Chapter 9: Magnetic Properties

ISSUES TO ADDRESS...

- What are the important magnetic properties?
- How do we explain magnetic phenomena?
- How are magnetic materials classified?
- What is superconductivity and how do magnetic fields effect the behavior of superconductors?

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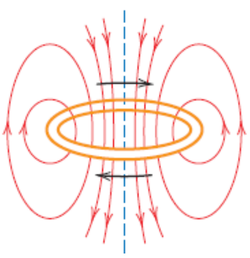
MAGNETIC DIPOLES

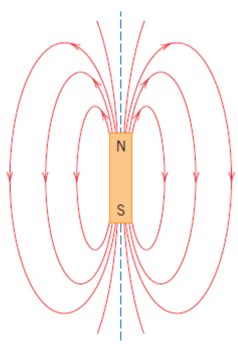
•Magnetic forces are generated by moving electrically charged particles

•Many times it is convenient to think of magnetic forces in terms of fields.

•Imaginary lines of force may be drawn to indicate the direction of the force at positions in the vicinity of the field source.

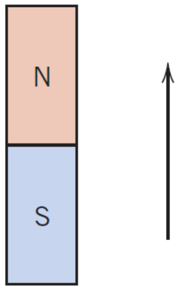


Magnetic field lines of force around a current loop and a bar magnet.

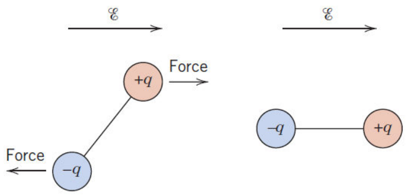


•Magnetic dipoles may be thought of as small bar magnets composed of north and south poles instead of positive and negative electric charges.

•Magnetic dipole moments are represented by arrows.



•Magnetic dipoles are influenced by magnetic fields in a manner similar to the way in which electric dipoles are affected by electric fields:



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•When a magnetic field is applied, the force of the field itself exerts a torque that tends to orient the dipoles with the field.

•A magnetic compass needle lines up with the earth's magnetic field.

Before discussing the origin of magnetic moments in solid materials, we describe magnetic behavior in terms of several field vectors:

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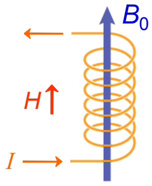
Generation of a Magnetic Field -- Vacuum

- 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:

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

- 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)

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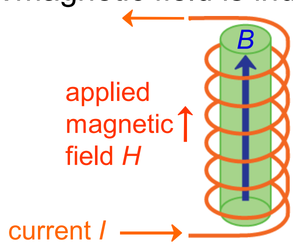
Generation of a Magnetic Field -- within a Solid Material

- A magnetic field is induced in the material



B = Magnetic Induction (tesla) inside the material

(Represents the magnitude of the internal field strength within a substance that is subjected to an H field.)

$$B = \mu H$$

permeability of a solid

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

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

•the permeability or relative permeability of a material is 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.

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Magnetization:

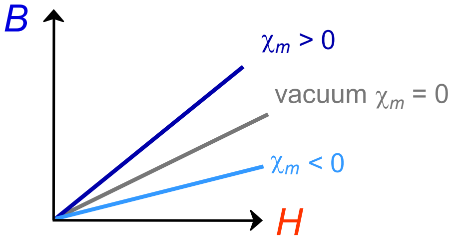
•Another field quantity, M, called the **magnetization** of the solid:

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

$M = \chi_m H$

Magnetic susceptibility (dimensionless)

•In the presence of an H field, the magnetic moments within a material tend to become aligned with the field and to reinforce it by virtue of their magnetic fields.



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

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Origins of Magnetic Moments

•The macroscopic magnetic properties of materials are a consequence of magnetic moments associated with individual electrons.

•Each electron in an atom has magnetic moments that originate from two sources.

