CHAPTER 5: MAGNETIC PROPERTIES

and Magnetic Materials

ISSUES TO ADDRESS...

- Why do we study magnetic properties?
- What is magnetism?
- How do we measure magnetic properties?
- What are the atomic reasons for magnetism?
- How are magnetic material classified?
- Materials design for magnetic storage.

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Chapter Outline

1. Why study the magnetic properties?
2. What is magnetism ?
3. Classification of Magnetic Materials
4. Magnetic Dipoles and Magnetic Moments
5. Magnetization, Permeability, and the Magnetic Field
6. Diamagnetic, Paramagnetic, Ferromagnetic, Ferrimagnetic, and Superparamagnetic Materials
7. Domain Structure and the Hysteresis Loop
8. The Curie Temperature
9. Applications of Magnetic Materials
10. Metallic and Ceramic Magnetic Materials

Why Study the *Magnetic Properties* of Materials?

- An understanding of the mechanism that explains the permanent magnetic behavior of some materials
  - may allow us to alter and
  - in some cases tailor the magnetic properties.

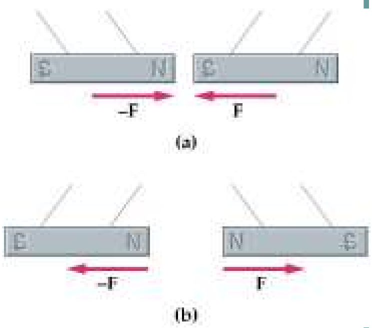
•Iron, some steels, and
•the naturally occurring mineral lodestone (Magnetite) are wellknown examples of materials that exhibit magnetic properties.

Why Study the *Magnetic Properties* of Materials?

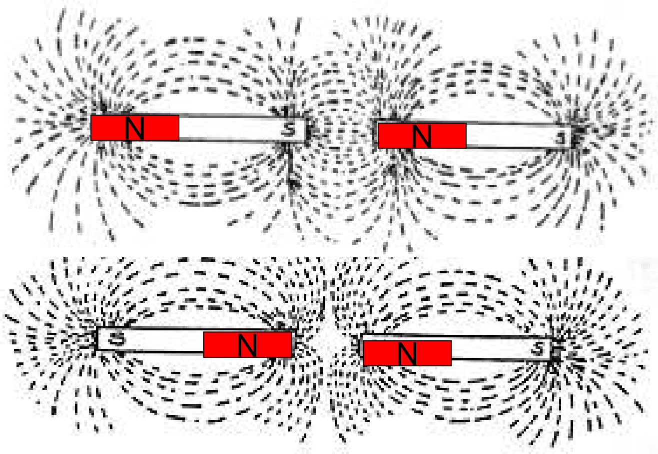
- Many of our modern technological devices rely on magnetism and magnetic materials:
  - electrical power generators
  - transformers,
  - electric motors,
  - radio, television, telephones,
  - computers, and
  - components of sound and video reproduction systems.

The Magnetic Field

- Magnetic poles
  - All magnetic materials have two poles: north pole and south pole
- Just as in electrostatics, like repels like and opposites attract.
  - N repels N, S repels S, N attracts S
- Magnetic field lines
  - Similar to electric field lines.
  - The more closely spaced the lines, the more intense the field.
  - Magnetic field lines point away from north poles and toward south poles, always form closed loops.



Magnetic Dipoles

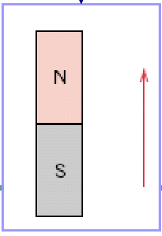


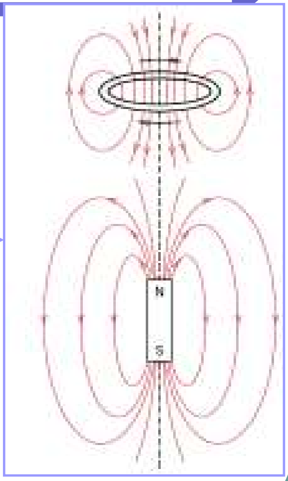
Magnetic Dipoles

Magnetic Dipoles

Magnetic field lines of force around a current loop and
a bar magnet.(Callister,2Ed.)

