Magnetic Properties

Outline

- Introduction
- Basic Concepts
- Magnetic Suscheptibility
  - *Dia-, Para-, Ferro-, Anti- and Ferri-magnetic materials*
- Temperature Effect
- Magnetic Hestresis loops
  - *Soft vs Hard Magnets*
- Examples
  - *Magnetic Storage and Magnetic Resonance Imaging*

Introduction

- Magnet name comes from the ancient Greek city of …………, at which many natural magnets were found.
- Now, we refer to these natural magnets as lodestones (also spelled loadstone; *lode means to lead or to attract*) which contain **magnetite**, a natural magnetic material Fe_3O_4.
- Pliny the Elder (23-79 AD Roman) wrote of a hill near the river Indus that was made entirely of a stone that attracted iron.
- Chinese as early as 121 AD knew that an iron rod which had been brought near one of these natural magnets would acquire and retain the magnetic property, and this rod would align itself in a north-south direction, when suspended from a string.
- Use of magnets to aid in navigation can be traced back to at least the **eleventh** century.

Basically, we knew the phenomenon existed and we learned useful applications for it but we did not understand it.

Introduction

- In 1820, Danish scientist Hans Christian Ørsted (1777-1851) observed that a compass needle in the vicinity of a wire carrying electrical current was deflected; therefore a connection between electrical and magnetic phenomena was shown.
- In 1831, Michael Faraday (1791-1867) discovered that a momentary current existed in a circuit, when the current in a nearby circuit was started or stopped. Shortly thereafter, he discovered that motion of a magnet toward or away from a circuit could produce the same effect.
- Joseph Henry (1797-1878) observed the same 6-12 months before Faraday but failed to publish his findings.

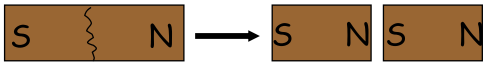
While Henry was doing these experiments, Michael Faraday did similar work in England. Henry was always slow in publishing his results, and he was unaware of Faraday's work. Today Faraday is recognized as the discoverer of **mutual inductance** (*the basis of transformers*), while Henry is credited with the discovery of **self-inductance**.

Introduction

- In summary, Ørsted showed that magnetic effects could be produced by moving electrical charges; Faraday and Henry showed that electric currents could be produced by moving magnets. →*All magnetic phenomena result from forces between electric charges in motion.*
- Ampere first suggested in 1820 that magnetic properties of matter were due to tiny atomic currents.
- All atoms exhibit magnetic effects.
- Medium in which charges are moving has profound effects on

Every magnet has at least one north pole and one south pole. If you take a bar magnet and break it into two pieces, each piece will again have a North pole and a South pole. If you take one of those pieces and break it into two, each of the smaller pieces will have a North pole and a South pole.

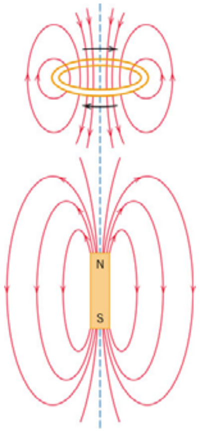
No matter how small the pieces of the magnet become, each piece will have a North pole and a South pole.

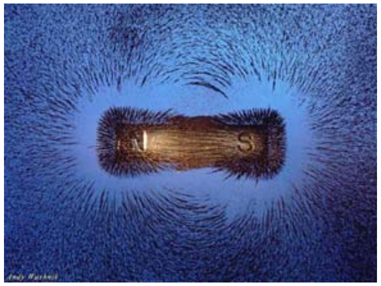


Basic Concepts

- Electrically charged particles generate magnetic forces.
- A magnetic field exerts a torque which orients dipoles with the field.
- Externally applied magnetic field is called the magnetic field strength, H (amperes/meter)

Magnetic field lines describe the structure of magnetic fields in three dimensions.





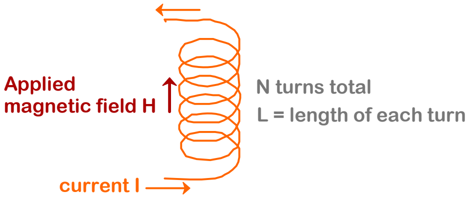
By convention, we say that the magnetic field lines leave the North end of a magnet and enter the South end of a magnet.

