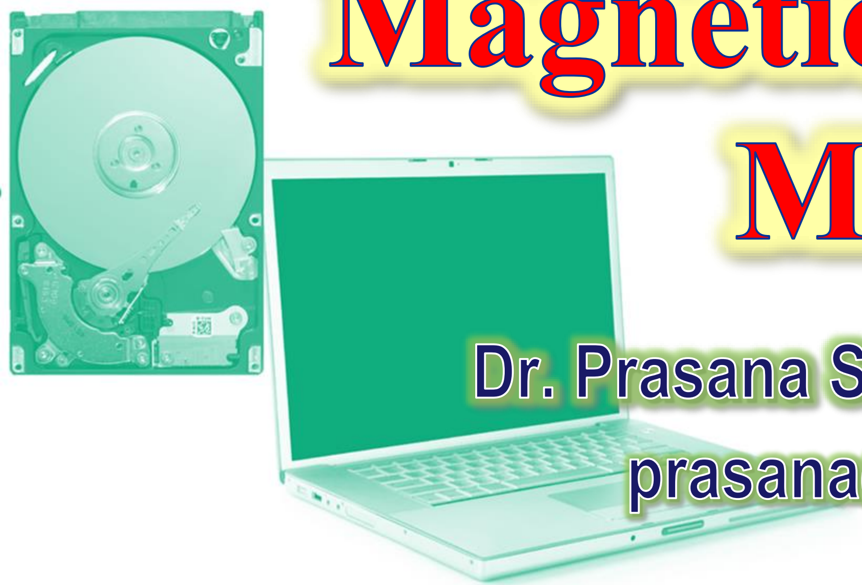
MS31007 : Chapter 10

Magnetic Properties of Materials



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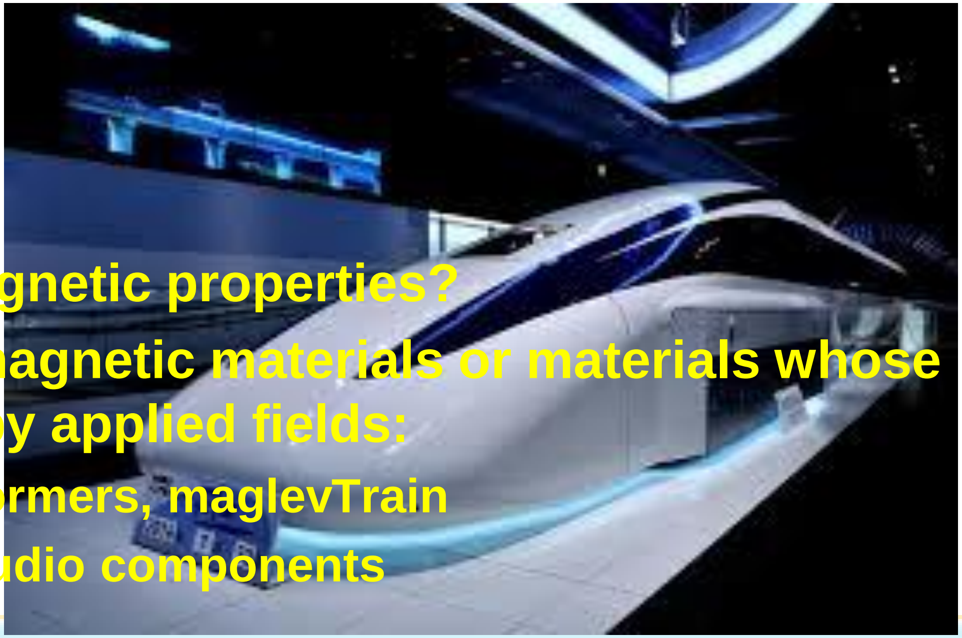


Motivation

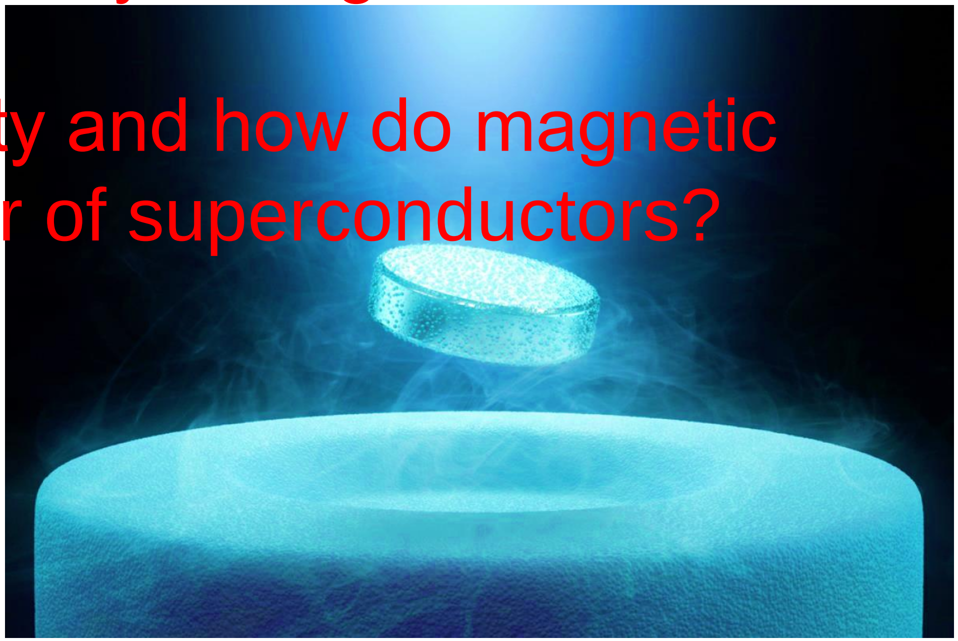
– **Why would you care about magnetic properties?**

– **The following devices utilize magnetic materials or materials whose properties can be moderated by applied fields:**

- **TVs, Power generators/transformers, maglevTrain**
- **Computers, Phones, Radio, Audio components**

ISSUES TO ADDRESS...

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

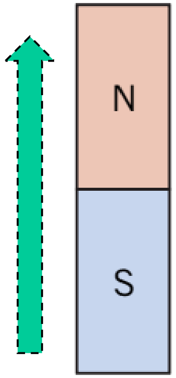


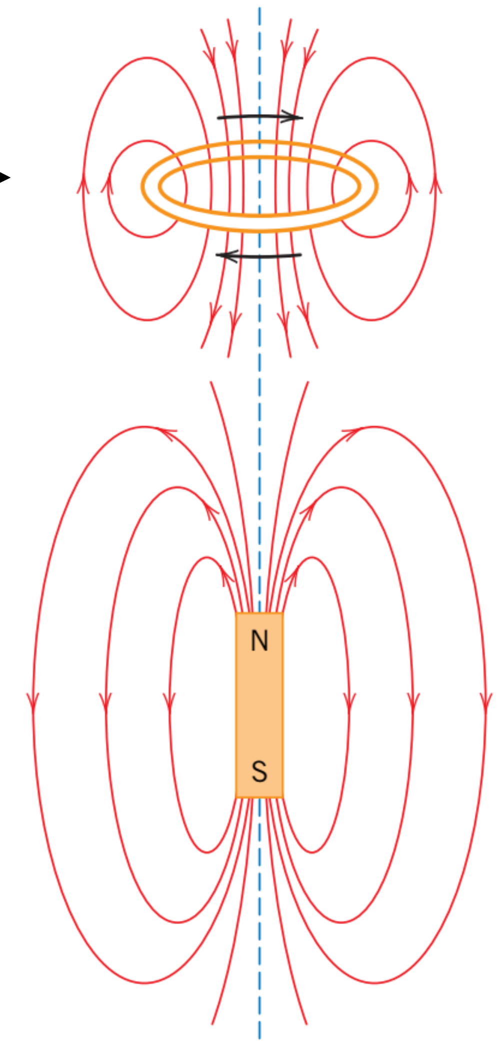
Basic Concepts: Magnetism

- By moving electrically charged particles magnetic forces are generated – these magnetic forces are often described as fields
- **Magnetic dipoles** – exist in magnetic materials, analogous to electric dipoles.

  - Can be thought of as tiny bar magnets
- Magnetic dipoles are induced in magnetic fields in a manner similar to electrical dipoles in electric fields
- Field exerts a torque that

drives alignment of the dipoles

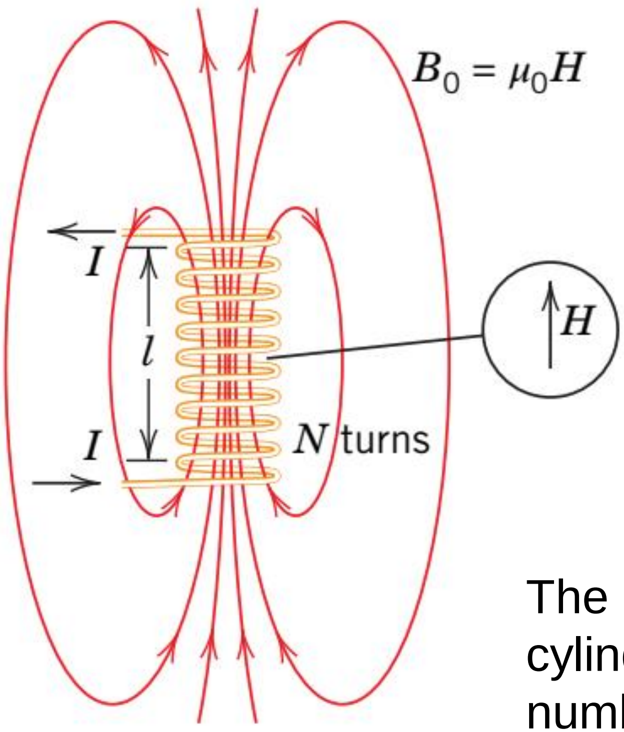


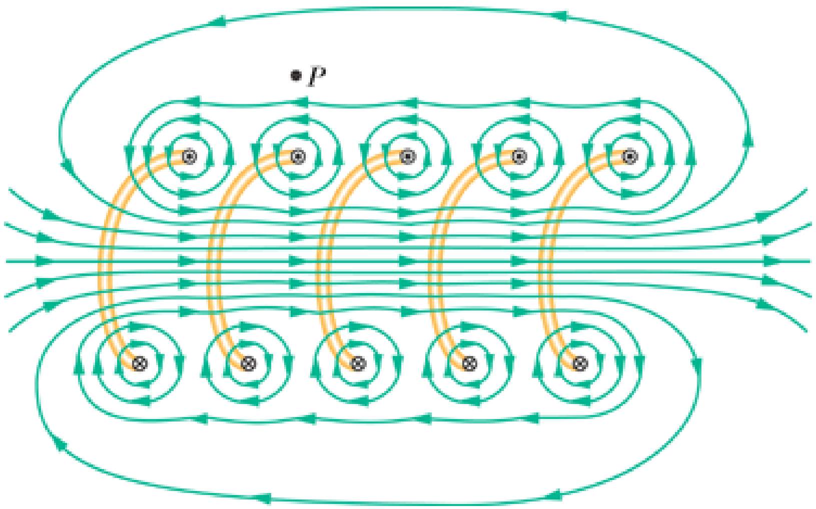


Magnetic field lines of force around a current loop and a bar magnet.

Generation of a Magnetic Field - Vacuum

- Created by current through a coil:





H = externally applied magnetic field
magnetic field strength (A/m)

The magnetic field *H* as generated by a cylindrical coil is dependent on current *I*, number of turns *N*, and coil length *l*,

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

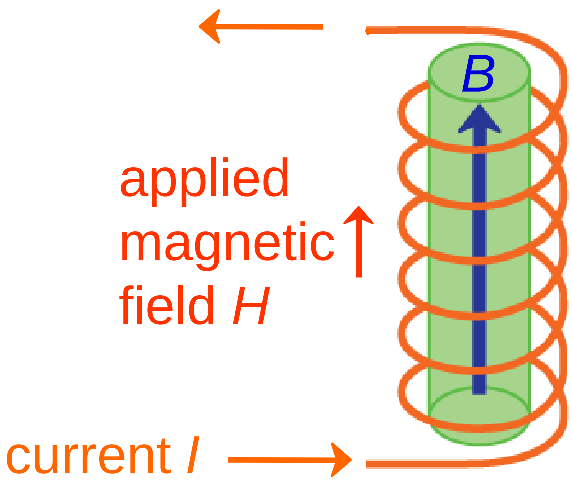
The **magnetic induction,** or **magnetic flux density** B_0 is the magnitude of the internal field strength within a substance that is subjected to an *H* field.

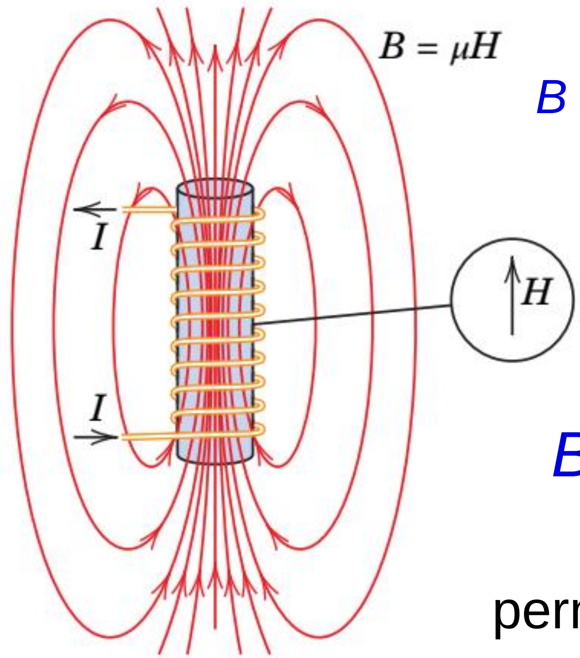
The unit for *B* is *tesla*

$$B_0 = \mu_0 H$$

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

- A magnetic field is induced in the material





B = Magnetic Induction (tesla) inside the material

$$B = \mu H$$

permeability of a solid

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

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

Generation of a Magnetic Field -within a Solid Material

Magnetization or magnetic polarization is the vector field that expresses the density of permanent or induced magnetic dipole moments in a magnetic material.

