BEEE201L- Electronic Materials

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BEEE102L- Basic Electrical and Electronics Engineering

Module-3 : Magnetic material

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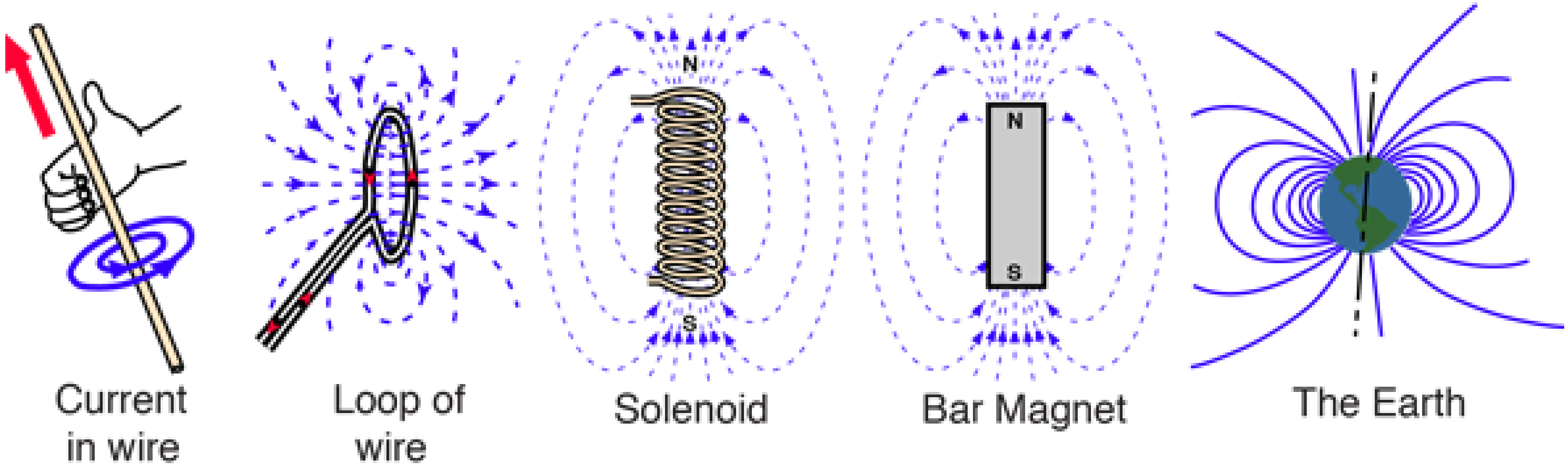
CONTENT

- Introduction of Magnetic properties,
- Classification of magnetic materials,
- Concept of ferromagnetism, Saturation magnetization;
- Curie and Neel temperature, Temperature dependence of conductivity materials;
- Magnetostriction, magnetic anisotropy, spin-orbit interaction ;
- Superconductivity.

What is Magnetic properties of Materials ?

It is common characteristics of Materials. Magnetic properties of **material involve concept based** on the **magnetic dipole moment**. Some of the material has the ability to create internal dipole moment . For this reason this kinds of material present special type of properties. Some common characteristics of this material is …

1. Attracting other magnetic material.
2. Inducing pole within the material .
3. The polarity of two pole are opposite .
4. When magnetizing occurring then some parameter of material is changed (Current, Magnetic flux).



Magnetic Field Sources

Although the magnetic properties of electrons must ultimately be explained with quantum mechanics, the magnetism arising whenever we have **charge in motion**. This motion can be that of an electron (either spinning or orbiting) or it can be in the form of a current.

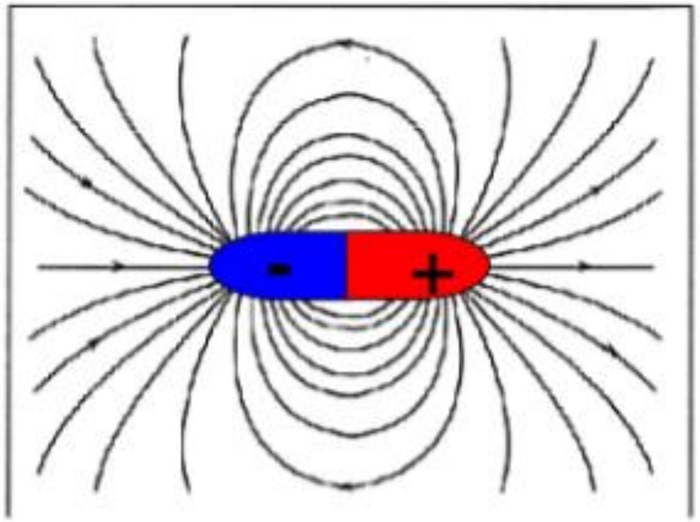
Remember: Moving charges produce magnetic fields, and external magnetic fields exert a magnetic force on moving charges.

Magnetic Dipoles

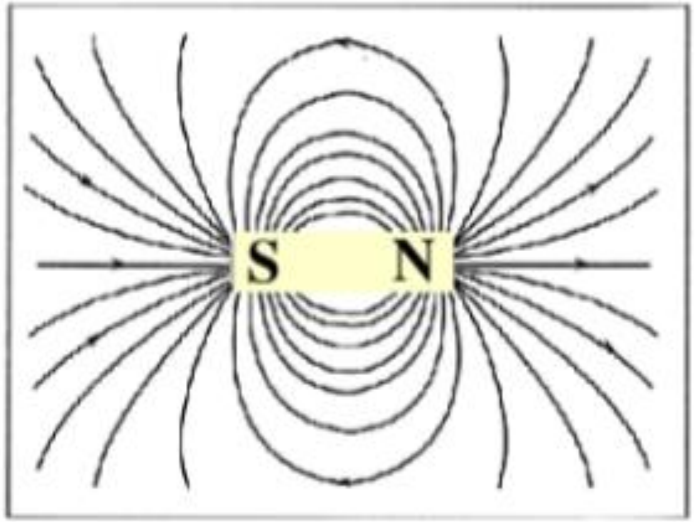
We know that an electric dipole consists of two equal but opposite charges separated by some distance, such as in a polar molecule.

Every magnet is a magnetic dipole. A bar magnet is a simple example. Note how the E field due an electric dipole is just like the magnetic field (B field) of a bar magnet. Field lines emanate from N pole and reenter the S pole. Although they look the same, they are different kinds of fields.

E fields affect any charge in the vicinity, but a B field only affects moving charges. As with charges, opposite poles attract and like poles repel.



Electric dipole and ***E*** field



Magnetic dipole and ***B*** field

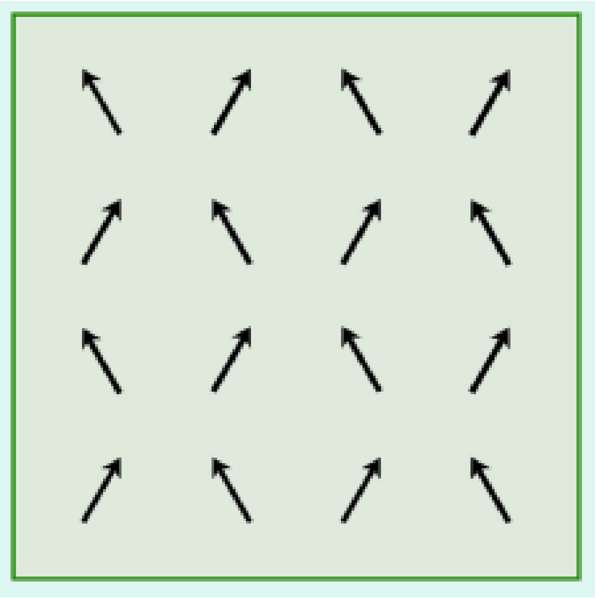
Sources of Magnetism

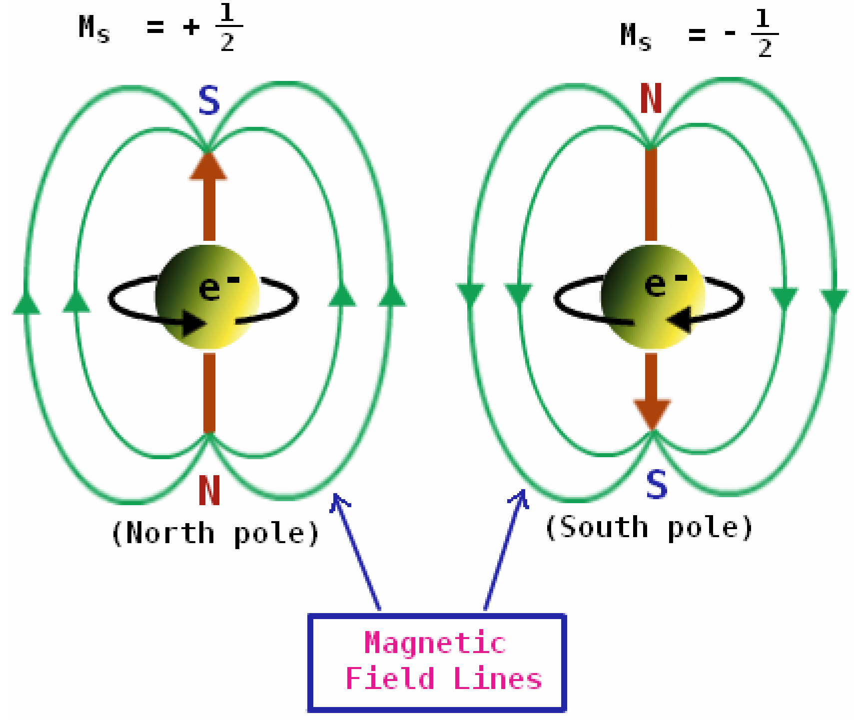
We have seen **charges in motion (as in a current) produce magnetic fields**. This is one source of magnetism.

Another source is the electron itself. Electrons behave as if they were tiny magnets. Quantum mechanics is required to explain fully the magnetic properties of electrons, but it is helpful to relate these properties back to the motion of charges. Every electron in an atom behaves as a magnet in two ways, each having two magnetic dipole moments:

1. **Spin magnetic dipole moment** - due to the "rotation" of an electron.
2. **Orbital magnetic dipole moment** - due to the "revolution" of an electron around the nucleus.

Note: Electrons are **not** actually little balls that rotate and revolve like planets, but imagining them this way is useful when explaining magnetism without quantum mechanics.





Magnetism:

Magnetism is the force of attraction or repulsion of a magnetic material due to the arrangement of its atoms, particularly its electrons.

MAGNETIC DIPOLE:

- Any two opposite poles separated by a finite distance constitute a magnetic dipole.
- Magnetization depends on the arrangement of the magnetic dipoles within the material.

Introduction of Magnetic Properties

Magnetism in matter

Magnetization Vector (M) and Magnetic Field Strength H

The magnetic state of a substance is described by a quantity called the magnetization vector **M**. The magnitude of this vector is defined as the magnetic moment per unit volume of the substance. (magnetic moment /cm^3).

Magnetic moment, is also called a **magnetic dipole moment** (Ampere)(meter)^2, is a measure of the object's tendency to align with a magnetic field. Its positive direction depends on the way the object responds to the magnetic field.

The total magnetic field Induction at a point within a substance depends on both the applied (external) field and the magnetization **M** of the substance. Recognizing the similarity between M and H, we can write:

$$\mathbf{B} = \mu_o (\mathbf{H} + \mathbf{M})$$

μ_o is a constant called the permeability of free space = $4\pi \times 10^{-7}$ $(H.m^{-1})$

H magnetic field strength within the substance (A/m).

The quantities H and M have the same units. Because M is magnetic moment per unit volume, its SI units are: (Ampere)(meter)^2/(meter)^3= (A/m).

So, for these substances placed in an external magnetic field, we can write:

$$\mathbf{M} = \chi \mathbf{H}$$

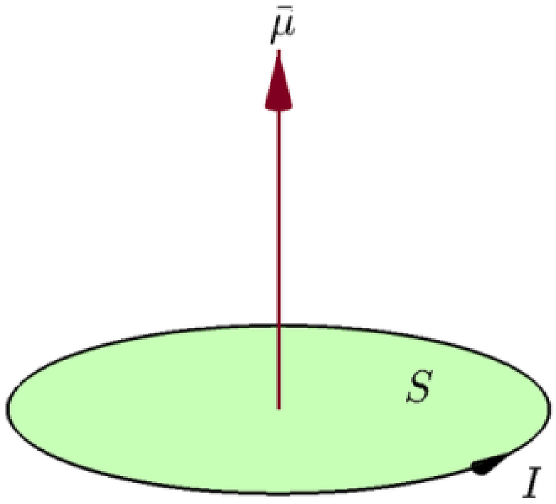
where χ (Greek letter Chi) is a dimensionless factor called the **magnetic susceptibility**.

Magnetic moment μ_m :

A vector quantity associated with the magnetic properties of electric current loops or, more generally, magnets. It is equal to the amount of current flowing through the loop multiplied by the area encompassed by the loop, and its direction is established by the **right hand rule** for rotations $\mu_m = I . A . u_n$

u_n = A unit vector induced from loop as right hand rules.

I = Circulating current ; A = Area coverage by loop



Orbital, spin magnetic movement of an electron are

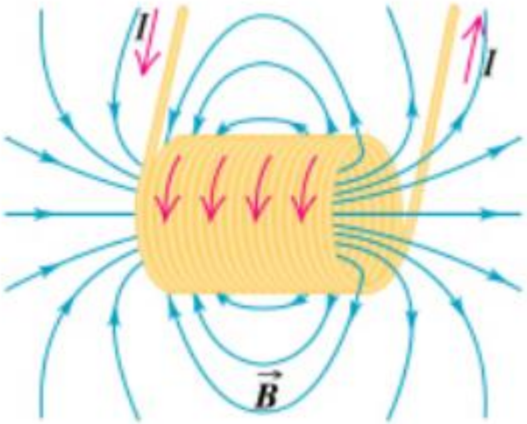
$$\mu_{orb} = -\frac{e}{2m_e}L \qquad \mu_{spin} = -\frac{e}{m_e}S$$

Magnetic field intensity (H)

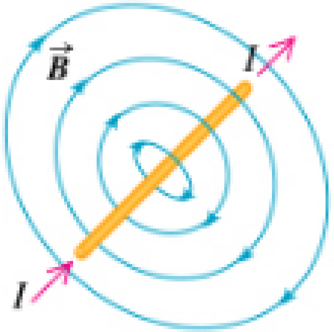
A field of force associated with changing **electric fields**, as when electric charges are in motion. Magnetic fields exert deflective forces on moving electric charges. Most **magnets** have **magnetic fields as a result of the spinning motion of the electrons orbiting the atoms** of which they are composed; **electromagnets** create such fields from electric current moving through coils.

Total magnetic field density B in the material is given by

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



$$H = \frac{B}{\mu_0} - M$$



Relation between B and H

$$B = H.\mu \qquad i.e\ \mu = \mu_0\mu_r$$

$$H = {}^{B}/_{\mu}$$

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Magnetization Vector M

The Average dipole moment per unit volume is called Magnetization vector M , Suppose that there are N atoms in a small volume ΔV and each atom i has a magnetic moment $\boldsymbol{\mu}_{mi}$ (where $i = 1$ to N).

$$\mathbf{M} = \frac{1}{\Delta V} \sum_{i=1}^{N} \boldsymbol{\mu}_{mi} = n_{\text{at}} \boldsymbol{\mu}_{\text{av}}$$

where n_{at} is the number of atoms per unit volume and $\boldsymbol{\mu}_{\text{av}}$ is the average magnetic moment per atom.

Magnetic permeability(μ) and susceptibility χ_{m}

In electromagnetism, the **magnetic susceptibility** χ_m is a dimensionless proportionality constant that **indicates the degree of magnetization of a material in response to an applied magnetic field**.

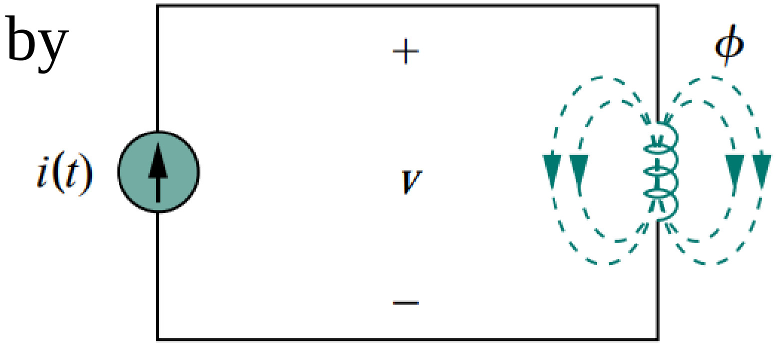
$$\mathrm{M} = \chi_m H$$

The Relation Between χ_{m} and μ_{r} ,

$$\mu_r = 1 + \chi_m$$

$$We\ know\ \mu = \mu_0 \mu_r \qquad \mu = \mu_0 (1 + \chi_m)$$

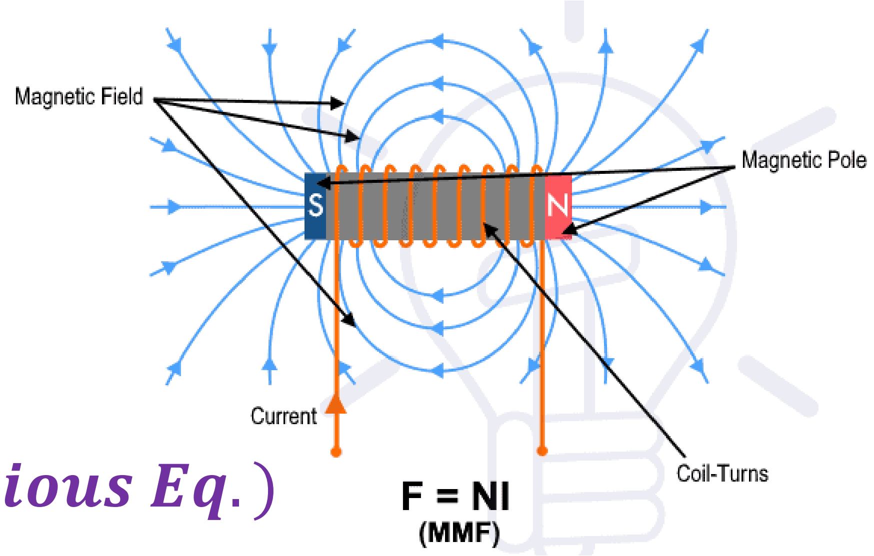
Analysis of Magnetic Circuits



Magnetic Flux (Φ) : Magnetic flux is defined as the no. of flux lines of induction passing thorough a surface. It is denoted by 'Φ' and unit is Weber's.

$$\textit{Magnetic Flux } (\Phi) = \frac{mmf}{reluctance}$$

MMF (Magneto Motive Force): Magneto motive force is a force which produce a flux passing or flowing through a coil.



$$Magneto\ Motive\ Force = Ampere \times Turn$$

MMF = N.I

Units: Ampere-turn

$$Magneto\ Motive\ Force = flux \times reluctance\ (from\ previous\ Eq.)$$

Reluctance (S): Reluctance is property of medium which oppose the passage (or) flow of flux.

$$S = \frac{mmf}{flux} = \frac{ampere-turn}{weber}$$

$$S= \frac{l}{\mu_0 \mu_r A} \;[Units = H^{-1}]$$

Where, l = length of the core (m)

μ_0= Permeability= $4\pi \times 10^{-7}$

μ_r= Relative Permeability (H/m)

A= Cross-sectional area (m^2)

Magnetic Filed Intensity (H): It is defined as mmf per unit length.

$$H = \frac{mmf}{l} = \frac{ampere-turn}{meter}$$

Magnetic Flux Density (B): It is flux per unit area. **units : Tesla (or)** $^{weber}/_{meter^2}$

$$B = \frac{\Phi}{A}$$

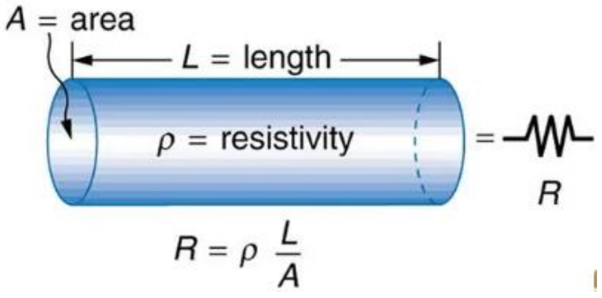
$$B= H \times \mu_0 \mu_r \,, \quad H= \frac{B}{\mu_0 \mu_r}$$

Resistance ($\boldsymbol{\Omega}$)

$$R = \frac{V}{I}$$

$$R = \frac{\rho l}{A}$$

Where, $\rho = Resistivity\ (\boldsymbol{\Omega} - m)$,
l= length of the conductor (m),
A=Area of cross section ($\boldsymbol{m^2}$)