Applied Magnetic Field

- For a solenoid:

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

- H field creates magnetic induction
- B is the magnetic induction; the magnitude of the internal field within a substance (in ………)


Applied magnetic field H

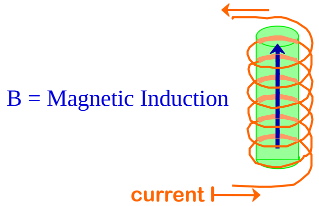
N turns total

L = length of each turn

current I

Created by current through a coil

Tesla. Scientists Can Be Famous, Too!


B = Magnetic Induction

current I

Magnetic Field Parameters

$$B = \mu H$$

- μ is the permeability of the medium (henries per meter)
- For a vacuum:

$$B_0 = \mu_0 H$$

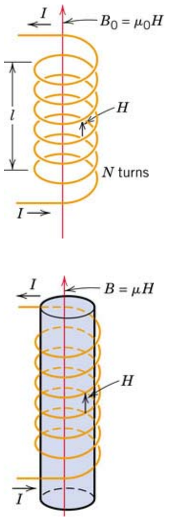
- μ_0 is the permeability of a vacuum

$$\mu_r = \frac{\mu}{\mu_0}$$

- μ_r is the relative permeability

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

- M is **magnetization** of the solid

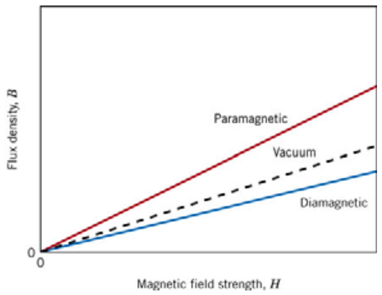


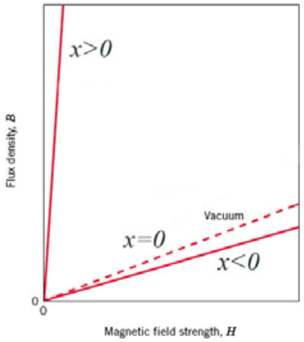
Magnetic Susceptibility

$$M = \chi_m H$$

$$\chi_m = \mu_r - 1$$

x_m is the magnetic …………… . It measures the material response relative to a vacuum (*Dimensionless*)





- Diamagnetism
- Paramagnetism
- Ferromagnetism
  - Antiferromagnetism
  - Ferrimagnetism

Magnetic Moments

- **Macroscopic properties are the result of electron magnetic moments**
- **Moments come from 2 sources:**
  - Orbital motion around a nucleus
  - Spinning around an axis
- **Fundamental Magnetic Moment: Bohr Magneton = 9.27*10^{-24} A.m^2.**

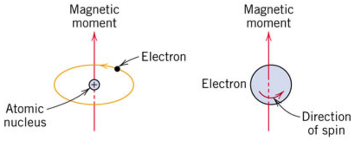
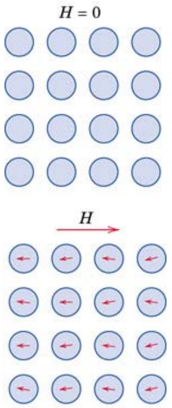


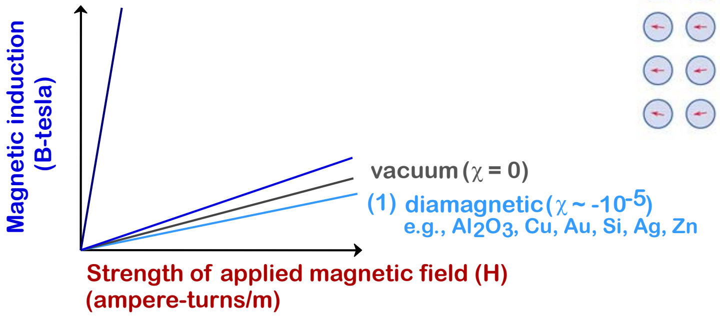
Fig. 20.4, ***Callister 8e.***

- The net magnetic moment for an atom is the sum of the magnetic moments of constituent electrons
- Atoms with completely filled electron shells are incapable for permanent magnetization
- All materials exhibit some form of magnetization.
- Three types of response; ferro, dia and paramagnetic.

