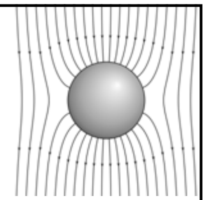
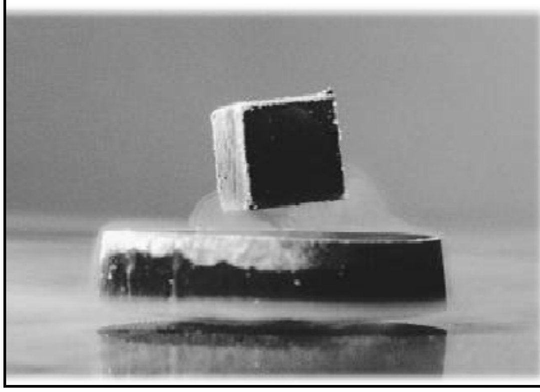


# Magnetics



Sections:
Kasap **Ch. 8**

**Handouts: #6 & #7**

*Now to other things!*
*And I'll begin to treat by what decree*
*Of Nature it came to pass that iron can be*
*By that stone drawn which Greeks the magnet call*
*After the country's name (its origin Being in country of Magnesian folk).*
*This stone men marvel at; and sure it oft Maketh a chain of rings, depending, lo,*
*From off itself! Nay, thou mayest see at times*
*Five or yet more in order dangling down*
*And swaying in the delicate winds, whilst one*
*Depends from other, cleaving to under-side,*
*And ilk one feels the stone's own power and bonds-*
*So over-masteringly its power flows down.*
- ON THE NATURE OF THINGS by Titus Lucretius Carus, 50 BC

## Mysterious Attraction

- There are many curious paradoxes relating the workings of magnet.
- Lodestone was known for its magnetic property and eluded people since antiquity

"The discovery of magnetism began with a type of rock. Magnetite is a mineral with chemical formula $Fe_3O_4$ … it gets its name from Magnesia, a region of central Greece … This mysterious [magnetic attraction] was known by the Greeks (it is mentioned by Thales of Miletus in $6^{th}$ century BCE) and also to the Chinese (there is a reference to magnetism in literature of the $4^{th}$ century BCE)." – Stephen Blundell

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## Fatal Attraction

- Modern thinking about magnets started with Gilbert.
- William Gilbert wrote about magnets, apart from many other matters of science, in the courts of Queen Elizabeth I in 1600.
- He originated scientific understanding of magnetic properties and the term 'electricity'.

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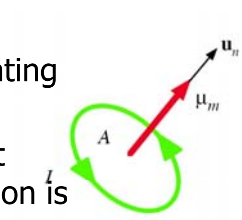
## Prolegomena

- In the World, greater than 20,000 TWh of electricity are generated in 2012, electrical power in this quantity would be hopelessly impractical without large quantities of expertly controlled ferromagnetic material
- The majority of engineering devices use farromagnetic and ferrimagnetic materials.
- But there is also the immensely interesting property of **superconductivity** which is related to the magnetic properties of solids
- High-temperature superconductivity was doscovered in 1986



## Magnetization of solids




- Consider a current loop where there is a circulating current I.
- The area enclosed by the loop is A and the unit vector $\mathbf{u}_n$ comes out of the plane and its direction is such that looking along it, the current ciculates clockwise.
- Then the **magnetic dipole moment** is defined as:

$$\boldsymbol{\mu}_m = IA\mathbf{u}_n$$

Magnetic moment

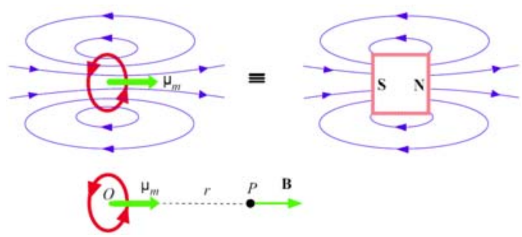
Current

Area circled by current

Unit vector normal to the surface

## Magnetic dipole moment

- The magnetic moment, when placed in a magnetic field, experiences a torque – this torque tries to align the dipole axis with the magnetic field
- Also since the dipole is a current loop, it gives rise to a magnetic field **B.**




- The **B** at a distance r from the magnetic moment is: **B** $\propto \mu_m/r^3$.

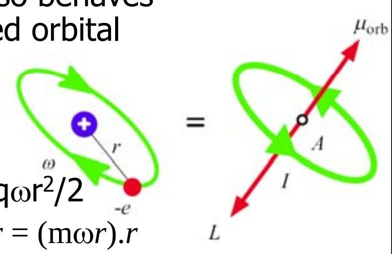


## Atomic moment

- Extending the idea of magentic moment, an electron orbiting around a nucleus also behaves like a current loop, and has associated orbital magnetic moment $\mu_{orb}$.
- I = charge flowing per unit time = -q/period = -q$\omega$/2$\pi$.
- Moment = current[I] x area[$\pi r^2$] = -q$\omega r^2$/2
- Orbital angular momentum $L = (mv).r = (m\omega r).r$
- Then

$$\mu_{\text{orb}} = -\frac{q}{2m_e}L$$

- Thus $\mu_{orb} \propto$ orbital angular momentum and the proportionality constant is electron charge-to-mass ration, i.e. gyromagnetic ratio.



- The electron also has an intrinsic angular momentum – spin. And this relates to spin magnetic moment

$$\mu_{\text{spin}} = -\frac{q}{m_e} S$$

- Overall magnetic moment for an electron is $\mu_{orb}$ + $\mu_{spin}$.
- The total megnetic moment for the whole atom consists of orbital motions and spins of all the electrons – but electrons from only unfilled sub-shells contribute to the overall magnetic moment.
- Because L ans S are quantized, and in a closed shell, these values get netly canceled.



## Bohr Magneton

- Let us consider an atom of closed inner shells ($l=0$) and a single electron in an s-orbital.
- This means that orbital magnetic moment = 0, thus $\mu_{atom}$ = $\mu_{spin}$
- Now in the presence of an external $\mathbf{B}_z$ along z-direction, the magnetic moment cannot simply rotate and align itself to z-direction.
- Since $S_z$ must be space quantized, i.e. $S_z$ must have values ±1/2 ħ.
- The torque experienced by the spinning electron causes the spin moment to precess about the z-axis; such that $S_z$ = -1/2 ħ
- The average magnetic moment thus becomes,

$$\mu_z = -\frac{e}{m_e} S_z = -\frac{e}{m_e}(m_s \hbar) = \frac{e\hbar}{2m_e} = \mu_B$$

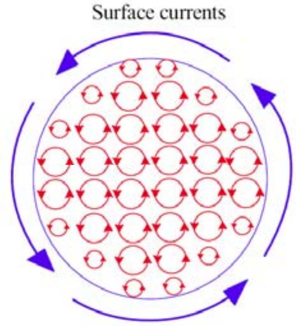
- $\mu_B$ is called the Bohr magneton and has the value $9.27\times10^{-24}$ A $m^2$ or J $T^{-1}$.