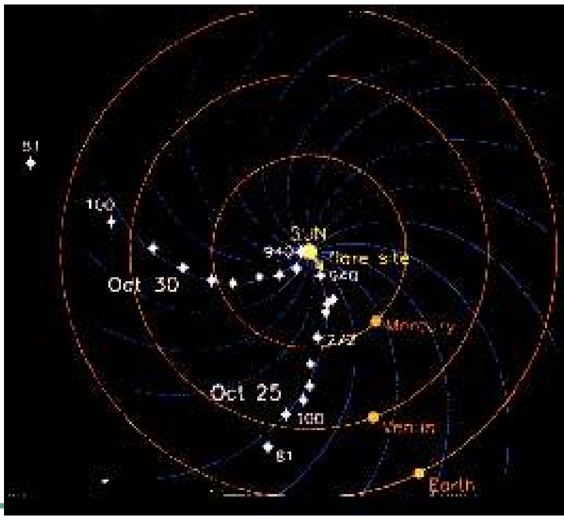
Magnetic dipole
moments are represented by arrows, as shown





Large Magnet

The magnetic field of the sun

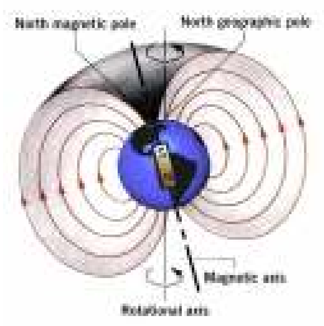


The Earth's Magnetic Field

- Geomagnetism

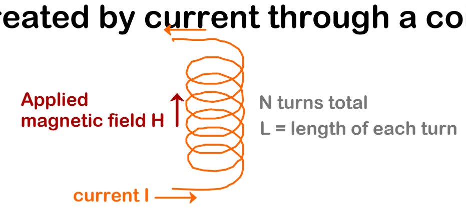
  - The earth produces its own magnetic field, which is inclined at an angle of about 11.5° with its rotational axis.

  - The geographic north pole of the Earth is actually the south magnetic pole of the Earth's magnetic field



MAGNETIC FIELD STRENGTH: APPLIED MAGNETIC FIE

- **Created by current through a coil:**



- **Relation for the Magnetic Field Strength, H:**

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

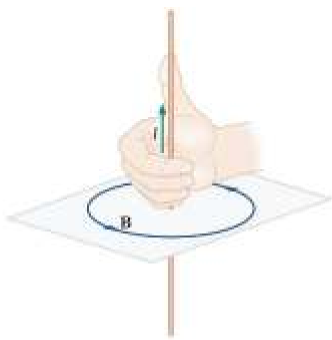
current

The externally applied magnetic field:the **magnetic field strength,** *H*. Here the magnetic field is generated by means of a cylindrical coil (or solenoid) consisting of *N* closely spaced turns, having a length *l*, and carrying a current of magnitude*I*.

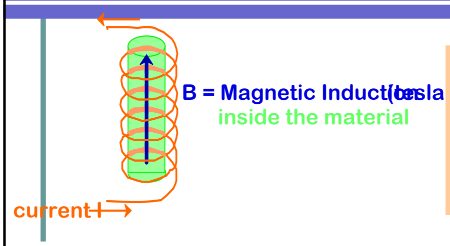
MAGNETIC FIELD STRENGTH: APPLIED MAGNETIC FIELD

- Magnetic field right-hand rule

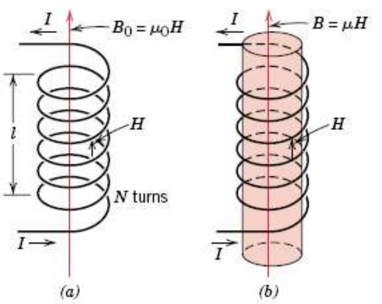
  To find the direction of the magnetic field due to a current-carrying wire, point the thumb of your right hand along the wire in the direction of the current I. Your fingers are now curling around the wire in the direction of the magnetic field



The Magnetic Induction (Magnetic Flux Density): RESPONSE TO A MAGNETIC FIELD



The **magnetic induction,** or **magnetic flux density,** denoted by *B*, represents the magnitude of the internal field strength within a substance that is subjected to an *H* field.