Diamagnetism

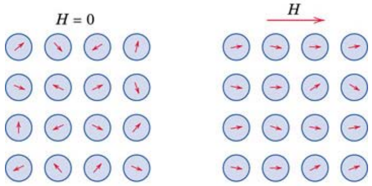
- Very weak and in opposite direction of applied field
- Exists only during application of external field
- Induced by change in orbital motion of electrons
- Found in all materials
- μ_r slightly less than 1 and χ_m negative
- This form of magnetism is of no practical importance

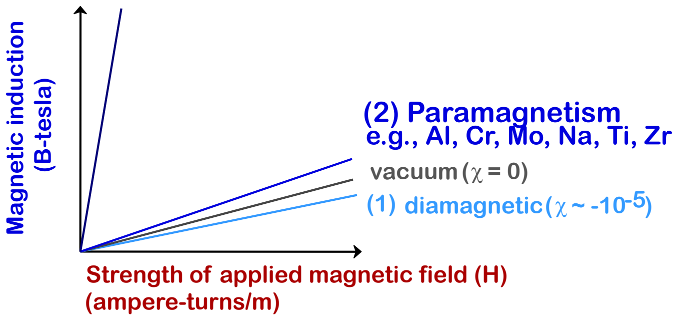




Paramagnetism

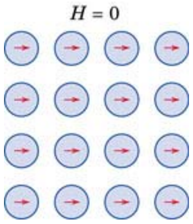
- In some solids, atoms posses permanent dipole moments
- Dipoles align with external field
- Enhances external field
- Increases μ_r

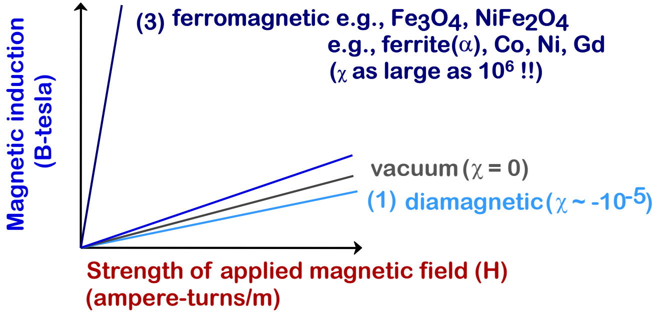




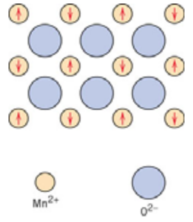
Ferromagnetism

- No external field required
- Very large and permanent magnetizations
- Moments primarily due to electron spin
- Coupling interaction causes adjacent atoms to align
- Often found in transition metals
- Large χ_m, H<<M and B ~ μ_0*M





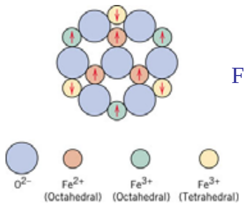
Antiferromagnetism



MnO

- Atoms' spin moments couple in opposite directions
- No magnetic moment

Ferrimagnetism

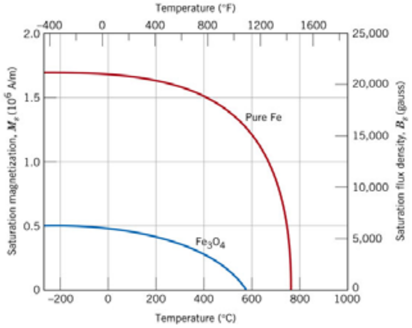


Fe_3O_4

- Permanent magnetization
- Similar macroscopic characteristics with ferromagnetism
- Source of moment is incomplete cancellation of spin moments

Fe^{3+} complete cancellation
Fe^{2+} there is net magnetic moment

Temperature and Magnetic Behavior



Increasing temp:

- increases thermal vibrations in atoms
- Moments are more randomly aligned
- Thermal motions counteract coupling forces
- Decrease in saturation magnetization

Saturation Magnetization, Ms:
Maximum possible magnetization (*all dipoles aligned with external field*)

Ms= net magnetic moment for each atom * number of atoms

- Maximum saturation at 0 K. Why? ....
- Saturation abruptly drops to zero at the Curie Temp., T_c
- At T_c, mutual spin coupling is destroyed
- Above T_c, ferromag. and ferrimag. materials become paramag.

