Fundamentals of Magnetism & Magnetic Materials

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Overview: 2015 IEEE Summer School Lectures

- **Fundamentals of Magnetism** (L. H. Lewis, Northeastern U., USA)
- **Magnetic Measurements and Imaging** (R. Goldfarb, NIST, USA)
- **Magnetization Dynamics** (B. Hillebrands. TU Kaiserslautern, Germany)
- **Spintronics and Promising Applications** (J. P. Wang, U. Minnesota, USA)
- **Magnetic Data Storage Technologies** (K. Gao, Seagate, USA)
- **Magnetic Materials and Applications** (R. Schaefer, IFW Dresden, Germany)
- **Modeling and Simulation** (G. Bauer, Tohoku University, Japan, and TU Delft, The Netherlands)
- **Magnetic Materials in Biomedical Applications** (T. St.Pierre, U. W. Australia)

Anticipated Outcomes from these Lectures

At the end of this lecture, students will know something about…..

- How magnetism benefits society
- Basic electromagnetism
- Magnetic exchange
- Paramagnetism, ferromagnetism, antiferromagnetism
- Magnetic anisotropy
- Magnetic domains
- Magnetofunctional effects and order parameters
- Magnetic materials selection
- Magnetism units
- Resources for textbooks

Overview:

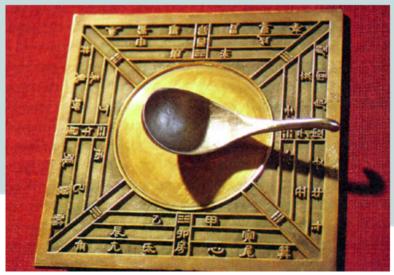
Magnetism – History, Context, Applications

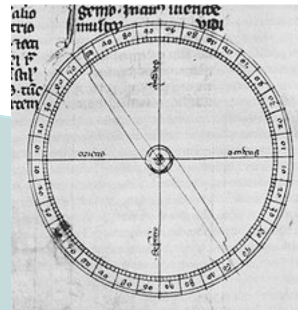
(*or: "why should I care?"*)

Magnetism History and Context

Lodestone (magnetite, Fe_3O_4) attracting nails. Magnetized by lightning?

Han Dynasty (2nd century BCE to 2nd century CE). Navigation? Feng Shui?





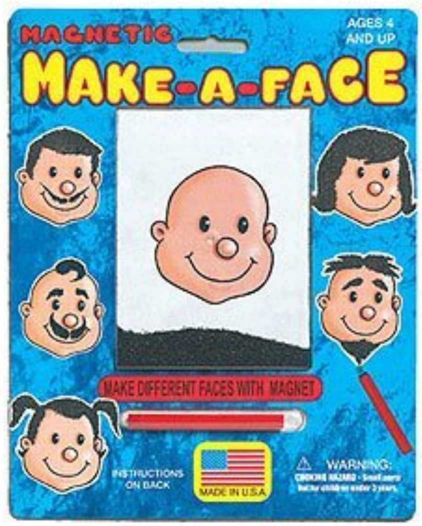
Pivoting compass needle in a 14th century copy of Epistola de magnete of Peter Peregrinus (1269)

Animal magnetism?

William Gilbert,1544-1603 **De Magnete** ("On the Magnet", 1600) quickly became the standard work throughout Europe on electrical and magnetic phenomena. Gilbert tested many folk tales such as, *Does garlic destroy the magnetic effect of the compass needle?*