Inductance (H)

$$L = \frac{\psi}{I} = \frac{N\phi}{I}$$

$$L = \frac{\boldsymbol{\mu_0 \mu_r N^2 A}}{l}$$

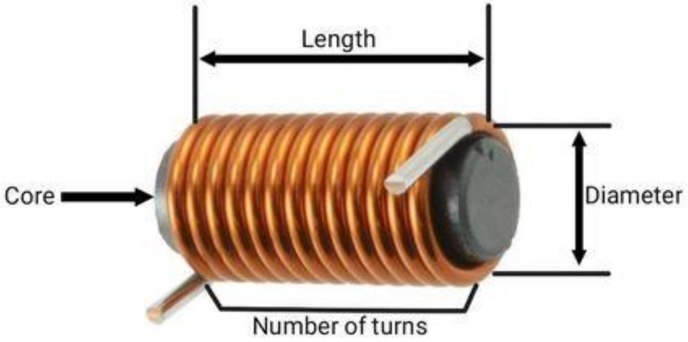
Where, l = length of the core (m)

μ_0= Permeability= $4\boldsymbol{\pi} \times 10^{-7}$

μ_r= Relative Permeability (H/m)

A= Cross-sectional area (m^2)

N=Number of turns



Capacitance (F)

$$C = \frac{\boldsymbol{Q}}{V}$$

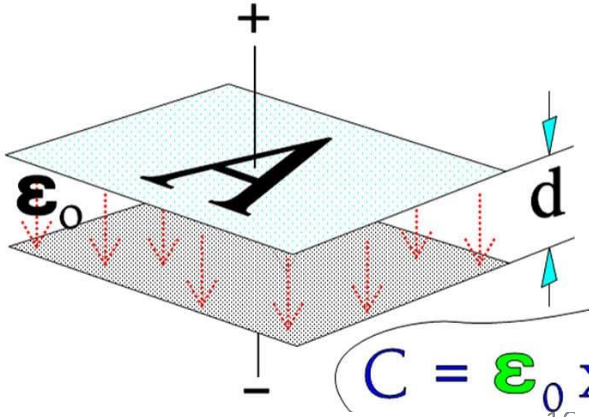
$$C = \frac{\boldsymbol{\epsilon_0 \epsilon_r A}}{d}$$

Where, d = distance between conducting plates(m)

ϵ_0= Primitivity= 8.854×10^{-12}

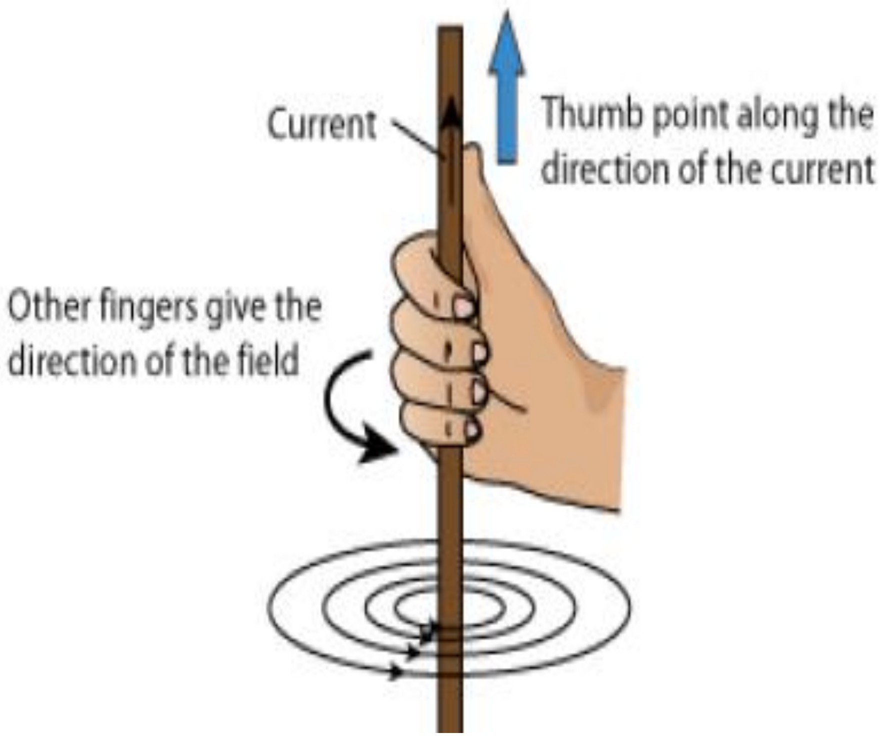
ϵ_r= Relative Primitivity(F/m)

A= Area of plate (m^2)



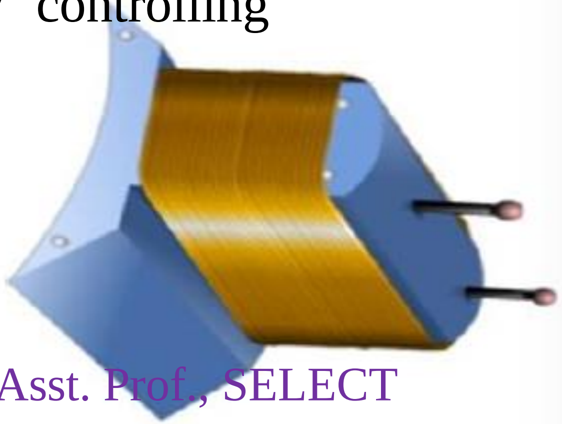
Maxwell Right Hand Rule

- Assume that the current carrying conductor is held in the right hand so that the fingers wrap around the conductor and the thumb is stretched. If the thumb is along the direction of current, wrapped fingers will show the direction of circular magnetic field lines.



Electromagnet

- An electromagnet is a type of magnet in which the magnetic field is produced by an electric current.
- Electromagnets usually consists of wire wound into a coil.
- The main advantage of an electromagnet over a permanent magnet is that the magnetic filed can be quickly changed by controlling amount of electric current in the winding.



Toroidal core

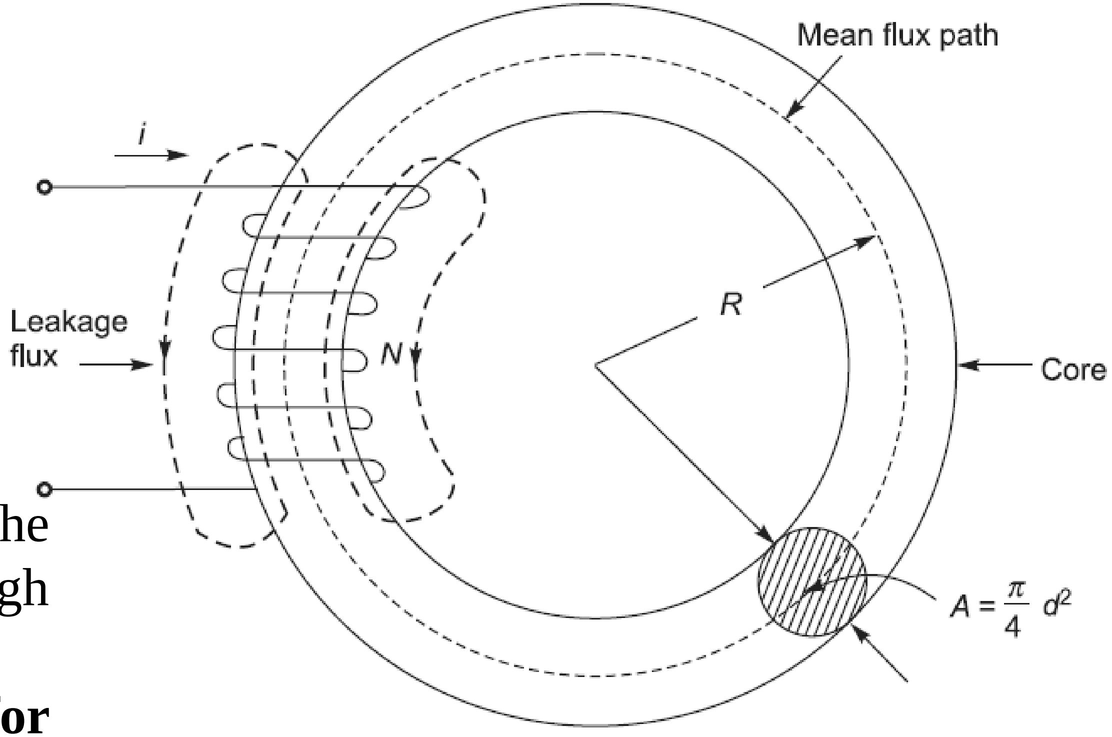
Consider a toroidal ring of ferromagnetic material of mean radius ‘R’ and circular cross section of diameter ‘d’ as shown in Figure. The ring termed core is excited by a coil wound round it with ‘N’ turns carrying a current ‘I’. By virtue of symmetry, flux established in the magnetic core is circular in shape.

The flux established along paths that lie mostly in air is very small compared to the core flux as the core has a permeability μ_r times that of air. ***This flux is called leakage flux***, i.e. it leaks through the core.

μ_r=1 for air and μ_r =5500 for iron core

Flux linkage is the linking of the magnetic field with the conductors of a coil when the magnetic field passes through the loops of the coil.

The flux linkage of a coil is simply an alternative term for total flux used for convenience in engineering applications.



Toroidal ring of ferromagnetic material with exciting coil

From Ampere’s law $Hl = Ni$

Therefore, the total energy or work required per unit volume to increase the magnetic field from an initial value B_1 to a final value B_2 in the toroid is

$$\boxed{E_{\text{vol}} = \int_{B_1}^{B_2} H\, dB}$$

Energy density of a magnetic field. It is used to find the energy per unit volume needed to establish the field B or field intensity H

$$\boxed{E_{\text{vol}} = \frac{1}{2}\mu_r\mu_o H^2 = \frac{B^2}{2\mu_r\mu_o}}$$

Magnetostatic energy in a linear magnetic medium

$$E_{\text{vol}} = \frac{1}{2}HB$$

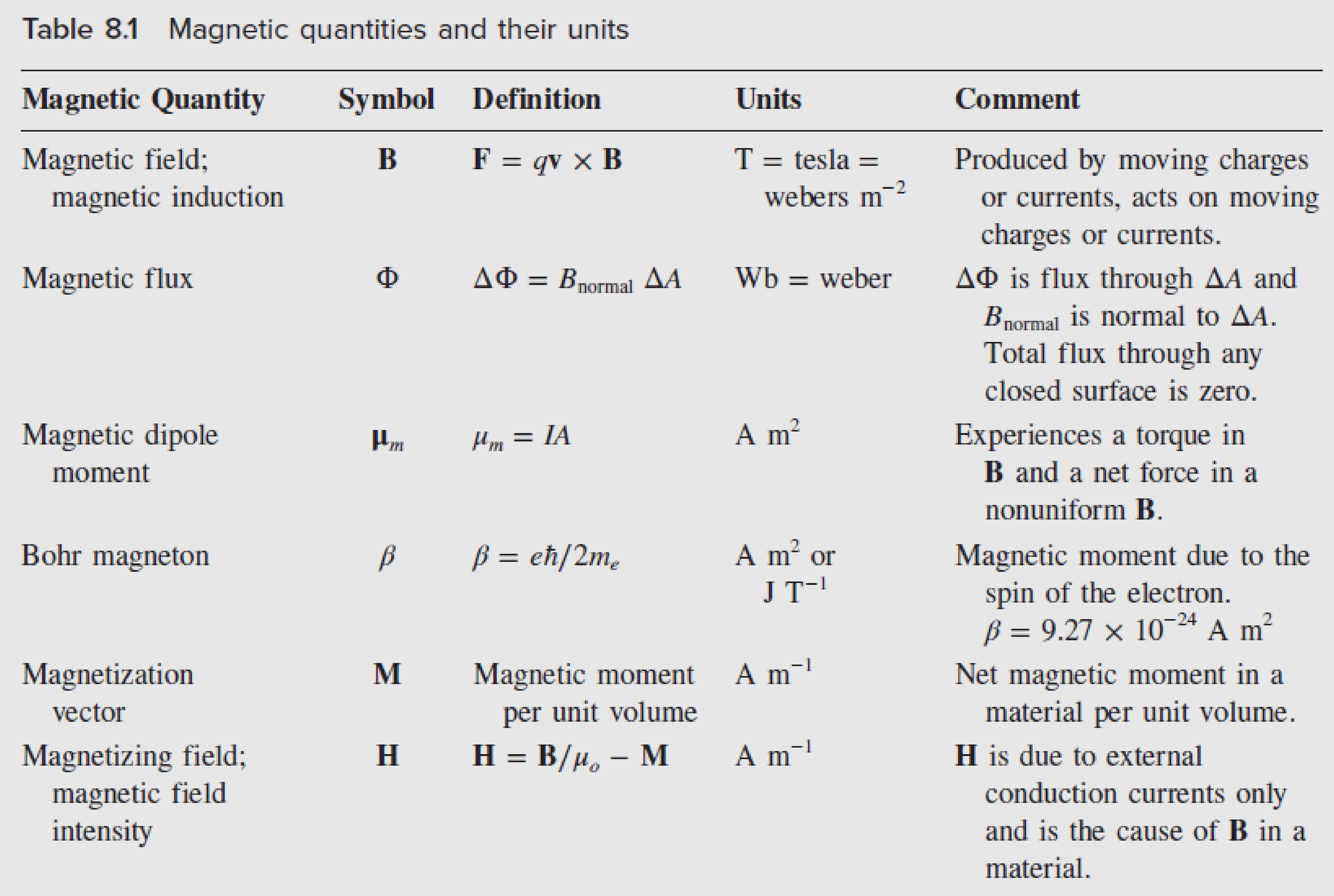
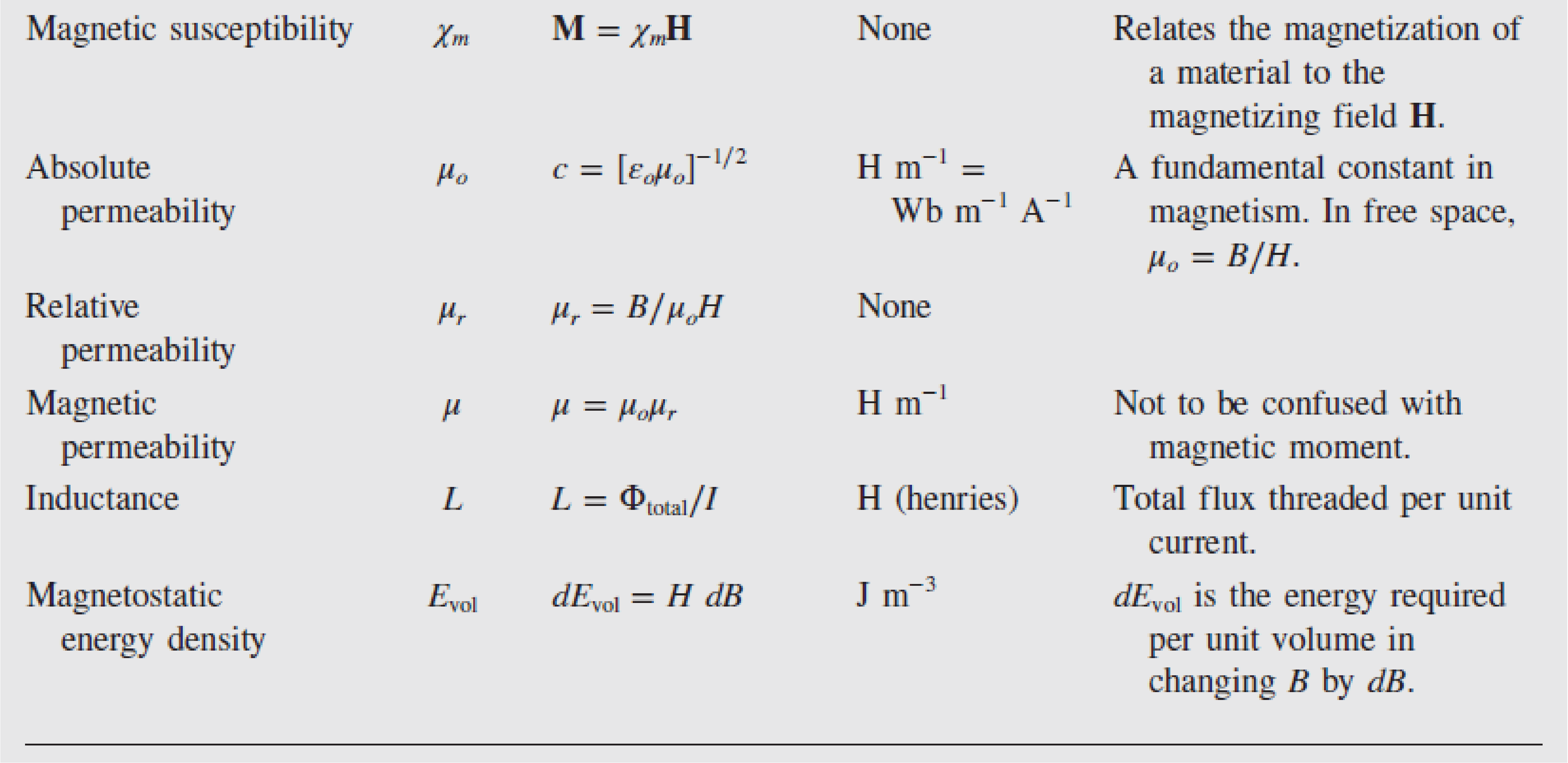


Table 8.1 Magnetic quantities and their units

Magnetic Quantity	Symbol	Definition	Units	Comment
Magnetic field; magnetic induction	$\mathbf{B}$	$\mathbf{F} = q\mathbf{v} \times \mathbf{B}$	T = tesla = webers m^{-2}	Produced by moving charges or currents, acts on moving charges or currents.
Magnetic flux	Φ	$\Delta\Phi = B_{\text{normal}}\,\Delta A$	Wb = weber	$\Delta\Phi$ is flux through ΔA and B_{normal} is normal to ΔA. Total flux through any closed surface is zero.
Magnetic dipole moment	$\boldsymbol{\mu}_m$	$\mu_m = IA$	A m^2	Experiences a torque in **B** and a net force in a nonuniform **B**.
Bohr magneton	β	$\beta = e\hbar/2m_e$	A m^2 or J T^{-1}	Magnetic moment due to the spin of the electron. $\beta = 9.27 \times 10^{-24}$ A m^2
Magnetization vector	$\mathbf{M}$	Magnetic moment per unit volume	A m^{-1}	Net magnetic moment in a material per unit volume.
Magnetizing field; magnetic field intensity	$\mathbf{H}$	$\mathbf{H} = \mathbf{B}/\mu_o - \mathbf{M}$	A m^{-1}	**H** is due to external conduction currents only and is the cause of **B** in a material.



Magnetic susceptibility	χ_m	$\mathbf{M} = \chi_m \mathbf{H}$	None	Relates the magnetization of a material to the magnetizing field **H**.
Absolute permeability	μ_o	$c = [\varepsilon_o \mu_o]^{-1/2}$	$\mathrm{H\ m^{-1}} = \mathrm{Wb\ m^{-1}\ A^{-1}}$	A fundamental constant in magnetism. In free space, $\mu_o = B/H$.
Relative permeability	μ_r	$\mu_r = B/\mu_o H$	None	
Magnetic permeability	μ	$\mu = \mu_o \mu_r$	$\mathrm{H\ m^{-1}}$	Not to be confused with magnetic moment.
Inductance	L	$L = \Phi_{\mathrm{total}}/I$	H (henries)	Total flux threaded per unit current.
Magnetostatic energy density	E_{vol}	$dE_{\mathrm{vol}} = H\ dB$	$\mathrm{J\ m^{-3}}$	dE_{vol} is the energy required per unit volume in changing B by dB.

Materials and Magnetism

- Each electron in an atom has two magnetic dipole moments associated with it, one for spin, and one for orbit. Each is a vector.
- These two dipole moments combine vectorially for each electron.
- The resultant vectors from each electron then combine for the whole atom, often cancelling each other out.
- For most materials the net dipole moment for each atom is about zero.
- For some materials each atom has a nonzero dipole moment, but because the atoms have all different orientations, the material as a whole remains nonmagnetic.
- **Ferromagnetic materials**, like iron, are comprised of atoms that each have net dipole moment. Furthermore, all the atoms have the same alignment, at least within very tiny regions called domains. The domains can have different orientations, though, leaving the iron nonmagnetic except when placed in an external field.
- Permanent magnets are produced when the domains in a ferromagnetic material are aligned.