## Magnetization Vector

- Consider an ideal solenoid – enclosing free space. If current flow through the wound wire, then a magnetic field $\mathbf{B}_o$ is observed.
- Now if the free space is filled with some material, the magnetic field changes from $\mathbf{B}_o$ to **B**.
- The medium gets magnetized.
- Each atom of the filling medium responds to $\mathbf{B}_o$ and acquires a net magnetic moment um along the applied field. The precession of each atomic magnetic moment about $\mathbf{B}_o$ gives rise to $\mu_m$.
- The magnetic vector **M** describes the extent of magnetization of the medium.
- **M** is defined as magnetic dipole moment per unit volume: $\mathbf{M} = n_{at} \cdot \mu_{av}$
- $n_{at}$ = no of atoms per unit volume, $\mu_{av}$ = avg magnetic moment per atom



- We can assume that each atom acquires $\mu_{av}$ along $\mathbf{B}_o$. Each of these magnetic moments can be viewed as elementary current loop at atomic scale. These current loops are due to electronic currents within the atom and arise from both orbital and spin motions of electrons.
- Magnetization = surface current
- Study Figure 8.7, page 690, Kasap.



## Magnetic Field Intensity H

- The magnetic field in a solenoid filled with a medium is given by $\underline{B} = \mu_o\,(I' + Im) = \mu_o I' + \mu_o I_m = \underline{B_o} + \mu_o \underline{M}$
- Here, I' is the conduction current per unit length of the solenoid, $I_m$ is the surface current
- The field inside the material is the sum of the applied field $\mathbf{B}_o$ and a contribution from the magnetization **M** of the material.
- The magnetization arises from the application of $\mathbf{B}_o$ due to the current of free carriers (conduction current) in the wires. It is useful to define a vector field that represents the effect of the external.
- So [$\mathbf{B} - \mu_o\mathbf{M}$] represents the **magnetizing field** caused by external effects: $$\mathbf{H} = \frac{1}{\mu_o}\mathbf{B} - \mathbf{M} = \frac{1}{\mu_o}\mathbf{B}_0$$
- This is also known as the magnetic field intensity, H = NI



## Permeability

- Permeability $\mu$ relates the effect B to the cause H at the some point inside a material. $$\mu = \frac{B}{H}$$
- It represents to what extent a medium is permeable by magnetic fields.
- μ indicates how permeable the material is to the magnetic field. A material which concentrates a large amount of flux density in its interior has a high permeability
- Relative permeability $\mu_r$ of a medium is the fractional increase in magnetic field with respect to the field in free space when a material medium is introduced $$\mu_r = \frac{B}{B_o} = \frac{B}{\mu_o H}$$
- And of course, $\mu = \mu_0 \cdot \mu_r$

## Susceptibility

- The properties of a material are defined not only by the magnetization, or the magnetic induction, but by the way in which these quantities vary with the applied magnetic field.
- The magnetization produced in a material depends on the magnetic field, and of course to the magnetic field intensity: $\mathbf{M} = \chi_m \mathbf{H}$
- The proportionality constant $\chi_m$ is the magnetic susceptibilty
- The susceptibility indicates how responsive a material is to an applied magnetic field – the degree of magnetization of a material in response to an applied magnetic field.
- $\chi_m$ is a small number and rarely exceeds $10^{-5}$
- Note: the above relations is only true for isotropic [properties are same in all directions] material.
- $B = \mu_o.[H + M] = \mu_o H + \mu_o M = \mu_o H + \mu_o \chi_m H = \mu_o[1+\chi_m]H$
- Therefore, $\mu_r = 1 + \chi_m$
- The inductance of a solenoid with a magnetic medium inside increases by a factor of $\mu_r$.



Table 8.1

| 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 | $\Phi$ | $\Delta\Phi = B_{normal}\,\Delta A$ | Wb = weber | $\Delta\Phi$ is flux through $\Delta A$ and $B_{normal}$ is normal to $\Delta A$. Total flux through any closed surface is zero. |
| Magnetic dipole moment | $\boldsymbol{\mu}_m$ | $\mu_m = IA$ | A $m^2$ | Experiences a torque in $\mathbf{B}$ and a net force in a nonuniform $\mathbf{B}$. |
| Bohr magneton | $\beta$ | $\beta = e\hbar/2m_e$ | 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 $m^{-1}$ | $\mathbf{H}$ is due to external conduction currents only and is the cause of $\mathbf{B}$ in a material. |
| Magnetic susceptibility | $\chi_m$ | $\mathbf{M} = \chi_m \mathbf{H}$ | None | Relates the magnetization of a material to the magnetizing field $\mathbf{H}$. |
| Absolute permeability | $\mu_o$ | $c = [\varepsilon_o \mu_o]^{-1/2}$ | H $m^{-1}$ = Wb $m^{-1}$ $A^{-1}$ | A fundamental constant in magnetism. In free space, $\mu_o = B/H$. |
| Relative permeability | $\mu_r$ | $\mu_r = B/\mu_o H$ | None | |
| Magnetic permeability | $\mu$ | $\mu = \mu_o \mu_r$ | H $m^{-1}$ | Not to be confused with magnetic moment. |
| Inductance | $L$ | $L = \Phi_{total}/I$ | H (henries) | Total flux threaded per unit current. |
| Magnetostatic energy density | $E_{vol}$ | $dE_{vol} = H\,dB$ | J $m^{-3}$ | $dE_{vol}$ is the energy required per unit volume in changing $B$ by $dB$. |

## Quantum Magnetism

- If one assumes nothing more than Classical Physics and then go on modeling a solid material as a system of electric chanrges, then one can show that the system can have **NO** magnetization – Bohr - van Leeuwen Theorem
- In other words, there can be no natural/permanent magnets: the lodestone should not exist
- Yet lodestonses exist in nature and magnets do stick to your refrigerator and that shows that quantum world is no less real.
- In 1920s and 1930s, physicists applied the newly developed quantum theories to magnetism and found that magnetic properties of many real materials can be explained by quantum theories
- Many materials are known to be weakly diamagnetic, and when placed under a magnetic field, they become weakly magentic in the opposite direction – water is an example
- This phenomena is the background of Andre Geim's famous experiemnt of levitating frog



## Geim's frog

- Read Andre Geim's Nobel lecture 2010 :

http://www.nobelprize.org/nobel_prizes/physics/laureates/2010/geim-lecture.html

- Read Handout # 6 for quantum explanations of magnetic properties

## Magnetic Materials*

"A sensitive compass having a Bi needle would be ideal for the young man going west or east, for it always aligns itself at right angles to the magnetic field". - William H. Hayt Jr., Engineering Electromagnetics, 1958

- The magnetic properties of electrons combine to produce the magnetic properties of atoms
- When the atoms aggregate in a solid, the individual magnetic properties of solids combine to produce a resultant magnetic moment.
- The electrons that are responsible for chemical bonds are also responsible for magnetic properties
- The fixed ions have filled shells, hence they do not contribute to magnetism
- However the conduction electrons' spin do align and give rise to magnetic properties

[1] A good references is **Magnetic Materials** by Nicola Spaldin, 2nd Ed, Cambridge University Press, 2011



## Magnetic Materials

- Remember that we have **four** main classes of magnetic materials: the para-, antiferro-, ferro-, and ferrimagnets.