http://www.bbc.co.uk/programmes/p003k9dd

Novelty applications of magnetism



Magnetic nail polish

Magnetic pain treatment

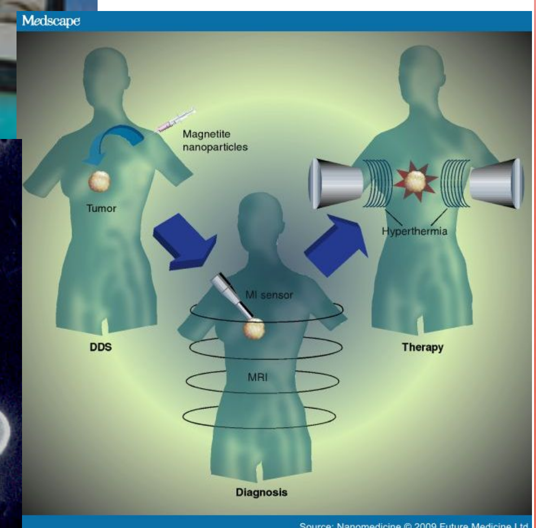
"Magnetic Snore Relief Device Aids in Reducing Snoring to Provide Good Nights Sleep (**comfortable**, small size as a wedding ring)"

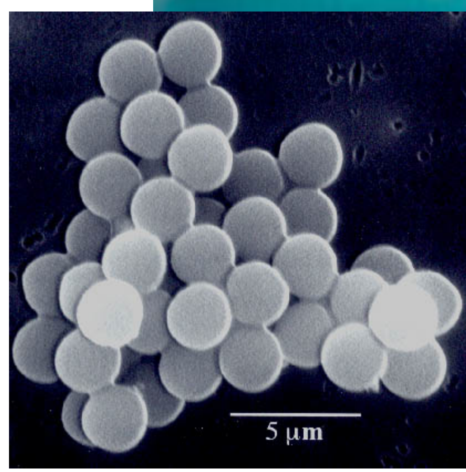
Therion Magnetic Pet Bed

Modern Magnetic Technology – Everywhere!