- Magnetization $M = \chi_m H$

χ_m Magnetic susceptibility (dimensionless)

Magnetic flux density (B)—as a function of magnetic field strength and magnetization of a material

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

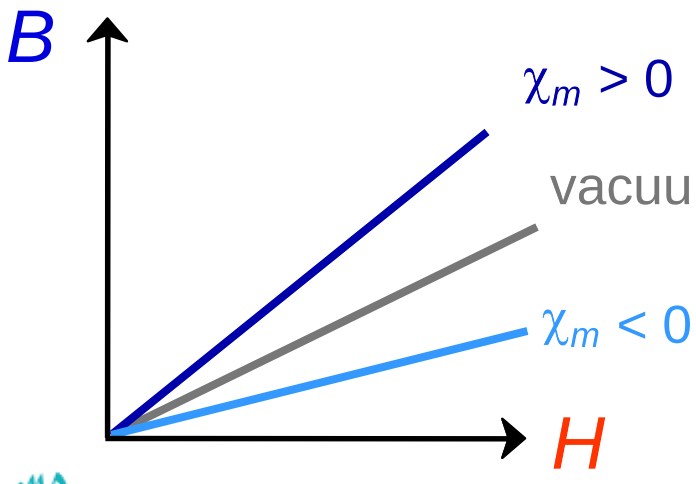
In the presence of an external field (H) the magnetic moments in a material tend to align – the term $\mu_o M$ is a measure of this

- Combining the above two equations:

$$B = \mu_0 H + \mu_0 \chi_m H$$

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

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



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

$$\chi = (\mu - \mu_0)/\mu_0 = \mu_r - 1$$

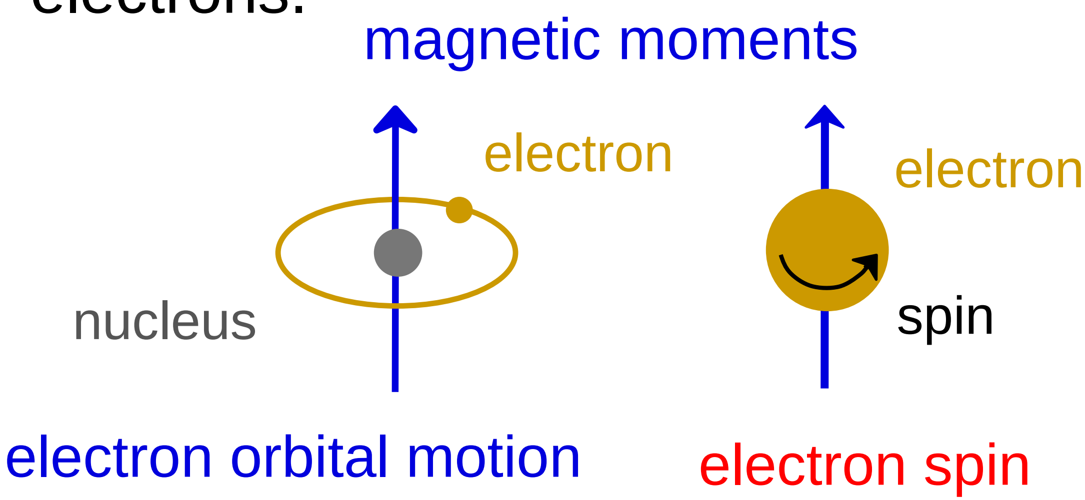
Magnetic Units and Conversion Factors for the SI and cgs–emu Systems

		SI Units			
Quantity	***Symbol***	***Derived***	***Primary***	***cgs–emu 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]	$kg \cdot m/C^2$	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.

Origins of Magnetic Moments

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



- **Orbital motion around the nucleus**: electron can be thought of as a small current loop, generating a very small magnetic field
- **Spin**: electron spins around an axis (remember spin up and spin down?), generating a magnetic moment

Origin of magnetic moments

- Most fundamental magnetic moment (for electron) is the Bohr magneton

  μ_B ; $(eh/4\pi m_e)$ the value of this is 9.27 x 10^{-24} A-m^2
- For each electron in an atom the spin magnetic moment is **+/- μ_B**
- The orbital magnetic moment contribution is $m_l\mu_B$, where m_l is the magnetic quantum number

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

Many of these magnetic moments can cancel one another

Substances where all the electrons are paired cannot be permanently magnetized (He, Ne, Ar…)

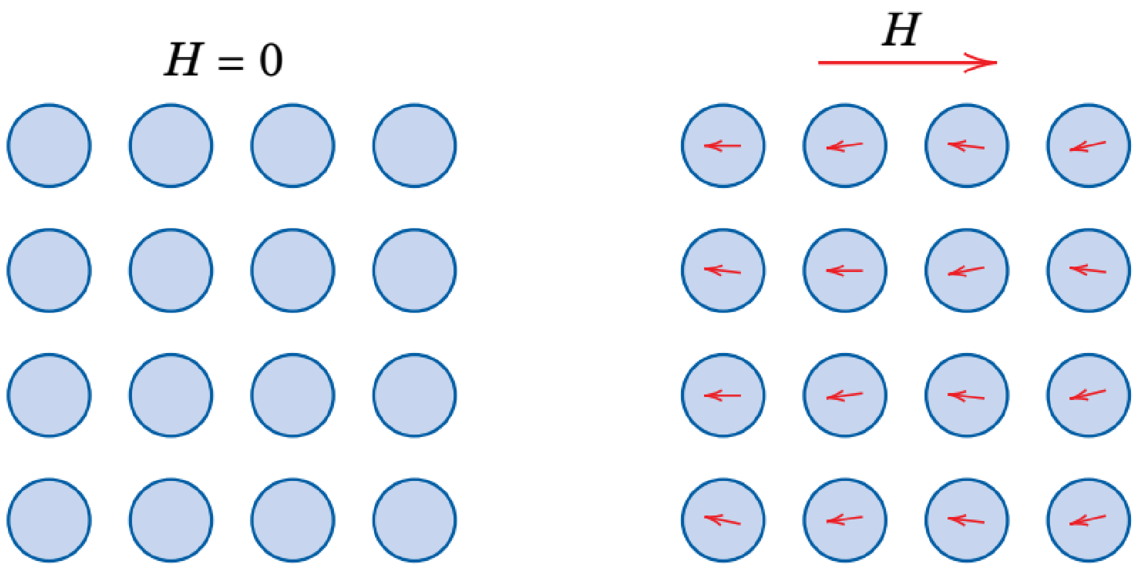
Diamagnetism

Diamagnetism – very weak form of magnetism

- These are materials where there is no permanent magnetic dipole moment
- Persists in a material only while an external (*H*) field is applied (i.e. it is not permanent)
- Due to a change in the orbital electrons motion due to the applied field

– It is very small in a direction opposite to that of the applied field

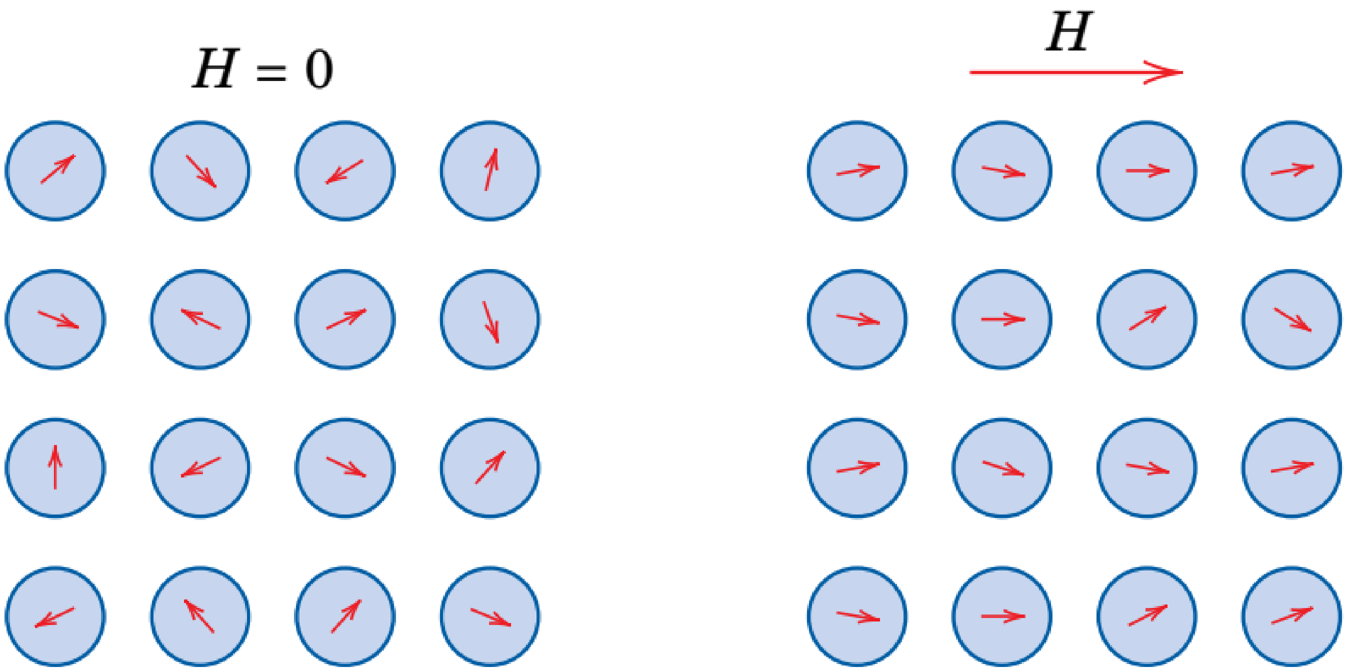
- $\mu_r < 1$, and χ_m is negative
- In other words, the induced field *B* in a diamagnetic material is less than that in a vacuum ($\chi_m \sim -10^{-5}$)



The atomic dipole configuration for a diamagnetic material with and without a magnetic field. ***In the absence of an external field, no dipoles exist****; in the presence of a field, dipoles are induced that are aligned opposite to the field direction.*

Paramagnetism

- In some materials atoms can possess a permanent magnetic dipole moment due to incomplete cancellation of electron spin and/or orbital magnetic moments
- Without external field, the orientation of these moments is random
- In the presence of an external field they can align – this is called paramagnetism (acted on individually by the field)



Atomic dipole configuration with and without an external magnetic field for a paramagnetic material

Ferromagnetism

Possess a permanent magnetic moment in the absence of an external field

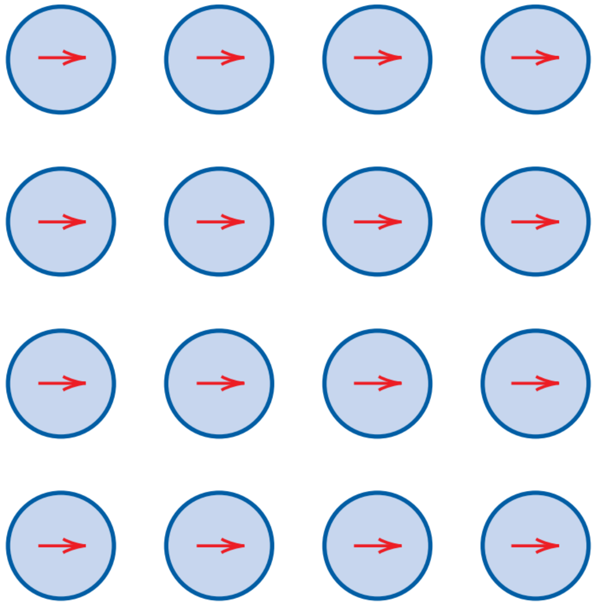
- Manifest a very large and permanent magnetization

- The permanent magnetic dipole moments result from atomic magnetic moments due to electron spin (i.e. unpaired electrons, consequence of electronic structure)
- Another difference: coupling interactions causes magnetic moments of adjacent atoms to align *even in the absence of an external field*
- Regions this occurs over are called domains or spin domains

- Can have χ_m values as large as 10^6
- So, *H* << *M* (i.e. you have a large induced magnetization) and

$$B = \mu_o H + \mu_o M \Longrightarrow B \cong \mu_o M$$

$H = 0$



- Transition metals – Fe, Co, Ni, some rare earth metals - 2.22, 1.72, and 0.6 Bohr magnetons per atom, respectively
- **Saturation magnetization M_s**, or the maximum possible magnetization – magnetization when all the magnetic dipoles are aligned with the field
- Equals the product of the net magnetic moment of each atom times the number of atoms

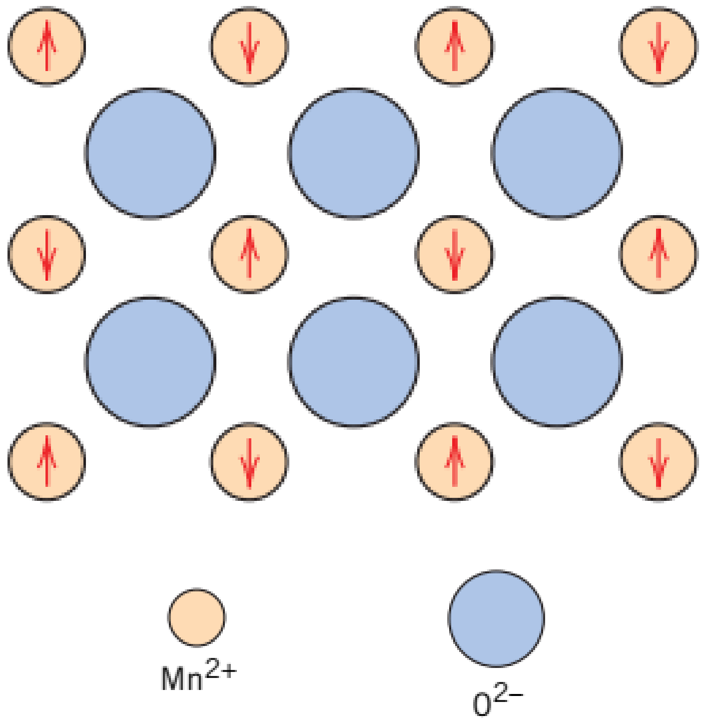
Anti-ferromagnetism and **Ferrimagnetism** are considered to be subclasses of ferromagnetism

Anti-ferromagnetism

The phenomenon of magnetic coupling between adjacent atoms/ions occurs in materials besides ferromagnets

- **Antiferromagnetic materials**
  - In these materials the coupling results in anti-parallel alignment of the spins (e.g. MnO)
  - **The magnetic moments cancel**

    – no net magnetic moment



Schematic representation of antiparallel alignment of spin magnetic moments for antiferromagnetic manganese oxide

No net magnetic moment is associated with the O^{2-} ions because there is a total cancellation of both spin and orbital moments.