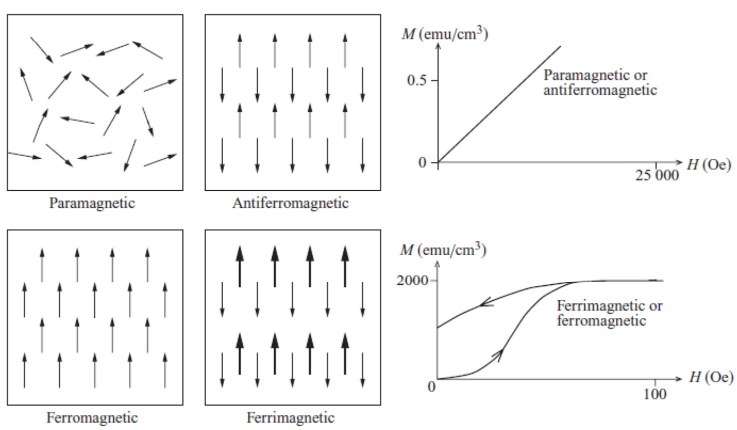
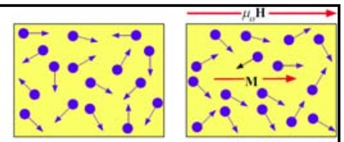



Figure 10.1 Ordering of the magnetic dipole moments in the main types of magnetic materials, and the resulting magnetization-versus-magnetic-field behavior.

## Paramagnets




$\mu_{av} = 0$ and $\mathbf{M} = 0$ (a)

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

- The individual atoms or ions have magnetic moments, but these moments are disordered, so that there is no net magnetization.
- The susceptibility is positive, because the external field causes the moments to partially align with it; and it is small, because the thermal energy which tends to disorder the moments is large compared with the magnetic energy that tends to align them along the field direction.
- Many metals are paramagnetic – due to the alignment of the majority of spins of conduction electrons with the field

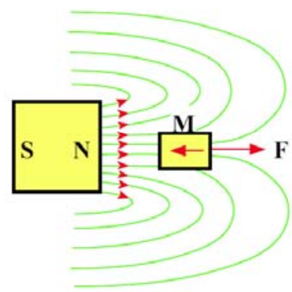


## Magnetic Materials

- **Antiferromagnets**. Here the magnetic moments on the individual atoms or ions align in an antiparallel fashion so as, overall, to cancel each other out. As in the case of the paramagnets, there is no net zero-field magnetization and a small positive susceptibility; note that the microscopic structure is very different, however.
- **Ferromagnets**. In the ferromagnets the moments align parallel to each other, yielding a large net magnetization. The susceptibility can be very large and is often hysteretic because the magnetization process proceeds via domain-wall motion.
- **Ferrimagnets**. The ferrimagnets are microscopically similar to the antiferromagnets, in that they consist of two sublattices within which the moments are aligned parallel, with the two sublattices aligned antiparallel to each other. However, the magnitudes of the magnetic moments in the two sublattices are different, so that there is a net magnetization. As a result they behave macroscopically like the ferromagnets, with large positive susceptibility and hysteresis.

## Diamagnets

- Diamagnetism is such a weak phenomenon that only those atoms which have no net magnetic moment as a result of their shells being filled are classified as diamagnetic.
- Having closed sub-shells and shells means that each constituent atom has no permanent magnetic moment in the absence of an applied field.
- We stated that the susceptibility of a diamagnetic material is negative, that is, the magnetization decreases as the magnetic field is increased. Daimagnets try to expel the applied magnetic field




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



**Table 8.2** Classification of magnetic materials

| Type | $\chi_m$ (typical values) | $\chi_m$ versus $T$ | Comments and Examples |
|---|---|---|---|
| Diamagnetic | Negative and small ($-10^{-6}$) | $T$ independent | Atoms of the material have closed shells. 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. |
| | Negative and large ($-1$) | Below a critical temperature | Superconductors |
| Paramagnetic | Positive and small ($10^{-5}$–$10^{-4}$) | Independent of $T$ | Due to the alignment of spins of conduction electrons. Alkali and transition metals. |
| | Positive and small ($10^{-5}$) | Curie or Curie–Weiss law, $\chi_m = C/(T - T_C)$ | Materials in which the constituent atoms have a permanent magnetic moment, *e.g.*, gaseous and liquid oxygen; ferromagnets (Fe), antiferromagnets (Cr), and ferrimagnets ($Fe_3O_4$) at high temperatures. |
| Ferromagnetic | Positive and very large | Ferromagnetic below and paramagnetic above the Curie temperature | May possess a large permanent magnetization even in the absence of an applied field. Some transition and rare earth metals, Fe, Co, Ni, Gd, Dy. |
| Antiferromagnetic | Positive and small | Antiferromagnetic below and paramagnetic above the Néel temperature | Mainly salts and oxides of transition metals, *e.g.*, MnO, NiO, $MnF_2$, and some transition metals, $\alpha$–Cr, Mn. |
| Ferrimagnetic | Positive and very large | Ferrimagnetic below and paramagnetic above the Curie temperature | May possess a large permanent magnetization even in the absence of an applied field. Ferrites. |

Table 8.2

## Origin of ferromagnetism exchange interaction

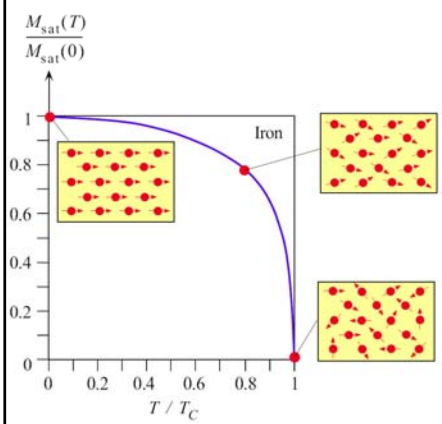
- **Self study**:
  - Section 8.3, Kasap
  - Handout#6, Blundell



## Curie temperture

- When all the atomic magnetic moments are aligned as mush as possible, at that instant the magnetization in a ferromagnet does not increase any fruther
- This is saturation magnetization $M_{sat}$.
- For an iron crystal, $M_{sat}$ corresponds to each Fe atom with an effective spin magnetic moment of 2.2 Bohr magneton aligning in the same direction to give $\mu_o M_{sat}$ = 2.2 Tesla
- Now if you increase the temperature of the material, lattice vibrations become more energetic – disrupting the spin alignment
- The ferromagetic property dissappears at some elevated temperature called the **Curie temperture**, $T_c$.
- Above $T_c$, the material behaves as if its paramagnetic.