Classification of magnetic materials

An atom is said to be magnet if it carries a permanent dipole moment.

The magnetic materials are classified into five groups depending on their response to the magnetic field.

1. **Diamagnetic Materials**
2. **Paramagnetic Materials**
3. **Ferromagnetic Materials**
4. **Anti-ferromagnetic Materials**
5. **Ferrimagnetic Materials**

1. Diamagnetism

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

Typical diamagnetic materials have a magnetic susceptibility that is negative and small. For example, the silicon crystal is diamagnetic with $\chi_m = -5.2 \times 10^{-6}$. The relative permeability of diamagnetic materials is slightly less than unity. When a diamagnetic substance such as a silicon crystal is placed in a magnetic field, the magnetization vector **M** in the material is in the *opposite* direction to the applied field $\mu_o\mathbf{H}$ and the resulting field **B** within the material is less than $\mu_o\mathbf{H}$.

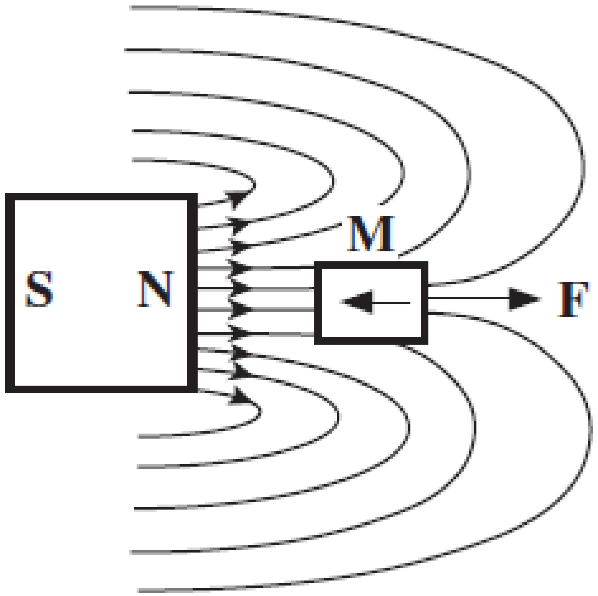
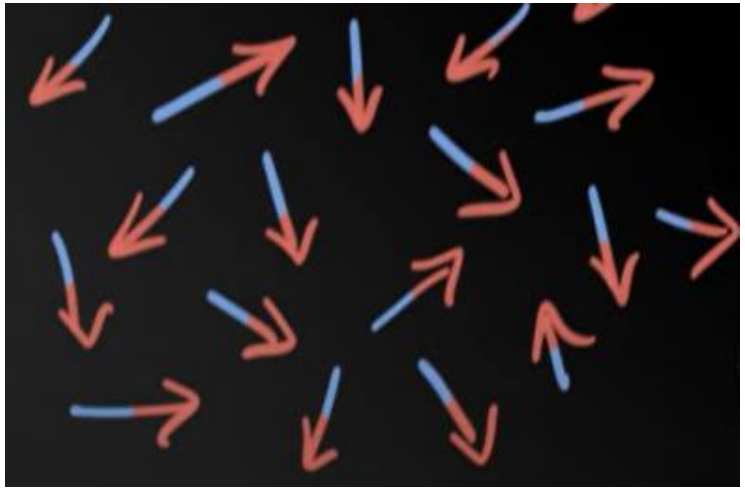
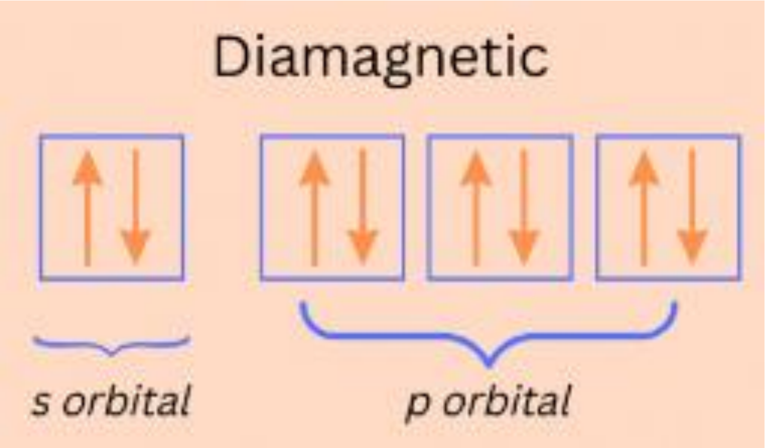


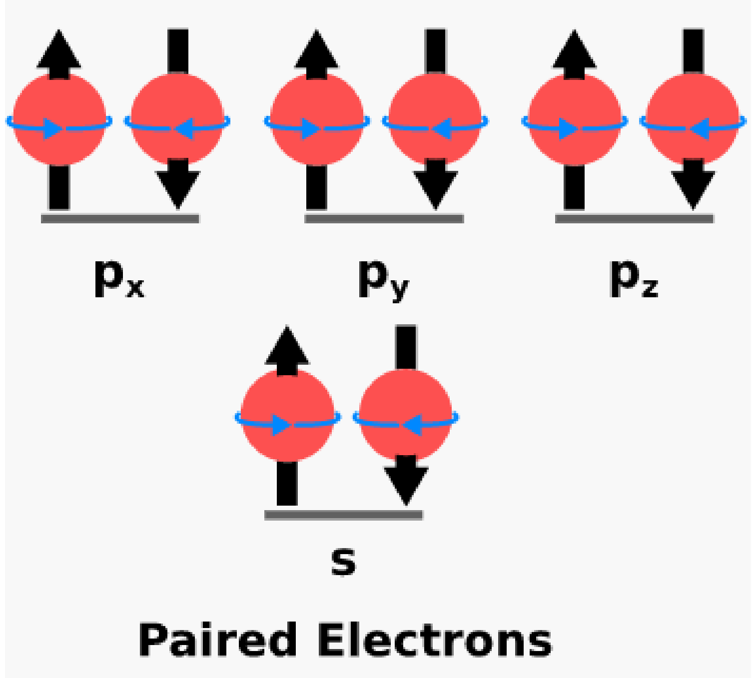
Figure 8.12 A diamagnetic material placed in a nonuniform magnetic field experiences a force toward smaller fields.

This repels the diamagnetic material away from a permanent magnet.

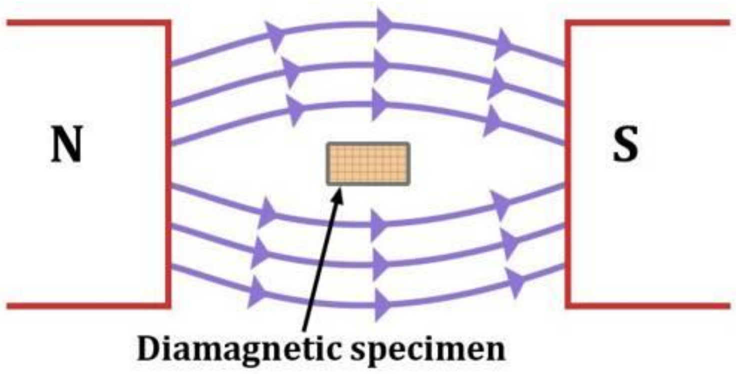
- An electron moving around the nucleus results in magnetic moment.
- Due to different orientations of various orbits of an atom, the net magnetic moment is zero in diamagnetic materials.
- Similarly, all the spin moments are almost paired i.e they have even number of electrons and has equal number of electrons spinning in two opposite directions as shown in figure. Hence the net magnetic movement in the diamagnetic material is zero.

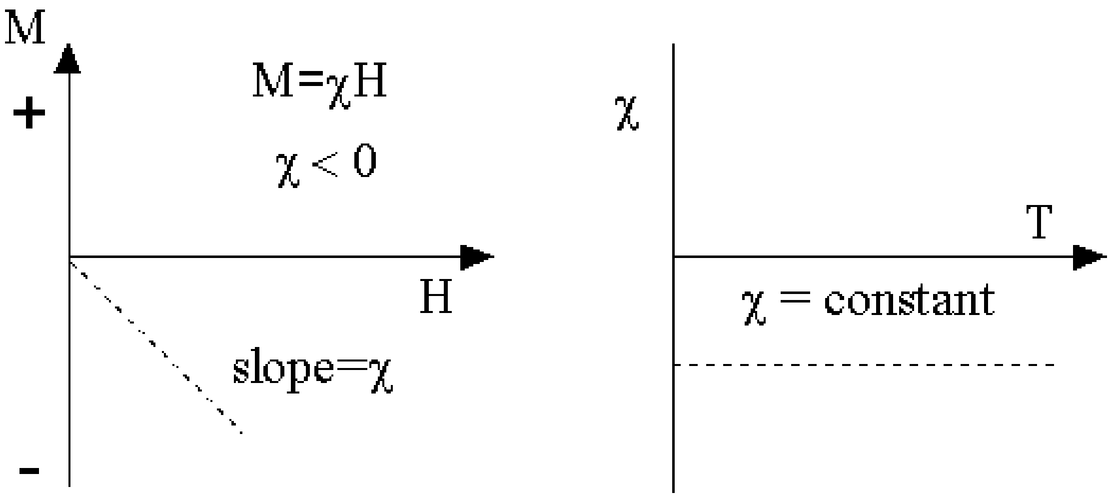






- When an external field is applied the motion of electrons in their orbits changes resulting in induced magnetic moment in a direction opposite to the direction of applied field.
- The magnetization induced by the applied magnetic field is very weak and the magnetic lines of force are repelled.
- This magnetism is also exist in substances with magnetic atoms, but very weak and completely masked by the contribution of magnetic atoms.
- The magnetic susceptibility is independent of applied magnetic field strength.



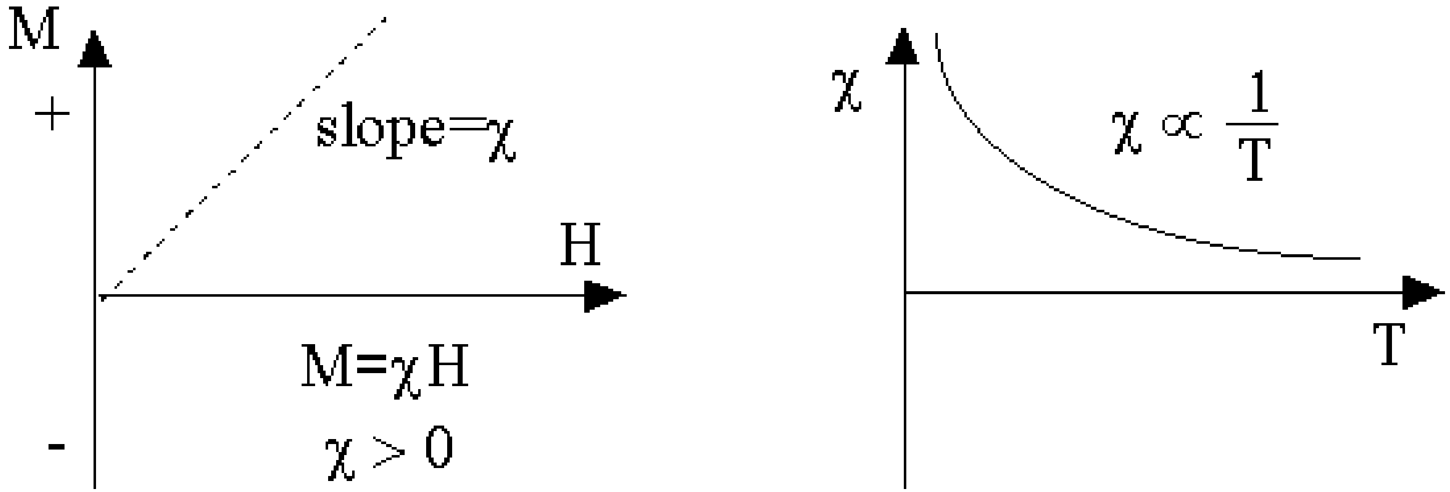


Diamagnetism characterizes the substances that have only non-magnetic atoms (lack of permanent diople moment).

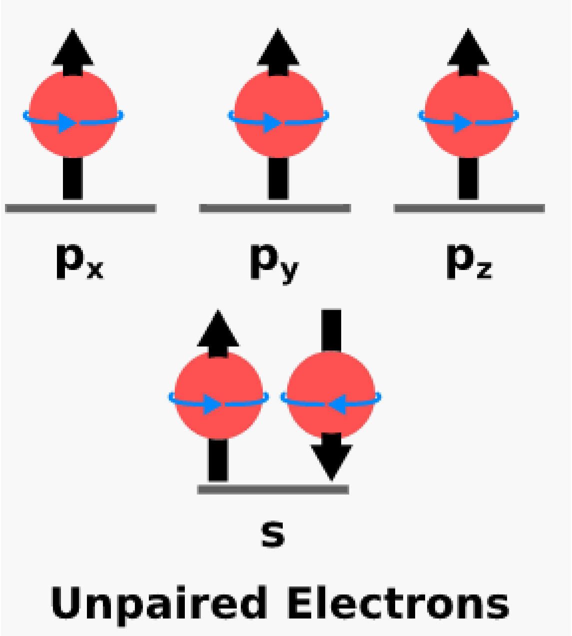
Magnitude of susceptibility	**Temperature dependence**	**Examples**
Small & negative (-10^{-6})	Independent	Organic materials, e.g., many polymers; covalent solids, e.g., Si, Ge, diamond; some ionic solids, e.g., alkalihalides; some metals, e.g., Cu, Ag, Au.
Intermediate & negative	Below 20K varies with field and temperature	Alkali earhs, Bismuth
Large & Negative (-1)	Exists only below critical temperature (Meissner effect)	Superconducting materials

2. Paramagnetism

- This class of materials, some of the atoms or ions in the material **have a net magnetic moment due to unpaired electrons in partially filled orbitals**.
- However, in the **absence of external field** the magnetic movements are oriented randomly, due to this random orientation magnetic movements get cancelled and possess almost zero magnetization like diamagnetism.
- In the presence of a field, there is now a partial alignment of the atomic magnetic moments in the direction of the field, resulting in a net positive magnetization and positive susceptibility.



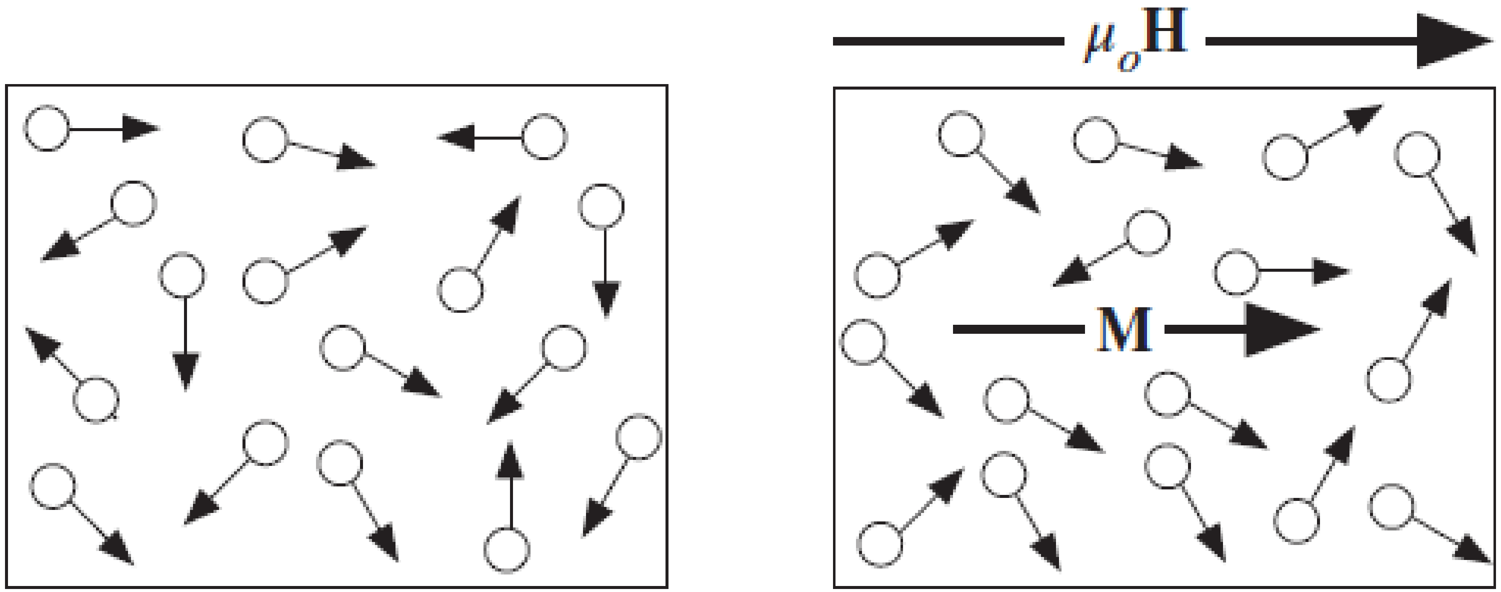
Paramagnetism



Unpaired Electrons

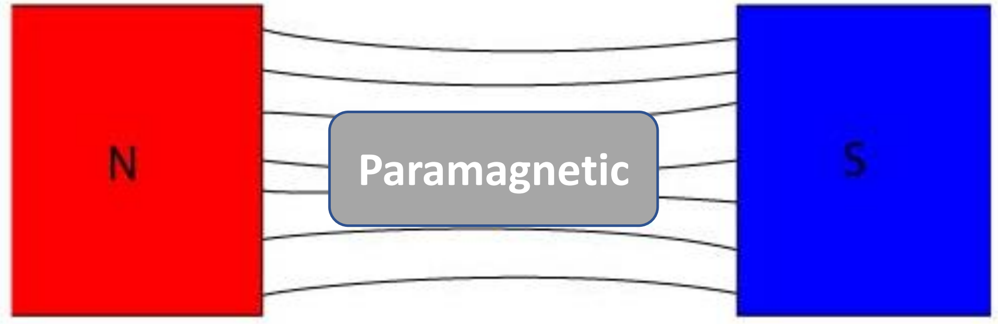
- The paramagnetic substances consists of magnetic atom that posses permanent dipole moment.
- Each electron in an orbit has an orbital magnetic moment and a spin magnetic moment.
- When the shells are unfilled there is net magnetic moment.
- In the absence of the external field the net moments of the atoms are arranged in random directions because of thermal fluctuations. Hence there is no magnetization.
- When external magnetic field is applied, there is tendency for the dipoles to align with the field giving rise to an induced positive dipole moment. The induced magnetism is the source for paramagnetic behavior.
- Paramagnetic susceptibility is small and positive and is independent of applied field strength.

✓Spin alignment is random.



(a) $\mu_{av} = 0$ and M = 0   (b) $\mu_{av} \neq 0$ and $M = \chi_m H$

Figure 8.13 (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 field, individual magnetic moments take alignments along the applied field and **M** is finite and along **B**.



- When a paramagnetic substance is placed in a nonuniform magnetic field, the induced magnetization M is along B and there is a net force toward greater fields.
- Magnetization M typically decreases with increasing temperature because at higher temperatures there are more molecular collisions, which destroy the alignments of molecular magnetic moments with the applied field.
- When the temperature is increases, the paramagnetism/magnetization effect will decrease. Also, it directly converted into diamagnetic material if the temperature above the critical temperature i.e Curie temperature.

Magnitude of susceptibility	**Temperature dependence**	**Examples**
Small & positive $(+10^{-5}\ to + 10^{-4})$	Curie law $\chi = \frac{C}{T}$	Due to the alignment of spins of conduction electrons. Alkali and transition metals.

3. Ferromagnetism

- Ferromagnetic materials such as iron can possess large permanent magnetizations even in the absence of an applied magnetic field.
- The magnetic susceptibility χ_m is typically positive and very large (even infinite) and, further, depends on the applied field intensity.
- The relationship between the magnetization **M** and the applied magnetic field μ_o**H** is highly nonlinear.
- At sufficiently high fields, the magnetization **M** of the ferromagnet saturates.
- The origin of ferromagnetism is the quantum mechanical exchange interaction between the constituent atoms that results in regions of the material possessing permanent magnetization.
- When placed inside a magnetic field, it attracts the magnetic lines of force very strongly.