The magnetic field strength(H) and flux density(B) are related according to

$$B = \mu H$$

μ :the permeability

μ_0 : the ***permeability of a vacuum***, a universal constant, $4\pi\ 10^{-7}$ (1.257 10^{-6}) Henries/m

Magnetic Units

Magnetic Field Strength (H)

SI unit:Ampere.meter^{-1}

1Oe= 79.577 A m^{-1}

Magnetic Induction(B)

SI unit: Tesla(T)

- The Tesla is a fairly large unit of magnetic strength, another commonly used unit of magnetism is the Gauss (G):
- The earth's magnetic field is about 0.5G

Typical Magnetic Fields

Physical system	Magnetic field (G)
Earth	0.5
Bar magnet	100
Sunspots	1000
Low-field MRI	2000
High-field MRI	15,000
Strongest manmade magnetic field	6×10^5
Magnetar (a magnetic neutron star formed in a supernova explosion)	10^{15}

$$1\ Gauss = 1\ G = 10^{-4}\ T$$

Magnetic Units and Conversion Factors

Table 18.1 Magnetic Units and Conversion Factors for the SI and cgs–emu Systems

		SI Units		cgs–emu	
Quantity	*Symbol*	*Derived*	*Primary*	*Unit*	*Conversion*
Magnetic induction (flux density)	B	tesla (Wb/m^2)[a]	kg/s-C	gauss	1 Wb/m^2 = 10^4 gauss
Magnetic field strength	H	amp-turn/m	C/m-s	oersted	1 amp-turn/m = $4\pi \times 10^{-3}$ oersted
Magnetization	M (SI) I (cgs–emu)	amp-turn/m	C/m-s	maxwell/cm^2	1 amp-turn/m = 10^{-3} maxwell/cm^2
Permeability of a vacuum	μ_0	henry/m[b]	kg-m/C^2	Unitless (emu)	$4\pi \times 10^{-7}$ henry/m = 1 emu
Relative permeability	μ_r (SI) μ' (cgs–emu)	Unitless	Unitless	Unitless	$\mu_r = \mu'$
Susceptibility	χ_m (SI) χ'_m (cgs–emu)	Unitless	Unitless	Unitless	$\chi_m = 4\pi \chi'_m$

[a] Units of the weber (Wb) are volt-seconds.
[b] Units of the henry are webers per ampere.

Definitions summary

- **Magnetic Field Strength**, H: The externally applied magnetic field
- **Magnetic Induction,B:**The magnitude of the internal field strength within a substance that is subjected to an *H* field.
- **Magnetic permeability(μ) -** The ratio between magnetic induction and magnetic field.

$$B = \mu H$$

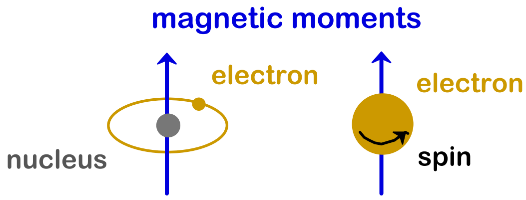
Definitions summary

Magnetization (M) - **The total magnetic moment per unit volume.**
Magnetic susceptibility(χ_m)- **The ratio between magnetization and the applied field.**

$$M = \chi_m H$$

MAGNETIC SUSCEPTIBILITY

- **Measures the response of electrons to a magnetic field.**
- **Electrons produce magnetic moments:**



Adapted from Fig. 20.4, *Callister 6e.*

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

THE INFLUENCE OF TEMPERATURE ON MAGNETIC BEHAVIOR

Temperature can also influence the magnetic characteristics of materials.
Raising the temperature of a solid results in an increase in the magnitude of the thermal vibrations of atoms .

The saturation magnetization is a maximum at 0 K, at which temperature the thermal vibrations are a minimum.

With increasing temperature, the saturation magnetization diminishes gradually and then abruptly drops to zero at what is called the **Curie temperature** *Tc*.

Curie temperatures:

Fe: $T_c = 1043\,K$ (770°C)

Ni: $T_c = 627\,K$ (354°C)

Co: $T_c = 1388\,K$ (1115°C)

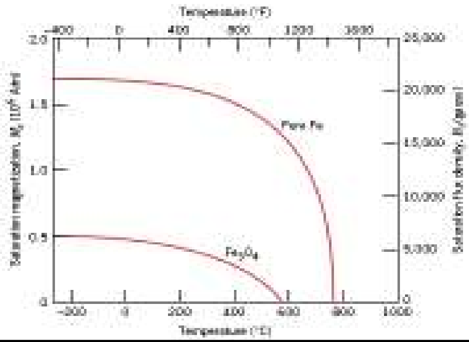
Classification of Magnetic Materials

The material types can be divided into several main categories:

- Ferromagnetism
- Ferrimagnetism
- Diamagnetism
- Paramagnetism
- Antiferromagnetism

Ferromagnetic

- **A ferromagnetic material produces a magnetic field even in the absence of an external magnetic field.**
- Exists up to T_C , the Curie temperature
- Only certain materials are ferromagnetic



Ferromagnetism

The most important class of magnetic materials is the *ferromagnets*: iron, nickel, cobalt and manganese, or their compounds (and a few more exotic ones as well).

although pure manganese is not ferromagnetic the name of that element shares a common root with magnetism: the Greek *mágnes lithos* - "stone from Magnesia" (now Manisa in Turkey).