However, the Mn^{2+} ions possess a net magnetic moment that is predominantly of spin origin. These Mn^{2+} ions are arrayed in the crystal structure such that the moments of adjacent ions are antiparallel.

Mn Electron configuration: [Ar] $3d^5 4s^2$

Mn^{2+} Electron configuration: [Ar] $3d^5$

O Electron configuration [He] $2s^2\ 2p^4$

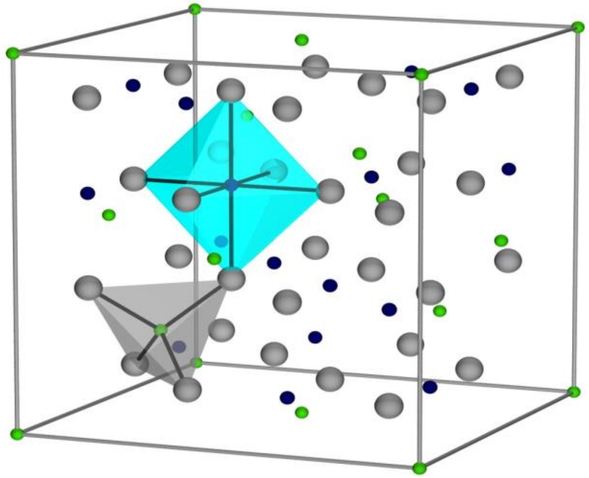
O^{2-} Electron configuration [He] $2s^2\ 2p^6$

Ferrimagnetism

Ferrimagnetism – term used to describe ceramics that exhibit permanent magnetization

- **The macroscopic magnetic properties of ferro- and ferri- magnetic materials are similar**
  - **– the source of the net magnetic moments is (somewhat) different**
- **Example compounds – ferrites** (*this is not the α phase of iron)
- **MFe_2O_4** – M can be nearly anything, but typically divalent

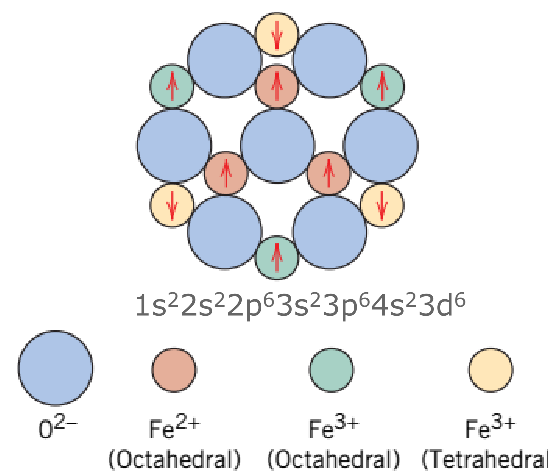
Fe_3O_4 (Magnetite, also called Lodestone) - $Fe^{+2}O^{2-}$ - $Fe^{+3}{}_2O^{2-}{}_3$



Unit cell of magnetite. The **gray spheres are oxygen**, **green are divalent iron**, **blue are trivalent iron.** Also shown are an iron atom in an octahedral space (light blue) and another in a tetrahedral space (gray).

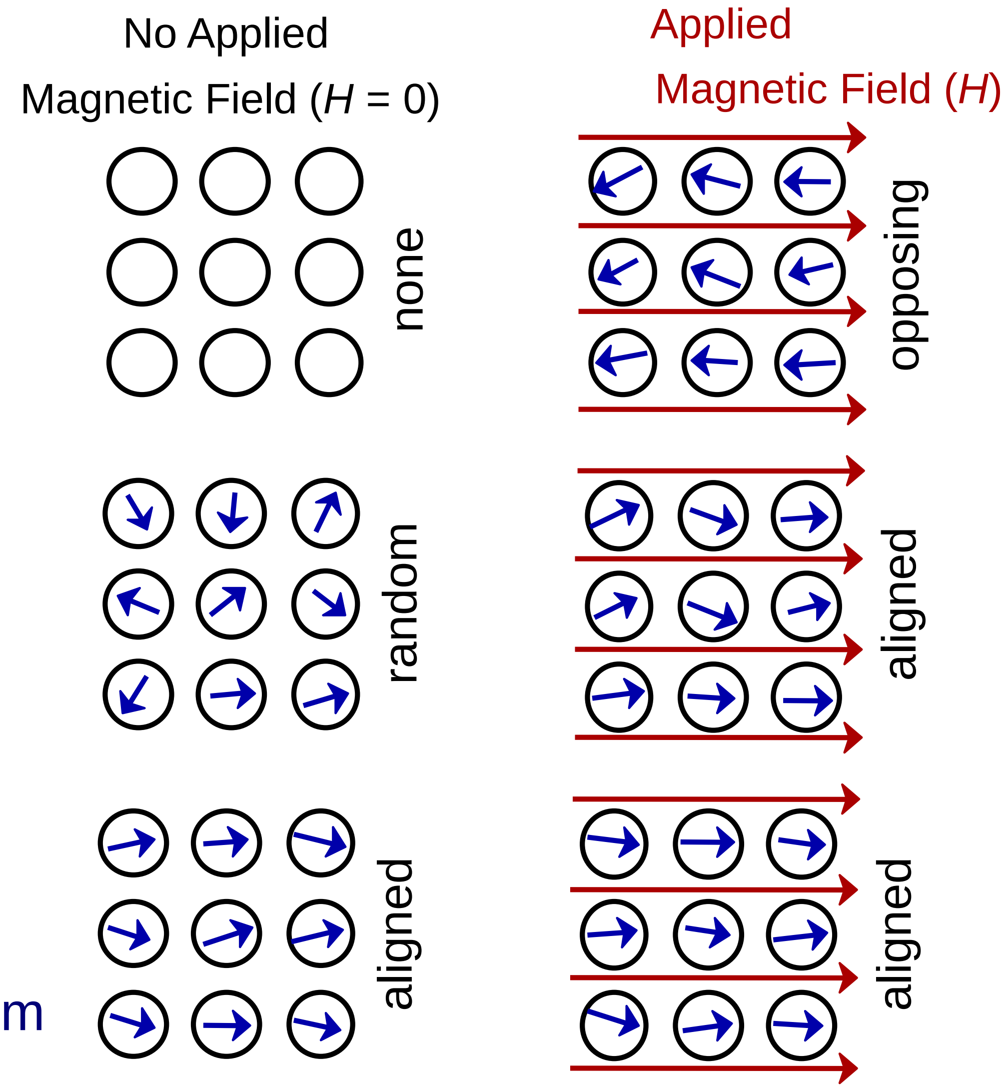
- ✓ Half the trivalent (Fe^{3+}) ions are situated in octahedral positions and the other half in tetrahedral positions. The divalent Fe^{2+} ions are all located in octahedral positions.
- ✓ Spin moments of all Fe^{3+} ions cancel one another and make no net contribution to the magnetization of the solid.
- ✓ All the Fe^{2+} ions have their moments aligned in the same direction; this total moment is responsible for the net magnetization.
- ✓ The **Saturation magnetization** ~ product of the net spin magnetic moment for each Fe^{2+} ion and the number of Fe^{2+} ions.
- ✓ M^{2+} may represent divalent ions such as Ni^{2+}, Mn^{2+}, Co^{2+}, and Cu^{2+}

Cation	*Octahedral Lattice Site*	*Tetrahedral Lattice Site*	*Net Magnetic Moment*
Fe^{3+}	↑↑↑↑ ↑↑↑↑	↓↓↓↓ ↓↓↓↓	Complete cancellation
Fe^{2+}	↑↑↑↑ ↑↑↑↑	—	↑↑↑↑ ↑↑↑↑



Magnetic Responses for main 3 Types

The types of magnetism include **diamagnetism**, **paramagnetism**, and **ferromagnetism**; in addition, **antiferromagnetism** and **ferrimagnetism** are considered to be subclasses of ferromagnetism.