## Curie temperture

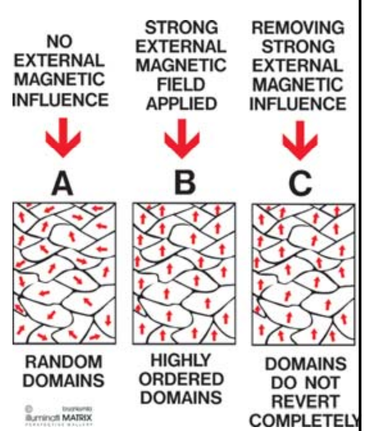



- $M_{sat}$ decreases from its maximum value at absolute zero to zero value at $T_c$
- The thermal energy at $T_c$ is $kT_c$ and it is an order of magnitude approximation to the exchange interaction $E_{ex}$.
- For Iron, $T_c$ = 1043K, $E_{ex}$ = 0.09eV
- For Cobalt, $T_c$ = 1400K, $E_{ex}$ = 0.1eV

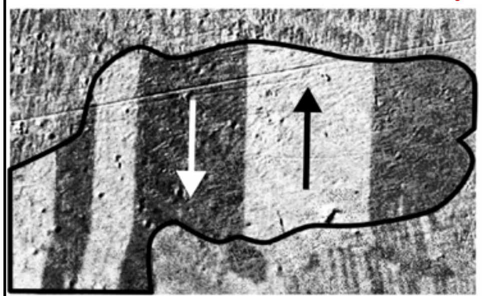


## Magnetic Domains

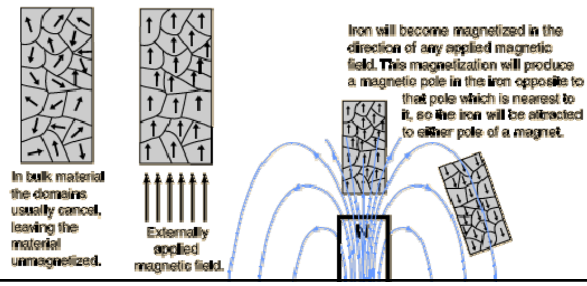
- A magnetic domain is a region of the crystal in which all the spin magnetic moments are aligned to produce a magnetic moment in some direction
- The magnetization of each domain is normally along one of the preferred directions in which the atomic spin alignments are easiest ($E_{ex}$ is strongest)
- For Iron, the magnetization is easiest along the six directions of ⟨100⟩ family.
- Along the boundaries of micro-regions having different net magnetization, there are Domain walls.



## Magnetic domains

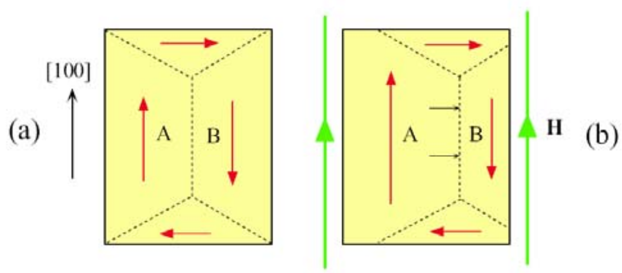


- Magnetic domains in a single grain (outlined with a black line) of non-oriented electrical steel. The photo shows an area 0.1 mm wide. The sample was polished and photographed under Kerr-effect microscope. The polishing was not perfect - there is an angled scratch through the whole width of image (top half of the photo). The area outside of the grain has different crystallographic orientation, so the domain structure is much more complex. The arrows show the direction of magnetisation in each domain - all white domains are magnetised "up", all dark domains are magnetised "down".






## Magnetic Domains




- In an unmagnetized crystal of iron in the absence of an applied magnetic field, domains A and B are the same size and have opposite magnetizations.
- When an external field is applied the domain wall migrates into domain B which enlarges A and B. The result is that the specimen now acquires net magnetization **M** along **H**.
- Self-study, section 8.5.3 Domain Walls, Kasap

Think:

1. *What causes the migration of the domain walls?*

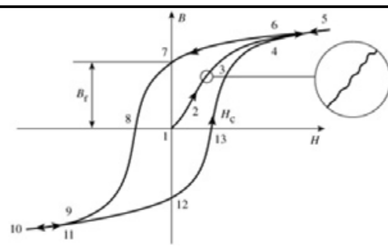
## Magnetization Curves

- Let us consider a single-crystal unmagnetized iron – there are lots of domain, and the magnetization in each domain is ine one of six easy directions.
- Now apply a magnetic field along one of the easy directions
- As the field increases, domains in the direction of the applied field will increase at the expense of other domains, untill the whole material contains only one single domain
- Since the domain walls move easily, the magnetic field required to reach $M_{sat}$ is small.
- The scenario is slightly different when the magnetic filed is applied along [111] direction.



## B-H curves

- The magnetization curve of a typical ferromagnetic material exhibits hysteresis.

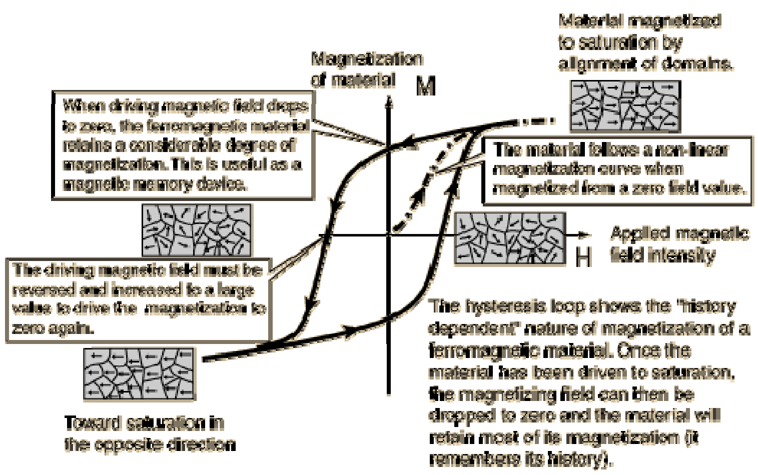



- Starting with a completely demagnetized material, we move up the curve along 2, 3, 4, 5 as the magnetic field is increased. Reducing then the magnetic field, we get back to point 6, which is identical with point 4, but further decrease takes place along a different curve. At 7 there is no applied magnetic field, but B is finite. Its value, $B = B_r$, is the so called remanent flux density. Reducing further, the magnetic field B takes the values along 8, 9, 10.
- Returning from 10, we find that 11 is identical with 9 and then proceed further along 12 and 13 to reach finally 4.
- The loop 4, 7, 8, 9, 12, 13, 4 is referred to as the hysteresis loop. It clearly indicates that the magnetization of iron is an irreversible phenomenon.
- Note that the value of H at 13 is called the coercivity, denoted by $H_c$. It represents the magnetic field needed for the flux density to vanish.

## B-H Curves

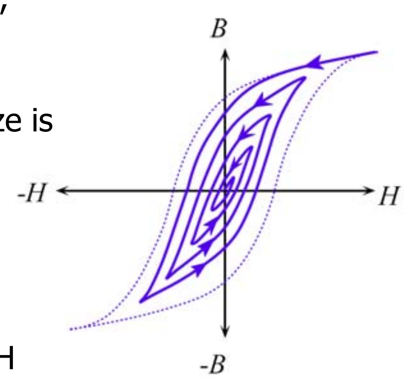
- The paths 4, 5 and 9,10 suggest that rotation from easy into difficult directions is reversible, thus the causes of irreversibility should be sought in domain movement.
- Because of the presence of all sorts of defects in a real material, the domain walls move in little jerks, causing the magnetization to increase in a discontinuous manner (region 2, 3 magnified in Fig).
- The walls get stuck once in a while and then suddenly surge forward, setting up in the process some eddy currents and sound waves, which consume energy. Sudden jerks in wall motions lead to small jumps in the magnetization of the material – This is called **Birkhausen Effect**.
- If energy is consumed, the process cannot be reversible, and that is the reason for the existence of the hysteresis loop.