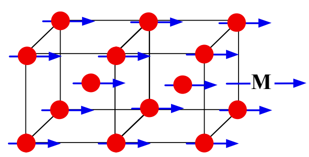
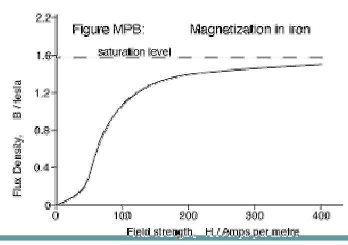
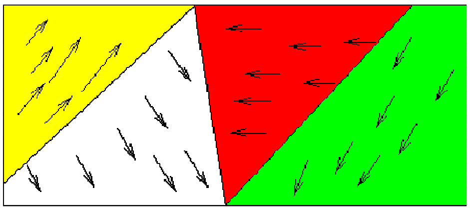


Fig. 8.15: In a magnetized region of a ferromagnetic material such as iron all the magnetic moments are spontaneously aligned in the same direction There is a strong magnetization vector **M** even in the absence of an applied field.



Making a Magnet from a Ferromagnetic Material

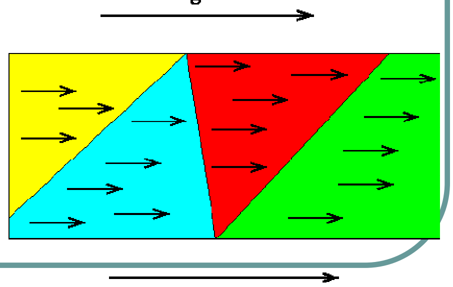


• domains in which the magnetic fields of individual atoms align

• orientation of the magnetic fields of the domains is random

• no net magnetic field.

External Magnetic Field



• when an external magnetic field is applied, the magnetic fields of the individual domains line up in the direction of the external field
• this causes the external magnetic field to be enhanced

Ferrimagnetism

- **Magnetic behavior obtained when ions in a material have their magnetic moments aligned in an antiparallel arrangement such that the moments do not completely cancel out and a net magnetization remains even when there is no applied field (similar to ferromagnetic).**

Almost every item of electronic equipment produced today contains some *ferrimagnetic* material: loudspeakers, motors, deflection yokes, interference suppressors, antenna rods, proximity sensors, recording heads, transformers and inductors are frequently based on *ferrites*.

Ferrimagnetism

They are, in general, oxides of iron combined with one or more of the transition metals such as manganese, nickel or zinc, e.g. $MnFe_2O_4$.

Permanent ferrimagnets often include barium. (BaO.6Fe2O3)

The raw material is turned into a powder which is then fired in a kiln or *sintered* to produce a dark gray, hard, brittle ceramic material having a cubic crystalline structure.

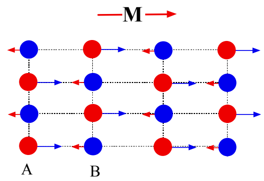


Illustration of magnetic ordering in a ferrimagnetic crystal. All A–atoms have their spins aligned in one direction and all B–atoms have their spins aligned in the opposite direction. As the magnetic moment of an A–atom is greater than that of a B–atom, there is net magnetization, M, in the crystal.

Ferro and Ferri Magnets

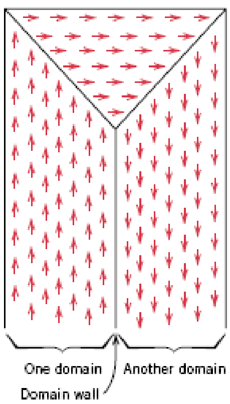


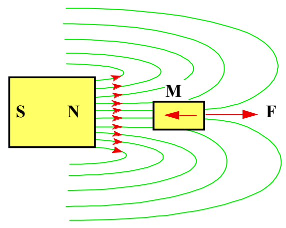
Figure 18.11 Schematic depiction of domains in a ferromagnetic or ferrimagnetic material; arrows represent atomic magnetic dipoles. Within each domain, all dipoles are aligned, whereas the direction of alignment varies from one domain to another.