(1) diamagnetic

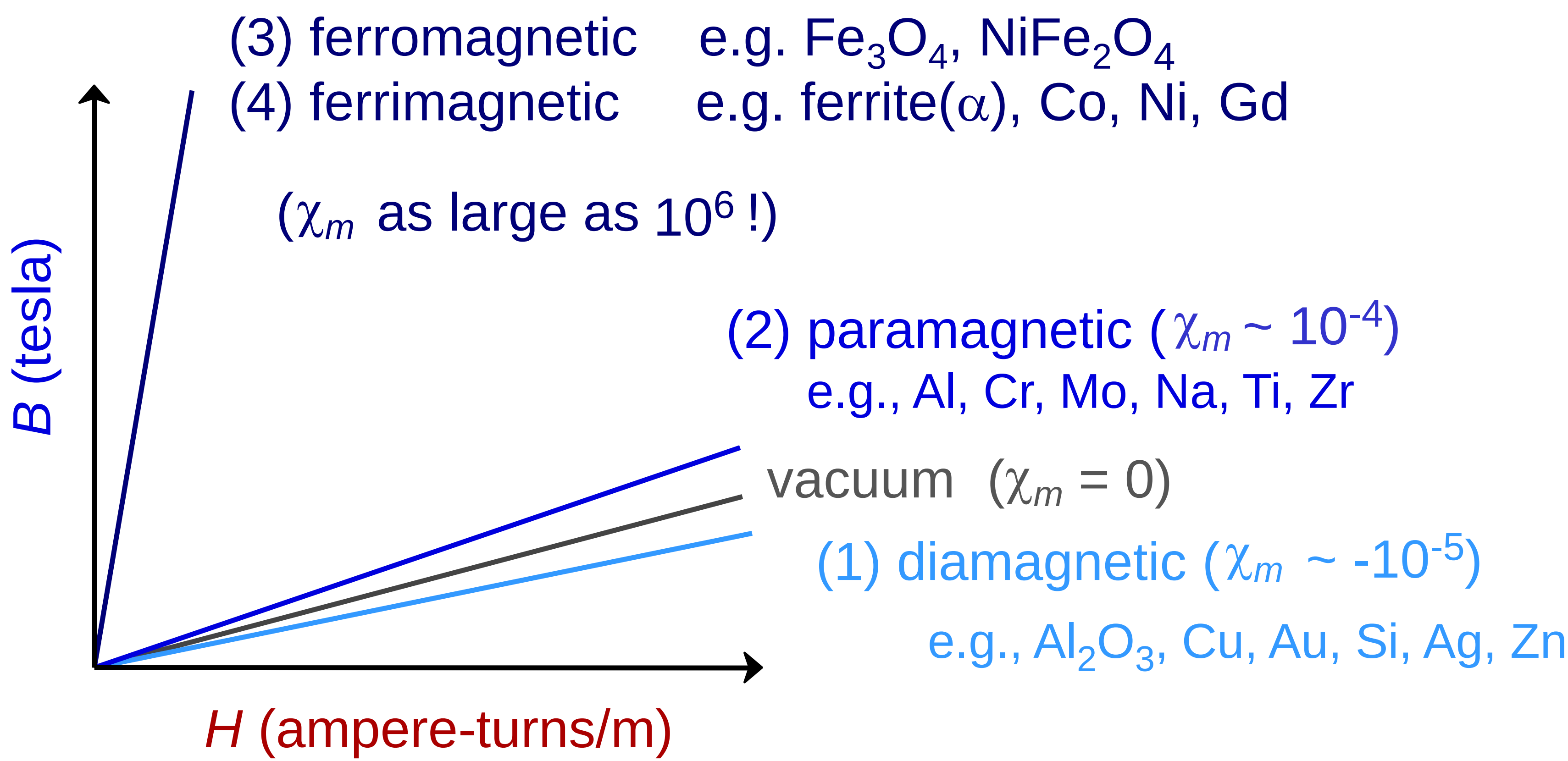
(2) paramagnetic

(3) Ferromagnetic
- Ferrimagnetic
- Antiferromagnetism

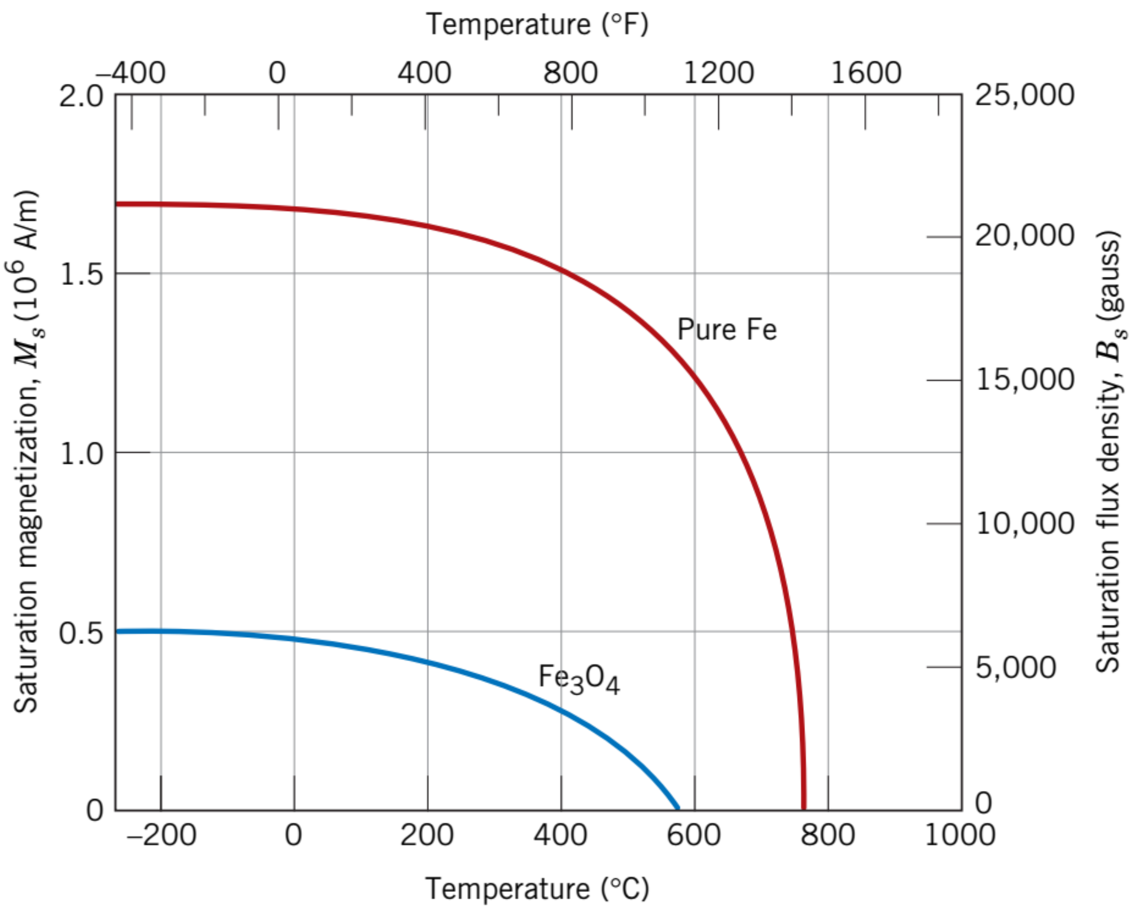
Different Types of Magnetism

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

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



Influence of Temperature on Magnetic Behavior



The atomic thermal motions counteract the coupling forces between the adjacent atomic dipole moments, causing some dipole misalignment, regardless of whether an external field is present. This results in a decrease in the saturation magnetization for both ferro- and ferrimagnets.

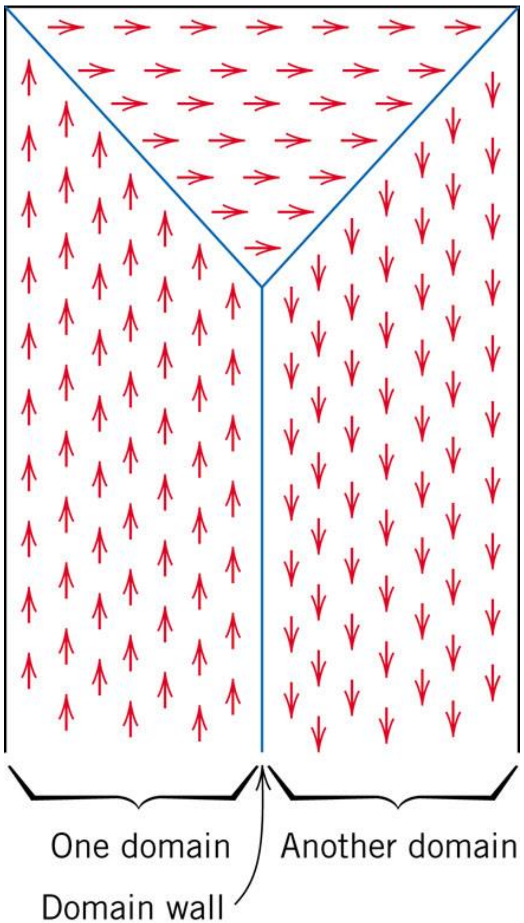
With increasing temperature, the saturation magnetization diminishes gradually and then abruptly drops to zero at what is called **Curie Temperature Tc**.

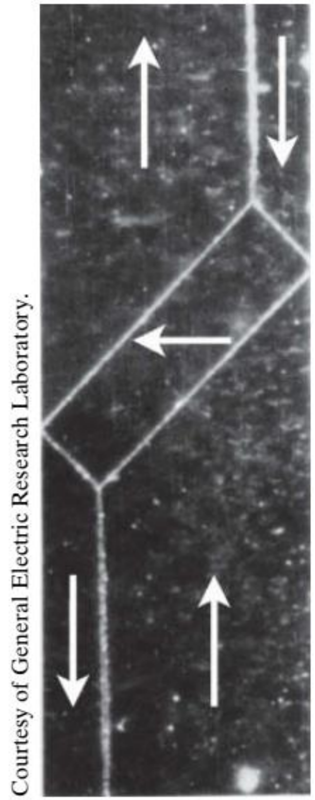
Antiferromagnetism; this behavior vanishes at what is called the *Néel temperature.*

At temperatures above this point, antiferromagnetic materials also become paramagnetic.

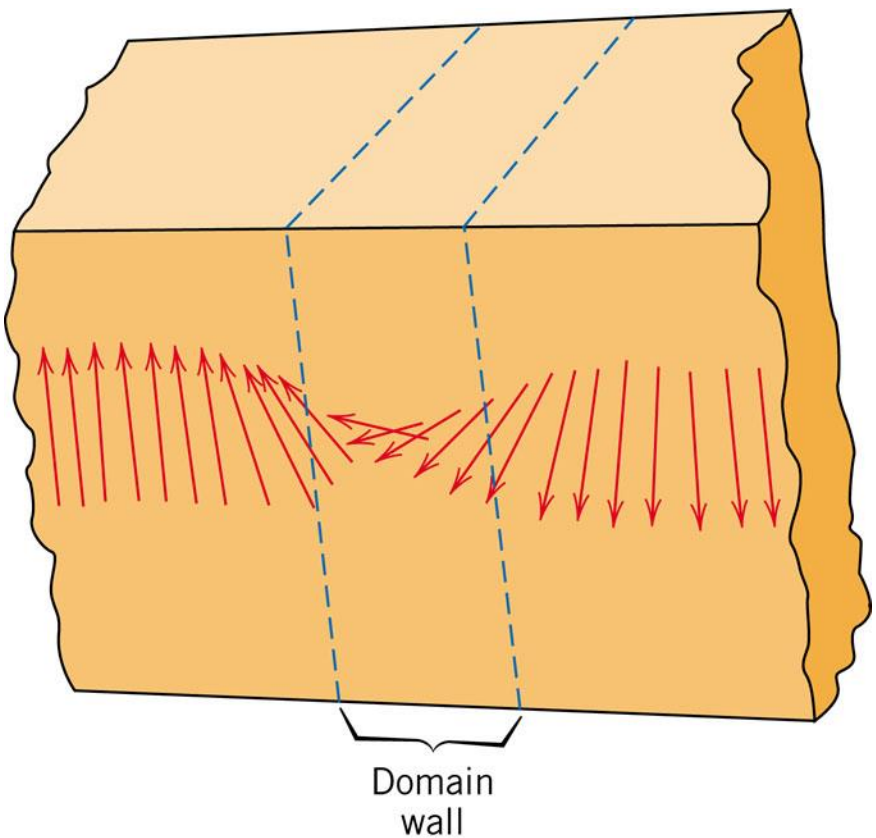
Magnetic Domains

Any ferro- or ferrimagnetic material at a temperature below T_c is composed of small volume regions in which there is a mutual alignment in the same direction of all magnetic dipole moments. Such a region is called a *domain,* and each one is magnetized to its saturation magnetization.





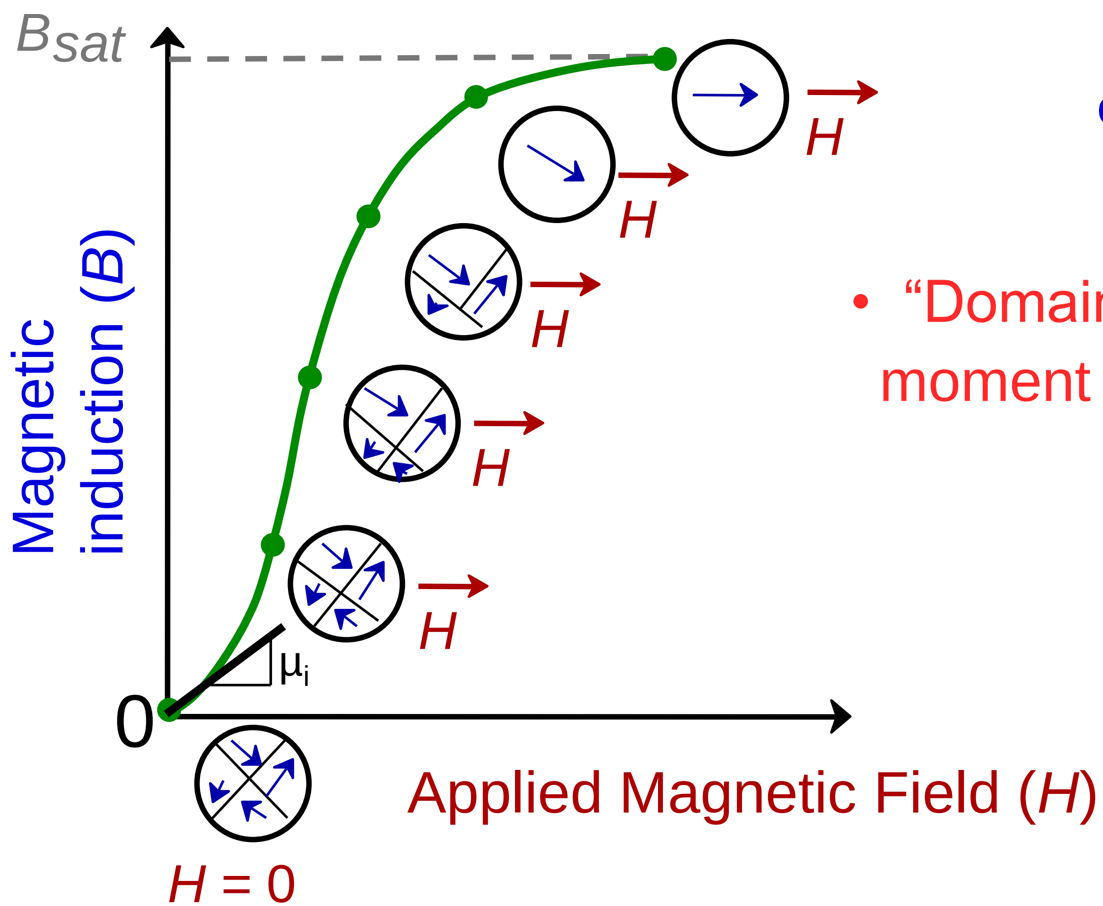
Photomicrograph showing the domain structure of an iron single crystal (arrows indicate directions of magnetization)



Adjacent domains are separated by domain boundaries or walls across which the direction of magnetization gradually changes

Domains in Ferro & Ferri - magnetic Materials

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



This maximum value of B is the saturation flux density B_s, and the corresponding magnetization is the saturation magnetization M_s

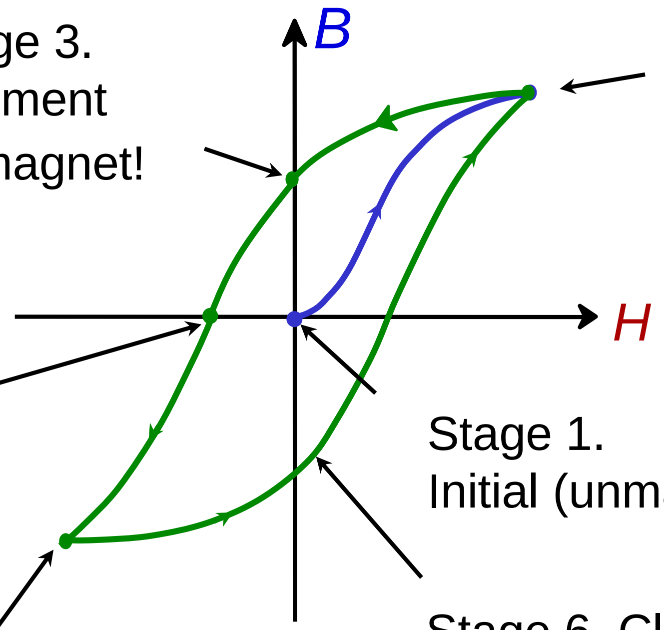
- "Domains" with aligned magnetic moment grow at expense of poorly aligned ones!

The slope of the B-versus-H curve at $H = 0$ is specified as a material property, which is termed the *initial permeability* μ_i

The magnetic hysteresis phenomenon

Stage 3.
Remove *H*, alignment remains! => permanent magnet!

Stage 2. Apply *H*, align domains



Stage 4.
Coercivity, H_C
Negative *H* needed to demagnitize!