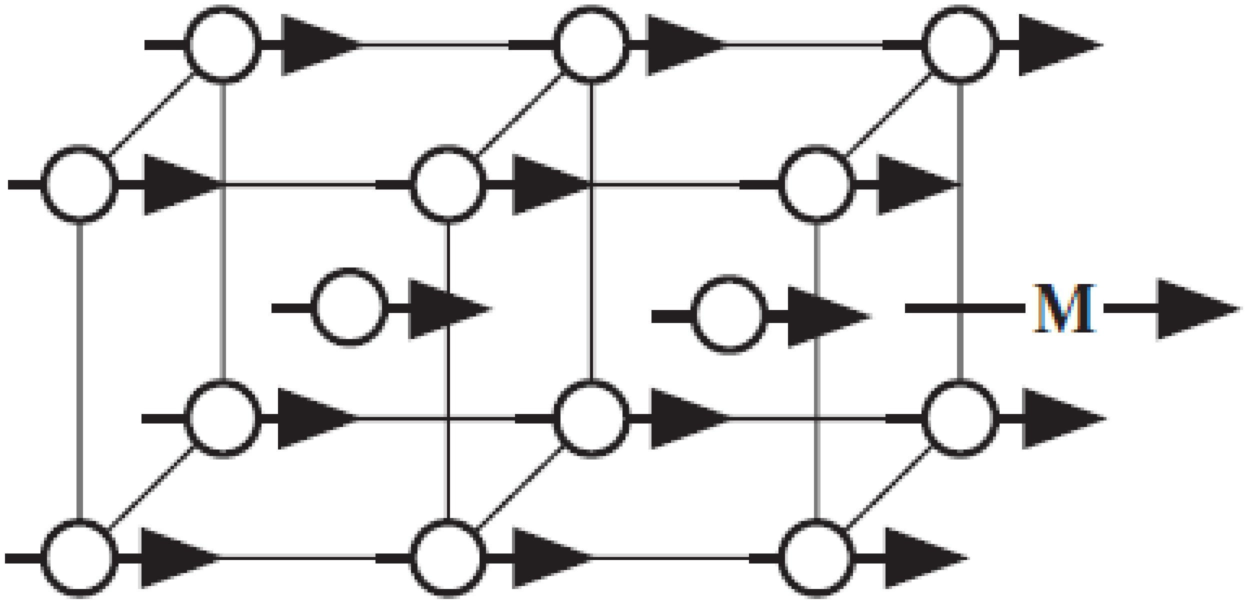
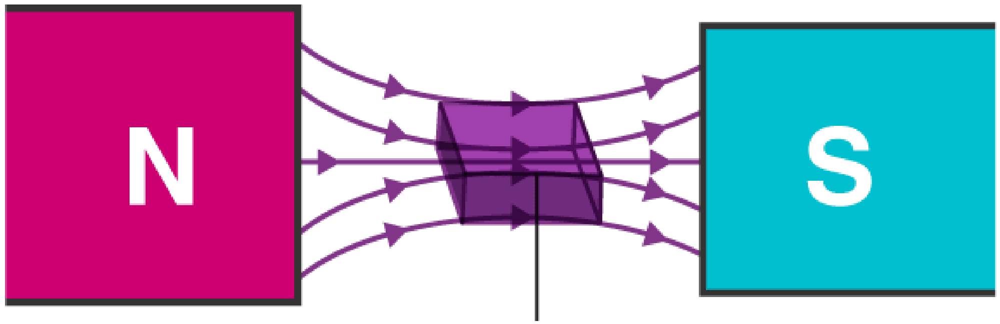


Figure 8.15 In a magnetized region of a ferromagnetic material such as iron, all the magnetic moments are spontaneously aligned in the same direction.

There is a strong magnetization vector **M** even in the absence of an applied field.



- Each ferromagnetic material has a characteristic temperature called the ferromagnetic Curie temperature θf. Below this temperature the spontaneous magnetization exists.
- Ferromagnetism occurs below a critical temperature called the Curie temperature $\boldsymbol{\theta_f}$ **or** $\boldsymbol{T_c}$. At temperatures above $\boldsymbol{\theta_f}$, ferromagnetism is lost and the material becomes paramagnetic.

Magnitude of susceptibility	Temperature dependence	Examples
Very large & positive	$\chi = \frac{C}{T - \theta_f}$ For $T > \theta_f$ paramagnetic behavior For $T < \theta_f$ ferromagnetic behavior	Fe, Co, Ni etc

4. Anti-ferromagnetism

- Antiferromagnetic materials such as chromium have a small but positive susceptibility.
- **They cannot possess any magnetization in the absence of an applied field**, in contrast to ferromagnets.
- Antiferromagnetic materials possess a magnetic ordering in which the magnetic moments of alternating atoms in the crystals align in opposite directions, as schematically depicted in Figure 8.16.
- The opposite alignments of atomic magnetic moments are due to **quantum mechanical exchange forces**. The net result is that in the absence of an applied field, there is no net magnetization.
- Antiferromagnetism occurs below a critical temperature called the Néel temperature T_N. Above T_N, antiferromagnetic material becomes paramagnetic.

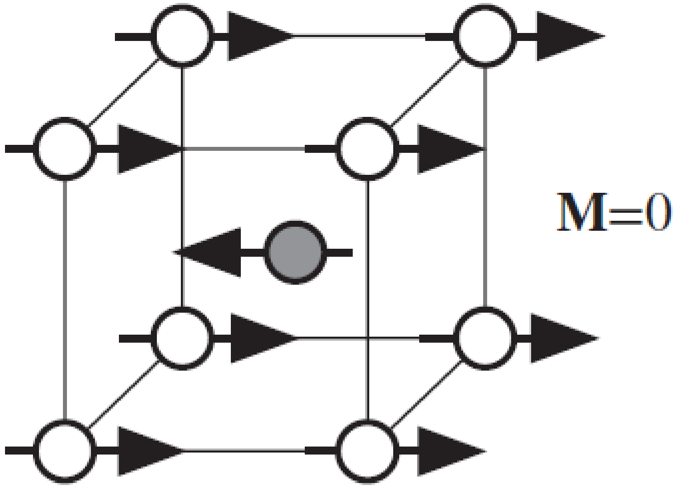
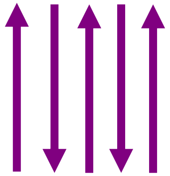


Figure 8.16 In this antiferromagnetic BCC crystal (Cr), the magnetic moment of the center atom is canceled by the magnetic moments of the corner atoms (one-eighth of the corner atom belongs to the unit cell).

- ✓ Spins are aligned antiparallel



- ✓ The magnetic susceptibility increase with the increase of temperature and reaches maximum at a certain temperature. This temperature is known as Neel temperature (θ or T_N). Above this temperature the susceptibility again decreases.
- ✓ These elements will be wise range of applications in magnetic storage devices.

Magnitude of susceptibility	**Temperature dependence**	**Examples**
small & positive	$\chi \propto T$ when T<TN $\chi = \frac{C}{T+\theta}$ when $T>T_N$	FeO, MnO_4, MnS, Cr_2O_3, $FeCl_2$

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5. Ferrimagnetism

- The origin of ferrimagnetism is based on magnetic ordering, as schematically illustrated in Figure 8.17. **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.

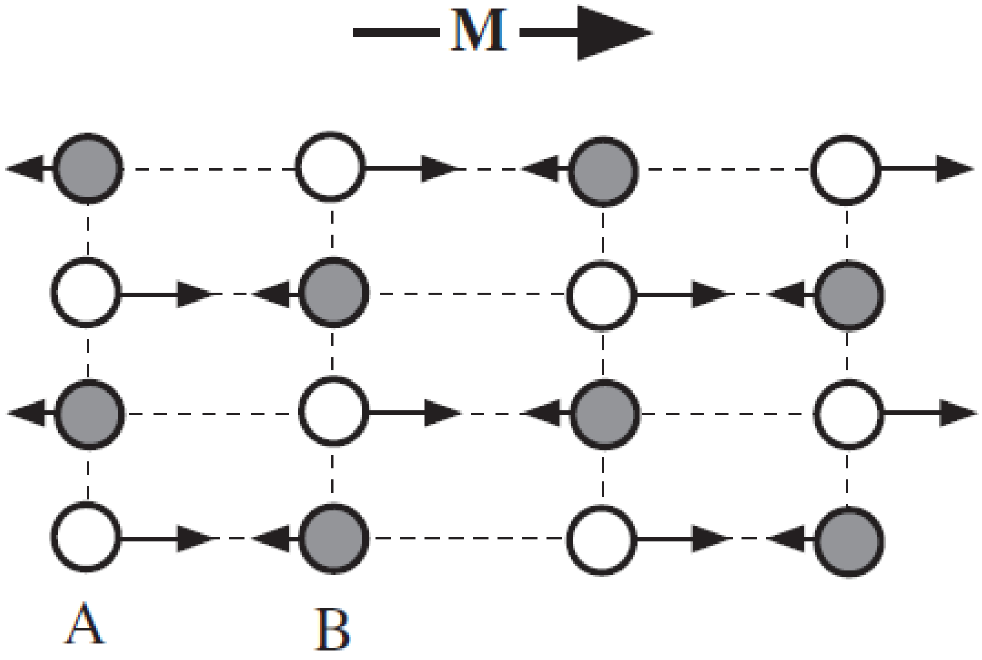
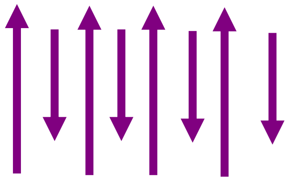


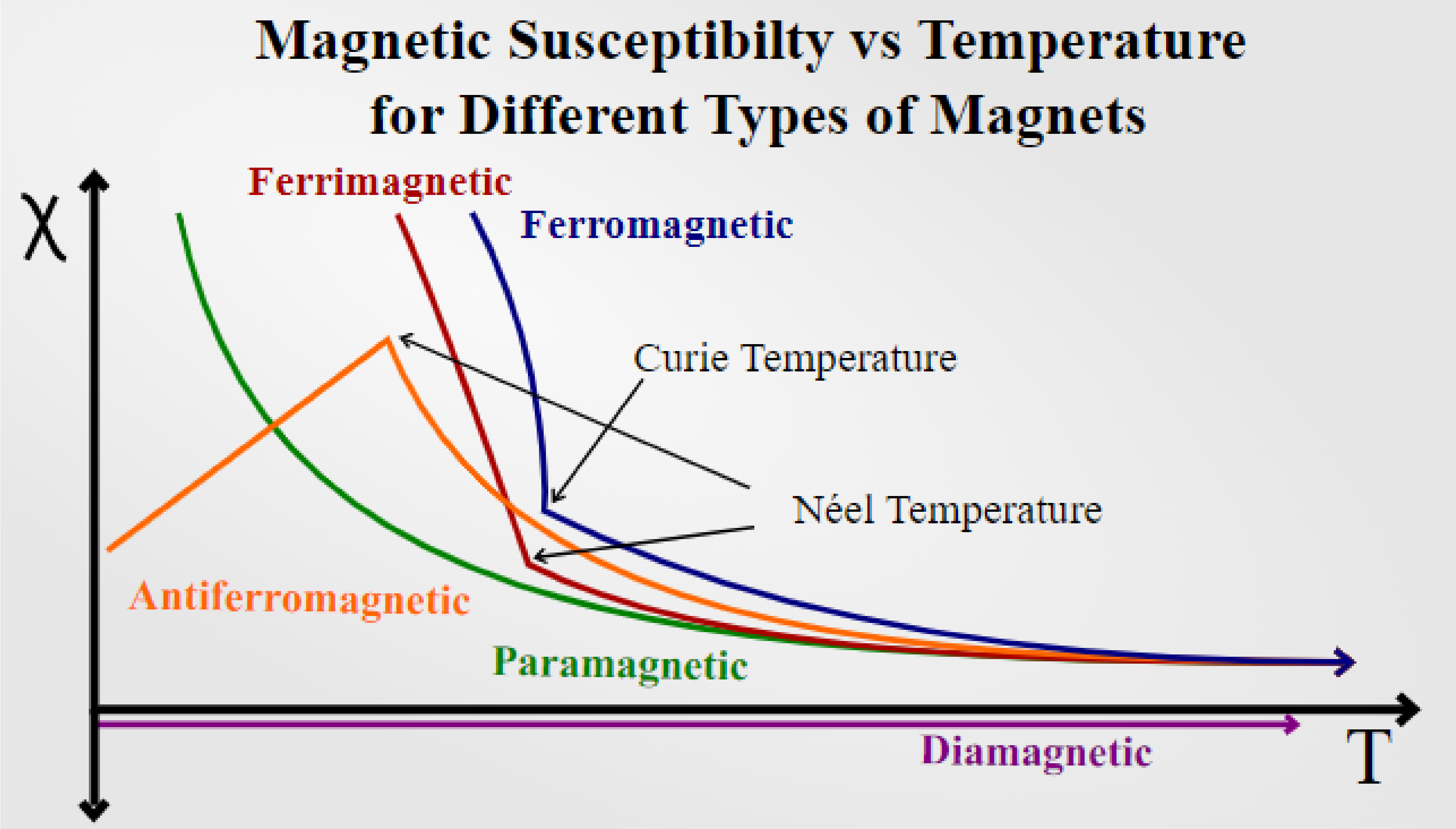
Figure 8.17 Illustration of magnetic ordering in the ferrimagnetic crystal.

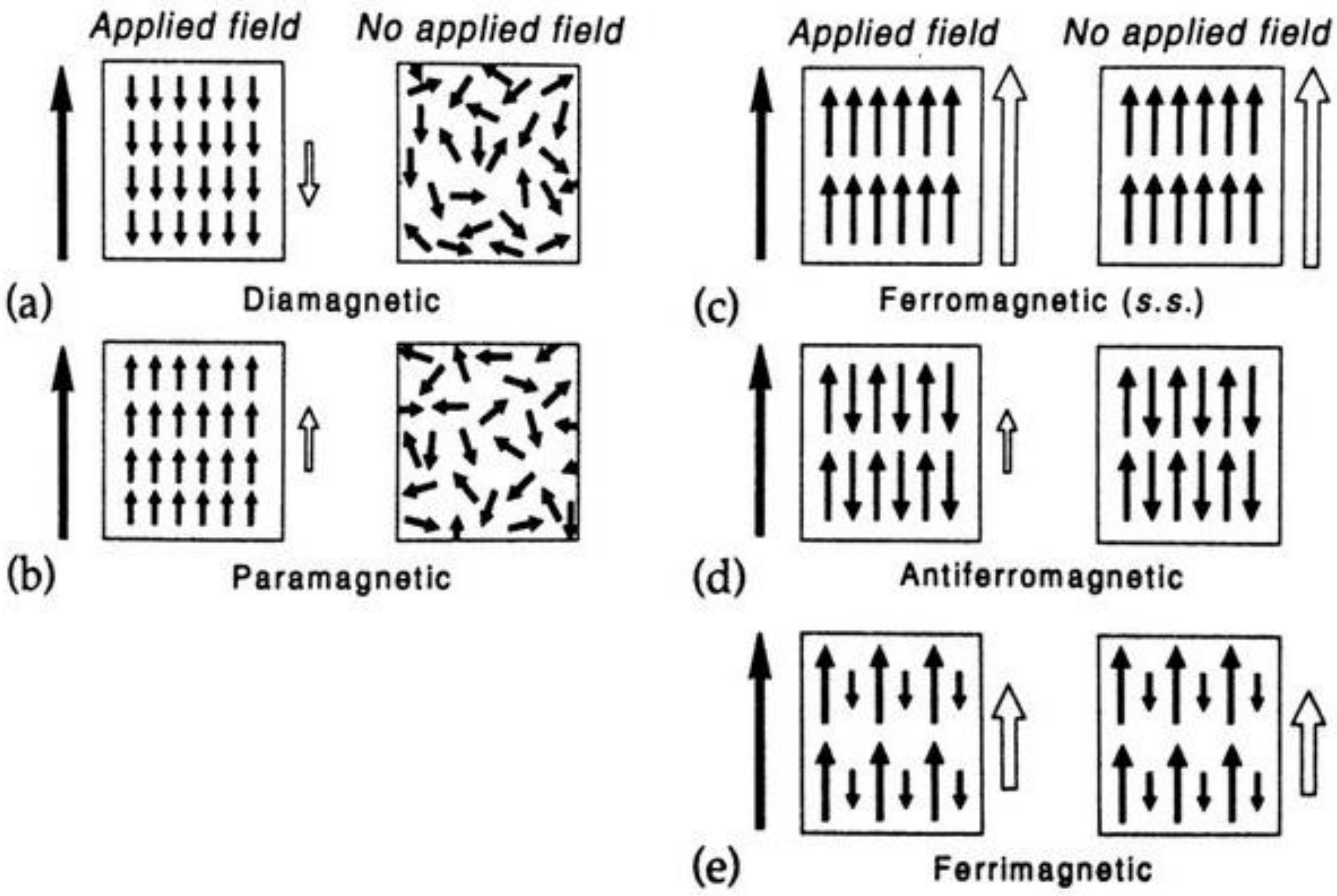
All A atoms have their spins aligned in one direction and all B atoms have their spins aligned in the opposite direction. As the magnetic moment of an A atom is greater than that of a B atom, there is net magnetization **M** in the crystal.

✓Spin alignment is antiparallel of different magnitudes.

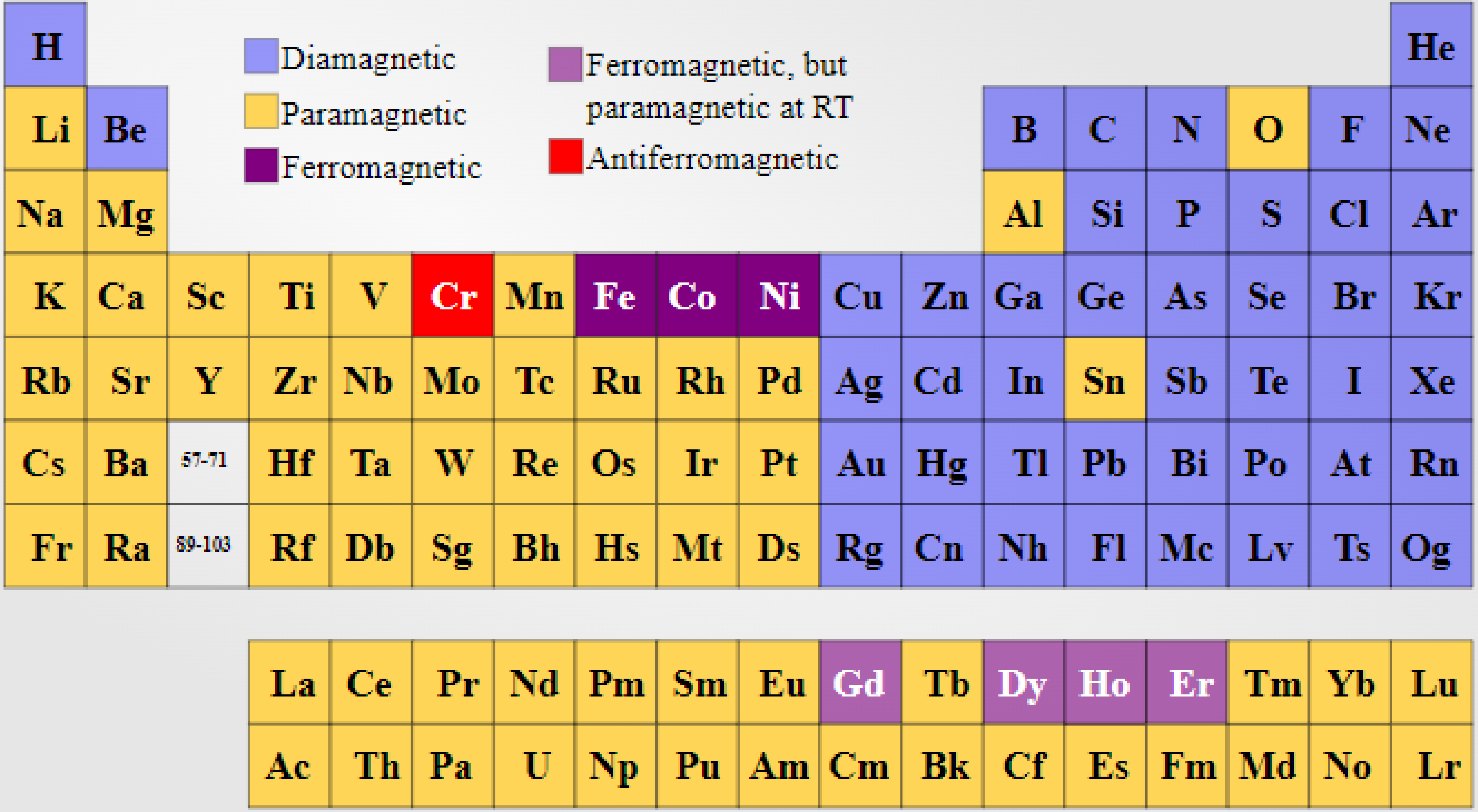


- **Unlike the antiferromagnetic case, the oppositely directed magnetic moments have different magnitudes and do not cancel**. The net effect is that the crystal can possess magnetization even in the absence of an applied field.
- Ferrimagnetic materials such as ferrites (e.g. Fe_3O_4) exhibit magnetic behavior similar to ferromagnetism below a critical temperature called the Curie temperature T_C. Above T_C, thermal energy randomizes the individual magnetic moments and the material becomes paramagnetic.
- Since ferrimagnetic materials are typically nonconducting and therefore do not suffer from eddy current losses, they are widely used in high-frequency electronics applications.
- All useful magnetic materials in electrical engineering are invariably ferromagnetic or ferrimagnetic.