Diamagnetism

A diamagnetic material placed in a non-uniform magnetic field experiences a force towards smaller fields. This repels the diamagentic material away from a permanent magnet.

Diamagnetism results from changes in electron orbital motion that are induced by an external field. The effect is extremely small and in opposition to the applied field.

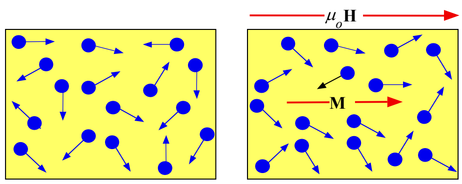
•All materials show at least a small diamagnetic effect.



Paramagnetism

(a) In a paramagnetic material each individual atom possesses a permanent magnetic moment but due to thermal agitation there is no average moment per atom and M=0

(b) In the presence of an applied external field, individual magnetic moments take alignments along the applied field and it develops a magnetization in the direction of the external field.



$\mu_{av} = 0$ and **M** = 0 μ_{av} ° 0 and **M** = χ_m**H**

(a)   (b)

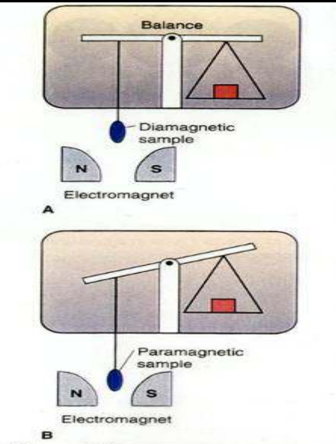
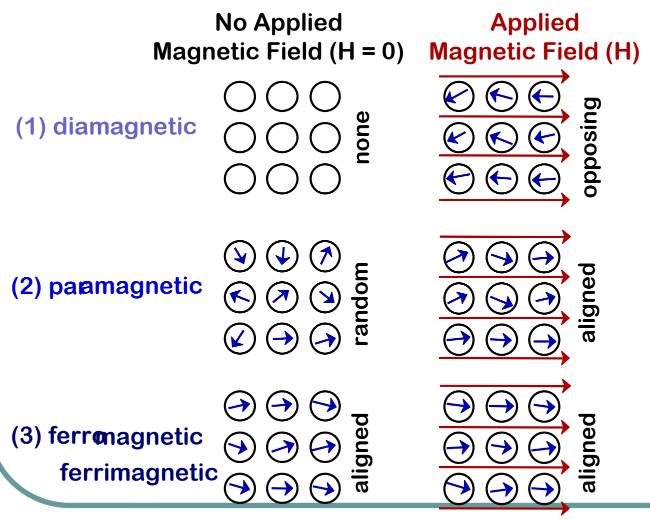


Figure 8.25 **Apparatus for measuring the magnetic behavior of a sample.** The substance is weighed on a very sensitive balance in the absence of an external magnetic field. **A,** If a substance is diamagnetic (has no unpaired electrons), its apparent mass is unaffected (or slightly reduced) when the magnetic field is "on." **B,** If a substance is paramagnetic (has unpaired electrons), its apparent mass increases when the field is "on" because the balance arm feels an additional force. This method is used to estimate the number of unpaired electrons in transition-metal compounds.

Figure 11.21 **The paramagnetic properties of O_2.** Liquid O_2 is attracted to the poles of a magnet because it is paramagnetic, as MO theory predicts. A diamagnetic substance would fall between the poles.

Magnetic Moments For 3 Types



Adapted from Fig. 20.5(a), *Callister 6e.*

Adapted from Fig. 20.5(b), *Callister 6e.*

Adapted from Fig. 20.7, *Callister 6e.*

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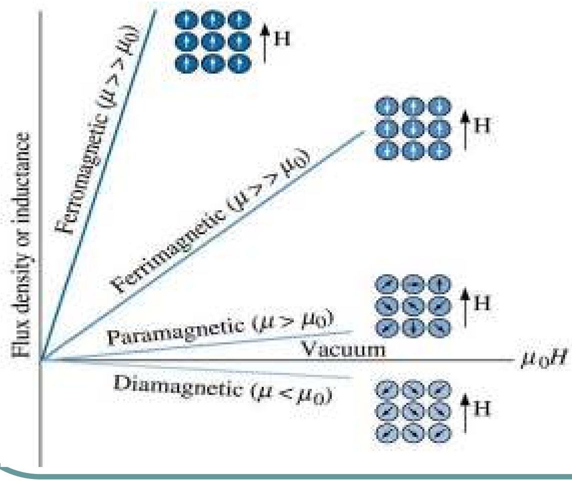
Magnetic permeability(μ) curves



The effect of the core material on the flux density. The magnetic moment opposes the field in diamagnetic materials. Progressively stronger moments are present in paramagnetic, ferrimagnetic, and ferromagnetic materials for the same applied field.