Stage 1.
Initial (unmagnetized state)

Stage 6. Close the hysteresis loop

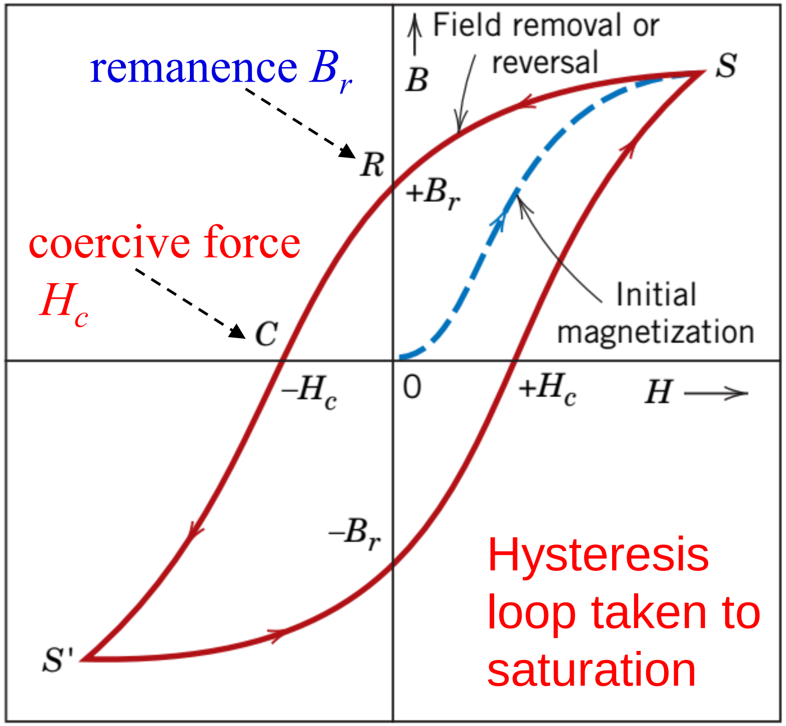
Stage 5.
Apply -*H*, align domains

A **hysteresis** effect is produced in which the *B* field lags behind the applied *H* field, or decreases at a lower rate.

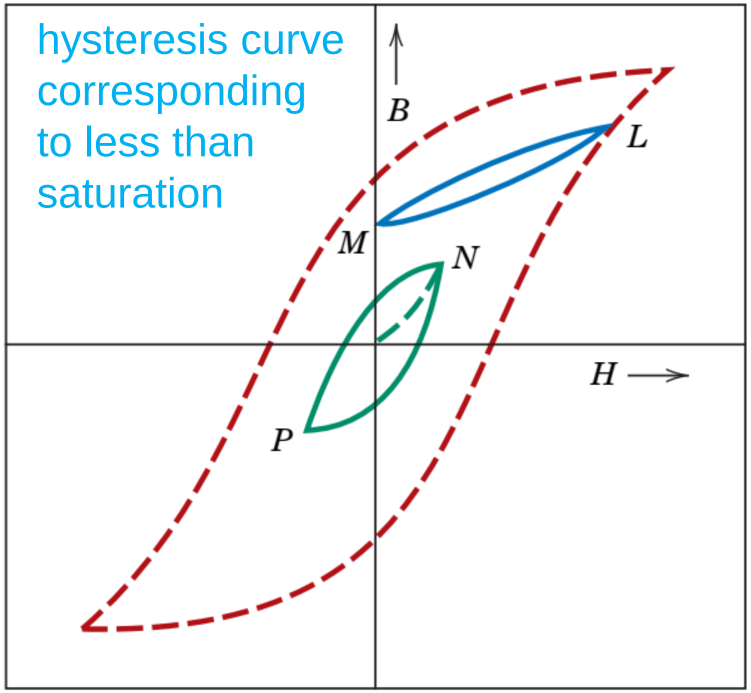
Magnetic Hysteresis effect

At zero H field, there exists a residual B field called the **remanence,** or *remanent flux density*, B_r; the material remains magnetized in the absence of an external H field.

To reduce the B field within the specimen to zero, an H field of magnitude $-Hc$ must be applied in a direction opposite to that of the original field; Hc is called the **coercivity,** or *coercive force*.



Magnetic flux density versus the magnetic field strength for a ferromagnetic material that is subjected to forward and reverse saturations (points S and S'). The hysteresis loop is represented by the solid red curve; the dashed blue curve indicates the initial magnetization.

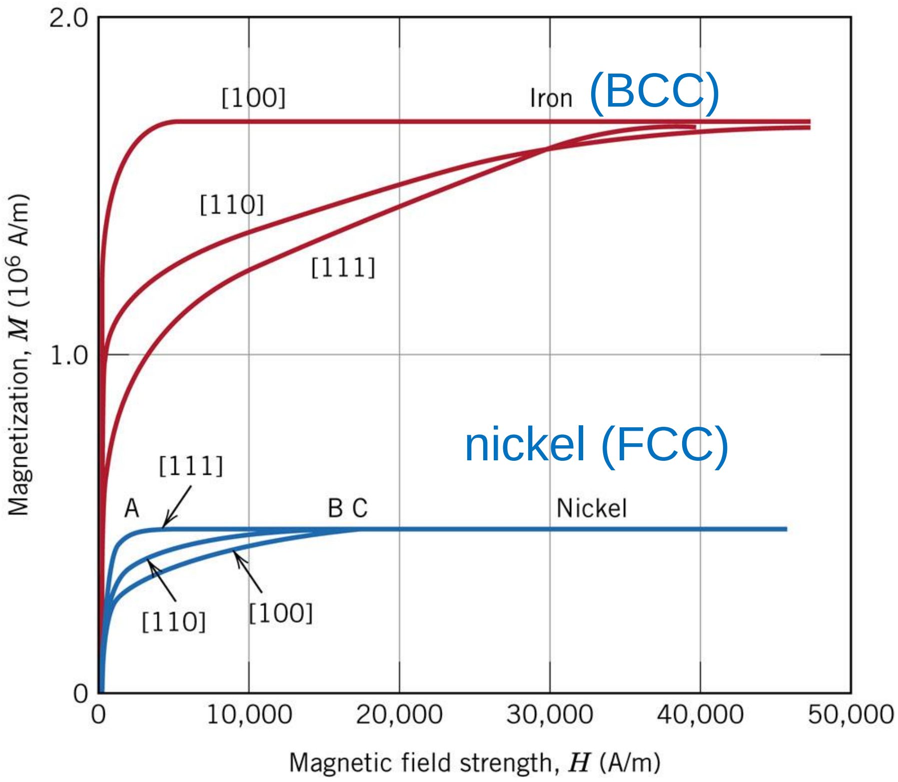


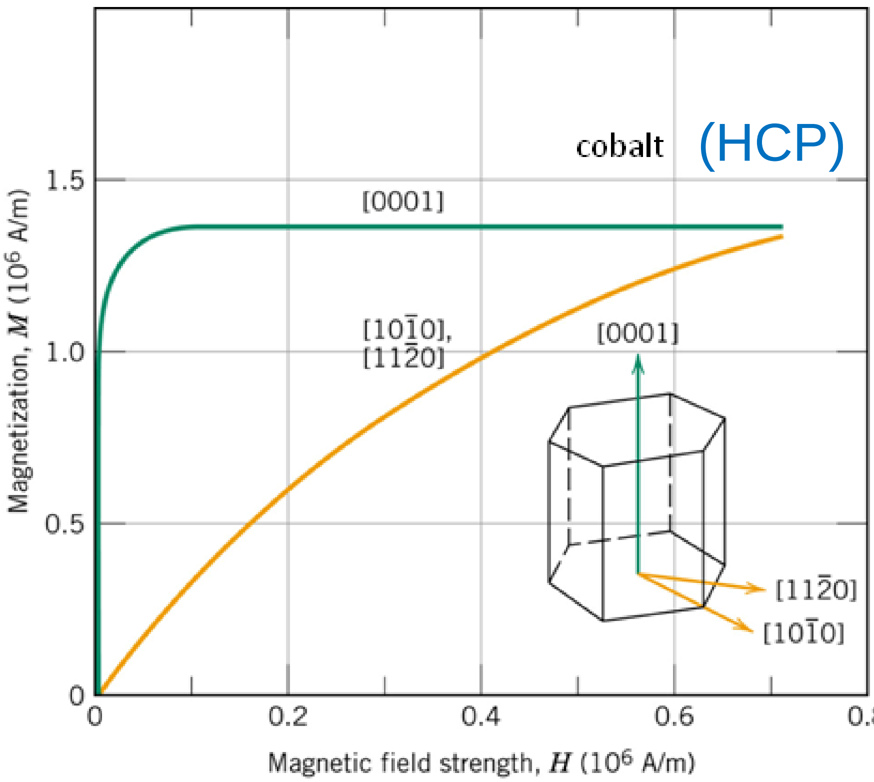
A hysteresis curve at less than saturation (curve *NP*) within the saturation loop for a ferromagnetic material. The *B–H* behavior for field reversal at other than saturation is indicated by curve *LM*.

Magnetic Anisotropy

Dependence of magnetic behavior on crystallographic orientation is termed *magnetic anisotropy*

Magnetization curves for single crystals of iron and nickel.





Saturation (of M) is achieved at the lowest H field

Easy magnetization direction:

Ni- [111], Fe- [100], Co- [0001].

Saturation magnetization is most difficult

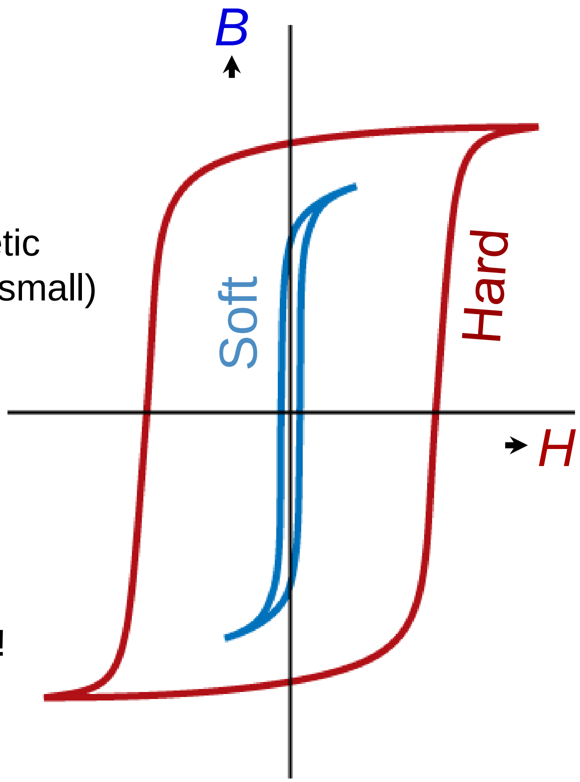
Hard magnetization direction:

Ni- [100], Fe- [111], Co- [1010][11$\bar{2}$0]

Magnetic Material: Soft and Hard

- Hysteresis loop (size/shape) has a physical meaning as well as a practical implication
- The area within the loop is the **magnetic energy loss per unit volume** (for a given magnetization-demagnetization cycle)
- This energy loss takes the form of heat – temperature goes up!

Magnetic materials are categorized as **"hard" or "soft"** materials based on the characteristics of the hysteresis loop



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

Soft Magnetic Materials

- Soft magnetic materials are used in devices subjected to alternating magnetic fields where the energy loss must be low (i.e. area in the hysteresis loop is small)
- Example – transformer cores

Want a thin, narrow hysteresis loop?

: High initial permeability, low coercivity

✓ Such a material will reach its saturation magnetization with a low applied field, with minimal hysteresis energy loss

✓ While the saturation properties of a material are solely determined by composition, the susceptibility and coercivity are highly structure dependent!

Another thing to consider – the electrical resistivity! Why?

Energy losses can also occur due to electrical currents induced in magnetic materials due to the field that varies in time and direction;

These are called **eddy currents**

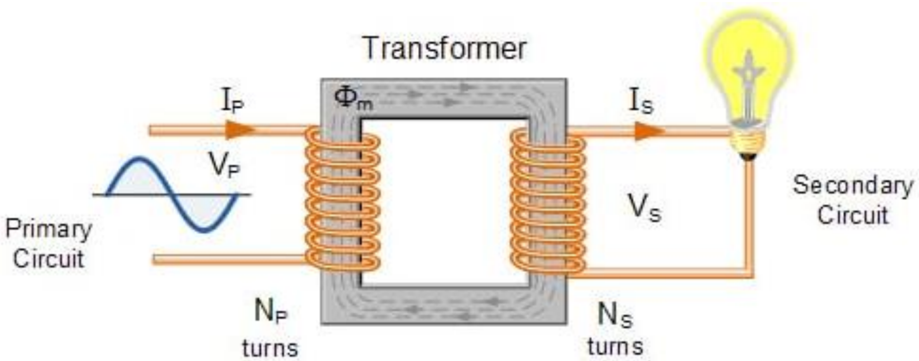
Want to minimize these! (* remember $\sigma = 1/\rho$ *)

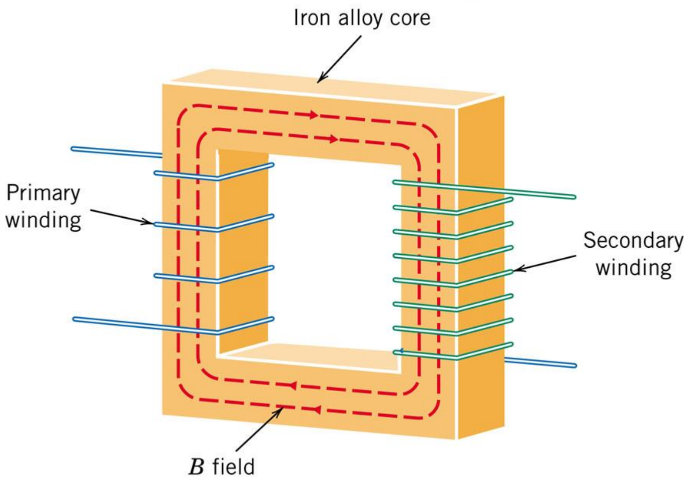
To do that increase the resistivity -- Can achieve that by alloying (solid solutions)

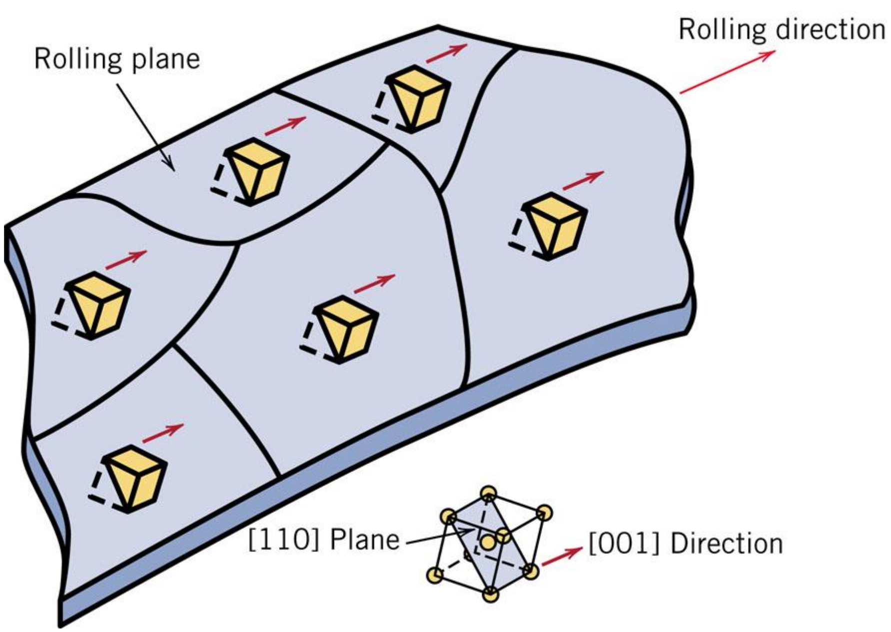
Iron-Silicon Alloy (97 wt% Fe – 3 wt% Si) in Transformer Cores

Transformer cores require soft magnetic materials, which are easily magnetized and de-magnetized, and have high electrical resistivity.