Magnetic Susceptibilty vs Temperature
for Different Types of Magnets
χ
Ferrimagnetic
Ferromagnetic
Curie Temperature
Néel Temperature
Antiferromagnetic
Paramagnetic
Diamagnetic
T


Applied field
No applied field
(a)
Diamagnetic
(b)
Paramagnetic
Applied field
No applied field
(c)
Ferromagnetic (s.s.)
(d)
Antiferromagnetic
(e)
Ferrimagnetic

PERIODIC TABLE



H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	57-71	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	89-103	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og
			La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
			Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

🟦 Diamagnetic

🟨 Paramagnetic

🟪 Ferromagnetic

▨ Ferromagnetic, but paramagnetic at RT

🟥 Antiferromagnetic

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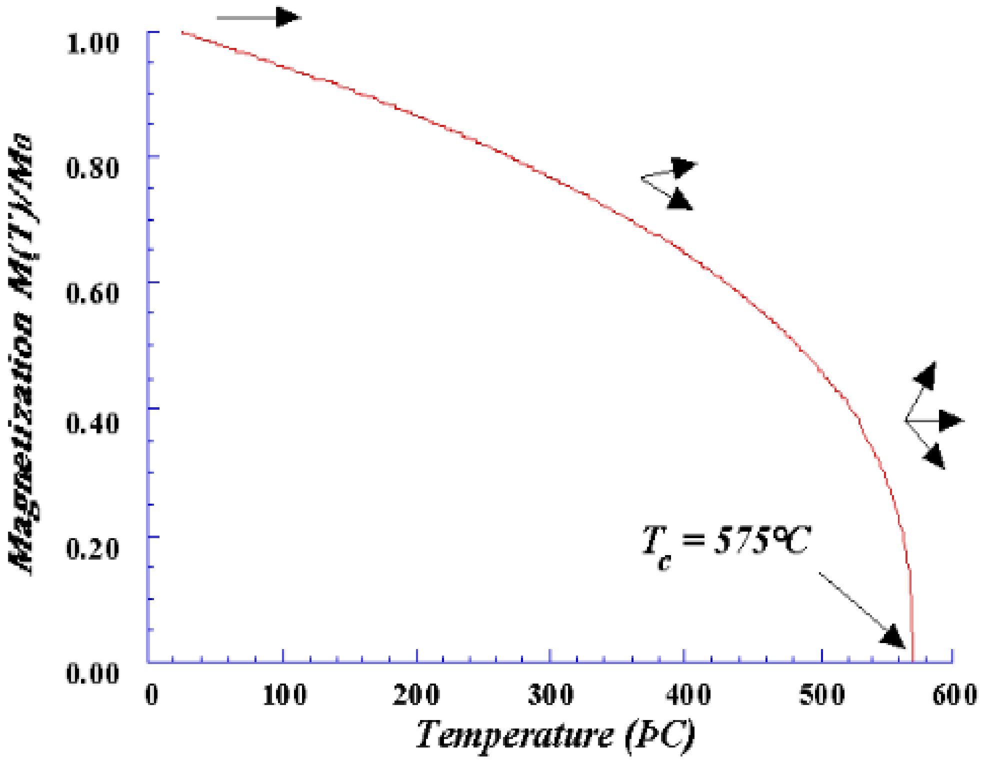
Application of magnetic materials

- **Electrical Transformers, Motor and Generator**
- **Electromechanical relays for protection**
- **Magnetic energy storage (Data Storage and electrical storage)**
- **Sound Systems and recording**
- **Magnetic relays and sensors**
- **Transportation and Communication**
- **Instrumentation (PMMC, MI, EMMC)**
- **Biomedical devices (MRI and CT Scans) and so on.**

Saturation Magnetization and Curie Temperature

- Even though electrons exchange forces in ferromagnets are very large, thermal energy eventually overcomes the exchange and produces a randomizing effect.
- This occurs at a particular temperature called the Curie temperature (T_C).
- Below the Curie temperature, the ferromagnet is ordered and above it, disordered.
- The saturation magnetization goes to zero at the Curie temperature. A typical plot of magnetization vs temperature for magnetite is shown below.



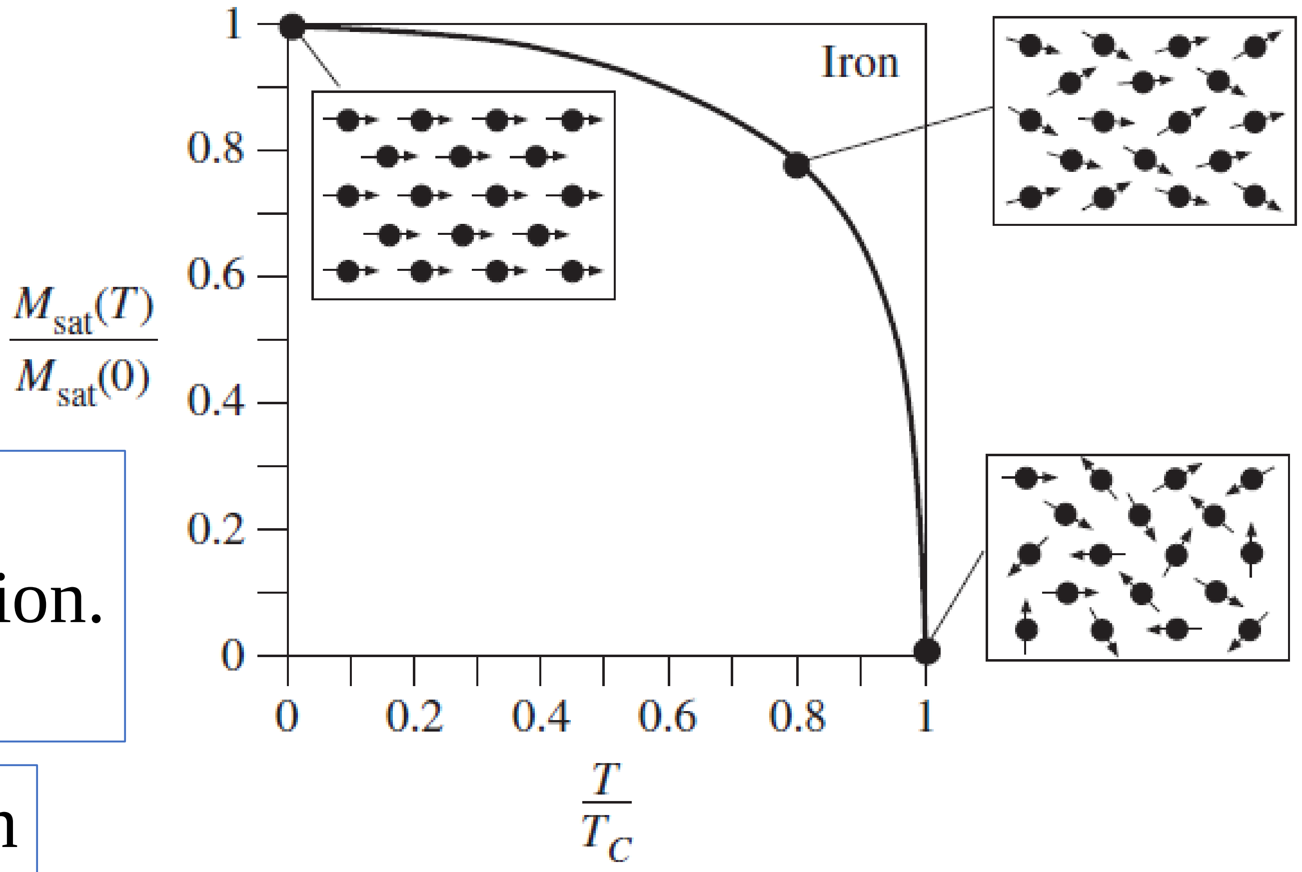


Fig. 8.21 Normalized saturated magnetization versus reduced temperature T/T_C where T_C is the Curie temperature (1043 K) for Fe.

In x-axis, T is varying from 0 to T_C
T_C = constant and used for normalization.
Here, $T < T_C$

In y-axis, $M_{sat}(T)$ is magnetization varying w.r.t T.
$M_{sat}(0)$ is the magnetization at absolute zero of temperature. It is used for normalization.

- The maximum magnetization in a ferromagnet when all the atomic magnetic moments have been aligned as much as possible is called the saturation magnetization M_{sat}.
- In the iron crystal, for example, this corresponds to each Fe atom with an effective spin magnetic moment of 2.2 Bohr magnetons aligning in the same direction to give a magnetic field $\mu o\ M_{sat}$ or 2.2 T.
- As we increase the temperature, lattice vibrations become more energetic, which leads to a frequent disruption of the alignments of the spins. The spins cannot align perfectly with each other as the temperature increases due to lattice vibrations randomly agitating the individual spins.
- The ferromagnetic behaviour disappears at a critical temperature called the **Curie temperature,** denoted by T_C. When the **thermal energy of lattice vibrations** in the crystal can overcome the **potential energy of the exchange interaction** and hence destroy the spin alignments.

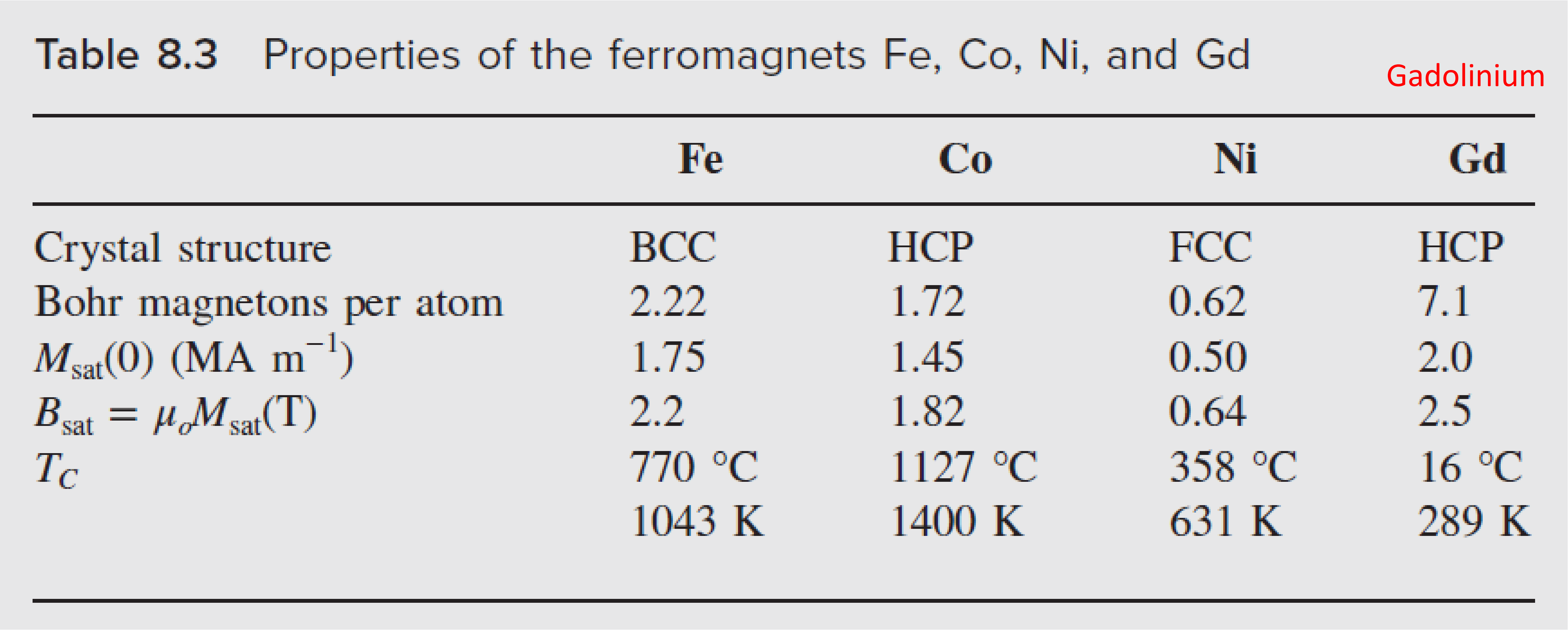


Table 8.3 Properties of the ferromagnets Fe, Co, Ni, and Gd

Gadolinium

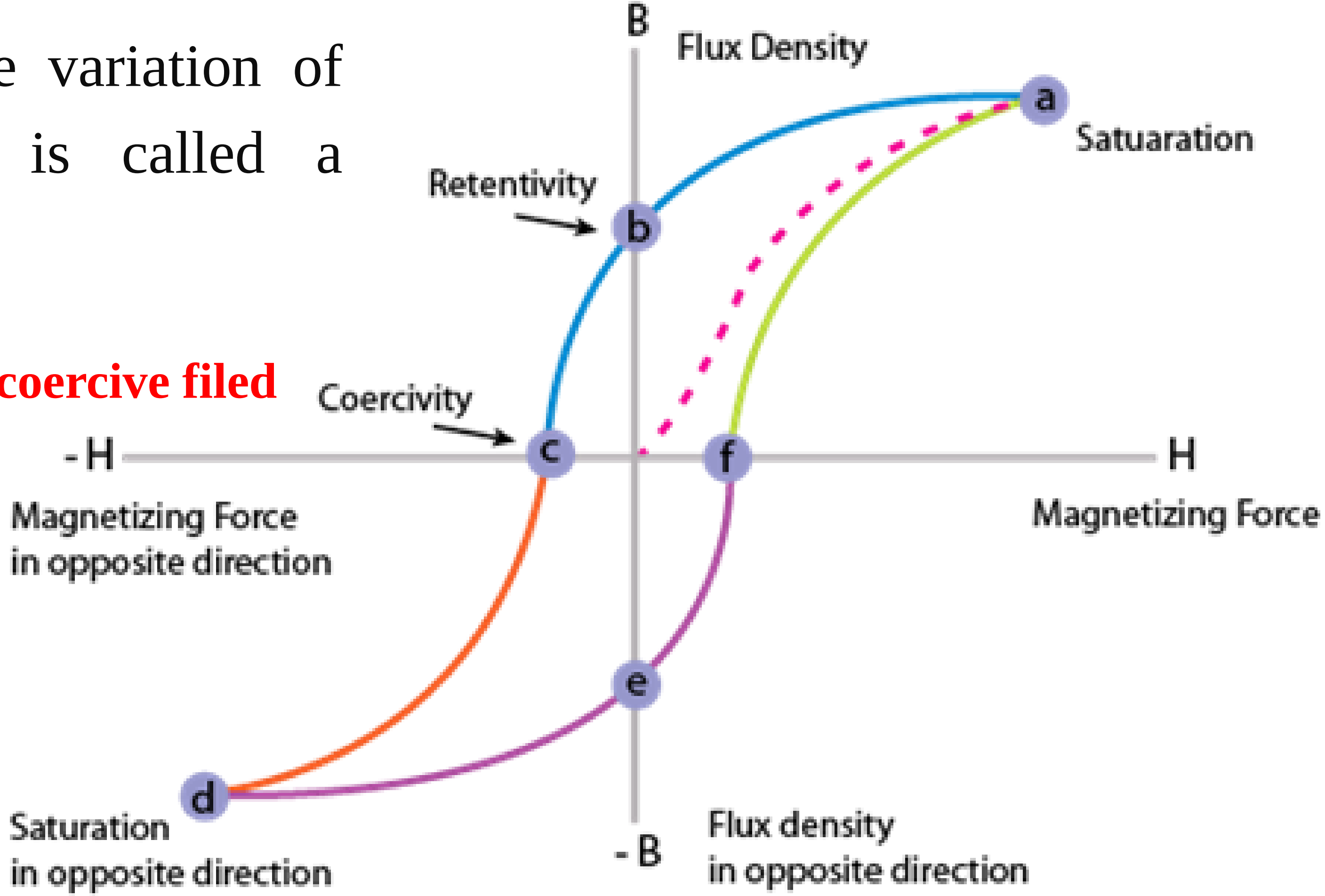
	Fe	**Co**	**Ni**	**Gd**
Crystal structure	BCC	HCP	FCC	HCP
Bohr magnetons per atom	2.22	1.72	0.62	7.1
$M_{sat}(0)$ (MA m^{-1})	1.75	1.45	0.50	2.0
$B_{sat} = \mu_o M_{sat}$(T)	2.2	1.82	0.64	2.5
T_C	770 °C	1127 °C	358 °C	16 °C
	1043 K	1400 K	631 K	289 K

Hysteresis Loop (or) B-H Curve

In addition to the Curie temperature and saturation magnetization, ferromagnetism can retain a memory of an applied field once it is removed. This behavior is called hysteresis and a plot of the variation of magnetization with magnetic field is called a hysteresis loop.

Retentivity or Residual or Remanent

Coercivity or coercive filed



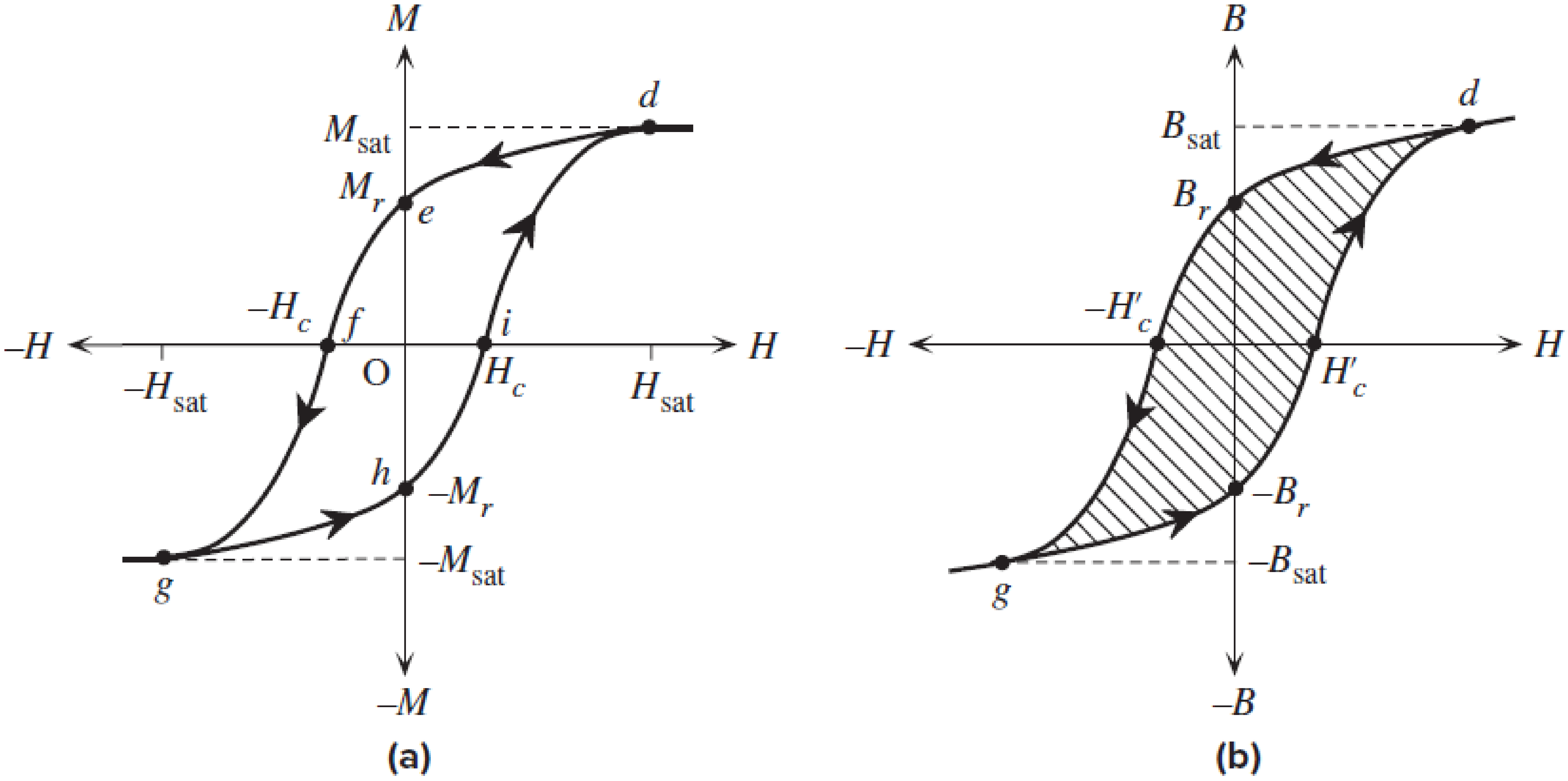


Figure 8.32 (a) A typical *M* versus *H* hysteresis curve. (b) The corresponding *B* versus *H* hysteresis curve. The shaded area inside the hysteresis loop is the energy loss per unit volume per cycle.