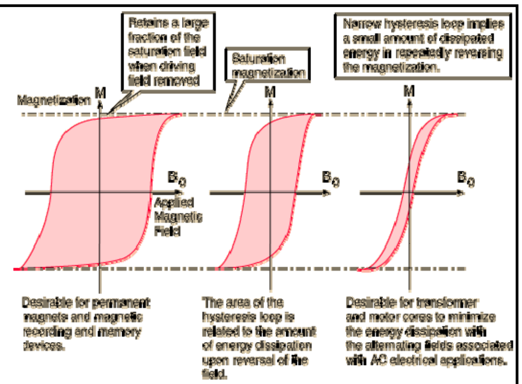


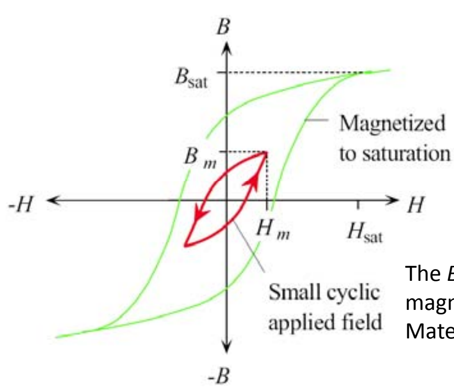
## Demagnetization

- It is easy to demagnetize – due to domain wall motions being reversible and as soon as the field is removed, there is some domain wall motion 'bouncing backwards' .
- The simplest method to demagnetize is to subject the material with ample magnitude of magnetic intensity to reach full saturation levels
- Then apply repeated cycles of hysteresis loop, each time with decreasing magnitude, untill the B-H loops are so small that they end up at the origin when H = 0.



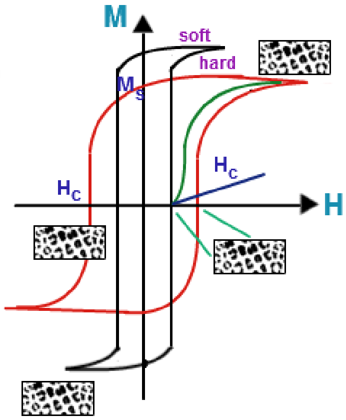



The *B* vs. *H* hysterisis loop depends on the magnitude of the applied field in addition to the Material and sample and size.

- How can we classify magnetic materials?
- There is a simple division into soft and hard magnetic materials.
- Why **soft** and **hard**?
- Well, the hard materials are those which are hard to magnetize and demagnetize.
- So materials which are easy to magnetize an demagnetize should be called easy materials. In fact, they are called soft materials, and there is nothing we can do about that.
- We have to remember, though, that these are only very tenuously related to mechanical properties, which may also be hard and soft.




**Soft magnet material**

Easily magnetized, easily demagnetized

Inductor and transformer cores, recordingheat

High saturation magnetization $M_s$
Lower coercivity $H_c$
High permeability $\mu$
Lower magnetoxrystailine antisotropy
Lower magnetostriction $\lambda_s$
Low core loss
High resistivirt

**Hard magnet material**

Difficult to magnetized, difficult to demagnetized

Permanent magnet, recording media

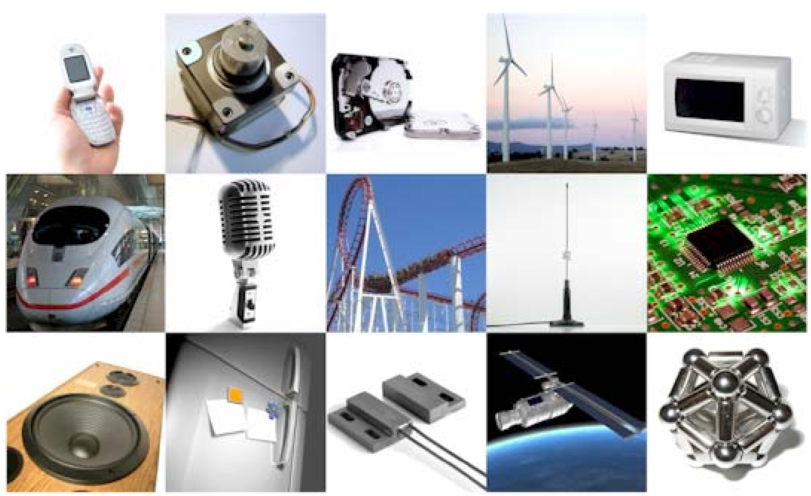
High saturation magnetization $M_s$
Lower coercivity $H_c$
Highly magnetoxrystailine antisotropy
Highly maximum energy product $(BH)_{max}$

## Hard and soft magnetic material



## Applications of Magnetism

- From Giant Magneto-Resistance (GMR) to spintronics, magnetism has diverse applications in everyday life
- Read Handout#6



## Applications of Magnetism

- Magnetic separators, magnetic holding devices, such as magnetic latches.
- Magnetic torque drives
- Magnetic bearing devices
- Magnetos
- Generators and alternators
- Eddy current brakes (used widely for watt-hour meter damping).
- Motors
- Meters
- Loudspeakers
- Relays
- Actuators, linear, and rotational
- Magnetic focused cathode-ray tubes
- Traveling Wave Tubes
- Magnetrons, BWO, Klystrons
- Ion Pumps
- Cyclotrons
- More applications at http://www.cndailymag.com/use.htm