- Magnetic Material Systems
  - Spintronics (electron + spin)
  - “Soft” magnets
  - “Hard” or permanent magnets
- Advanced Applications:
  - Computer technology
  - Electrical distribution transformers
  - Sensors, Motors
- Other Applications:
  - Drug delivery
  - Cancer therapies
  - Biosensors

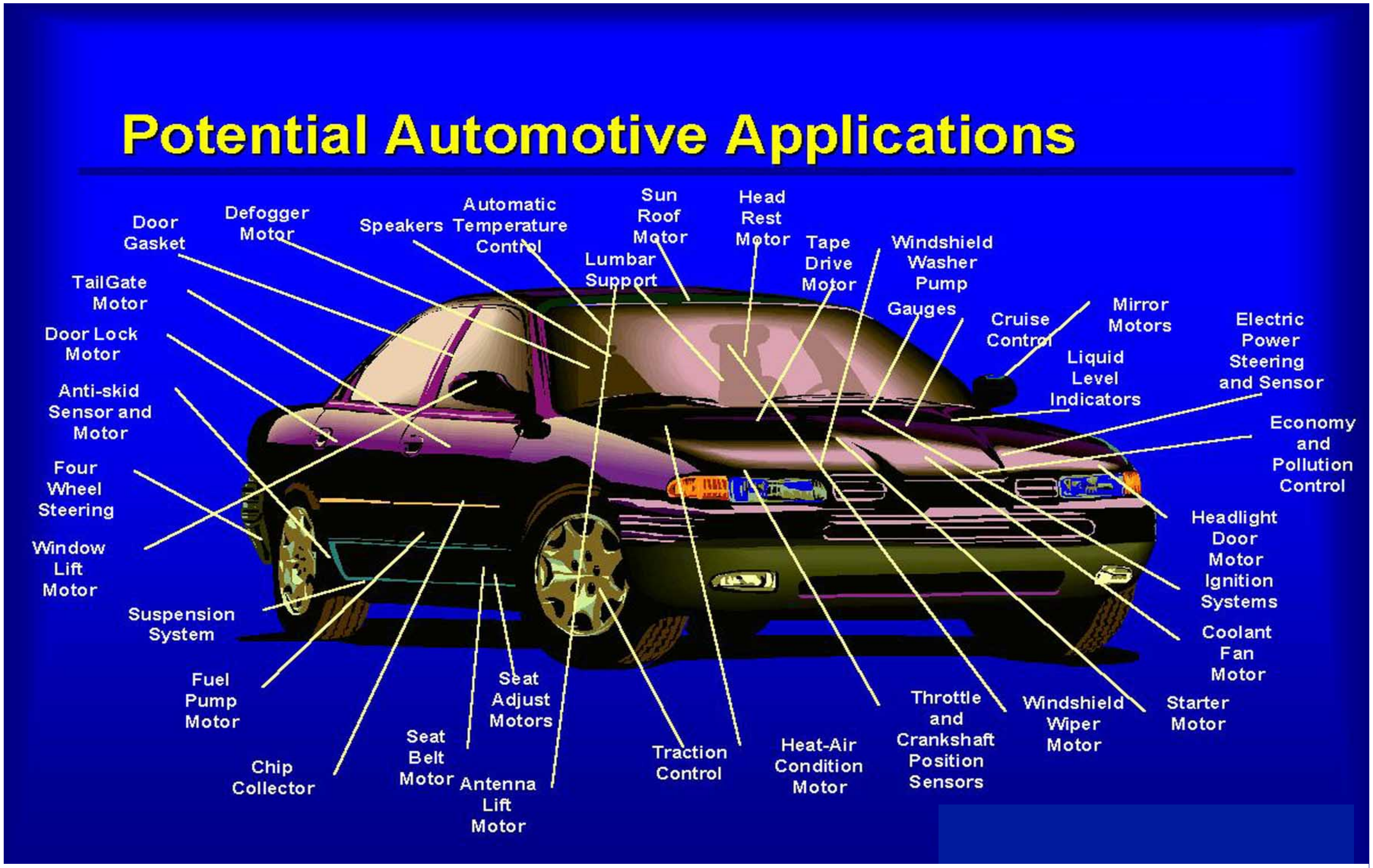
http://www.medscape.com/viewarticle/712338_7