Domains

- Any ferro- or ferri-magnetic material below T_c is composed of small volume regions with mutual alignment
- Adjacent domains have boundaries of gradual change in direction
- Magnitude of M field for the entire solid is the vector sum of the weighted magnetizations of domains

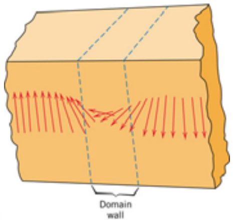
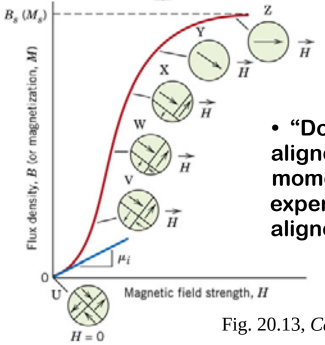


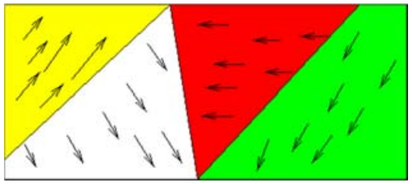
Fig. 20.12, *Callister 8e*.



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

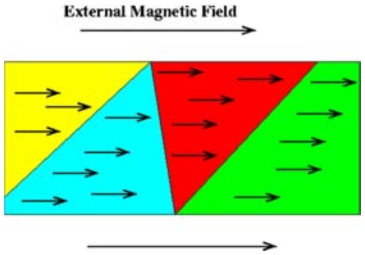
Fig. 20.13, *Callister 8e*.

Making a Magnet from a Ferromagnetic Material



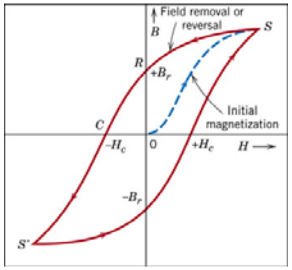
- domains in which the magnetic fields of individual atoms align
- orientation of the magnetic fields of the domains is random
- no net magnetic field.

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

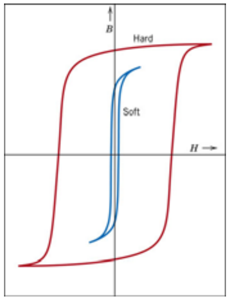


Magnetic Hysteresis Loops

- B field lags behind H field
- Remenance: residual B field at H = 0
  - Domains are resistant to movement
- Coercivity, H_c: H field magnitude required to set B = 0



Area within hysteresis loop is energy lost (usually heat)



- Soft Magnets
  - Small coercivity (*e.g., commercial iron 99.95 Fe*)
  - Good for varying fields (*e.g. electric motors*)
- Hard Magnets
  - High coercivity: add particles/voids to make domain walls hard to move (*e.g. tungsten steel*)
  - Good for ……………… magnets

Strategic nature of Permanent Magnets

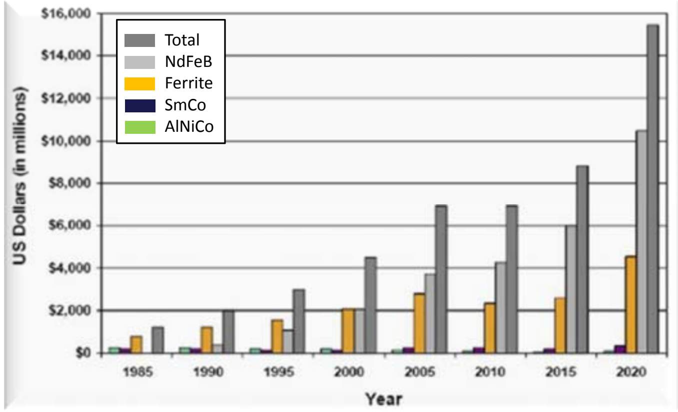
- Permanent magnets are strategic materials for many important applications: automotive, aerospace, defense, energy and electronics.
- Governments are realizing the vital importance of these technologies to security and to the economy and "*are acting*" to secure access to resources and **find alternatives.**
- May 29-30 , 2013: 3rd **EU-US-Japan** Trilateral Conference on Critical Materials in Brussels, Belgium – *e.g. neodymium is said to be one of fourteen elements critical to the EU economy*
- Alloying neodymium magnets with terbium (Tb) and dysprosium (Dy) preserves the magnetic properties at high temperatures – *very important for future car engines and wind turbines*
- China currently produces about 900 tonnes of Dy per year and estimates that it can mine a further 13,500 tonnes – *China is currently the only country that can refine rare earth elements*
- If we want electric cars, we must find magnets that do not rely on Dy, because we're going to be short of dysprosium in less than 15 years.