Electronic Structure and magnetism

Atomic number	Element	Electronic structure of 3*d*					Moment (μ_B)
21	Sc	↑					1
22	Ti	↑	↑				2
23	V	↑	↑	↑			3
24	Cr	↑	↑	↑	↑	↑	5
25	Mn	↑	↑	↑	↑	↑	5
26	Fe	↑↓	↑	↑	↑	↑	4
27	Co	↑↓	↑↓	↑	↑	↑	3
28	Ni	↑↓	↑↓	↑↓	↑	↑	2
29	Cu	↑↓	↑↓	↑↓	↑↓	↑↓	0

↑ = electronic spin orientation

Antiferromagnetism

- Arrangement of magnetic moments such that the magnetic moments of atoms or ions cancel out causing zero net magnetization.
- Type of magnetism in solids such as manganese oxide (MnO) in which adjacent ions that behave as tiny magnets (in this case manganese ions, Mn^{2+}) spontaneously align themselves at relatively low temperatures into opposite, or antiparallel, arrangements throughout the material so that it exhibits almost no gross external magnetism.
- In antiferromagnetic materials, which include certain metals and alloys in addition to some ionic solids, the magnetism from magnetic atoms or ions oriented in one direction is canceled out by the set of magnetic atoms or ions that are aligned in the reverse direction.

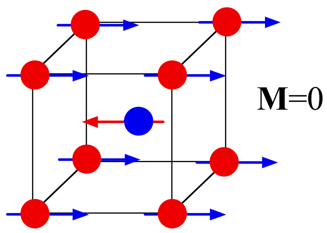
Antiferromagnetism

•In the periodic table the only element exhibiting antiferromagnetism at room temperature is **chromium.**

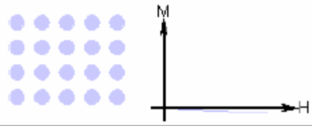
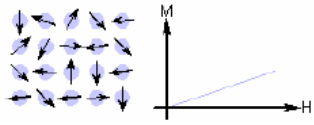
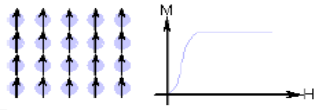
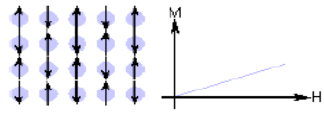
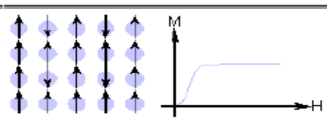
•Antiferromagnetic materials are very similar to ferromagnetic materials but the exchange interaction between neighbouring atoms leads to the anti-parallel alignment of the atomic magnetic moments.

•Therefore, the magnetic field cancels out and the material appears to behave in the same way as a paramagnetic material.

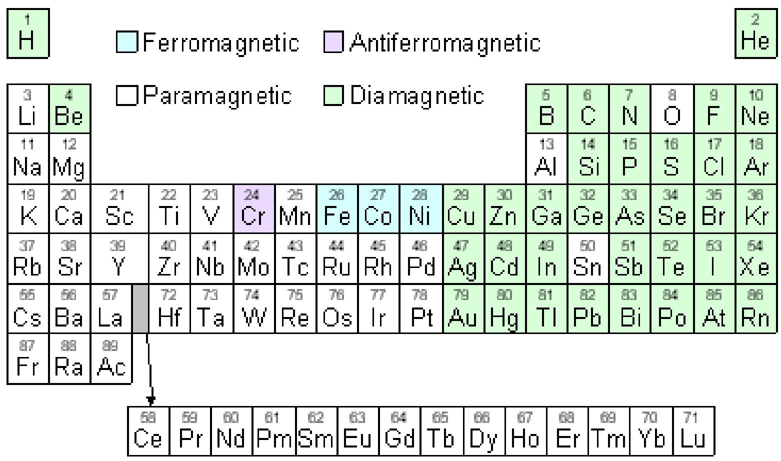
•Like ferromagnetic materials these materials become paramagnetic above a transition temperature, known as the Néel temperature, TN. (Cr: TN



In this antiferromagnetic BCC crystal (Cr) the magnetic moment of the center atom is cancelled by the magnetic moments of the corner atoms (a quarter of the corner atom belongs to the unit cell).

