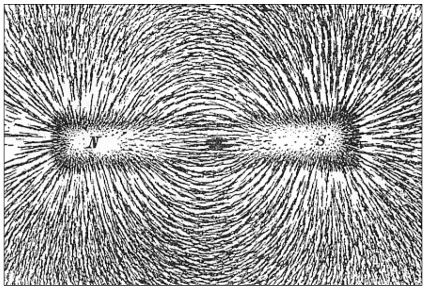
Class 6: Overview of Magnetism



Magnetic field lines of a bar magnet

PRIME Modules
Project-based Resources for Introduction to Materials Engineering

[*Practical Physics,* Macmillan]

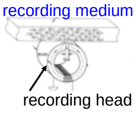
Reading and writing is done using a solenoid and a paramagnetic material.

A head flies over the hard disc. The head has separate, small read and write sensors on it.

Writing to the disc is done by magnetizing a recording head using a *solenoid*. The *paramagnetic material* inside sets up a field across the gap.

In reading, a field across the gap sets up a current in the solenoid.

Hard drive courtesy Martin Chen from International Business Machines Corporation.

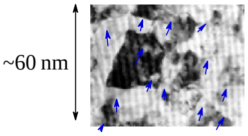


Adapted from Fig. 20.18, *Callister 6e.* (Fig. 20.18 from J.U. Lemke, *MRS Bulletin*, Vol. XV, No. 3, p. 31, 1990.)

Magnetic data is stored on domains of ferromagnets

The magnetic field across the gap causes *ferromagnetic domains* in the disc to align.

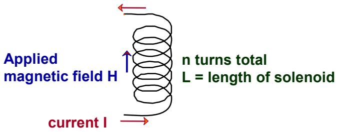
These domains are permanent magnets. They remained magnetized when the writing field is removed.



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

Adapted from Fig. 20.20(a), *Callister 6e.* (Fig. 20.20(a) from M.R. Kim, S. Guruswamy, and K.E. Johnson, *J. Appl. Phys.*, Vol. 74 (7), p. 4646, 1993.)

Current in a coiled wire creates an applied magnetic field



Relation for the applied magnetic field, H:

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

current

applied magnetic field units = (ampere-turns/m)

[Callister]

Three key magnetism terms are the magnetic field, magnetic permeability, and applied magnetic field

Variable	Meaning	Unit
B_o	Applied magnetic field	tesla Webers/m^2
μ_o	Magnetic permeability of free space	Webers/Amp-m
H	Applied magnetic field	Amps/meter

H comes from $\frac{nI}{l}$ **For a current loop inducing a magnetic field, *n* is the number of loops, *l* is the length of the coil**

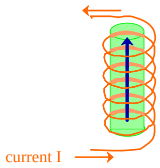
$$B_o = \frac{H}{\mu_o} \Rightarrow \frac{\text{Webers}}{\text{Amp}-\text{meters}}$$

Three more key terms are magnetic field vector, total magnetization, and magnetic susceptibility

Variable	Meaning	Unit
M	Magnetic field vector (due to H)	Amps/meter
B	Total magnetization $\mu_o(H+M) = \mu_o \mu_r H = \mu H$ $\mu = \mu_o \mu_r$	Webers/meters^2
χ_m	Magnetic susceptibility $M=\chi_m H$ $\chi_m = \mu_r - 1$	Dimensionless

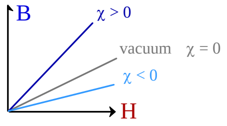
Magnetic susceptibility is a material property that tells how effective a magnetic field will be in magnetizing that material

In response to a magnetic field, magnetic induction is produced inside the material



B = Magnetic induction inside the material

B has units of Teslas or Webers/m²



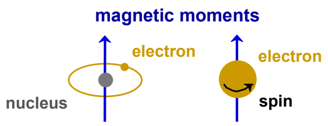
χ measures the material response relative to a vacuum

Magnetic susceptibility, χ (dimensionless)

[Callister] 3

Magnetic susceptibility (χ) measures the response of electrons to a magnetic field

Electrons produce magnetic moments:

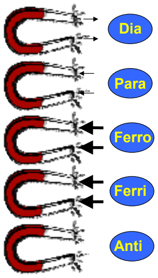


The net magnetic moment is the sum of the magnetic moments of all the electrons

[Adapted from Fig. 20.4, *Callister 6e*] 4

Different core materials result in different types of magnetism which can be categorized

The M that results from the applied field is a function of the material in the core