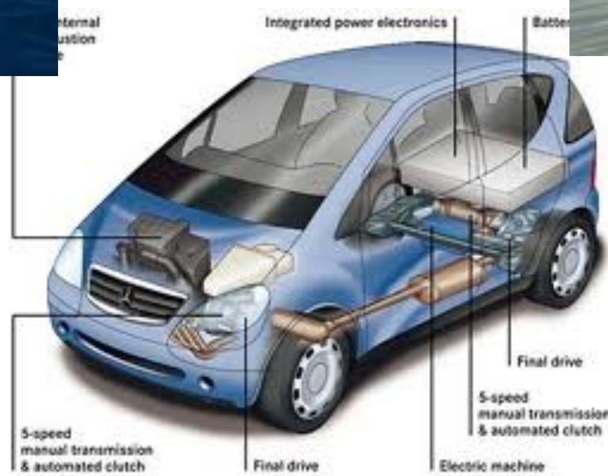
http://www.scs.illinois.edu/suslick/sonochemistry.html

Magnets and Transportation



Stronger, better magnets can save energy

Magnets and Energy

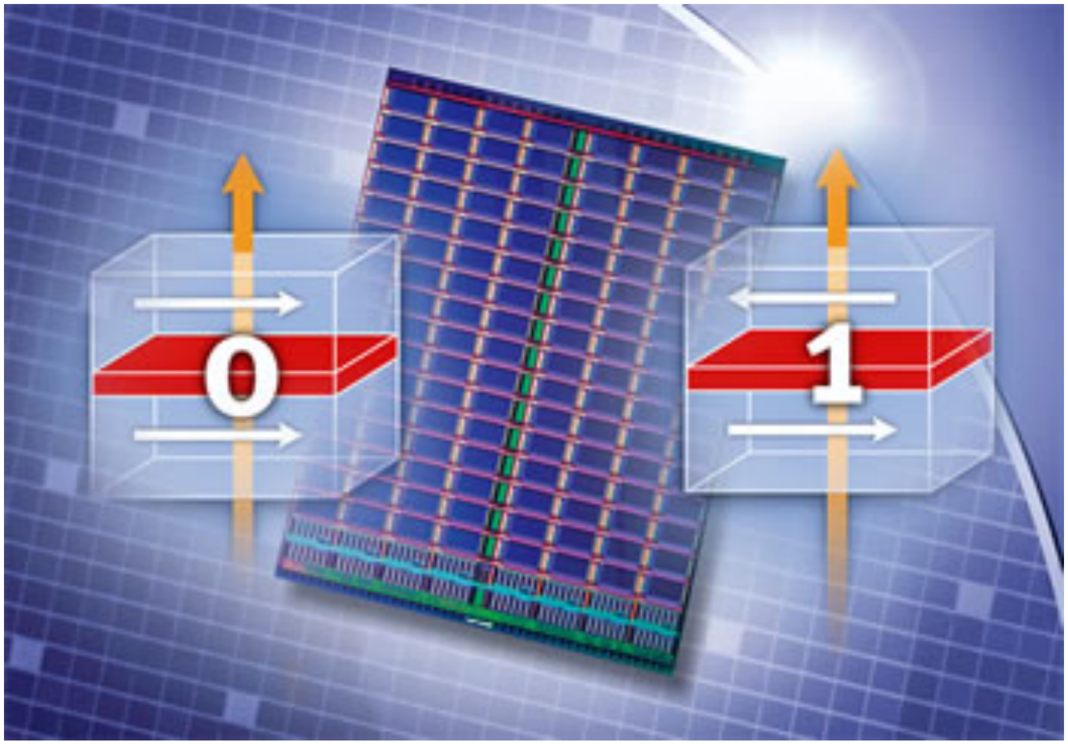


Magnets and the Military

Equipment/Hardware

Communications

Spintronics = “Spin transport electronics”

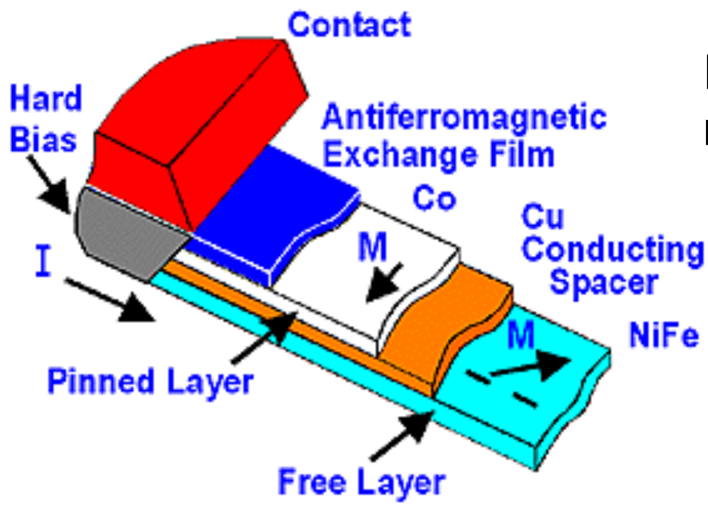


Create multi-state devices that utilize both **charge** & **spin** of electrons….

multi-component Modern Magnetic Devices:

- Majority of future magnetic devices will be based on a ***multi-component nanoscale architecture.***