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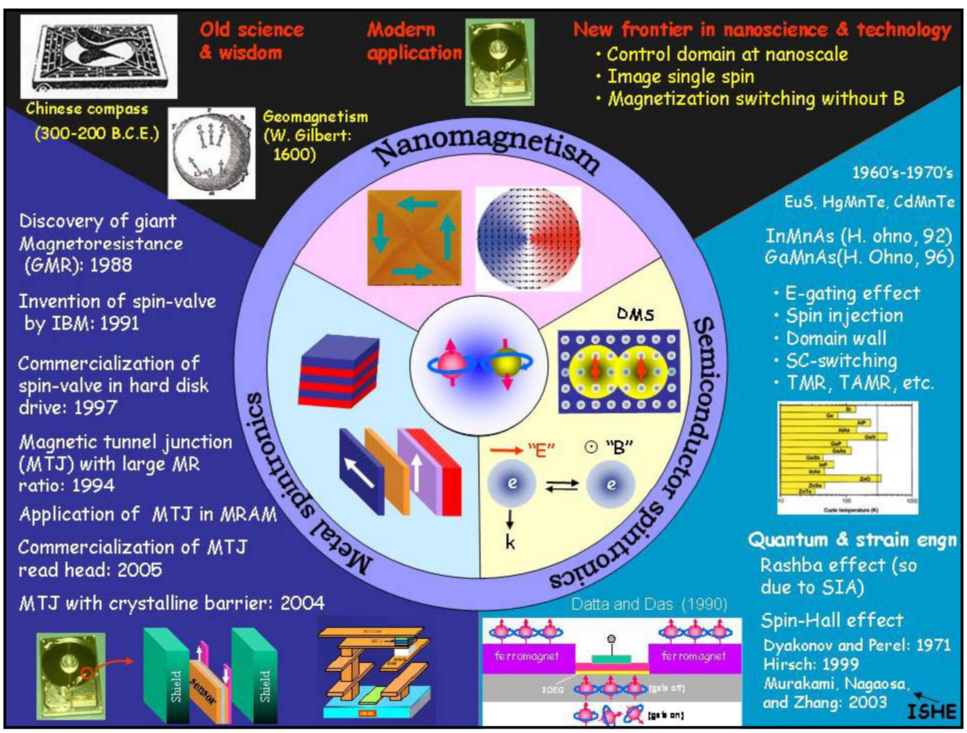
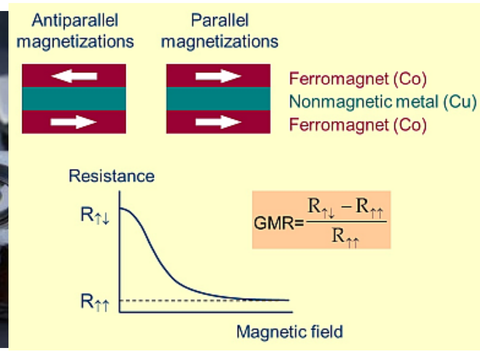
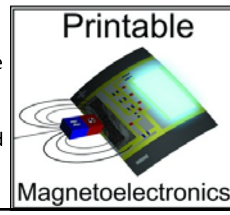


## Giant Magneto-Resistance

- Read the Nobel 2007 lecture by Albert Fert on GMR




**The first printable magnetic sensor relying on the giant magnetoresistance effect (GMR)** is demonstrated. It is prepared in the form of magneto-sensitive inks adherent to any kind of arbitrarily shaped surface. The fabricated sensor exhibits a room-temperature GMR of up to 8% showing great potential for contactless switching in hybrid electronic circuits (discrete semiconductor and printable elements) applied to the surface by regular painting.

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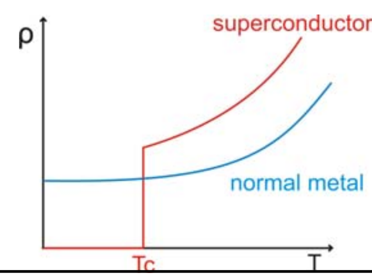
## The challenges of creating low temperatures

- Michael Faraday was the first to liquefy chlorine gas in 1823.
- He employed a technique to liquefy gas by producing high pressures in a sealed tube
- In 1852, James Joule and Lord Kelvin developed a method of cooling gases by rapid expansion
- Sir James Dewar on 10 May 1898 produced 20 $cm^3$ [= 5 teaspoonfuls] of liquid hydrogen.
- Howeever, it was Heike Kamerlingh Onnes who in 1908 liquefied helium at 4.2K
- And superconductivity began!

Read handout#7 for details on the hunt for cryogenics

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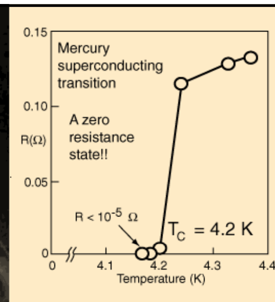
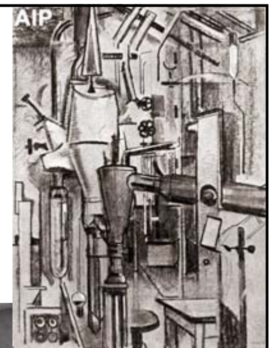



- "Faraday's problem as to whether all gases can be liquefied has now been solved step by step in the sense of van der Waals' words 'matter will always show attraction' and thus a fundamental problem has been removed"

  - H. K. Onnes



# Nobel Committee on Low Temperatures

- "As early as 100 years ago research into the behaviour of gases at various pressures and temperatures gave a great impetus to physics. Since this time the study of the connection between the pressure, the volume and the temperature of gases has played a very important part in physics, and particularly in thermodynamics - one of the most important disciplines of modern physics.
  In the years 1873 and 1880 Van der Waals presented his famous laws governing gases which, owing to their great importance for thermodynamics, were rewarded by the Royal Academy of Sciences in 1910 with the Nobel Prize for Physics.
  The thermodynamic laws of Van der Waals were laid down on atheoretical basis under the assumption that certain properties could be attributed to molecules and molecular forces. In the case of gases the properties of which are changed by pressure and temperature, or in one way or another do not agree with Van der Waals' hypothesis, deviations from these laws occur.
  A systematic experimental study of these deviations and the changes they undergo due to temperature and the molecular structure of the gas must therefore contribute greatly to our knowledge of the properties of the molecules and of the phenomena associated with them.
  It was for this research that Kamerlingh Onnes set up his famous laboratory at the beginning of the 1880's, and in it he designed and improved, with unusual success, the physical apparatus needed for his experiments.
  It is impossible to report briefly here on the many important results of this work. They embrace the thermodynamic properties at low temperatures of a series of monatomic and diatomic gases and their mixtures, and have contributed to the development of modern thermodynamics and to an elucidation of those associated phenomena which are so difficult to explain. They have also made very important contributions to our knowledge of the structure of matter and of phenomena related to it.
  Whilst important on its own account, this research has gained greater significance because it has led to the attainment of the lowest temperatures so far reached. These lie in the vicinity of so-called absolute zero, the lowest temperature in thermodynamics.
  The attainment of low temperatures in general was not possible until we learnt to condense the so-called permanent gases, which, since Faraday's pioneer work in this field in the middle of the 1820's, has been one of the most important tasks of thermodynamics.
  After Olszewski, Linde, and Hampson had prepared liquid oxygen and air in a variety of ways, and after Dewar, having overcome great experimental difficulties, had succeeded in condensing hydrogen, all temperatures down to -259°C, i.e. all temperatures down to 14° from absolute zero, could be attained.
  At these low temperatures all known gases can easily be condensed, except for helium, which was discovered in the atmosphere in the year 1895.
  Thus, by condensing this it would be possible to reach still lower temperatures. After both Olszewski and Dewar, Travers, and Jacquerod had tried in vain to prepare liquid helium, using a variety of met hods it was generally assumed that it was impossible.