Energy losses in transformers could be minimized if their cores were fabricated such that the easy magnetization direction is parallel to the direction of the applied magnetic field.



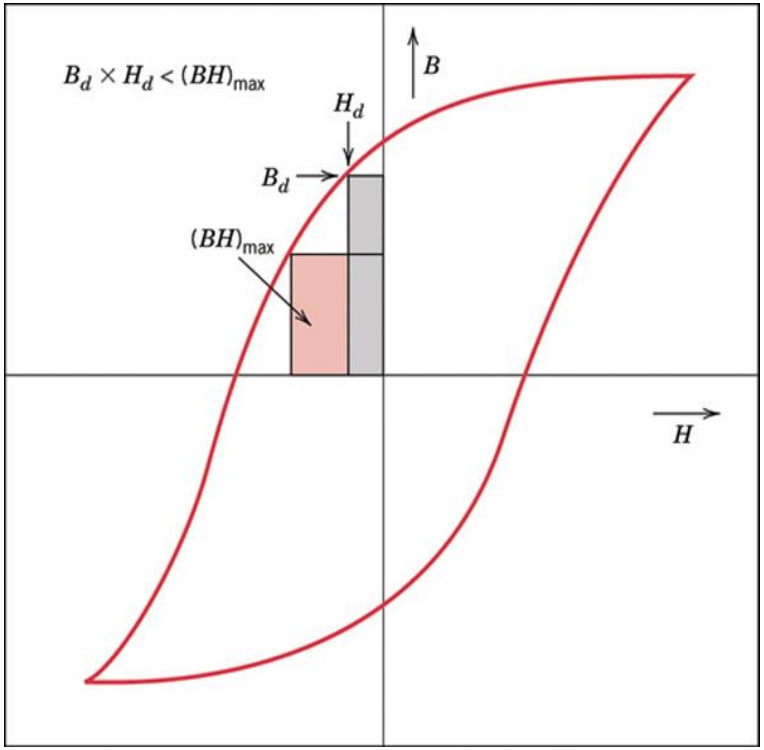




Hard Magnetic Materials

- Hard magnetic materials are used as permanent magnets – they must have a high resistance to demagnetization
- Hard magnets have a high remanance, coercivity, saturation flux density, and energy loss, but a low initial permeability

- Two most important properties – coercivity and the “energy product”, which is $(BH)_{max}$
- This value is representative of the energy needed to demagnetize a permanent magnet
- **“Harder” magnets have larger $(BH)_{max}$ values**



- Hard magnetic materials are classified as “conventional” or “high energy”
- Conventional materials – $(BH)_{max}$ between 2 – 80 kJ/m^3
- Include ferromagnetic materials – magnet steels, cunife (Cu-Ni-Fe) alloys and hexagonal ferrites

used in motors ; permanent magnets are superior to electromagnets (used in small hp units)

Cordless drills, video recorders

Magnetic Storage

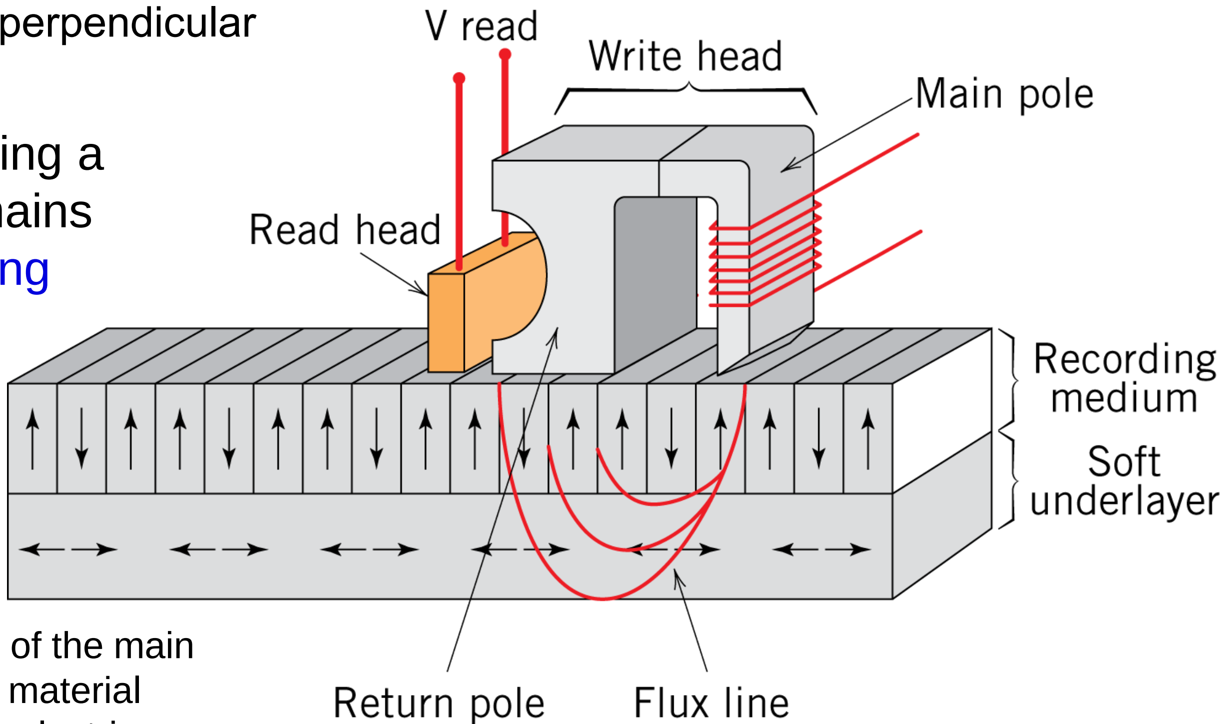
Digitized data in the form of electrical signals are transferred to and recorded digitally on a magnetic medium (tape or disk). This transference is accomplished by a recording system that consists of a read/write head

Hard Disk magnetic storage hard Drives (HDD) consist of rigid circular disks (Dia 65 mm - 95 mm), rotates 5400 and 7200 revolutions per min.

- "magnetic bits" point up or down perpendicular to the plane of the disk surface

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

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



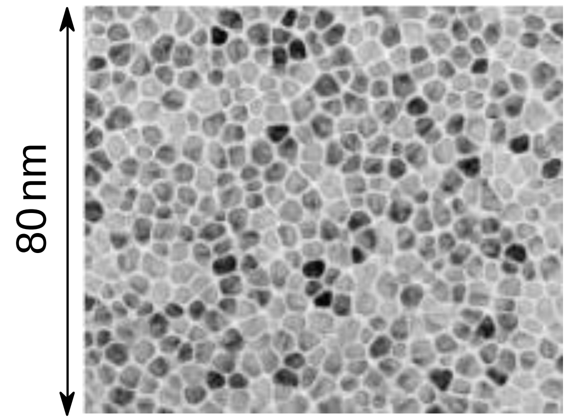
For one head design, a time-varying write magnetic flux is generated at the tip of the main pole—a ferromagnetic/ferrimagnetic core material around which a wire coil is wound—by an electric current (also time variable) that passes through the coil.

Digital data storage (as 1s and 0 s) is in the form of minute magnetization patterns; the 1s and 0s correspond to the presence or absence of magnetic reversal directions between adjacent regions.

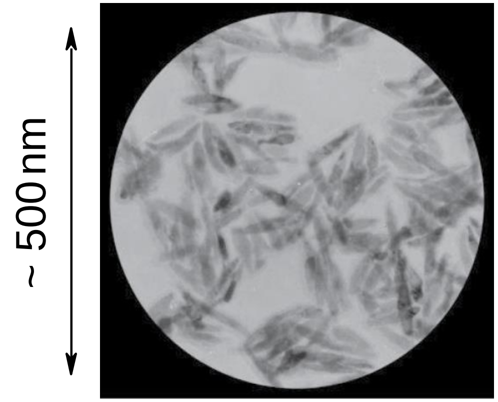
Magnetic Storage Media Types

- Hard disk drives (granular/perpendicular media):

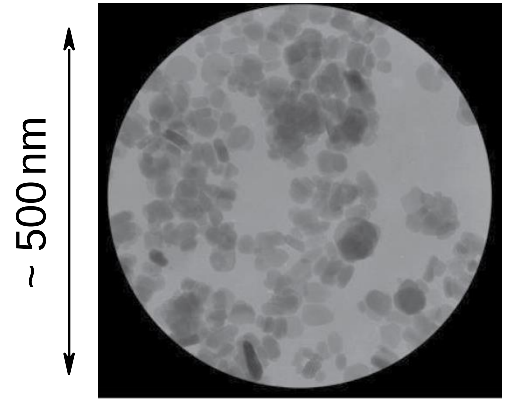
-- CoCr alloy grains (darker regions) separated by oxide grain boundary segregant layer (lighter regions)
-- Magnetization direction of each grain is perpendicular to plane of disk



- Recording tape (particulate media):



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

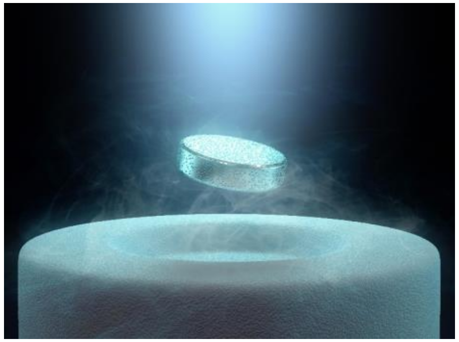


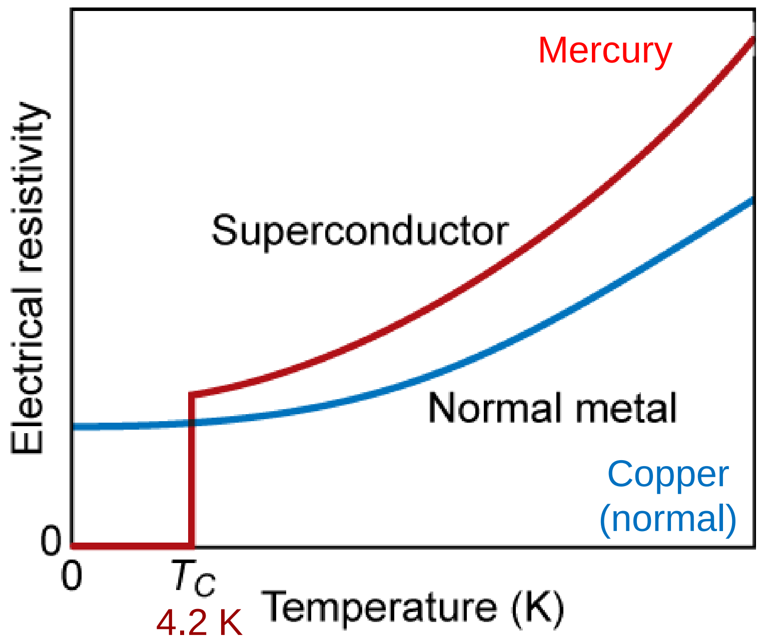
-- Tabular (plate-shaped) ferrimagnetic barium-ferrite particles

Superconductivity

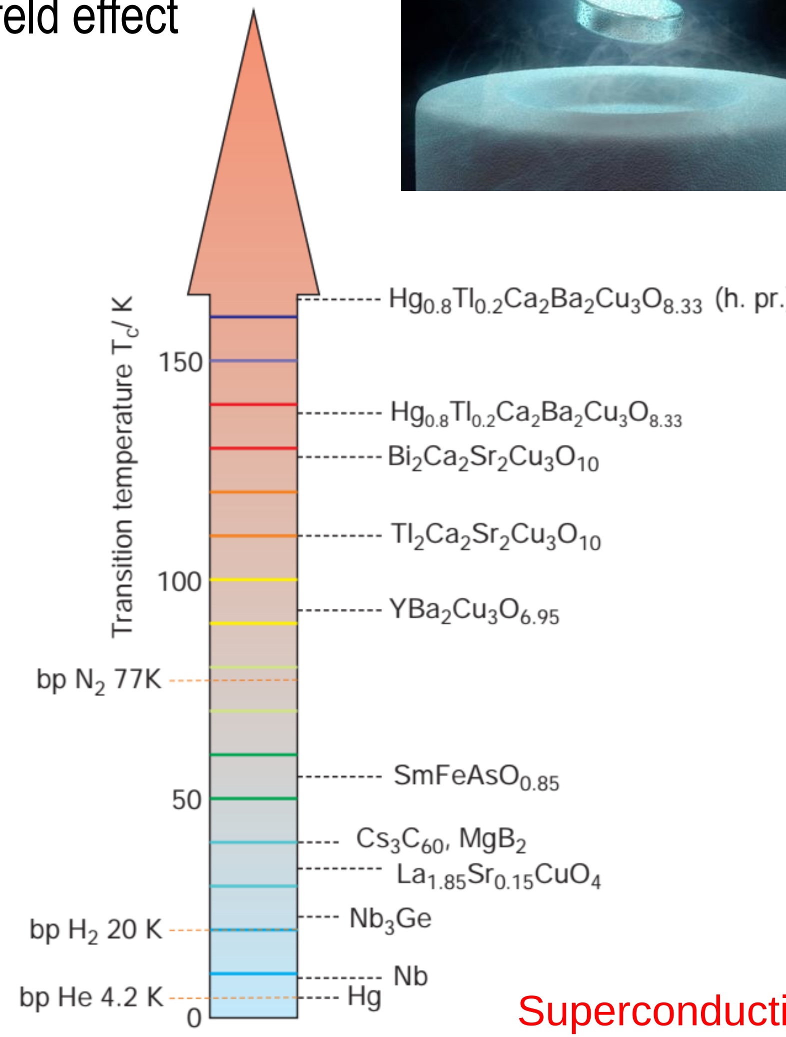
A material that exhibits zero electrical resistance under certain conditions and expels a magnetic field completely (perfect diamagnetic).