example: Giant magnetoresistive (GMR) “Spin valve”: SPINTRONICS

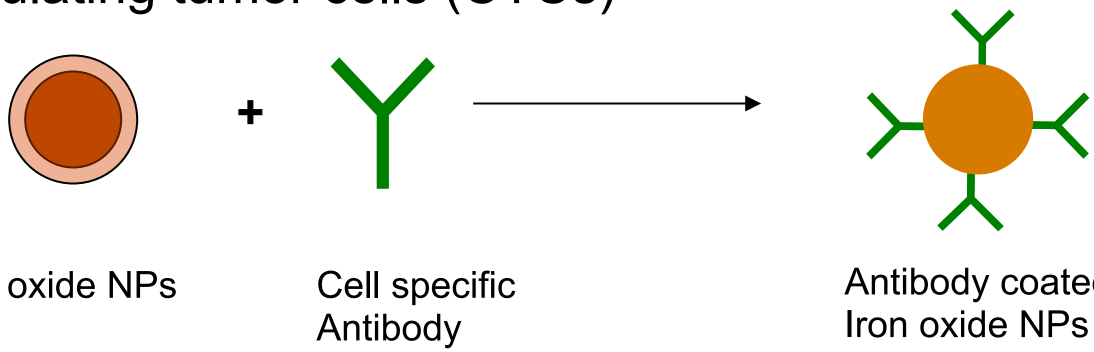


Electrical resistance varies with relative magnetic layer orietation

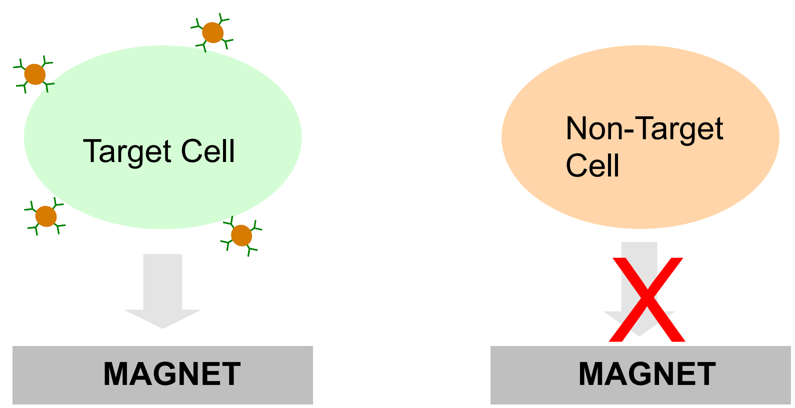
Typical dimensions < 200 Å

Medical Devices: Magnet in a Microfluidic Chamber

Step 1: Surface modification of Iron oxide NPs with antibodies to target circulating tumor cells (CTCs)



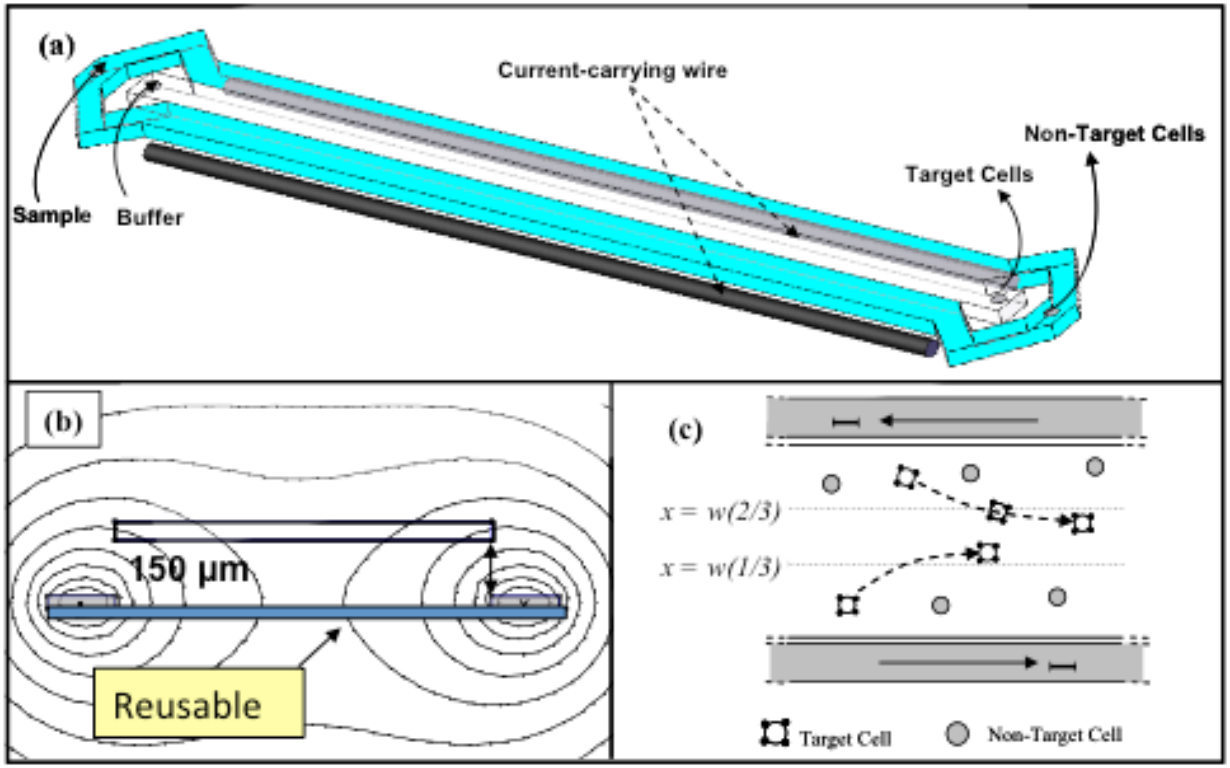
Step 2: Trapping of CTCs of interest in a microfluidic chamber using magnetic fields