Strategic nature of Permanent Magnets

Magnets are widely used for power, electrical, automotive and mechanical applications

NdFeB sales have now exceeded 55% of all permanent magnets sales on a ***dollar-basis***

On a ***weight-basis***, the inexpensive ferrite magnets represent more than 85% of permanent magnets sales. But their energy product is 10% of the NdFeB's.



Permanent magnet material sales by type

A. Lefévre, *et* al. Journal of Alloys and Compounds, 1998

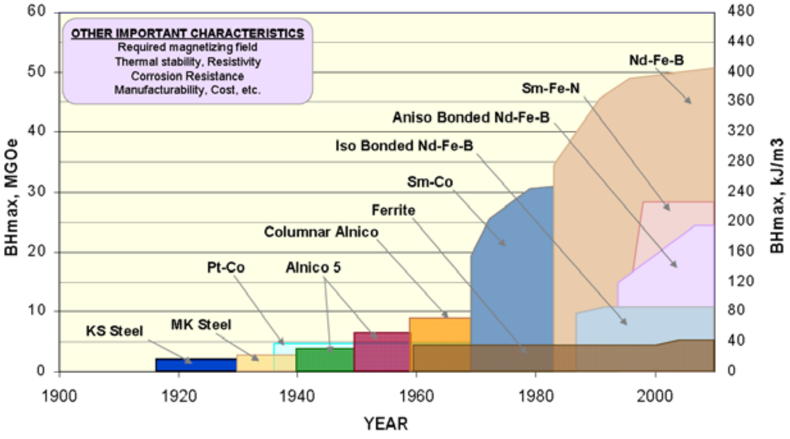
Strategic nature of Permanent Magnets

Permanent magnets development and characteristics.

- 1900 **Ferrite** is the best selling magnetic material in the world because of the low cost and abundance of the raw materials. This material is best suited for environments under 300˚ C. Energy products for ferrite materials range from 1 to 3.5 MGOe.
- 1935 **Alnico** magnets are the material of choice for very high temperature applications up to 550˚ C. Alnico is susceptible to stray magnetic fields, which can lead to demagnetization. Energy products for Alnico materials range from 1.5 to 7.5 MGOe.
- 1966 **SmCo** is an excellent material for applications that require high performance in a high temperature working environment. SmCo exhibits excellent thermal characteristics with several grades designed specifically for applications up to 300˚ C. Energy products for SmCo materials range from 16 to 32 MGOe.
- 1982 **NdFeB** is the material of choice for high performance applications. It is the highest energy material currently available. Energy products for NdFeB magnets range from 26 to 48 MGOe. NdFeB is sensitive to heat and should not be used in environments that exceed 150˚ C.

Strategic nature of Permanent Magnets

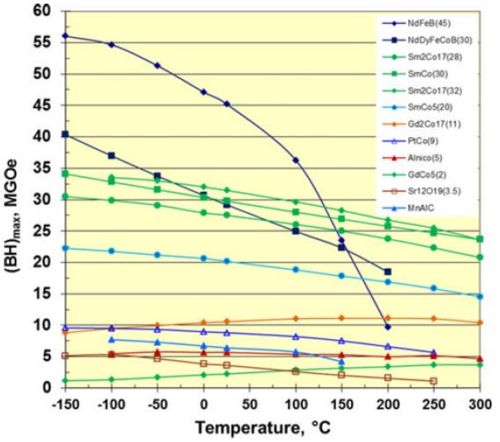
Historical trend of the permanent magnets improvement.



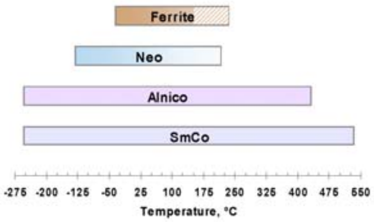
Steve Constantinides, ARPA-E Workshop, Rare Earth and Critical Materials, 2010 in Arlington, VA

Strategic nature of Permanent Magnets

The temperature performance of the maximum energy product as a function of temperature