SOFT AND HARD MAGNETIC MATERIALS

→ Based on their *B*–*H* behavior, engineering materials are typically classified into soft and hard magnetic materials.

→ Soft magnetic materials are easy to magnetize and demagnetize and hence require relatively low magnetic field intensities. The hysteresis loop has a small area, so the hysteresis power loss per cycle is small.

→ Soft magnetic materials are typically suitable for applications where repeated cycles of magnetization and demagnetization are involved, as in electric motors, transformers, inductors, and Electromagnetic relays where the magnetic field varies cyclically.

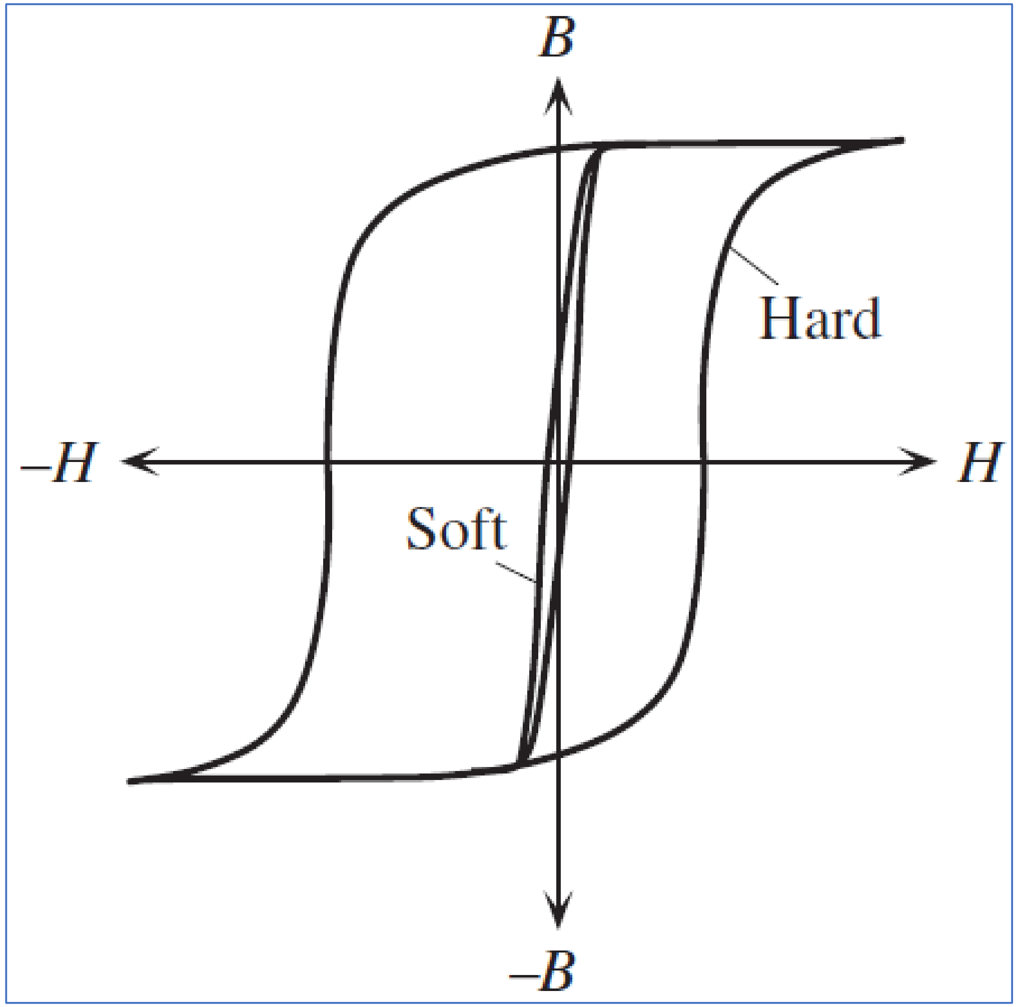


Figure 8.37 Soft and hard magnetic materials.

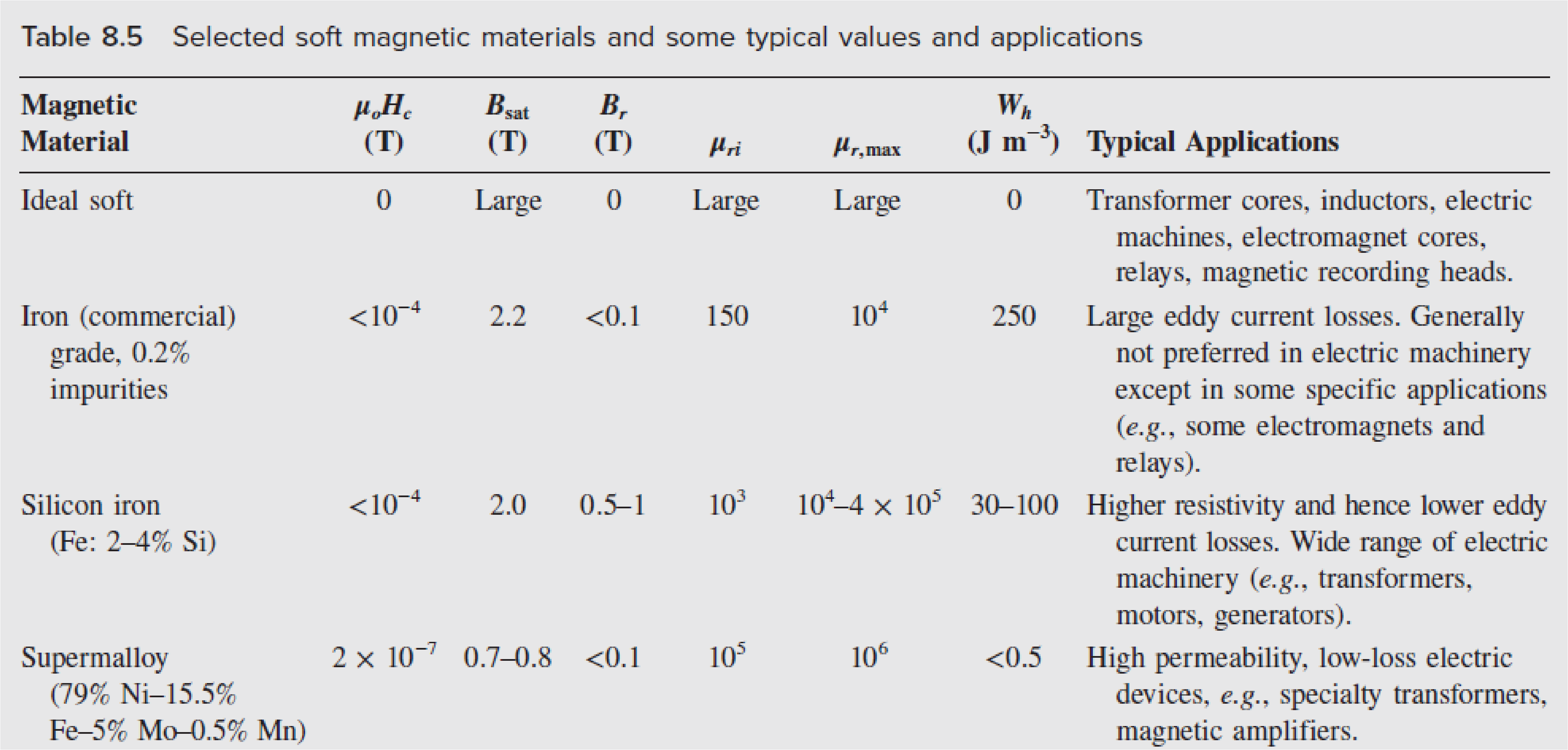


Table 8.5 Selected soft magnetic materials and some typical values and applications

Magnetic Material	$\mu_o H_c$ (T)	B_{sat} (T)	B_r (T)	μ_{ri}	$\mu_{r,\max}$	W_h (J m^{-3})	Typical Applications
Ideal soft	0	Large	0	Large	Large	0	Transformer cores, inductors, electric machines, electromagnet cores, relays, magnetic recording heads.
Iron (commercial) grade, 0.2% impurities	$<10^{-4}$	2.2	<0.1	150	10^4	250	Large eddy current losses. Generally not preferred in electric machinery except in some specific applications (*e.g.*, some electromagnets and relays).
Silicon iron (Fe: 2–4% Si)	$<10^{-4}$	2.0	0.5–1	10^3	10^4–4×10^5	30–100	Higher resistivity and hence lower eddy current losses. Wide range of electric machinery (*e.g.*, transformers, motors, generators).
Supermalloy (79% Ni–15.5% Fe–5% Mo–0.5% Mn)	2×10^{-7}	0.7–0.8	<0.1	10^5	10^6	<0.5	High permeability, low-loss electric devices, *e.g.*, specialty transformers, magnetic amplifiers.

→ **Hard magnetic materials**, on the other hand, are difficult to magnetize and demagnetize and hence require relatively large magnetic field intensities.

→ Their *B–H* curves are broad and almost rectangular. They possess relatively large coercivities, which means that they need large applied fields to be demagnetized. The coercive field for hard materials can be millions of times greater than those for soft magnetic materials. Their characteristics make hard magnetic materials useful as permanent magnets in a variety of applications.

→ From *B–H* curves, It has high retentivity (residual) magnetism property in the material.

→ It is also clear that the magnetization can be switched from one very persistent direction to another very persistent direction, from $+B_r$ to $-B_r$, by a suitably large magnetizing field intensity.

→ It is apparent that hard magnetic materials can also be used in magnetic storage of digital data, where the states $+B_r$ and $-B_r$ can be made to represent 1 and 0 (or vice versa).

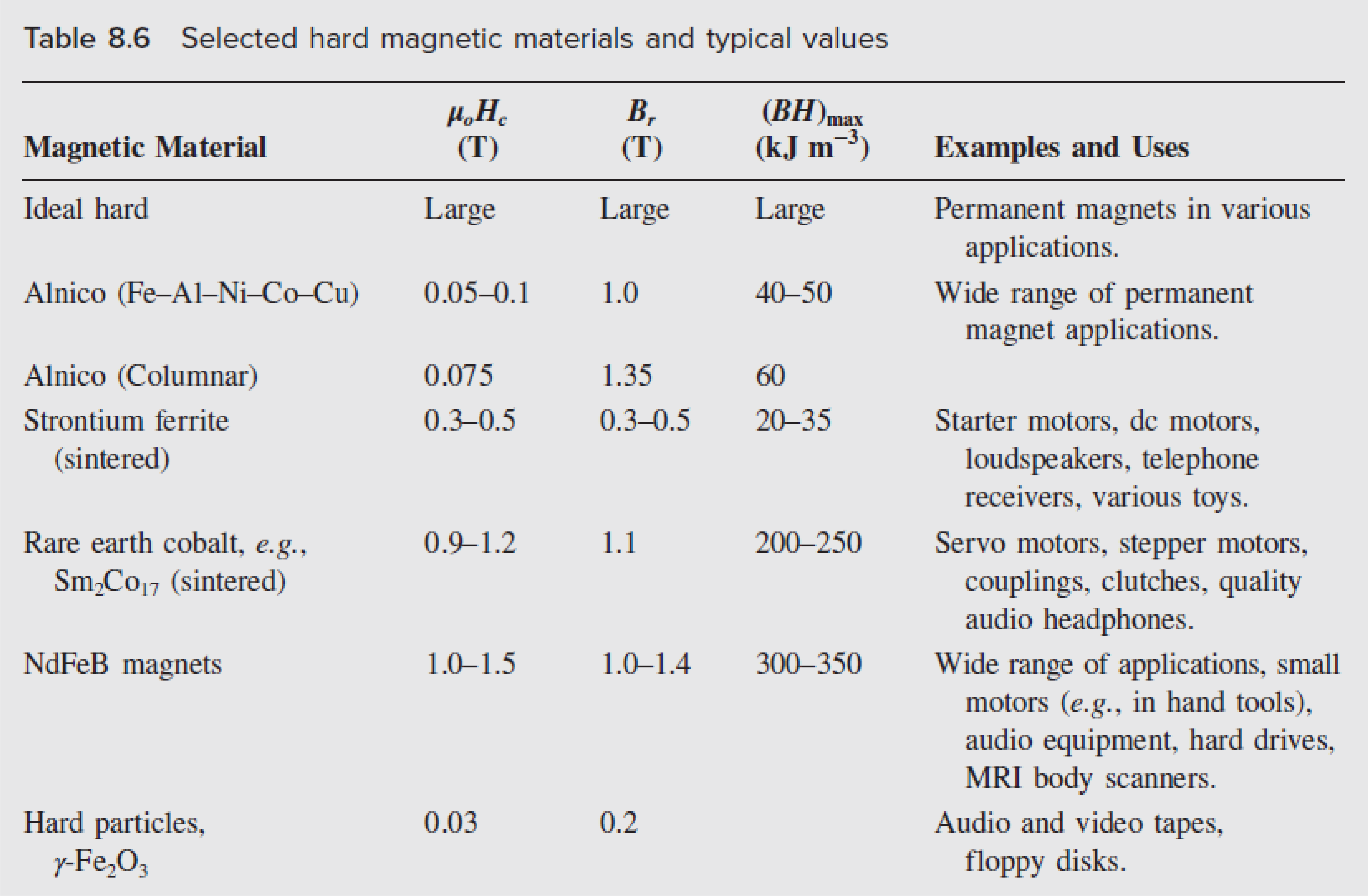


Table 8.6 Selected hard magnetic materials and typical values

Magnetic Material	$\mu_o H_c$ (T)	B_r (T)	$(BH)_{max}$ (kJ m^{-3})	Examples and Uses
Ideal hard	Large	Large	Large	Permanent magnets in various applications.
Alnico (Fe–Al–Ni–Co–Cu)	0.05–0.1	1.0	40–50	Wide range of permanent magnet applications.
Alnico (Columnar)	0.075	1.35	60	
Strontium ferrite (sintered)	0.3–0.5	0.3–0.5	20–35	Starter motors, dc motors, loudspeakers, telephone receivers, various toys.
Rare earth cobalt, *e.g.*, Sm_2Co_{17} (sintered)	0.9–1.2	1.1	200–250	Servo motors, stepper motors, couplings, clutches, quality audio headphones.
NdFeB magnets	1.0–1.5	1.0–1.4	300–350	Wide range of applications, small motors (*e.g.*, in hand tools), audio equipment, hard drives, MRI body scanners.
Hard particles, γ-Fe_2O_3	0.03	0.2		Audio and video tapes, floppy disks.

Magnetostriction

If we were to strain a ferromagnetic crystal (by applying a suitable stress) along a certain direction, we would change the interatomic spacing not only along this direction but also in other directions and hence change the exchange interactions between the atomic spins. This would lead to a change in the magnetization properties of the crystal.

In the converse effect, the magnetization of the crystal generates strains or changes in the physical dimensions of the crystal.

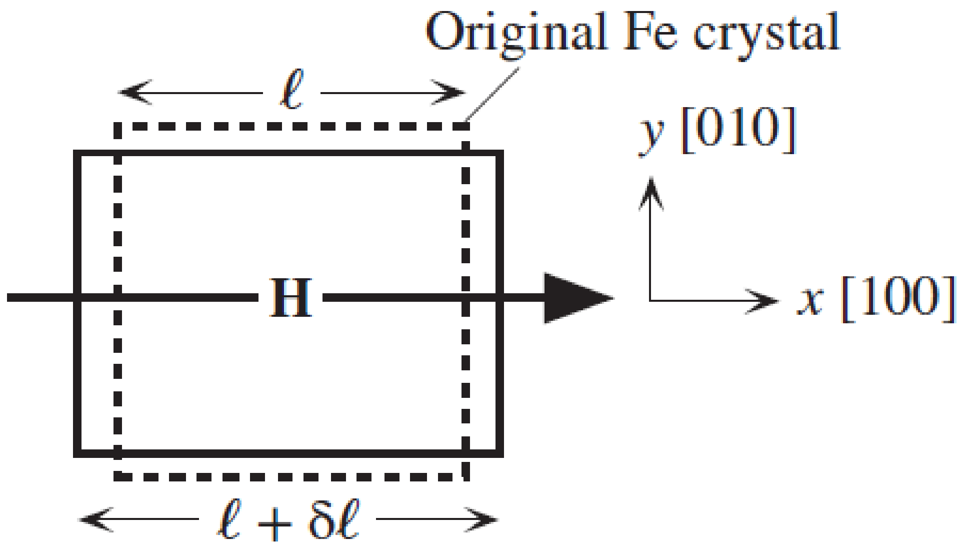


Figure 8.27 Magnetostriction means that the iron crystal in a magnetic field along x, an easy direction, elongates along x but contracts in the transverse directions (in low fields).

The longitudinal strain $\Delta\ell/\ell$ along the direction of magnetization is called the **magnetostrictive constant**, denoted by λ. The magnetostrictive constant depends on the crystal direction and may be positive (extension) or negative (contraction).

When the crystal reaches saturation magnetization, λ also reaches saturation, called **saturation magnetostriction strain** λ_{sat} .

The crystal lattice strain energy associated with magnetostriction is called the **magnetostrictive energy,** which is typically less than the anisotropy energy.

Magnetostriction is responsible for the transformer hum noise one hears near power transformers. As the core of a transformer is magnetized one way and then in the opposite direction under an alternating voltage, the alternating changes in the longitudinal strain vibrate the surrounding environment, air, oil, and so forth, and generate an acoustic noise at twice the main frequency, or 120 Hz, and its harmonics.

Magnetic Anisotropy

In general, **magnetoresistance** refers to the change in the resistance of a material (any material) when it is placed in a magnetic field.

When a magnetic metal, such as iron, is placed in a magnetic field, the change in the resistivity depends on the direction of the current flow with respect to the magnetic field.

The resistivity $\rho_{/\!/}$ for current flow parallel to the magnetic field decreases, and the resistivity $\rho_{\perp}$, perpendicular to the field, increases by roughly the same amount.

The change in the resistivity due to the applied magnetic field is *anisotropic* (depends on the direction) and is called **anisotropic magnetoresistance (AMR).** The change in resistivity is limited to a few, is still useful.

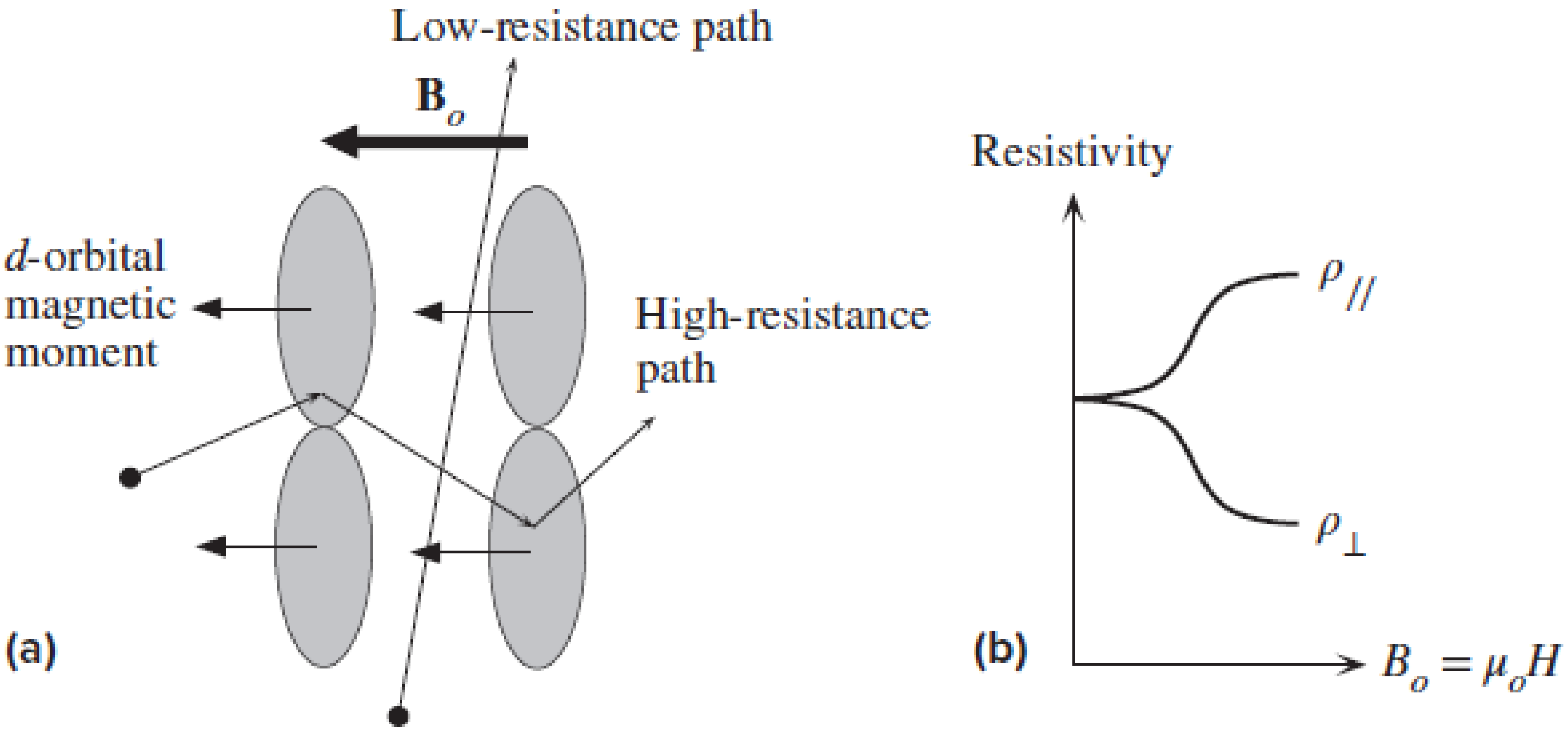


Figure 8.46 (a) The origin of anisotropic magnetoresistance (AMR). The electrons traveling along the field experience more scattering than those traveling perpendicular to the field. (b) Resistivity depends on the current flow direction with respect to the applied magnetic field.