Magnetic Cell Separation

Cancer Detection using Magnetic Nanoparticles

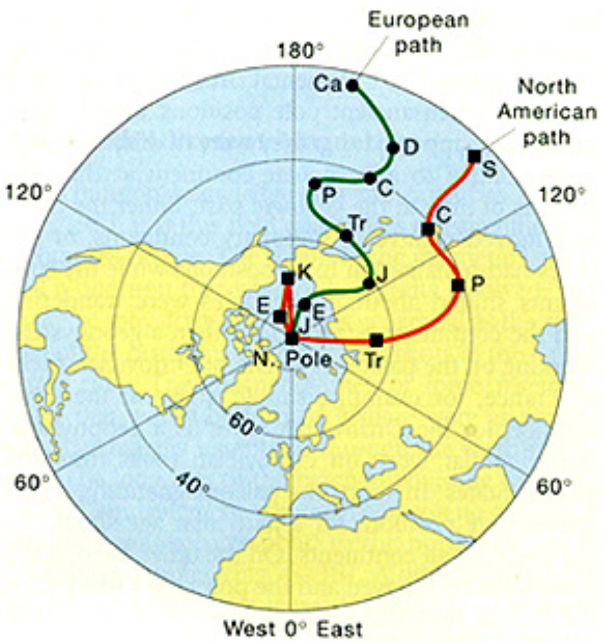
A important goal in biomedicine is the **detection of minute amounts of cancer cells** – especially in the earliest stage of development. Using MNPs as an agent for separation, a small number of cancer cells can be concentrated and collected for assaying.



B.D. Plouffe, L.H. Lewis, and S.K. Murthy. "Computational Design Optimization for Microfluidic Magnetophoresis," B*iomicrofluidics* 2011

Geomagnetism, Cosmomagnetism

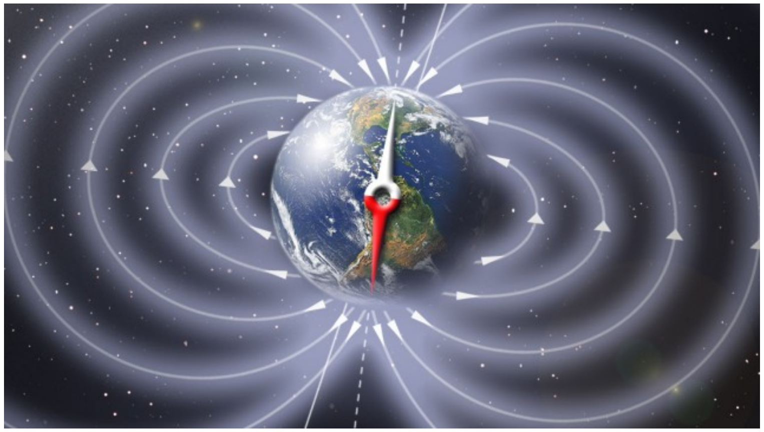
Wandering magnetic pole!