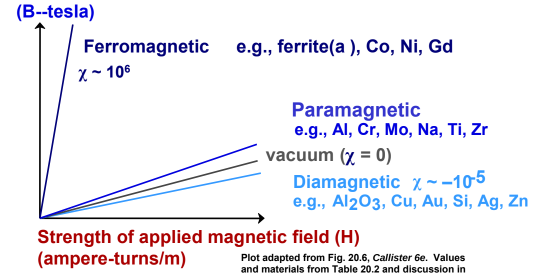


Diamagnetism	Dia	Weak repulsion to field
Paramagnetism	Para	Weak attraction to field
Ferromagnetism	Ferro	Strong attraction to field
Ferrimagnetism	Ferri	Strong attraction to field
Antiferromagnetism	Anti	No magnetic moment

Ferromagnetism can have a χ as large as 10^6 and diamagnetism can have a χ as small as -10^{-5}

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

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



Plot adapted from Fig. 20.6, *Callister 6e*. Values and materials from Table 20.2 and discussion in Section 20.4, *Callister 6e*.

[Callister] 5

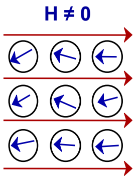
With diamagnetism, the resulting magnetic moment opposes the applied field

Diamagnetic

Without an applied field, the atoms have no magnetic dipole

With an applied magnetic field, the resulting magnetic moment opposes the applied field

Diamagnetic materials have negative susceptibility



M is opposite to H

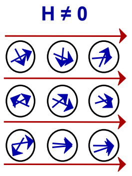
With paramagnetism, the resulting magnetic moment is aligned with the applied field

Paramagnetic

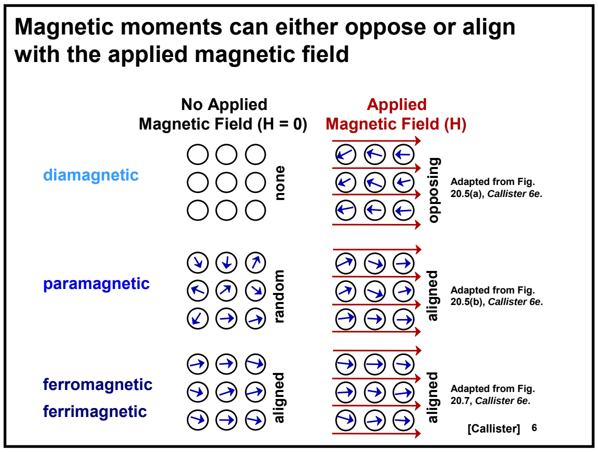
Without an applied field, the magnetic moments of all the atoms in the solid are randomly aligned

An applied magnetic field results in a magnetic moment aligned with the applied field

Paramagnetic materials have positive susceptibility



M in the same direction as H



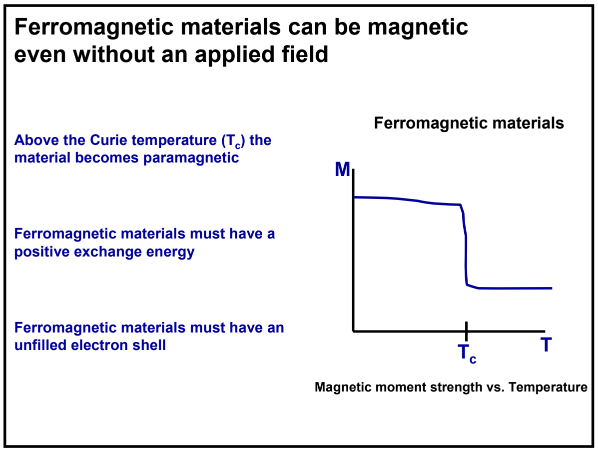
Magnetic moments can either oppose or align with the applied magnetic field

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

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

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

[Callister] 6



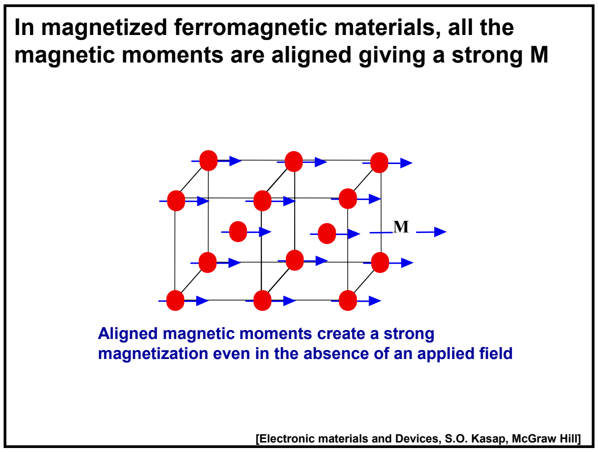
Ferromagnetic materials can be magnetic even without an applied field