On the other hand, a very large magnetoresistance, called **giant magnetoresistance (GMR),** has been observed in certain special multilayer structures, which exhibit substantial changes in the resistance (*e.g.*, more than 10 percent) when a magnetic field is applied

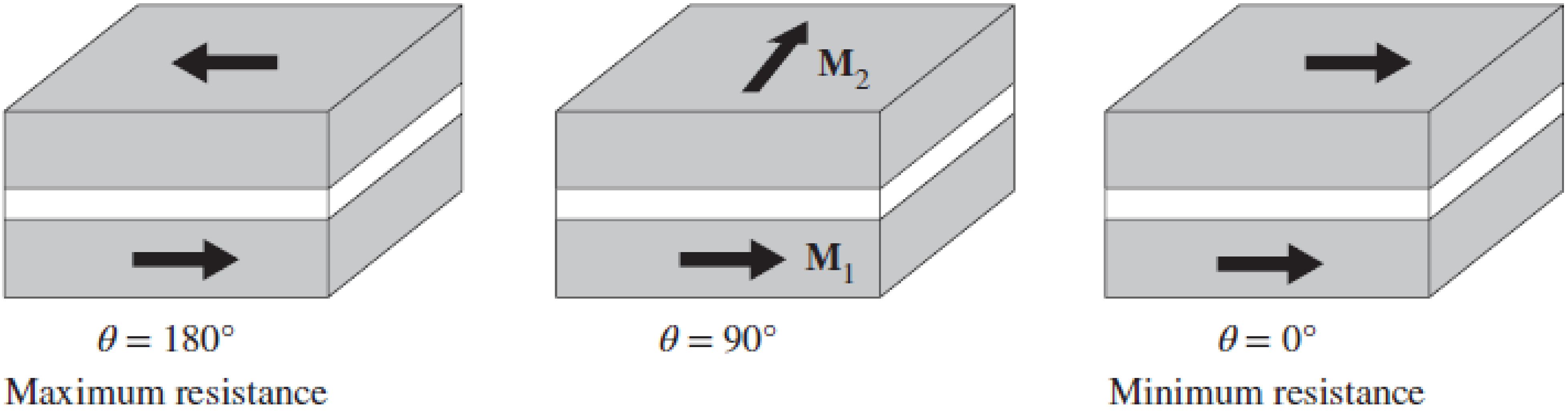


Figure 8.48 Resistance of the multilayer structure depends on the relative orientations of magnetization in the two magnetic layers.

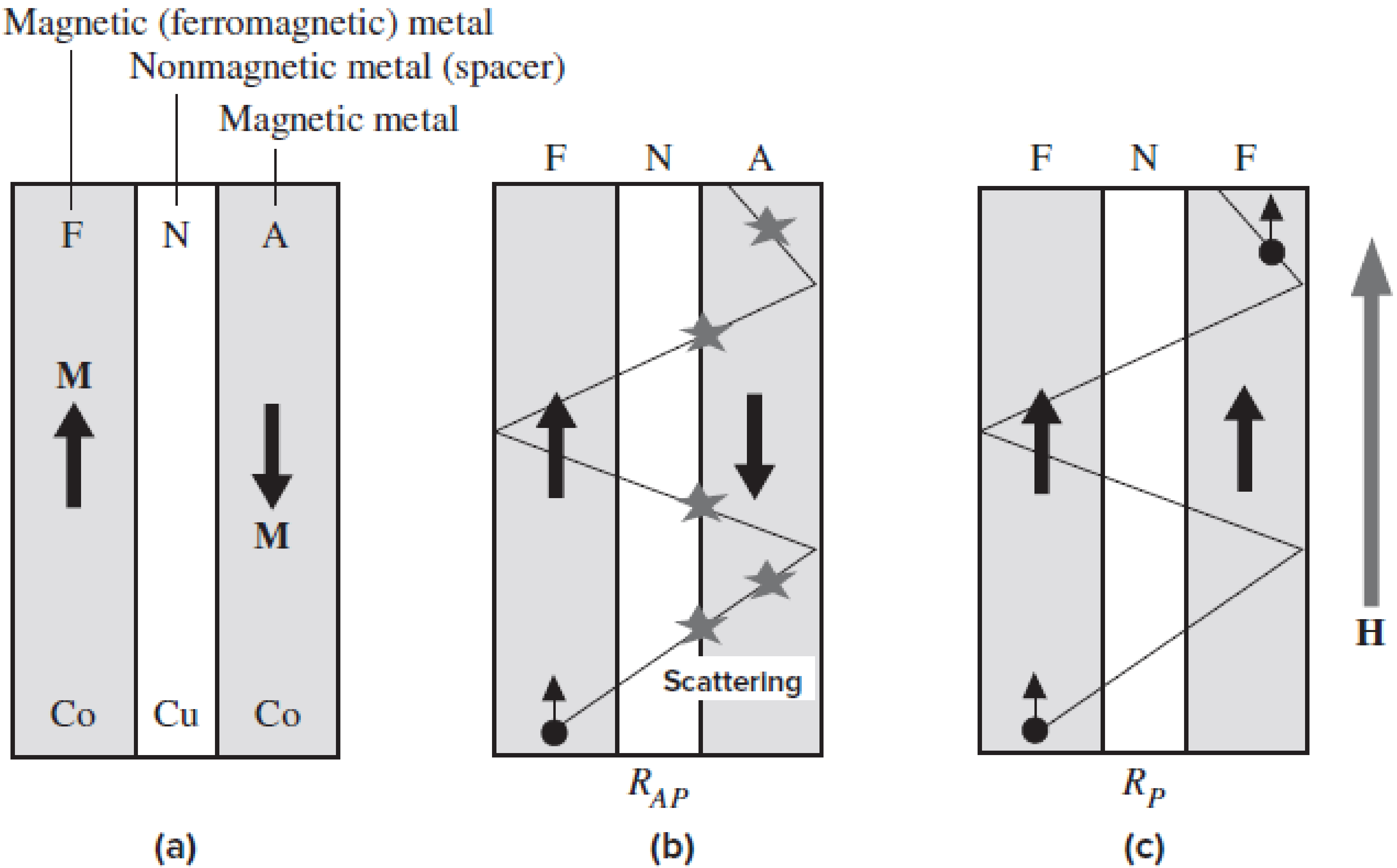


Figure 8.47 A highly simplified view of the principle of the giant magnetoresistance effect. (a) The basic trilayer structure. (b) Antiparallel magnetic layers with high resistance R_{AP}. (c) An external field aligns layers; parallel alignment has a lower resistance R_P.

In the absence of an external field, two magnetic layers are coupled in such a way that their magnetizations are *antiparallel* or in opposite directions; this arrangement is also called an *antiferromagnetically* coupled configuration. We will use the notation FNA to represent the antiparallel configuration, where N stands for the nonmagnetic metal.

We can apply an external magnetic field to one of the layers and rotate its magnetization so that the two magnetizations are now in parallel as in Figure 8.47c. This parallel configuration is frequently called *ferromagnetically* coupled layers and is denoted as FNF.

The resistance of the antiparallel FNA in Figure 8.47b structure is much higher than that of the parallel structure FNF in Figure 8.47c.

Spin-Orbit interaction

An electron in an atom will experience an internal magnetic field B_{int} . Because, from the electron's reference frame, it is the positive nucleus that is orbiting the electron. The electron will "see" the nucleus, take as charge $+e$, circling around it, which is equivalent to a current $I = +ef$. where f is the electron's frequency of rotation around the nucleus.

The current I generates the internal magnetic field B_{int} at the electron. From electromagnetism texts, B_{int} is given by

$$B_{int} = \frac{\mu_0 \, I}{2r}$$

where r is the radius of the electron's orbit and μ_o is the absolute permeability

Internal magnetic field at an electron in an atom

$$B_{int} = \frac{\mu_0\, e}{4\pi m_e r^3} L$$

Where, Orbital $angular\ velocity\ (L) = m_e\, v\, r = m_e\, (wr)r = m_e w r^2$

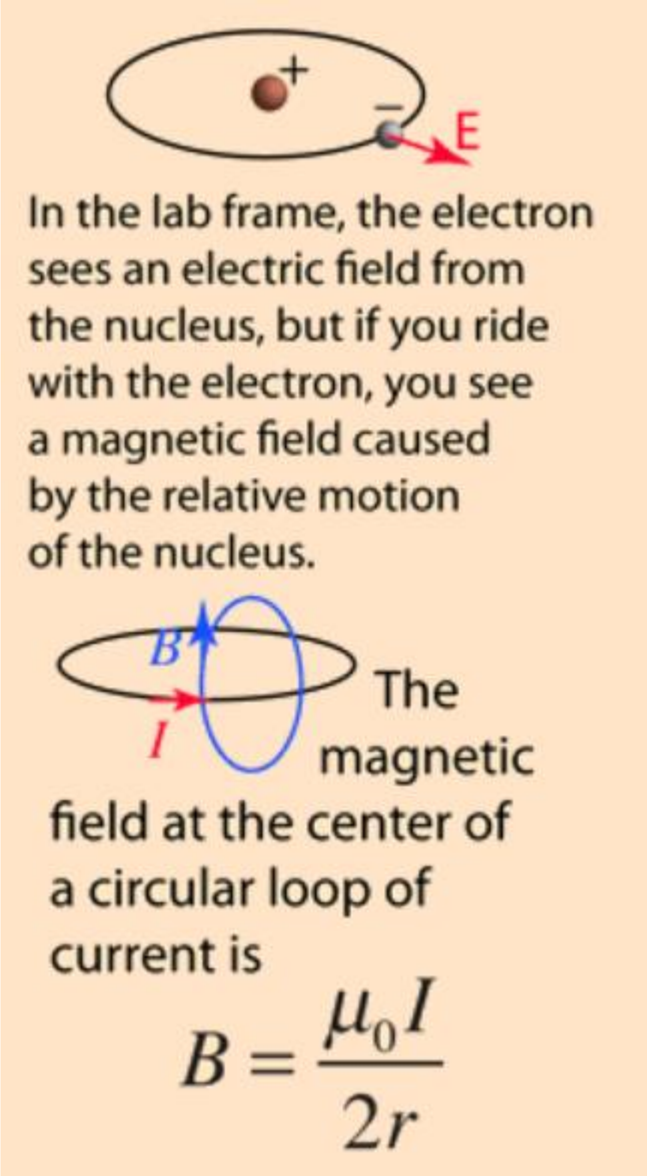
The electron's spin magnetic moment **μ_{spin}** will couple with this internal field, which means that the electron will now possess a magnetic potential energy E_{SL} that is due to the coupling of the *spin* with the *orbital motion*, called **spin-orbit coupling.** E_{SL} will be either negative or positive, with only two values, depending on whether the electron's spin magnetic moment is along or opposite $\mathbf{B}_{int}$, Take z along B_{int} so that **$E_{SL} = -B_{int}\, \mu_{spin,z}$,** where $\mu_{spin,z}$ is μ_{spin} along z, and then show that the energy E_2 of the $2p$ orbital splits into two closely separated levels whose separation is

Spin–orbit coupling potential energy

$$\Delta E_{SL} = \left(\frac{eh}{m_e}\right) B_{int}$$

Orbital, spin magnetic movement of an electron are

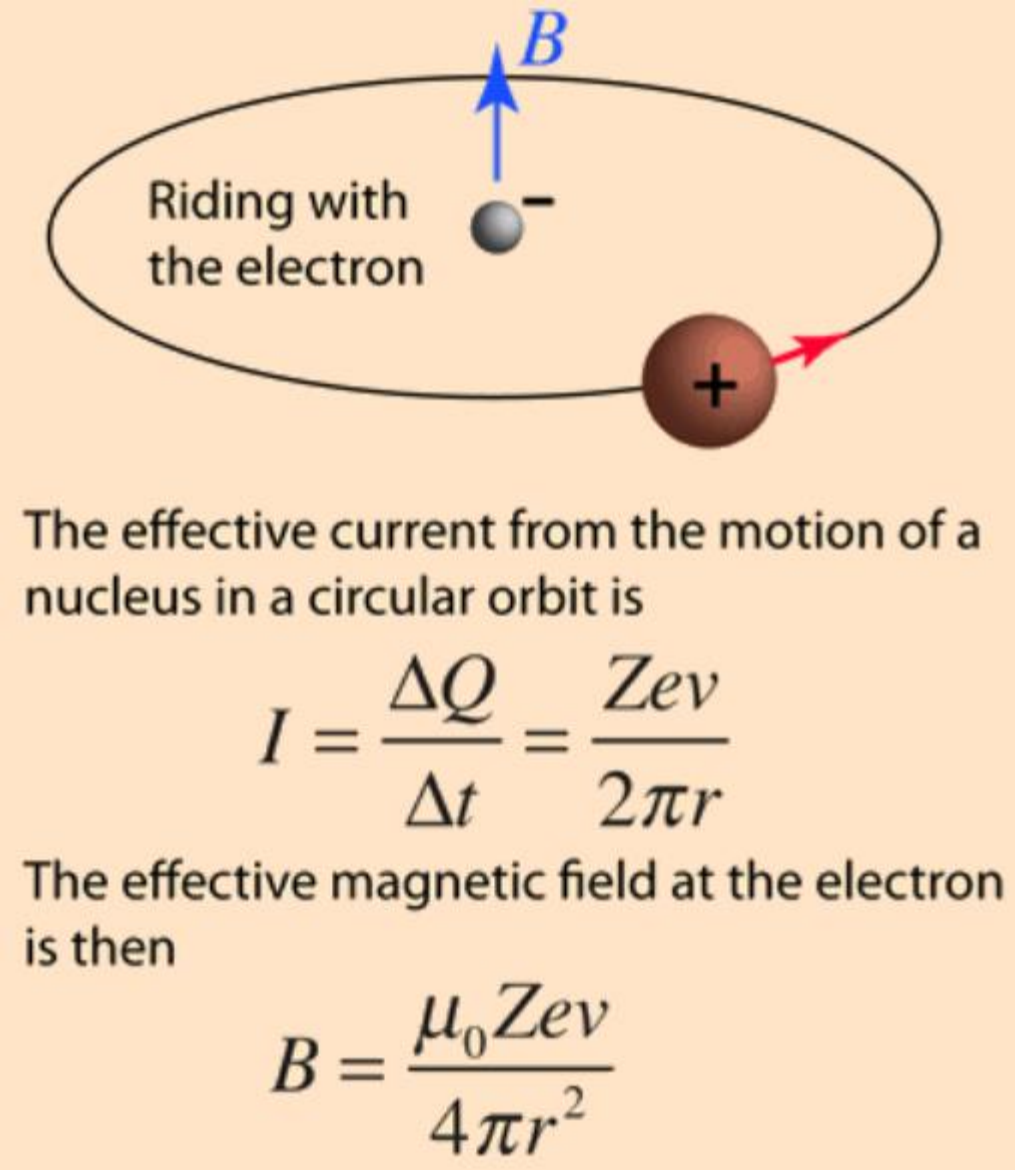
$$\mu_{orb} = -\frac{e}{2m_e} L \qquad \mu_{spin} = -\frac{e}{m_e} S$$



In the lab frame, the electron sees an electric field from the nucleus, but if you ride with the electron, you see a magnetic field caused by the relative motion of the nucleus.

The magnetic field at the center of a circular loop of current is

$$B = \frac{\mu_0 I}{2r}$$



The effective current from the motion of a nucleus in a circular orbit is

$$I = \frac{\Delta Q}{\Delta t} = \frac{Zev}{2\pi r}$$

The effective magnetic field at the electron is then

$$B = \frac{\mu_0 Zev}{4\pi r^2}$$

Superconductivity

- The superconductivity involves the vanishing of the resistivity of a conductor at low temperatures and is normally explained within quantum mechanics.
- All superconductors are perfect diamagnets and, further, they have present or potential uses that involve magnetic fields.
- In 1911, Kamerlingh Onnes observed that when a sample of mercury is cooled to below 4.2 K, its resistivity totally vanishes and the material behaves as a superconductor, exhibiting no resistance to current flow.
- There are many such substances, not simply metals, that exhibit superconductivity when cooled below a critical temperature Tc that depends on the material.
- There are also many conductors, including some with the highest conductivities such as silver, gold, and copper, that do not exhibit superconductivity. The resistivity of these normal conductors at low temperatures is **limited by scattering from impurities and crystal defects and saturates at a finite value** determined by the residual resistivity.

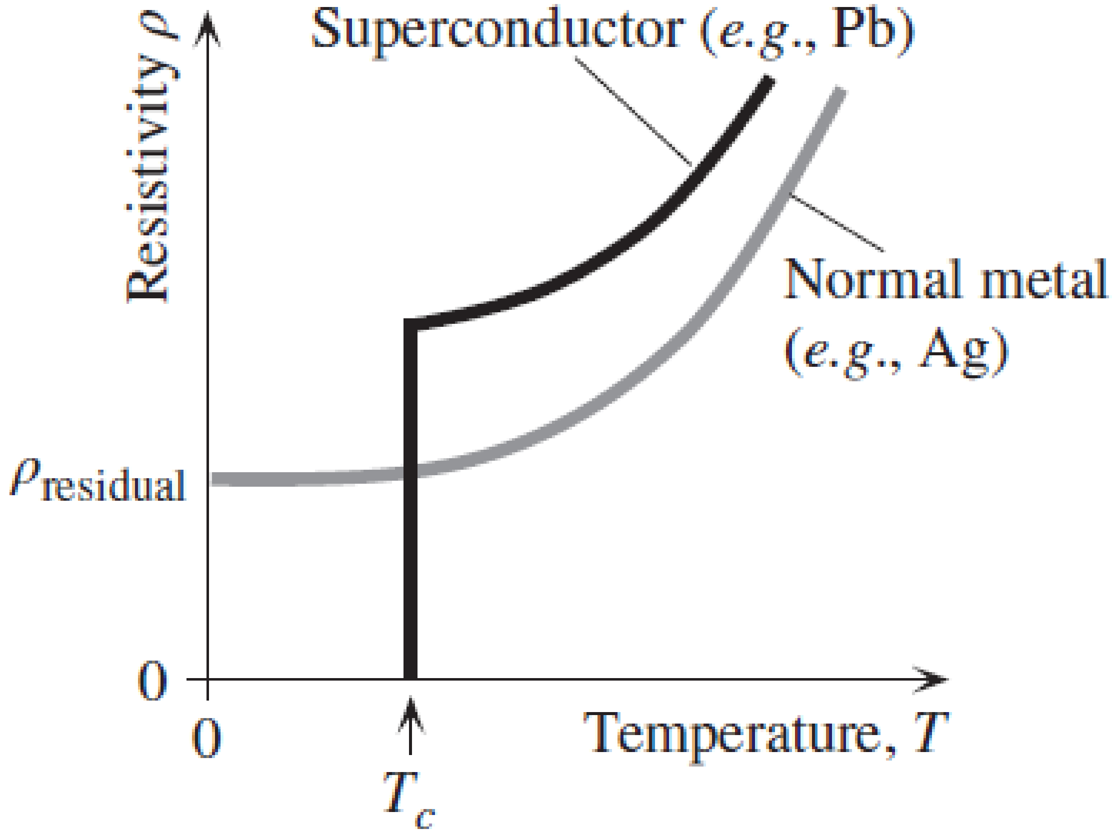


Figure 8.56 A superconductor such as lead evinces a transition to zero resistivity at a critical temperature T_c (7.2 K for Pb).