It is also known as the Meissner or Meissner-Ochsenfeld effect





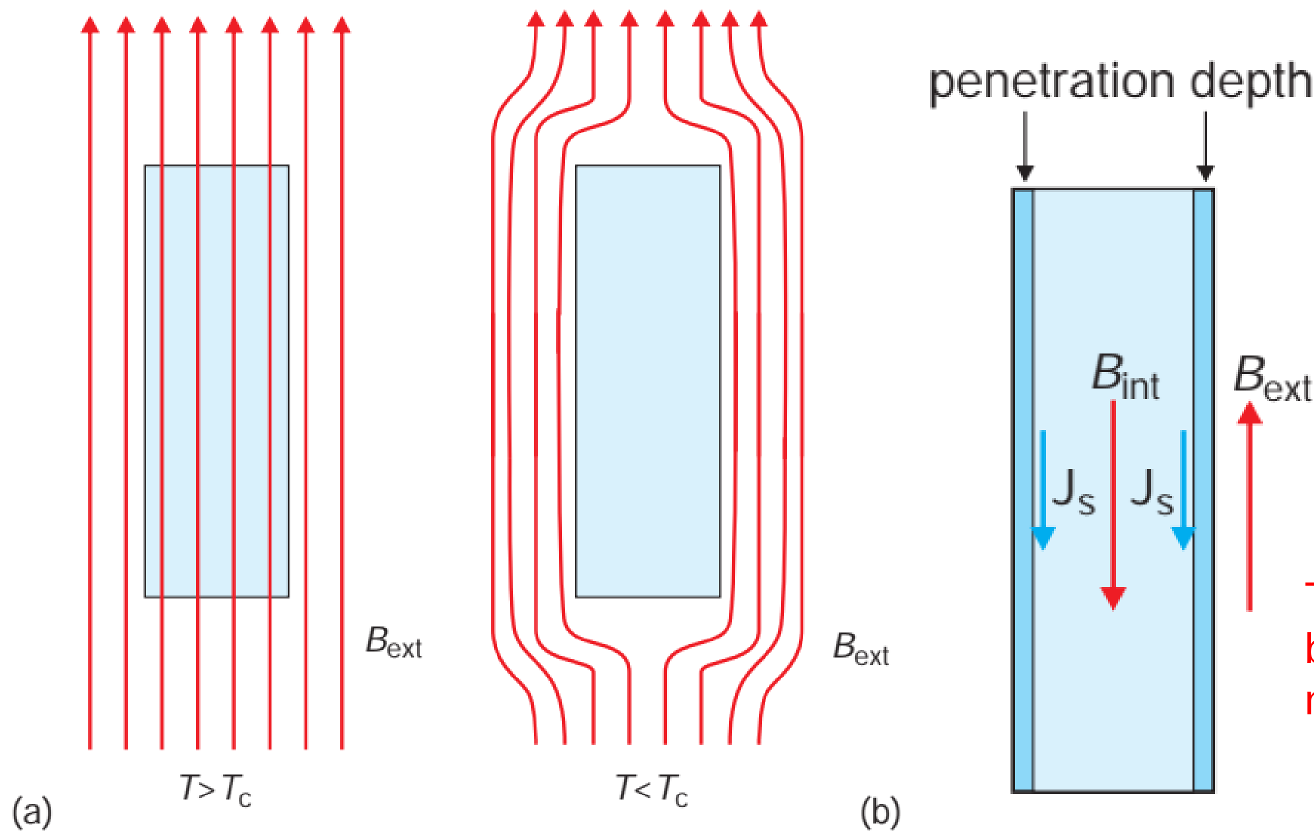
Critical Temperature (T_C): T at which the resistivity of the material plunges from a finite value to zero.



Superconducting transition temperatures

The effect of magnetic fields : Meissner effect

When a superconductor is cooled in a magnetic field it expels the magnetic induction, B, in its interior. This is called the Meissner effect.



The Meissner effect: (a) a normal metal or a superconducting metal above the transition temperature, Tc, allows the penetration of magnetic flux B into the bulk; (b) a superconducting metal below the transition temperature expels the magnetic flux; (c) a surface current, Js, is induced in the superconductor that creates an internal magnetic field that cancels the external flux.

In the superconducting state a surface current is produced that is sufficient to generate an internal magnetic field that exactly cancels the magnetic induction.

Penetration depth: 10-100 nm

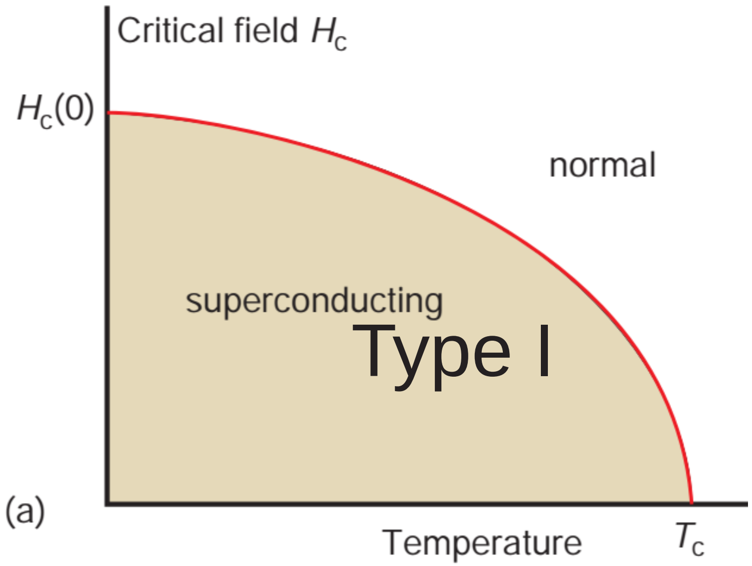
The critical field, H_c to revert back superconducting state to normal is

$$H_c \approx H_c(0)\left[1 - \left(\frac{T}{T_c}\right)^2\right]$$

where Hc(0) is the critical magnetic field at 0 K, and T is the absolute temperature.

Types of superconductors

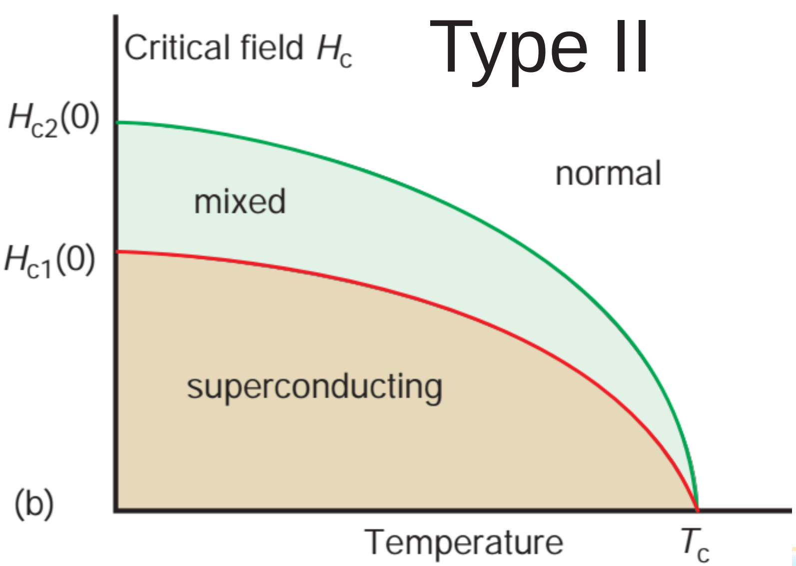
On the basis of the magnetic response, superconducting materials may be classified in

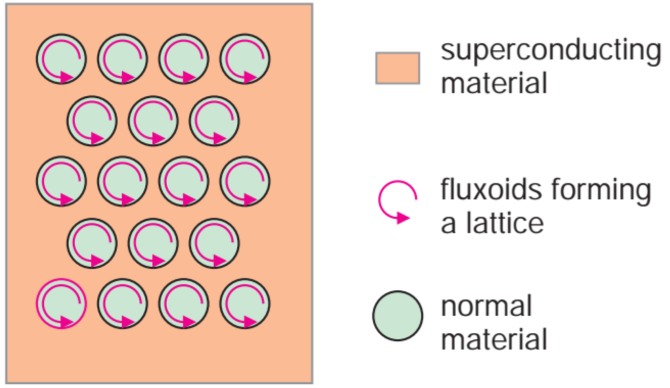


Type I : materials that in the superconducting state are completely diamagnetic (Meissner effect) and as the magnetic field is increased, the material remains diamagnetic until H_C is reached.

Type II : materials that in the superconducting state are completely diamagnetic (Meissner effect) and remain diamagnetic at low magnetic fields, however, the transition from the superconducting state to the normal state is gradual and occurs between the lower critical (H_{C1}) and upper critical (H_{C2}) fields.

In mixed phase: normal material are isolated from the superconducting matrix by surface currents, called vortices or fluxoids- that forms an ordered structure called a fluxon lattice, flux lattice or vortex lattice.



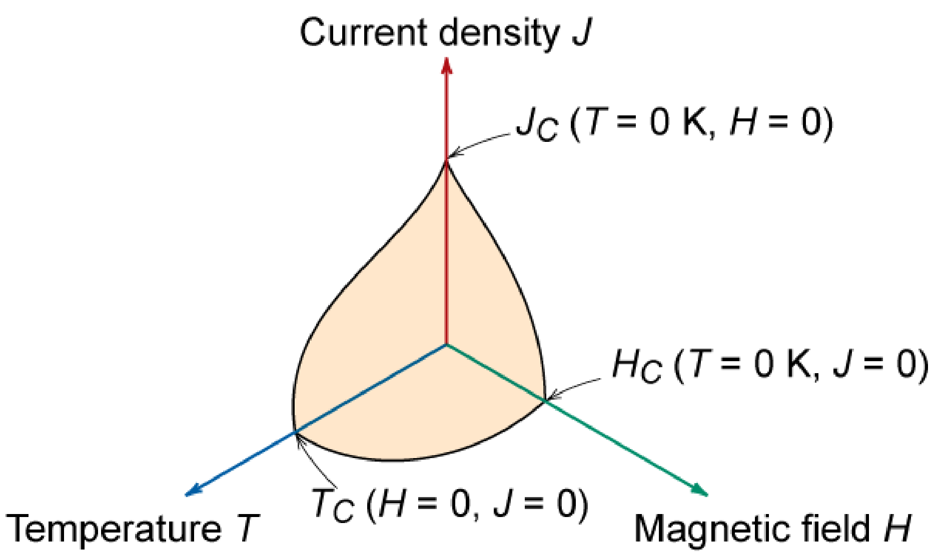


Type II superconductors are preferred over type I for most practical applications by virtue of their higher critical temperatures and critical magnetic fields.

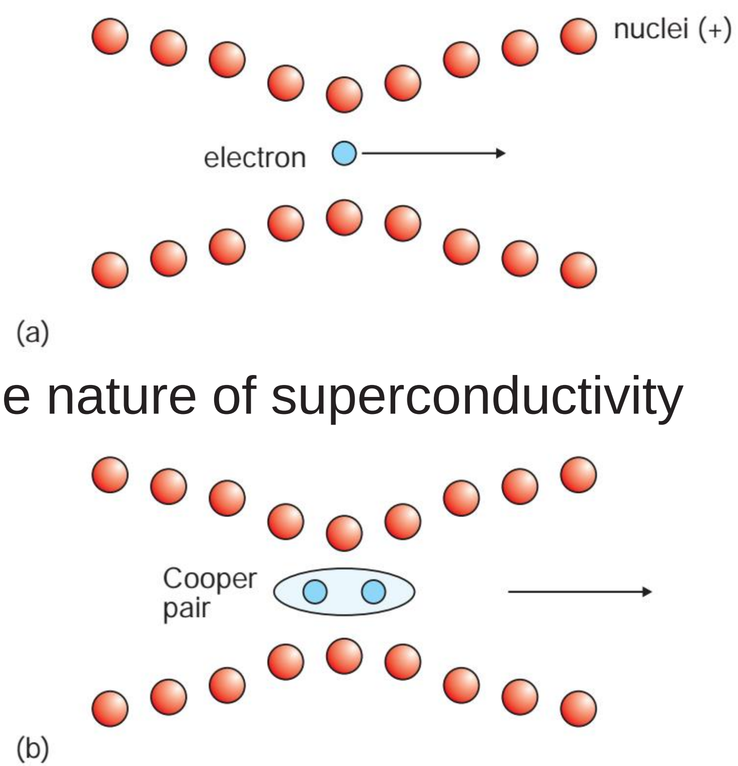
Critical Properties of Superconductive Materials

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

Although a superconducting solid exhibits no resistivity, at a certain current, the critical current, Jc, a superconductor reverts to a normal resistive state.