M.J. Kramer *et al*, JOM, Vol. 64, No. 7, 2012



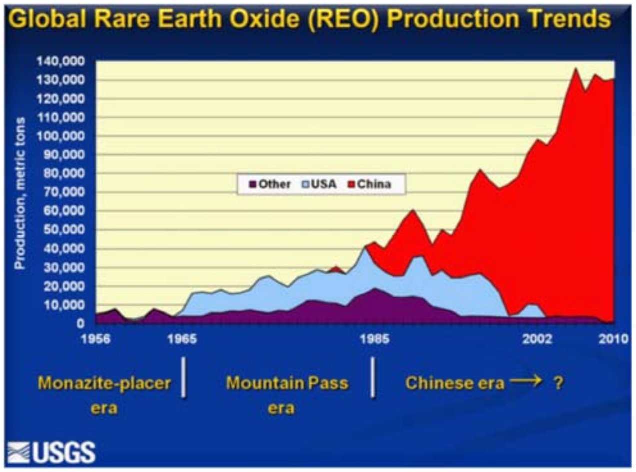
Steve Constantinides, ARPA-E Workshop, RE and Critical Materials, 2010 in Arlington, VA

Strategic nature of Permanent Magnets

The worldwide production of rare earth elements

The slow pace with which western governments are dealing with the supply situation is alarming.

In recent years, China has started to cut rare earth exports and is expected to limit exports to finished products.



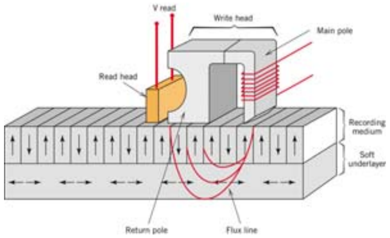
Pui-Kwan Tse, China's Rare-Earth Industry, USGS report, 2011

Strategic nature of Permanent Magnets

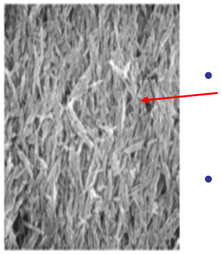
- ✓ Price for strong magnets depends on Nd and Dy price and has high fluctuations
- ✓ Already in 2010, the Chinese government started reducing the export of rare earth metals, including neodymium. In 2011, the export quota decreased even more. This caused a dramatic increase of Nd cost.
- ✓ Price for Nd in 2011 was 4.5 times higher compared to 2010
- ✓ Dy was trading near \$100/kg in early 2009 increased to \$3400/kg in August of 2011 and stayed around \$2000/kg through 2012.
- ✓ The growing world **demand** of permanent magnets and **rising costs** of the rare earth materials necessitates the development of **new Fe-based magnets** without or with a minimal amount of the rare earth additions.

Example: *Magnetic Storage*

- **Information stored by magnetizing material. Head can:**
  - Apply magnetic field H & align domains
  - Detect a change in the magnetization of the medium

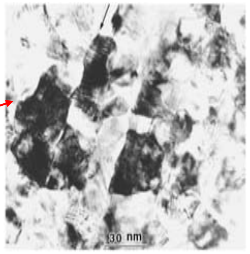


Media Types



γ-Fe_2O_3. +/- mag. moment along axis.

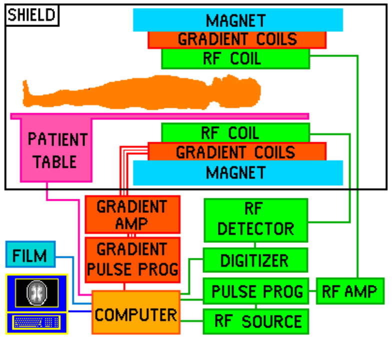
- **Particulate**
  - Needle shaped
  - Tape, floppy
- **Thin film**
  - Domains are 10-30nm
  - Hard drives



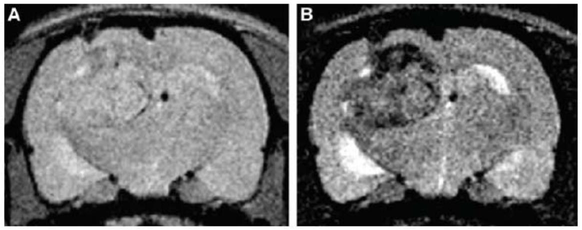
CoPtCr or CoCrTa alloys

Example: *MRI*

- Super paramagnetic Iron Oxide Nanoparticles Act as an MRI negative contrast agent.
- Produce predominately spin-spin effects
- Enhancement peaks at 24 hrs and decreases over several days
- Microglia, and other metabolically active cells, internalize these nanoparticles



A- Proton density and B- Tumor uptake of iron is evident in this image – higher contrast.



Next Time:

Optical Properties