Type of Magnetism	Susceptibility	Atomic / Magnetic Behaviour	Example / Susceptibility
Diamagnetism	Small & negative.	Atoms have no magnetic moment 	Au -2.74×10^{-6} Cu -0.77×10^{-6}
Paramagnetism	Small & positive.	Atoms have randomly oriented magnetic moments 	β-Sn 0.19×10^{-6} Pt 21.04×10^{-6} Mn 66.10×10^{-6}
Ferromagnetism	Large & positive, function of applied field, microstructure dependent.	Atoms have parallel aligned magnetic moments 	Fe ~100,000
Antiferromagnetism	Small & positive.	Atoms have mixed parallel and anti-parallel aligned magnetic moments 	Cr 3.6×10^{-6}
Ferrimagnetism	Large & positive, function of applied field, microstructure dependent	Atoms have anti-parallel aligned magnetic moments 	Ba ferrite ~3

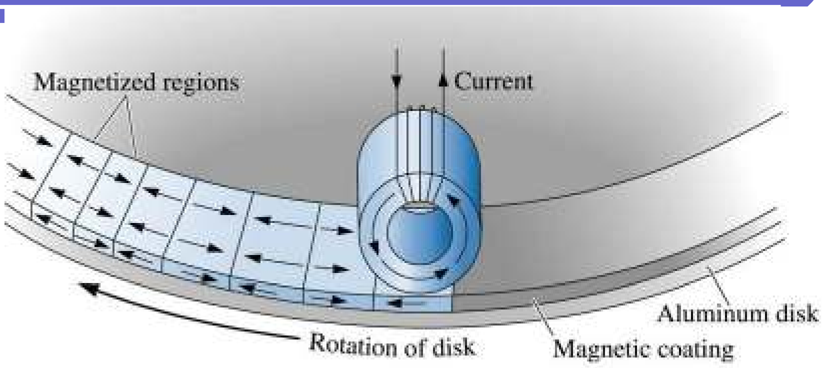
A periodic table showing the type of magnetic behaviour of each element at room temperature.



Applications of Magnetic Materials

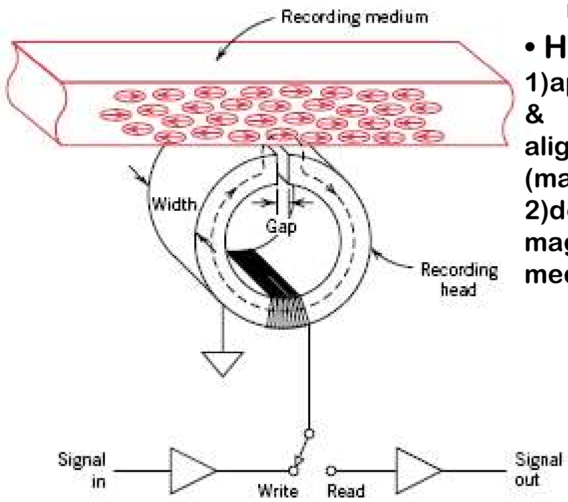
- Soft Magnetic Materials - Ferromagnetic materials are often used to enhance the magnetic flux density (*B*) produced when an electric current is passed through the material. Applications include cores for electromagnets, electric motors, transformers, generators, and other electrical equipment.
- Data Storage Materials - Magnetic materials are used for data storage.
- Permanent Magnets - Magnetic materials are used to make strong permanent magnets
- Power - The strength of a permanent magnet as expressed by the maximum product of the inductance and magnetic field.

Magnetic Storage



Information can be stored or retrieved from a magnetic disk by use of an electromagnetic head. A current in the head magnetizes domains in the disk during storage; the domains in the disk induce a current in the head during retrieval.

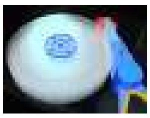
Magnetic Storage



• Head can...
1)apply magnetic field H
&
align domains
(magnetize the medium).
2)detect a change in the
magnetization of the
medium.

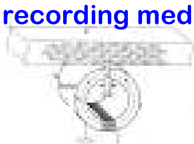
MAGNETIC STORAGE

• Information is stored by magnetizing material.