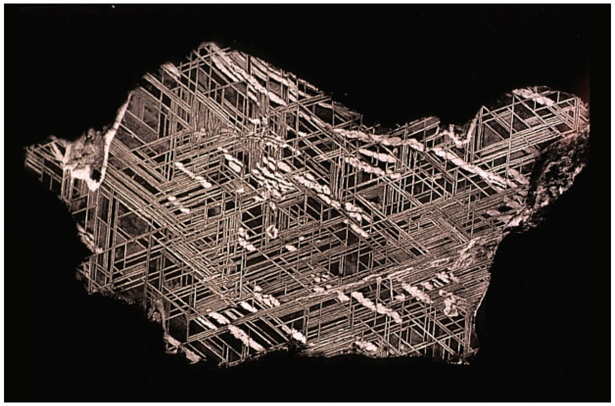
From H. Levin, The Earth Through Time, 4th Ed., Saunders

(from oldest to youngest: Ca = Cambrian; S = Silurian; D = Devonian; C = Carboniferous; P = Permian; T = Triassic; J = Jurassic; K = Cretaceous; E = Eocene)

Geomagnetic Reversal – Die-out of life on Earth?



http://cache.io9.com/assets/images/8/2011/02/earth-magfield.jpg



National Museum of Wales

Magnetism in meteorites contribute to understanding of origins of universe

Scientific & Technical Aspects of Magnetism

- Magnetism Basics
- Electrons & Atoms
- Clusters to Solids
  - Localized vs. Itinerant Electrons
  - Magnetic Domains
- Hysteresis
- Experimental Methods
- References

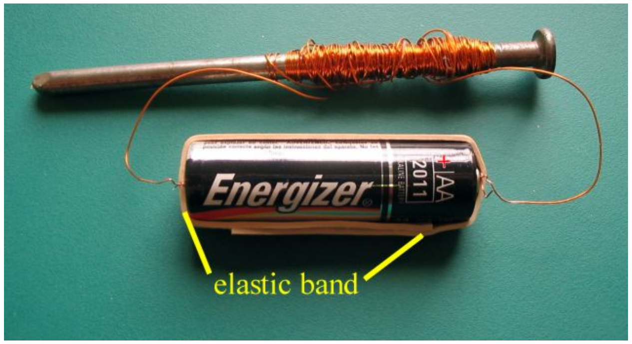
Magnetism Basics

Macroscopic Origins: Electricity and Magnetism

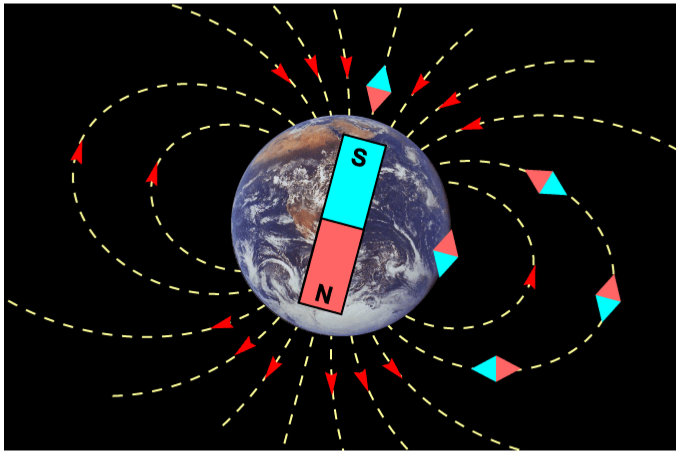
Magnets

Permanent Magnet

Electromagnet (wire coil)
"current-induced magnetism"



What about the earth?



Dynamo Effect
Due to convection of molten iron, within the outer liquid core, along with a Coriolis effect.

When conducting iron fluid flows across an existing magnetic field, electric currents are induced, which in turn creates another magnetic field to reinforce and sustain the field.

What is common about all these magnets?