- •One is related to its orbital motion around the nucleus; being a moving charge (*an electron may be considered to be a small current loop, generating a very small magnetic field, and having a magnetic moment along its axis of rotation*).
- •Each electron may also be thought of as spinning around an axis; the other magnetic moment originates from this electron spin, which is directed along the spin axis:

•Each electron in an atom may be thought of as being a small magnet having permanent orbital and spin magnetic moments.

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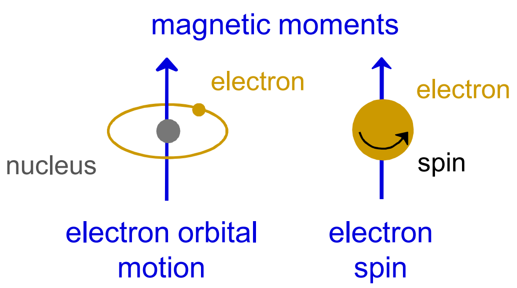
Origins of Magnetic Moments

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



Adapted from Fig. 20.4, *Callister & Rethwisch 8e*.

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

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•In each individual atom, orbital moments of some electron pairs cancel each other. For example, the spin moment of an electron with “spin up” will cancel that of one with “spin down”.

•The net magnetic moment, then, for an atom is just the sum of the magnetic moments of each of the constituent electrons, including both orbital and spin contributions, and taking into account moment cancellation.

•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. Thus materials composed of atoms having completely filled electron shells are not capable of being permanently magnetized.

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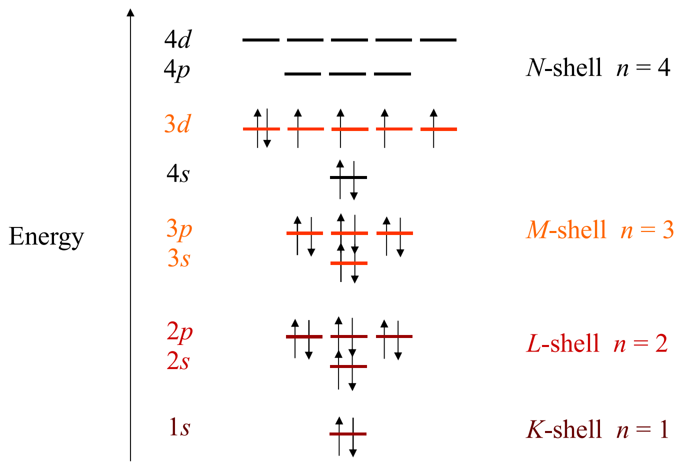
Electronic Configurations

ex: Fe - atomic # = 26 $1s^2$ $2s^2 2p^6$ $3s^2 3p^6 3d^6$ $4s^2$



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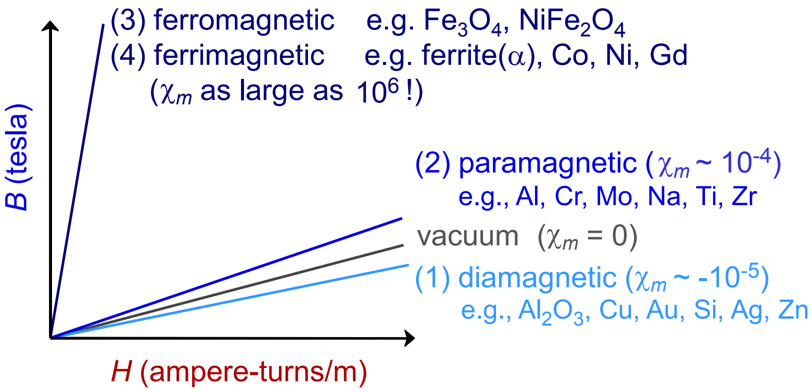
Types of Magnetism



Plot adapted from Fig. 20.6, *Callister & Rethwisch 8e*.
Values and materials from Table 20.2 and discussion in Section 20.4, *Callister & Rethwisch 8e*.

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➢DIAMAGNETISM:

•Diamagnetism is a very weak form of magnetism that is nonpermanent and persists only while an external field is being applied.