Simulation of hard drive courtesy Martin Chen.

recording medium

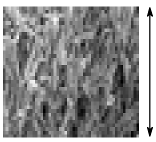


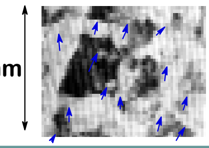
• Two media types:

1)Particulate: needle-shaped γ-Fe_2O_3. +/- mag. moment along axis. (tape, floppy)

2)Thin film: CoPtCr or CoCrTa alloy. Domains are ~ 10-30nm! (hard drive)

Adapted from Fig. 20.19, *Callister 6e.*





Adapted from Fig. 20.20(a), *Callister 6e.*

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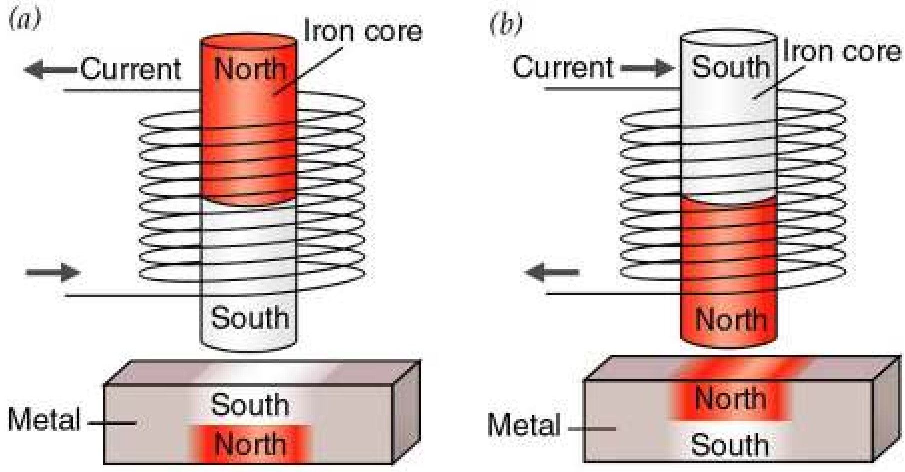
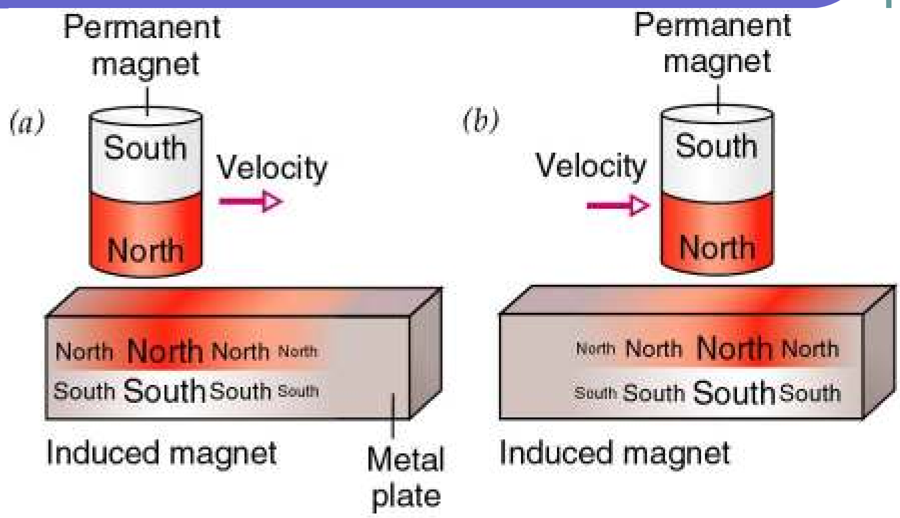
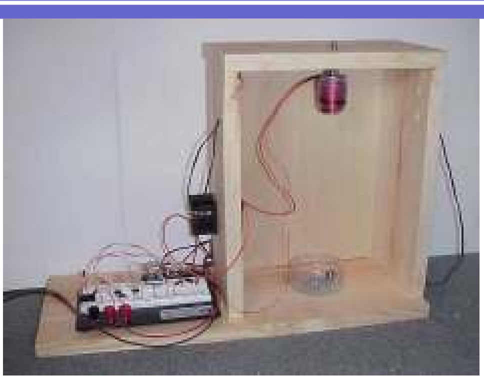
Magnetic Levitation: 1)Alternating Current Levitation



Magnetic Levitation: Electrodynamic Levitation



Maglev Experiment:



- http://www.oz.net/~coilgun/levitation/home.htm