Above the Curie temperature (T_c) the material becomes paramagnetic

Ferromagnetic materials must have a positive exchange energy

Ferromagnetic materials must have an unfilled electron shell

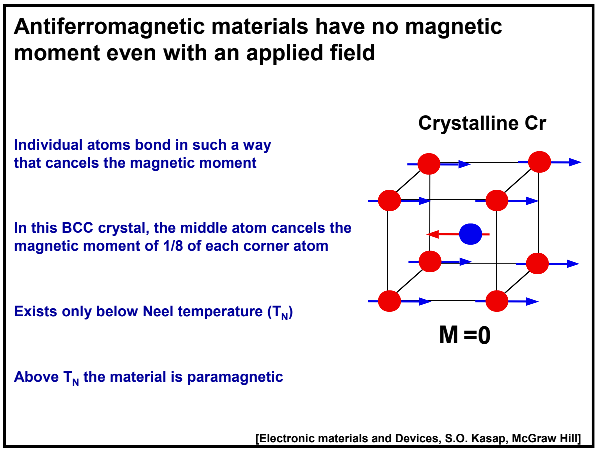
Magnetic moment strength vs. Temperature



In magnetized ferromagnetic materials, all the magnetic moments are aligned giving a strong M

Aligned magnetic moments create a strong magnetization even in the absence of an applied field

[Electronic materials and Devices, S.O. Kasap, McGraw Hill]



Antiferromagnetic materials have no magnetic moment even with an applied field

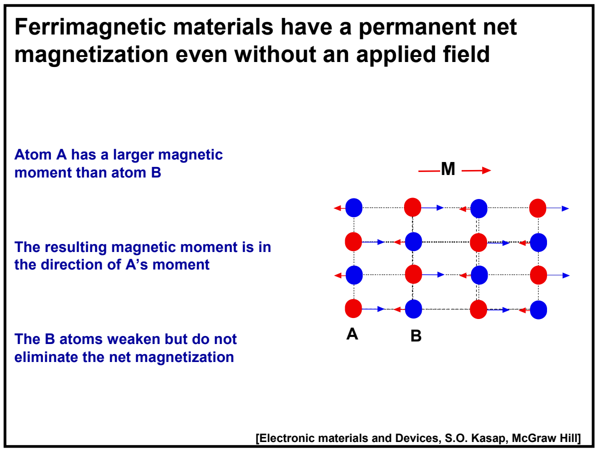
Individual atoms bond in such a way that cancels the magnetic moment

In this BCC crystal, the middle atom cancels the magnetic moment of 1/8 of each corner atom

Exists only below Neel temperature (T_N)

Above T_N the material is paramagnetic

[Electronic materials and Devices, S.O. Kasap, McGraw Hill]



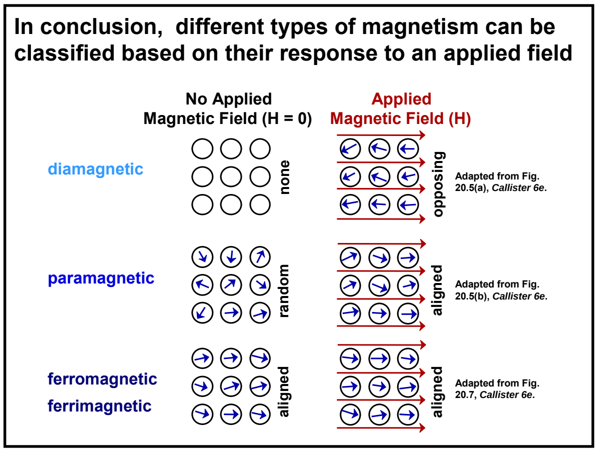
Ferrimagnetic materials have a permanent net magnetization even without an applied field

Atom A has a larger magnetic moment than atom B

The resulting magnetic moment is in the direction of A's moment

The B atoms weaken but do not eliminate the net magnetization

[Electronic materials and Devices, S.O. Kasap, McGraw Hill]



In conclusion, different types of magnetism can be classified based on their response to an applied field

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

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

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