"The question was solved in 1908, however, by Kamerlingh Onnes, who then prepared liquid helium for the first time. I should have to cover too much ground if I were to report here on the experimental equipment with which Kamerlingh Onnes was at last successful in liquefying helium, and on the enormous experimental difficulties which had to be overcome. I would only mention here that the liquefaction of helium represented a continuation of the long series of investigations into the properties of gases and liquids at low temperatures which Kamerlingh Onnes has carried out in so praiseworthy a manner. These investigations finally led to the determination of the so-called isotherms of helium and the knowledge gained here was the first step towards the liquefaction of helium. Kamerlingh Onnes has constructed cold baths with liquid helium which permit research to be done into the properties of substances at temperatures which lie between 4,3° and 1,15° from absolute zero.
The attainment of these low temperatures is of the greatest importance to physics research, for at these temperatures both the properties of the substances and also the course followed by physical phenomena, are generally quite different from those at our normal and higher temperatures, and a knowledge of these changes is of fundamental importance in answering many of the questions of modern physics.
Let me mention one of these particularly here.
Various principles borrowed from gas thermodynamics have been transferred to the so-called theory of electrons, which is the guiding principle in physics in explaining all electrical, magnetic, optical, and many heat phenomena. The laws which have been arrived at in this way also seem to be confirmed by measurements at our normal and higher temperatures. That the situation is at very low temperatures not the same, however, has, amongst other things, been shown by Kamerlingh Onnes' experiments on resistance to electrical conduction at helium temperatures and by the determinations which Nernst and his students have carried out in relation to specific heat at liquid temperatures.
It has become more and more clear that a change in the whole theory of electrons is necessary. Theoretical work in this direction has already been begun by a number of research workers, particularly by Planck and Einstein.
In the meantime new supports had to be created for these investigations. These could only be obtained by a continued experimental study of the properties of substances at low temperatures, particularly at helium temperatures, which are the most suitable for throwing light upon phenomena in the world of electrons. Kamerlingh Onnes' merit lies in the fact that he has created these possibilities and at the same time opened up a field of the greatest consequence and significance to physical science.
Owing to the great importance which Kamerlingh Onnes' work has been seen to have for research in physics, the Royal Academy of Sciences has found ample grounds for bestowing upon him the Nobel Prize for Physics for the year 1913.

http://www.nobelprize.org/nobel_prizes/physics/laureates/1913/press.html



## Superconductivity

- In 1911, Onnes discovered that when a sample of mercury is cooled below 4.2K, its resistivity just vanishes
- This is a state when there is no resistance to current flow – a state of **superconductivity**
- The critical temperature below which a material exhibits superconductivity is $T_c$ and it is different for different materials
- The resistivity of some normal conductors (Cu, Ag, Au) show a non-zero value at absolute zero – the residual resistivity arises from scattering and defects
- The early researches in superconductivity showcased quite a few alloys showing zero-resistivity at extremely low temperatures
- But later in the 1980's, researchers unveiled superconductivity at elevated temperatures – at present the highest $T_c$ is 133K for $HgBa_2Ca_2Cu_3O_8$ alloy.

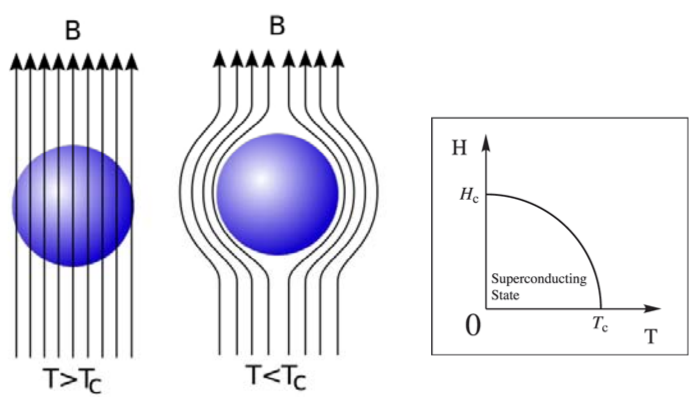
## Some superconductors

- The critical temperature and critical magnetic field (at T = 4.2 K) of the more important hard superconductors

| Material | $T_c$(K) | $H_c \times 10^{-7}$ (Am$^{-1}$) |
|---|---|---|
| Nb-Ti | 9 | 0.9 |
| $Pb_{0.9}Mo_{5.1}S_6$ | 14.4 | 4.8 |
| $V_3Ga$ | 14.8 | 1.9 |
| NbN | 15.7 | 0.8 |
| $V_3Si$ | 16.9 | 1.8 |
| $Nb_3Sn$ | 18.0 | 2.1 |
| $Nb_3Ga$ | 20.2 | 2.6 |
| $Nb_3(Al_{0.7}Ge_{0.3})$ | 20.7 | 3.3 |
| $Nb_3Ge$ | 22.5 | 2.9 |

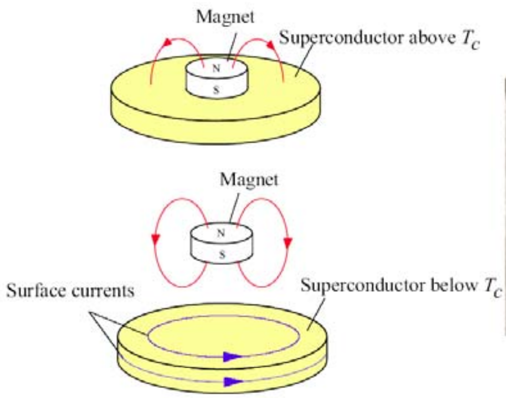


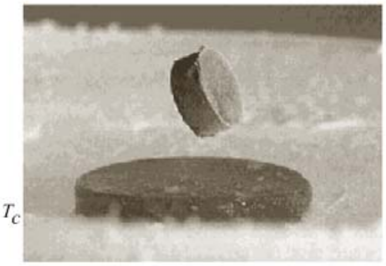
## Meissner effect




- A superconductor cooled below its critical temperature **expels** all magnetic field lines from the bulk by setting up a surface current.
- A perfect conductor (σ = ∞) shows no Meissner effect.

# Magnetic levitation



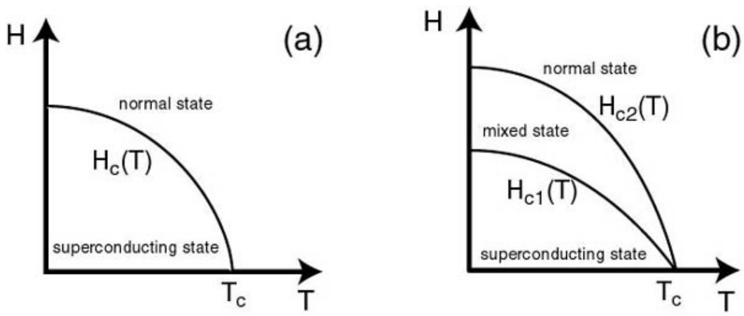



Left: A magnet over a superconductor becomes levitated. The superconductor is a perfect Diamagnet which means that there can be no magnetic field inside the superconductor.
Right: Photograph of a magnet levitating above a superconductor immersed in liquid nitrogen (77 K). This is the Meissner effect.