A normal conductor such as silver exhibits residual resistivity down to lowest temperatures.

- In 1986 Bednorz and Müller, at IBM Research Laboratories, discovered that a copper oxide–based ceramic-type compound La–Ba–Cu–O, which normally has high resistivity, becomes superconducting when cooled below 35 K.
- Following this Nobel prize–winning discovery, a variety of copper oxide–based compounds (called cuprate ceramics) have been synthesized and studied.

- At present the highest critical temperature for a superconductor is around 130 K (−143 °C) for Hg–Ba–Ca–Cu–O. These superconductors with Tc above ~30 K are now typically referred as high-Tc superconductors.

- High-T_c superconductors are already finding applications in such devices as superconducting solenoids, sensitive magnetometers, and high-Q microwave filters, power cables and superconducting current limiters and so on.

- The quest for a near-room temperature superconductor goes on, with many scientists around the world trying different materials, or synthesizing them, to raise Tc even higher.

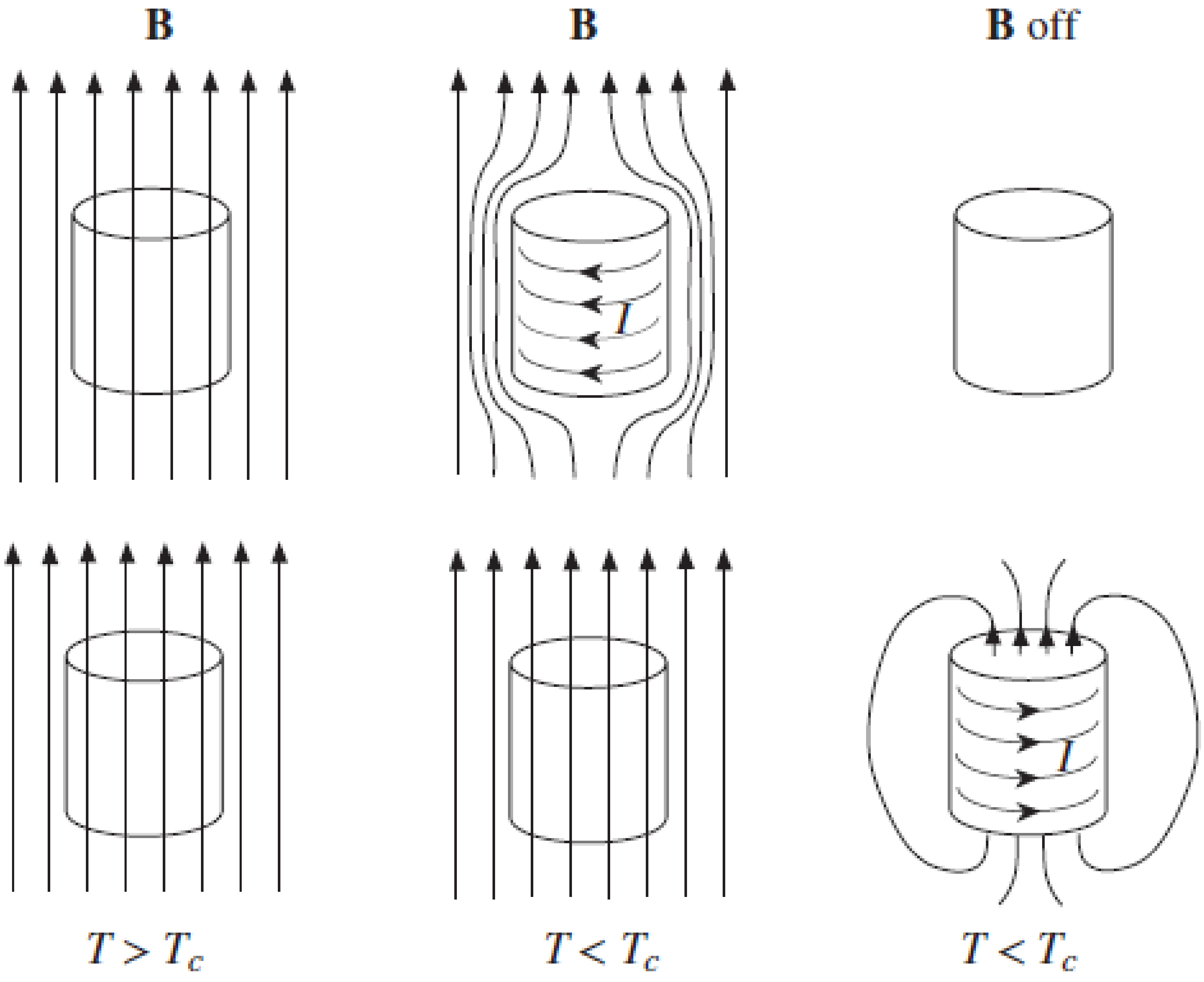
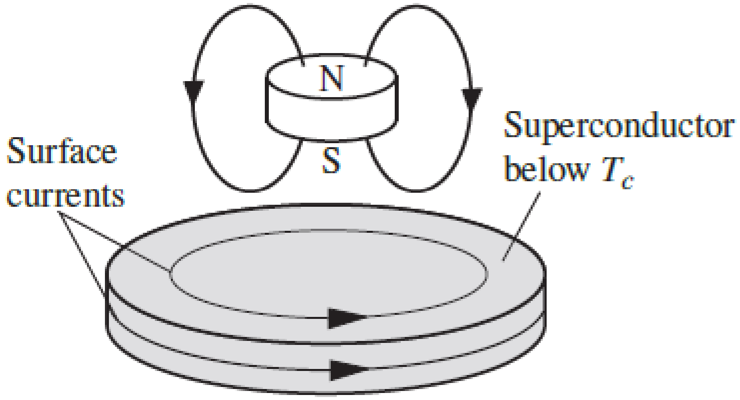
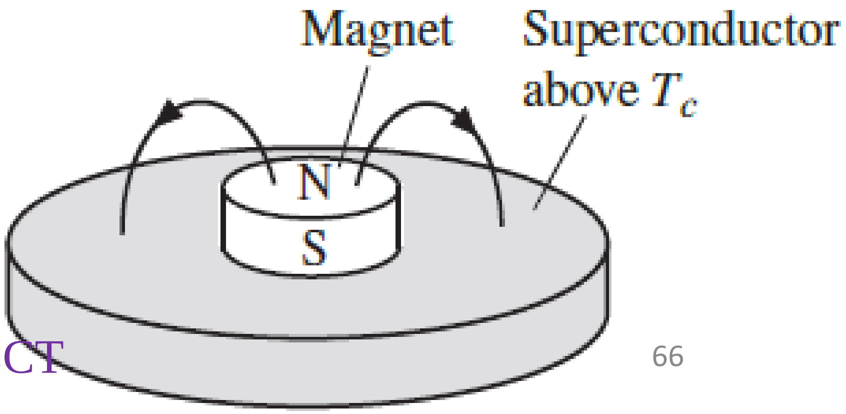


Figure 8.57 The Meissner effect.

Superconductor

Perfect conductor





- A superconductor below its critical temperature expels all the magnetic field from the bulk of the sample as if it were a perfectly diamagnetic substance. This phenomenon is known as the **Meissner effect**.
- However, **when the superconductor is cooled below Tc**, it rejects all the magnetic flux in the sample, as depicted in Figure 8.57. The superconductor develops a magnetization M by developing surface currents.
- Such that M and the applied field cancel everywhere inside the sample. Put differently μoM is in the opposite direction to the applied field and equal to it in magnitude. Thus, below T_c a superconductor is a perfectly diamagnetic substance ($\chi_m = -1$) and exhibits infinite conductivity, or $\rho = 0$.
- Suppose that we place a superconducting material in a magnetic field **above Tc**. The magnetic field lines will penetrate the sample, as we expect for any low μr medium.

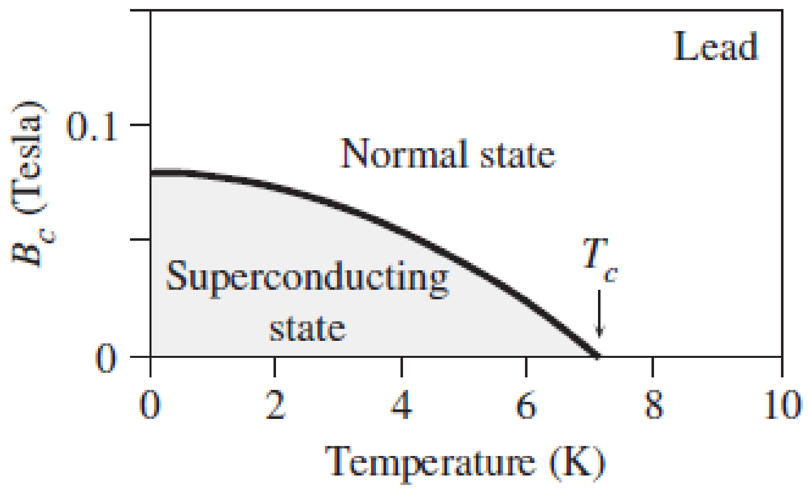


Figure 8.59 The critical field versus temperature in Type I superconductors.

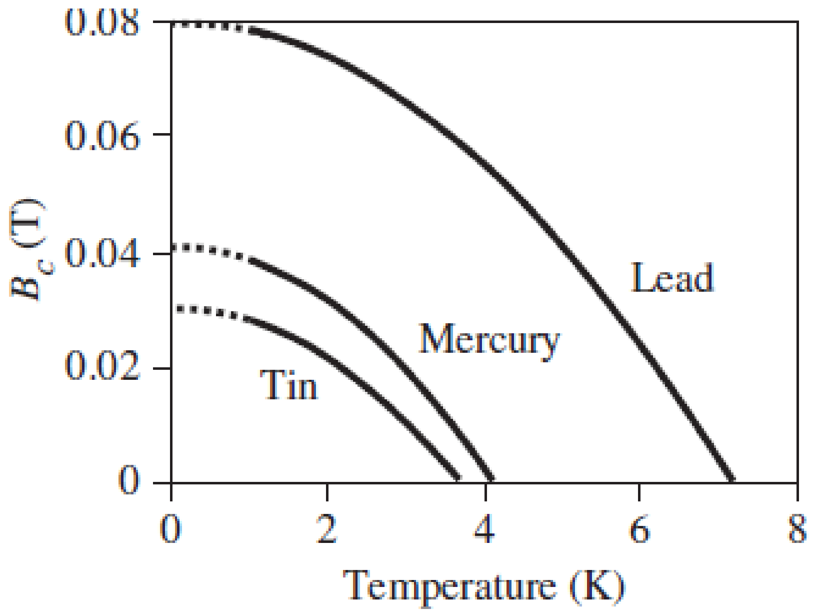


Figure 8.60 The critical field versus temperature in three examples of Type I superconductors.

$B = \mu_o H$ is the applied field

M is the overall magnetization of the sample.

Field inside the sample, **$B_{inside} = \mu_o H + \mu_o M$**

which is zero only for $B < B_c$ (Type I)

$B < B_{c1}$ (Type II).

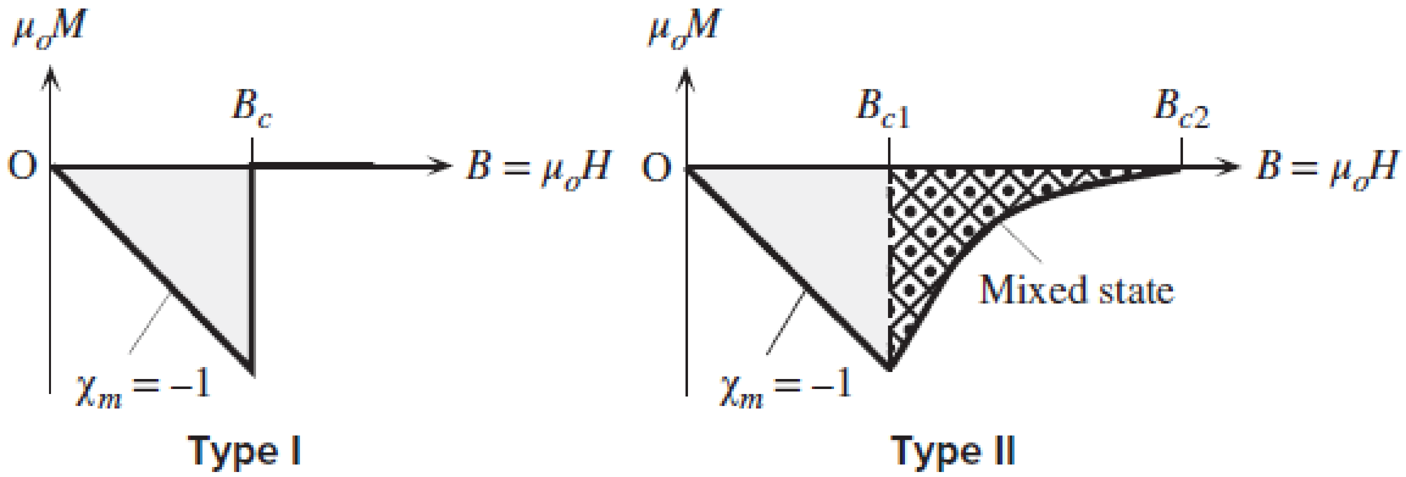


Figure 8.61 Characteristics of Type I and Type II superconductors. $B = \mu_o H$ is the

- The superconductivity below the critical temperature has been observed to disappear in the presence of an applied magnetic field exceeding a critical value denoted by B_c.
- This critical field depends on the temperature and is a characteristic of the material. Figure 8.59 shows the dependence of the critical field on the temperature. **The critical field is maximum, $B_c(0)$, when $T = 0$ K**.
- As long as the applied field is below B_c at that temperature, the material is in the superconducting state, but when the field exceeds B_c, the material reverts to the normal state.
- We know that in the superconducting state, the applied magnetic field lines are expelled from the sample and the phenomenon is called the Meissner effect. The external field penetrate the sample from the surface into the bulk, but the magnitude of this penetrating field decreases exponentially from the surface.

If the field at the surface of the sample is B_o, then at a distance x from the surface, the field is given by an exponential decay,

$$B(x) = B_o \exp\left(-\frac{x}{\lambda}\right)$$

$B_{inside} = \mu_o H + \mu_o M$

where λ is a "characteristic length" of penetration, called the penetration depth, and depends on the temperature and Tc (or the material).

At the critical temperature, the penetration length is infinite and any magnetic field can penetrate the sample and destroy the superconducting state.

Near absolute zero of temperature, however, typical penetration depths are 10–100 nm. Figure 8.60 shows the Bc versus T behavior for three example superconductors, tin, mercury, and lead.

Superconductors are classified into two types, called Type I and Type II, based on their diamagnetic properties.

A Type I superconductor below B_c is in the **Meissner state,** where it excludes all the magnetic flux from the interior of the sample. Above B_c it is in the normal state, where the magnetic flux penetrates the sample as it would normally and the conductivity is finite.

In the case of Type II superconductors, the transition does not occur sharply from the Meissner state to the normal state but goes through an intermediate phase in which the applied field is able to pierce through certain local regions of the sample.

As the magnetic field increases, initially the sample behaves as a perfect diamagnet exhibiting the Meissner effect and rejecting all the magnetic flux.

When the applied field increases beyond a critical field denoted as B_{c1}, the **lower critical field,** the magnetic flux lines are no longer totally expelled from the sample. The overall magnetization M in the sample opposes the field, but its magnitude does not cancel the field everywhere.

As the field increases, M gets smaller and more flux lines pierce through the sample until at B_{c2}, the **upper critical field,** all field lines penetrate the sample and superconductivity disappears. This behavior is shown in Figure 8.61. Type II superconductors therefore have two critical fields B_{c1} and B_{c2}.

CRITICAL CURRENT DENSITY

- Another important characteristic feature of the superconducting state is that when the current density through the sample exceeds a critical value J_c, it is found that superconductivity disappears. Since the current through the superconductor will itself generate a magnetic field.
- At sufficiently high current densities, the magnetic field at the surface of the sample will exceed the critical field and extinguish superconductivity.
- This plausible direct relation between B_c and J_c is only true for Type I superconductors, whereas in Type II superconductors, J_c depends in a complicated way on the interaction between the current and the flux vortices.

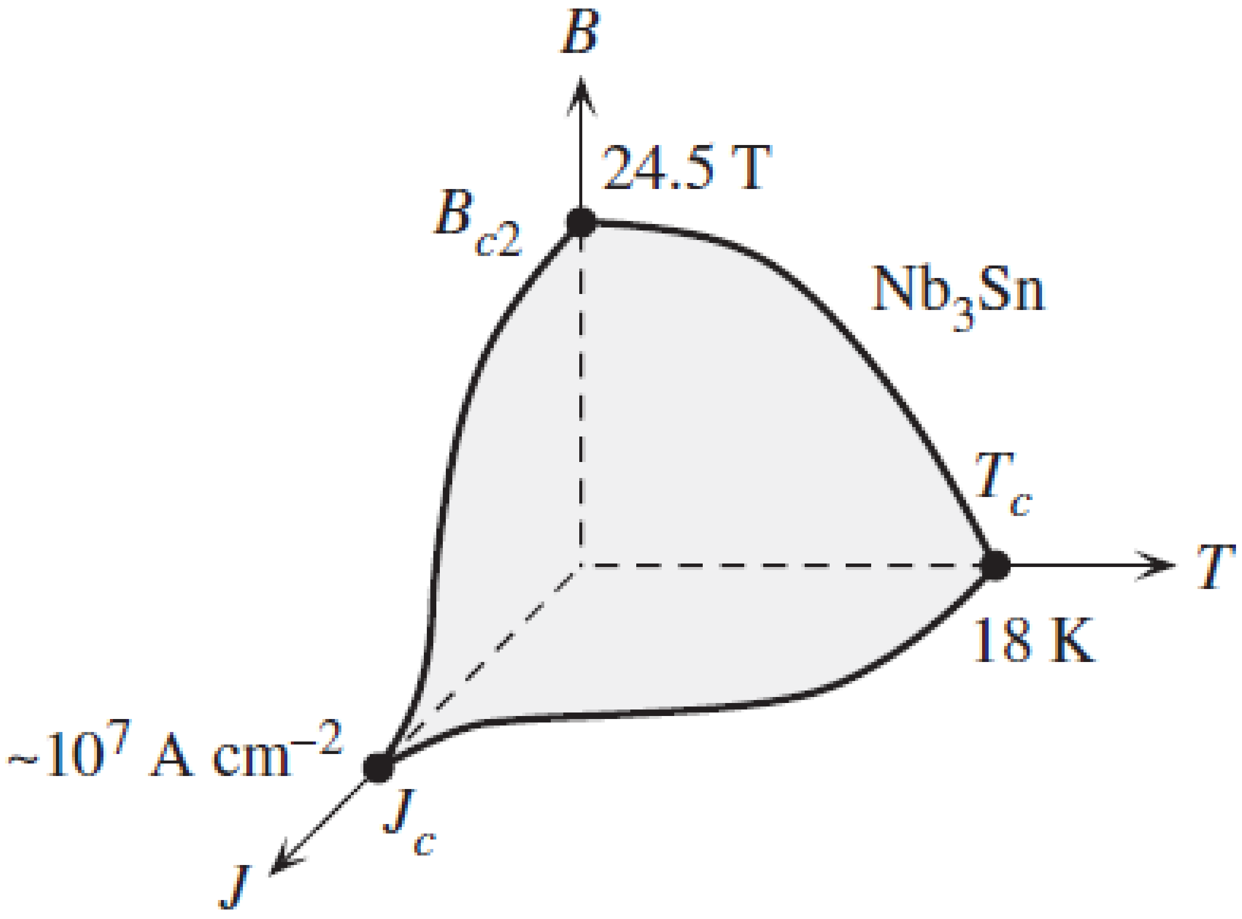


Figure 8.64 The critical surface for a niobium–tin alloy, which is a Type II superconductor.

EXAMPLE 8.3 from KASAP Textbook
(Saturation Magnetization practical example)

EXAMPLE 8.10 from KASAP Textbook
(Superconductivity practical example)

Example 6.18 from KASAP Textbook
(BJT Problem)

Numerical uploaded with separate file
(Related to Magnetic materials problems)


Thank You!