•It is induced by a change in the orbital motion of electrons due to an applied magnetic field.

•The magnitude of the induced magnetic moment is extremely small, and in a direction opposite to that of the applied field.

•The magnetic susceptibility is negative; that is, the magnitude of the *B* field within a diamagnetic solid is less than that in a vacuum.

•When placed between the poles of a strong electromagnet, diamagnetic materials are attracted toward regions where the field is weak.

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➢PARAMAGNETISM:

•For some solid materials, each atom possesses a permanent dipole moment by virtue of incomplete cancellation of electron spin and/or orbital magnetic moments.

•In the absence of an external magnetic field, the orientations of these atomic magnetic moments are **random**, such that a piece of material possesses no net macroscopic magnetization.

•These atomic dipoles are free to rotate, and paramagnetism results when they preferentially align, by rotation, with an external field.

•These magnetic dipoles are acted on individually with no mutual interaction between adjacent dipoles. Inasmuch as the dipoles align with the external field, they enhance it, giving rise to a relative permeability that is greater than unity, and to a relatively small but positive magnetic susceptibility.

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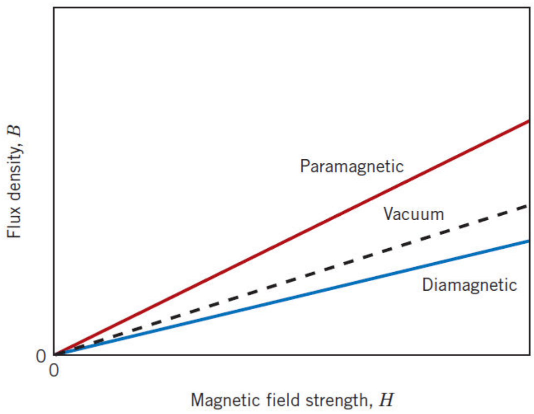
•Both **diamagnetic** and **paramagnetic** materials are considered to be **nonmagnetic** because they exhibit magnetization only when in the presence of an external field.



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➢FERROMAGNETISM:

•Certain metallic materials possess a permanent magnetic moment in the absence of an external field, and manifest very large and permanent magnetizations.

•They are displayed by the transition metals *iron* (as BCC ferrite), *cobalt*, *nickel*, and some of the rare earth metals such as *gadolinium* (Gd).

•Magnetic susceptibilities as high as are10^6 possible for ferromagnetic materials.

•Permanent magnetic moments in ferromagnetic materials result from atomic magnetic moments due to uncancelled electron spins as a consequence of the electron structure (*unfilled electron shells*).

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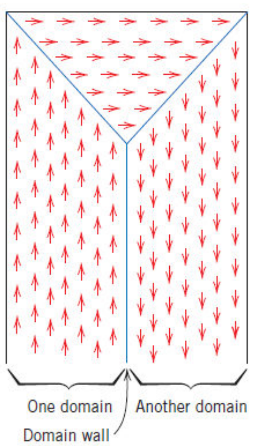
Ferromagnetism (cont.):

•There is also an orbital magnetic moment contribution that is small in comparison to the spin moment.

•Furthermore, in a ferromagnetic material, **"coupling interactions"** cause net spin magnetic moments of adjacent atoms to align with one another, even in the absence of an external field.

•This mutual spin alignment exists over relatively large volume regions of the crystal called **domains.**



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Ferromagnetism (cont.):

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

•The "**saturation magnetization**" is equal to the:

- •Product of the net magnetic moment for each atom,
- •The number of atoms present.