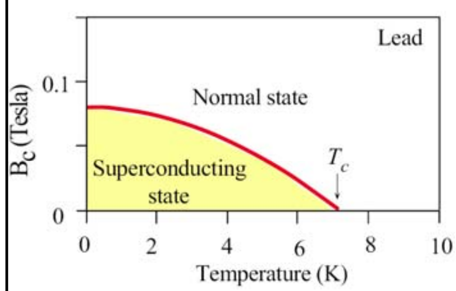
# Types of superconductors

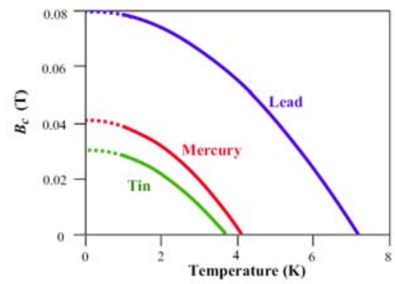
- Two types – type I and Type II, based on their diamagnetic properties



## Type I Superconductor

- In type I superconductors, as the applied magnetic field B increases, so does the opposing magnetizing field till the field reaches a critical value $B_c$, whereupon superconductivity disappears



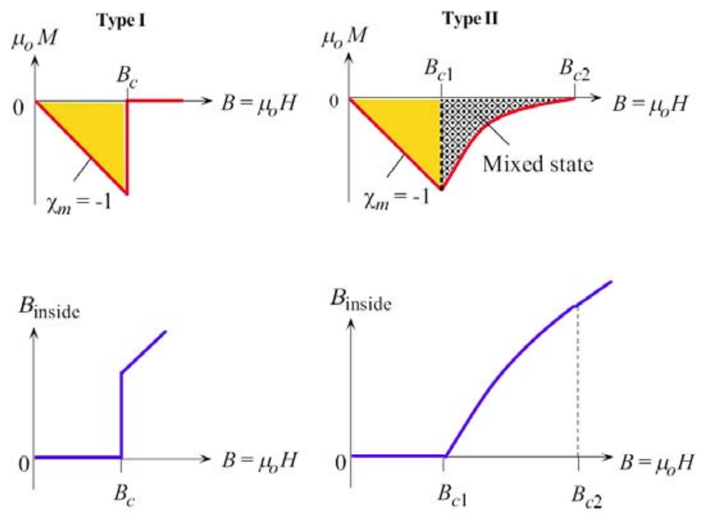




The critical field vs. temperature in Type I superconductors.



## Type II Superconductor

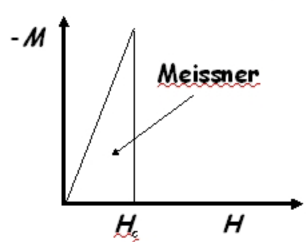
- In type II superconductors, the transition does not occur sharply from Meissner state to normal state
- There is an itermediate state in which the magnetic field is able to pierce through certain local regions of the sample
- As the magnetic field increases, initially the sample behaves as a perfect diamagnet – it exhibits Meissner effect and expels all magnetic flux
- As the field keeps on increasing beyond a critical value, $B_{c1}$, the magnetic flux lines are no longer totally expelled.
- As the field increases even further, more flux lines pierce through the sample till $B_{c2}$, when all fields penetrate the sample and superconductivity ceases to exist.
- Type II's have two critical fields – lower and upper critical fields, $B_{c1}$ and $B_{c2}$

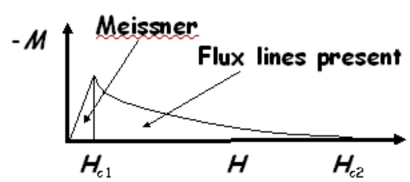



Characteristics of Type I and Type II superconductors. $B = \mu_o H$ is the applied field and $M$ is the overall magnetization of the sample. Field inside the sample,
$B_{\text{inside}} = \mu_o H + \mu_o M$, which is zero only for $B < B_c$ (Type I) and $B < B_{c1}$ (Type II).



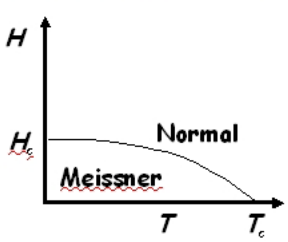
## Type-I & Type-II superconductors




Type-I superconductors are dogmatic:
"Superconductivity or nothing !"

Type-II superconductors are pragmatic:
"Compromise and survive !"



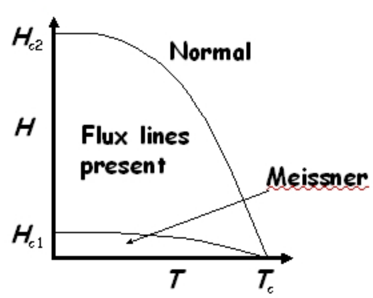



Table 8.7 Examples of Type I and Type II superconductors

| Type I | Sn | Hg | Ta | V | Pb | Nb |
|---|---|---|---|---|---|---|
| $T_c$ (K) | 3.72 | 4.15 | 4.47 | 5.40 | 7.19 | 9.2 |
| $B_c$ (T) | 0.030 | 0.041 | 0.083 | 0.14 | 0.08 | 0.198 |

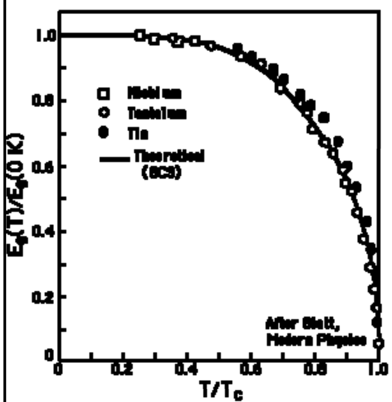
| Type II | $Nb_3Sn$ | $Nb_3Ge$ | $Ba_{2-x}Br_xCuO_4$ | Y–Ba–Cu–O ($YBa_2Cu_3O_7$) | Bi–Sr–Ca–Cu–O ($Bi_2Sr_2Ca_2Cu_3O_{10}$) | Hg–Ba–Ca–Cu–O |
|---|---|---|---|---|---|---|
| $T_c$ (K) | 18.05 | 23.2 | 30–35 | 93–95 | 122 | 130–135 |
| $B_{c2}$ (Tesla) at 0 K | 24.5 | 38 | ~150 | ~300 | | |
| $J_c$ (A cm$^{-2}$) at 0 K | ~$10^7$ | | | $10^4$–$10^7$ | | |



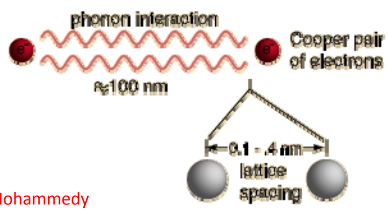
## Critical current density

- It is seen that if a critical current density $J_c$ passes through a superconductor, it will generate its own magnetic field and at sufficiently high values, the magnetic field at the surface of the sample will exceed the critical field and extinguish superconductivity
- This relation between $B_c$ and $J_c$ is only true for type I superconductors; and is complicated in case of type II's
- The **limits of superconductivity** are defined by – critical temperature $T_c$, critical magnetic field $B_c$, and critical current density $J_c$
- Thus, these are important engineering parameters to consider while designing superconducting coils in Maglev, or LHC tunnels or elsewhere.

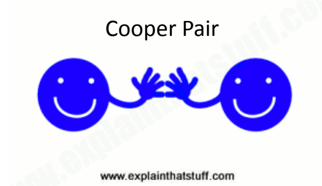
# BCS Theory



$E_g(T)/E_g(0\ K)$
$T/T_c$
0
0.2
0.4
0.6
0.8
1.0
Theoretical (BCS)

phonon interaction
Cooper pair of electrons
≈100 nm
0.1 - .4 nm
lattice spacing

Cooper Pair
www.explainthatstuff.com