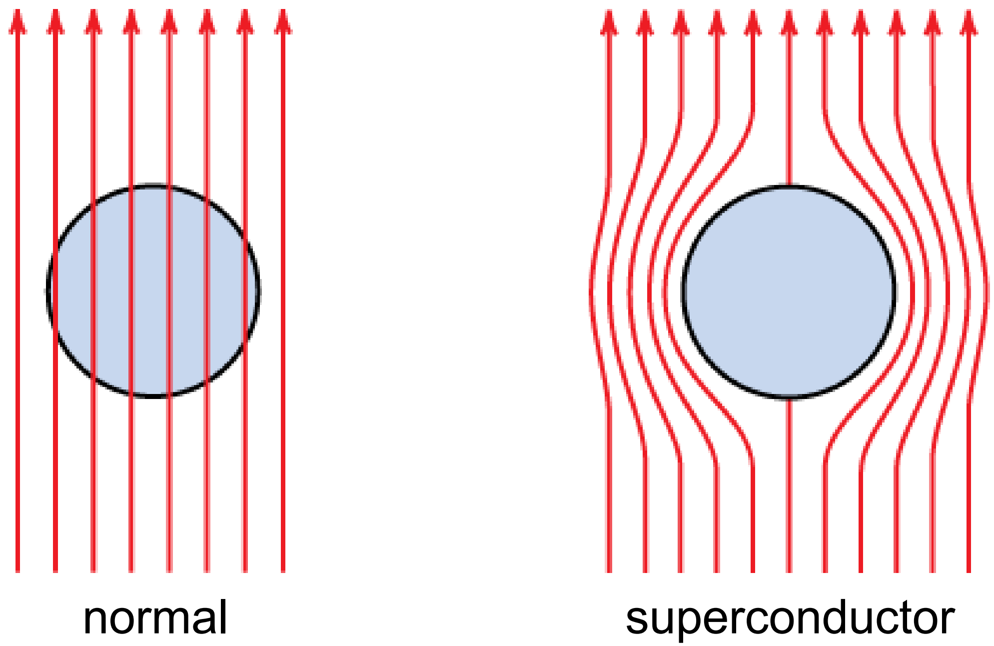


Fig. 20.28, *Callister & Rethwisch 10e*.

- This is why a superconductor will float above a magnet

Advances in Superconductivity

- Research in superconductive materials was stagnant for many years.
  - Everyone assumed $T_{C,max}$ was about 23 K
  - Many theories said it was impossible to increase T_C beyond this value
- 1987- new materials were discovered with T_C > 30 K
  - ceramics of form $Ba_{1-x}K_xBiO_{3-y}$
  - Started enormous race
    - $YBa_2Cu_3O_{7-x}$ $T_C = 90$ K
    - $Tl_2Ba_2Ca_2Cu_3O_x$ $T_C = 122$ K
    - difficult to make since oxidation state is very important
- The major problem is that these ceramic materials are inherently brittle.