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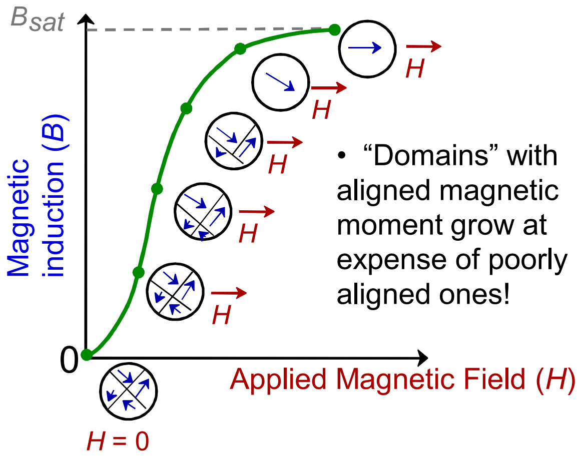
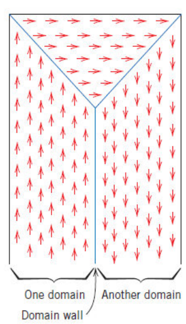
Domains in Ferromagnetic & Ferrimagnetic Materials

- 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!



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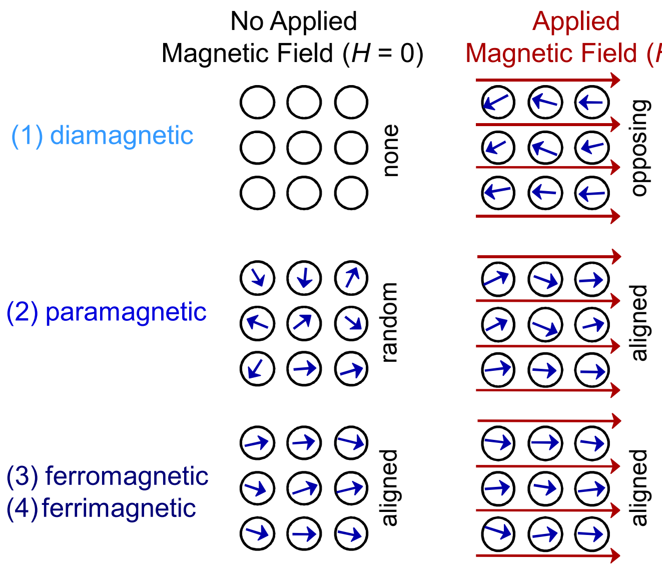
Magnetic Responses for 4 Types



Adapted from Fig. 20.5(a), *Callister & Rethwisch 8e.*

Adapted from Fig. 20.5(b), *Callister & Rethwisch 8e.*

Adapted from Fig. 20.7, *Callister & Rethwisch 8e.*

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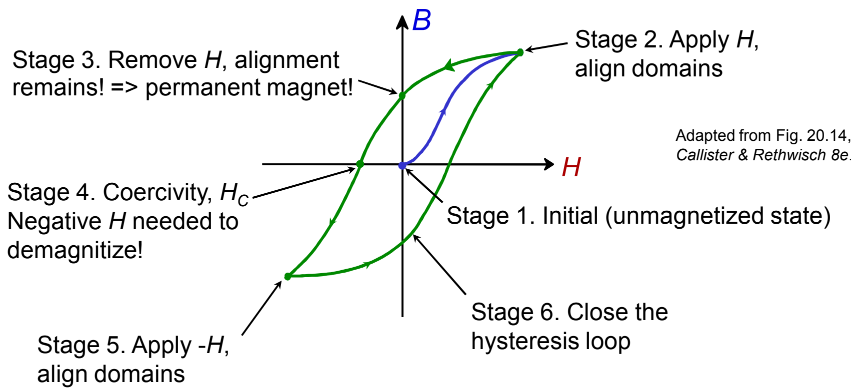
Hysteresis and Permanent Magnetization

- The magnetic hysteresis phenomenon



Adapted from Fig. 20.14, *Callister & Rethwisch 8e.*

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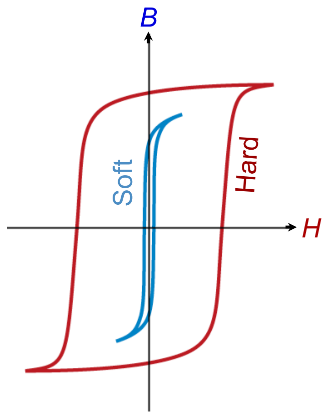
Hard and Soft Magnetic Materials