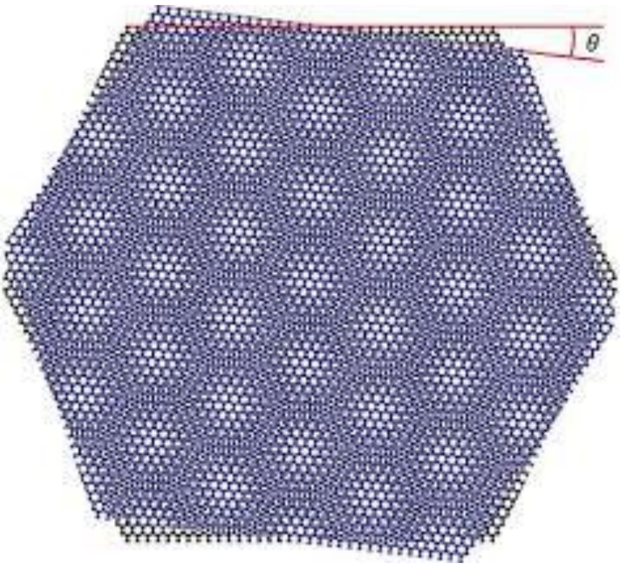


The origin of superconductivity is related to electron-phonon coupling and the resultant pairing of conduction electrons (Bardeen-Cooper-Schrifer or BCS Theory).

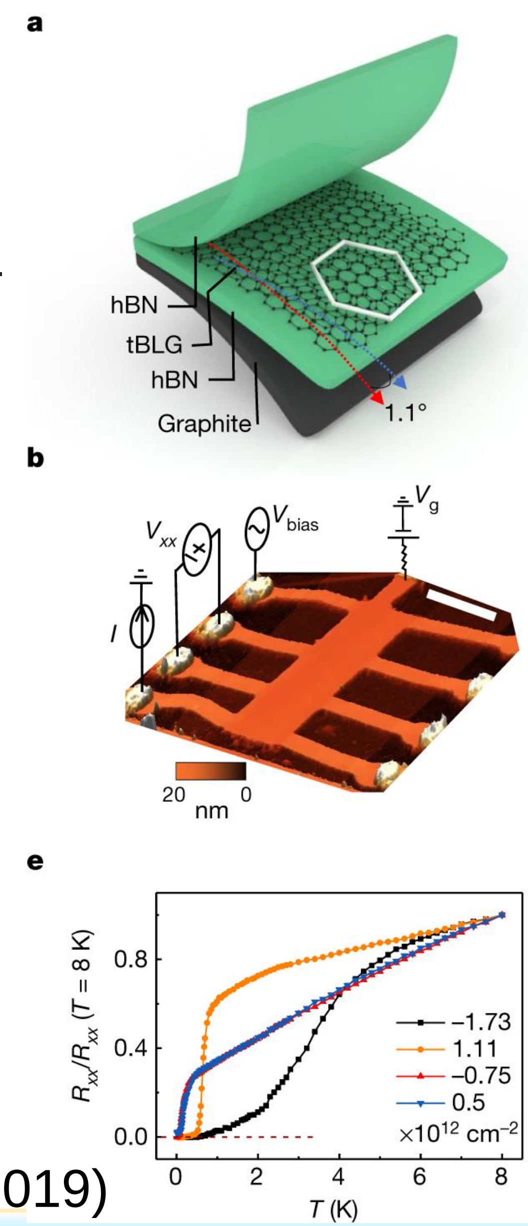


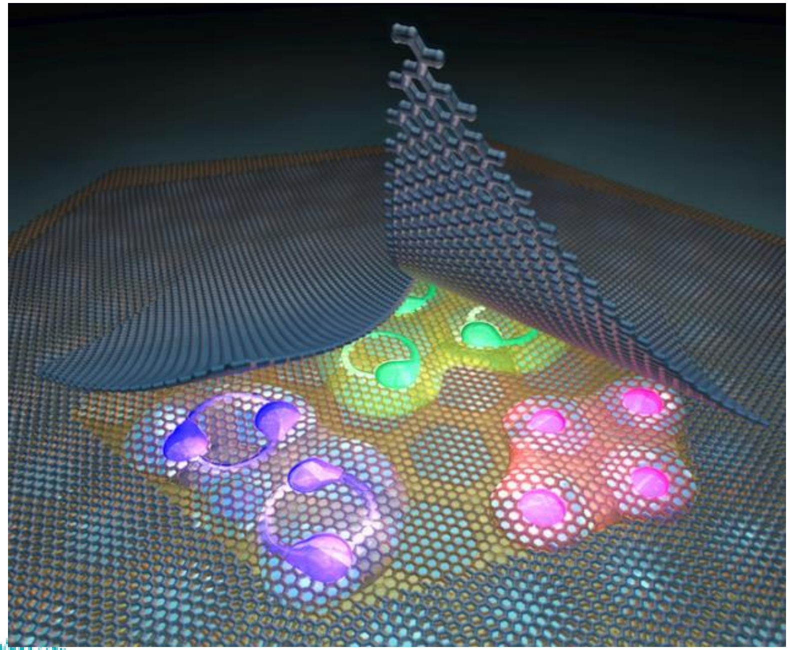
Cooper pairs: (a) an electron passing through a solid attracts the positively charged atomic nuclei slightly, creating a slightly distorted region of enhanced positive charge; (b) at low temperatures, another electron can be attracted into this region to form a Cooper pair, which behaves as a single particle.

Magic-angle graphene reveals a host of new states



Cao, Y. et al. Unconventional superconductivity in magic-angle graphene superlattices. *Nature* **556**, 43–50 (2018).





Nature **574**, 653(2019)

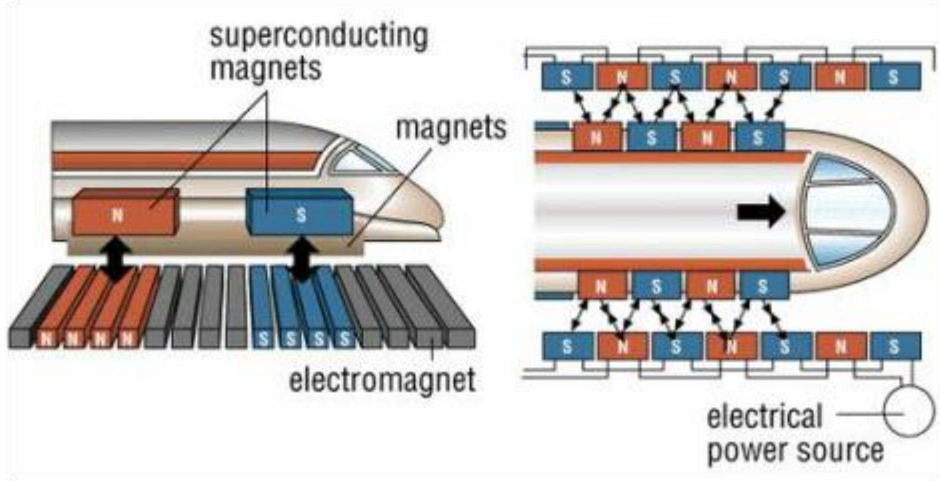
Applications

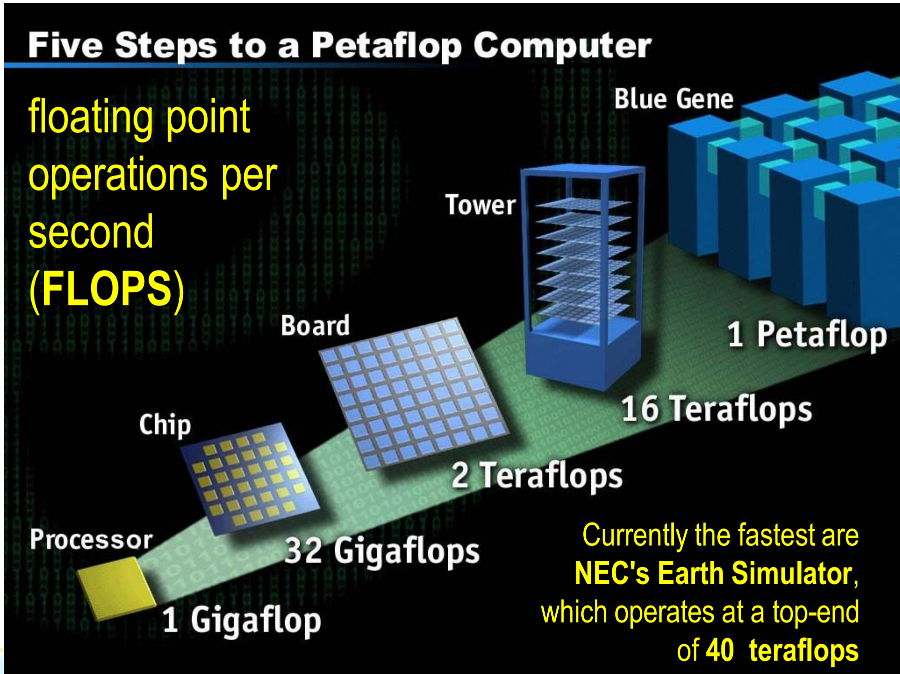
Magnetic Resonance Imaging (MRI)

The development of superconductors has improved the field of MRI as the superconducting magnet can be smaller and more efficient than an equivalent conventional magnet.

Levitation

'MagLev' trains





Superconductivity near room temperature?

Letter | Published: 22 May 2019

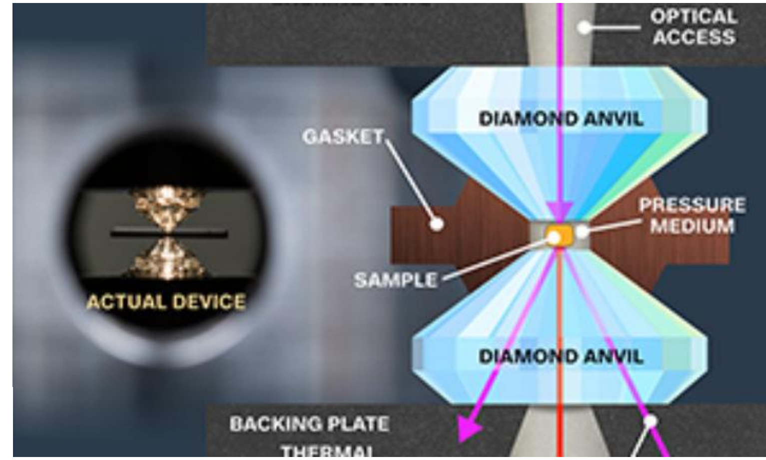
Superconductivity at 250 K in lanthanum hydride under high pressures

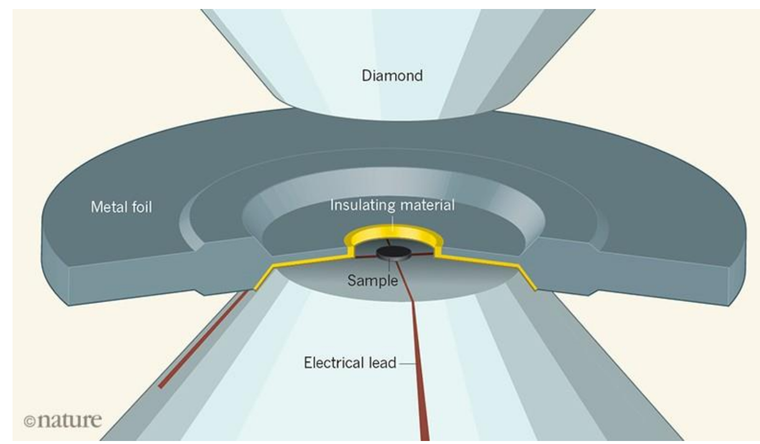
A. P. Drozdov, P. P. Kong, V. S. Minkov, S. P. Besedin, M. A. Kuzovnikov, S. Mozaffari, L. Balicas, F. F. Balakirev, D. E. Graf, V. B. Prakapenka, E. Greenberg, D. A. Knyazev, M. Tkacz & M. I. Eremets

Nature **569**, 528–531(2019) | Cite this article

Abstract

For LaH_{10} and YH_{10}, the onset of superconductivity is predicted to occur at critical temperatures between 240 and 320 kelvin at megabar pressures[3,4,5,6]. Here we report superconductivity with a critical temperature of around 250 kelvin within the Fm3¯mFm3¯m structure of LaH_{10} at a pressure of about 170 gigapascals. This is, to our knowledge, the highest critical temperature that has been confirmed so far in a superconducting material. Superconductivity was evidenced by the observation of zero resistance, an isotope effect, and a decrease in critical temperature under an external magnetic field, which suggested an upper critical magnetic field of about 136 tesla at zero temperature. The increase of around 50 kelvin compared with the previous highest critical temperature[1] is an encouraging step towards the goal of achieving room-temperature superconductivity in the near future.





https://www.youtube.com/watch?v=onB0w3_Su9I

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
- Magnetic storage media:
- Superconductors
    - Types, Properties and Applications

Practice Questions

Q.10.1 *A coil of wire 0.20 m long and having 200 turns carries a current of 10 A.*

(a) What is the magnitude of the magnetic field strength H?

(b) Compute *the flux density B if the coil is in a vacuum.*

(c) Compute the flux density inside a bar of titanium that is positioned within the coil. The susceptibility for titanium is found in Table 20.2.

(d) Compute the magnitude of the magnetization M.

Q 10.2 What is the (a) saturation magnetization and (b) saturation flux density for Ni (r = 8.90 g/cm^3)

Q 10. 3 Calculate saturation magnetization of Fe_3O_4 ; 8 Fe^{+2}, 16 Fe^{+3} per unit cell & *a* = 0.839 nm

Q 10.4 Compute **(a)** the saturation magnetization and **(b)** the saturation flux density for iron, which has a net magnetic moment per atom of 2.2 Bohr magnetons and a density of 7.87 g/cm3