Hard magnetic materials:
-- large coercivities
-- lower initial permeability
-- high magnetic energy loss
-- used for permanent magnets
-- example: tungsten steel --
H_c = 5900 amp-turn/m)

Soft magnetic materials:
-- small coercivities
-- high initial permeability
-- low magnetic energy loss
-- used for electric motors, dynamos, generators, switching circuits
-- example: commercial iron 99.95 Fe



Adapted from Fig. 20.19, *Callister & Rethwisch 8e*. (Fig. 20.19 from K.M. Ralls, T.H. Courtney, and J. Wulff, *Introduction to Materials Science and Engineering*, John Wiley and Sons, Inc., 1976.)

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Superconductivity

Found in 26 metals and hundreds of alloys & compounds

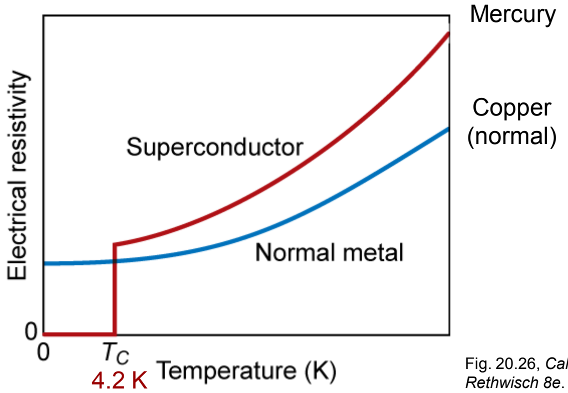

Fig. 20.26, *Callister & Rethwisch 8e*.

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

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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

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

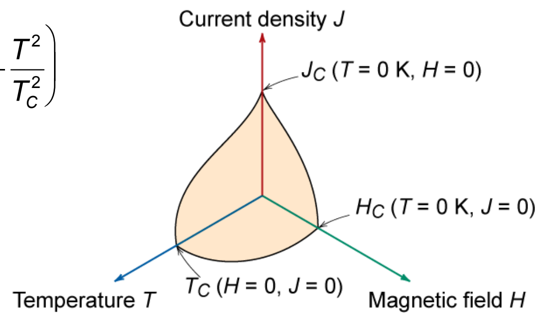

Fig. 20.27, *Callister & Rethwisch 8e.*

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Meissner Effect

- Superconductors expel magnetic fields

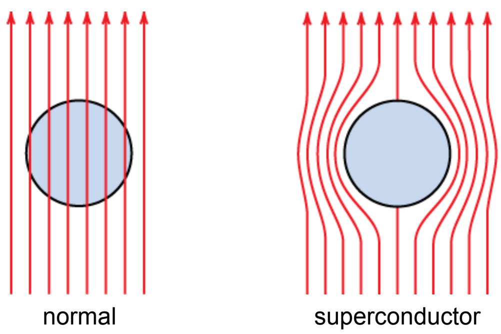

Fig. 20.28, *Callister & Rethwisch 8e.*

- This is why a superconductor will float above a magnet

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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 $Ba_{1-x} K_x BiO_{3-y}$
  - Started enormous race
    - $Y Ba_2Cu_3O_{7-x}$ 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.

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Summary

- A magnetic field is produced when a current flows through a wire coil.
- Magnetic induction (B):
  -- an internal magnetic field is induced in a material that is situated within an external magnetic field (H).
  -- magnetic moments result from electron interactions with the applied magnetic field
- Types of material responses to magnetic fields are:
  -- ferrimagnetic and ferromagnetic (large magnetic susceptibilities)
  -- paramagnetic (small and positive magnetic susceptibilities)
  -- diamagnetic (small and negative magnetic susceptibilities)
- Types of ferrimagnetic and ferromagnetic materials:
  -- Hard: large coercivities
  -- Soft: small coercivities

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