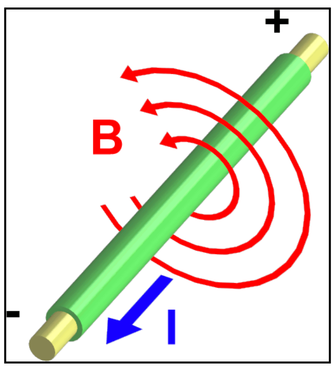
Origins of Magnetism

Magnetic fields are generated from **moving charges**.

Electromagnet

- an applied voltage makes electrons flow/move -

- moving electrons generate a magnetic field -



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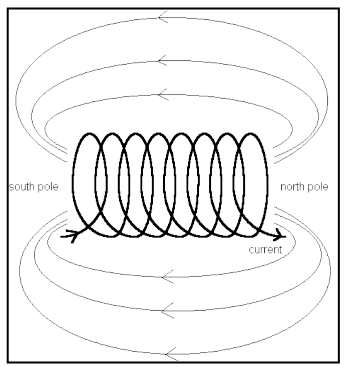

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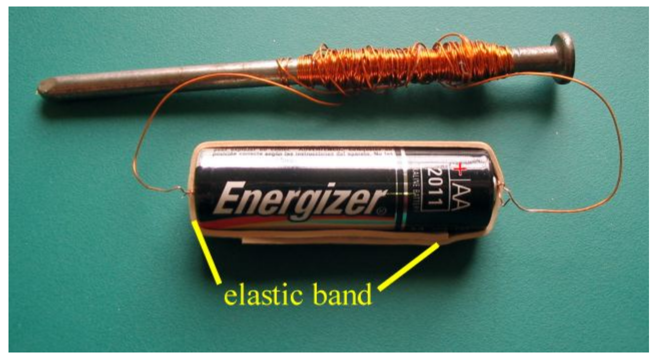
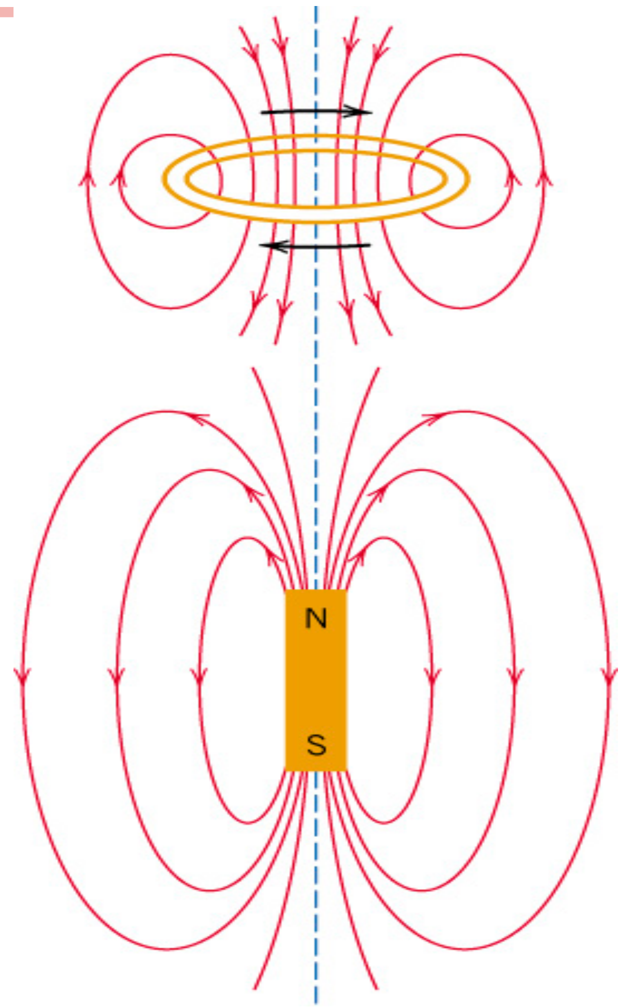


What about permanent magnets?
Where is the current?

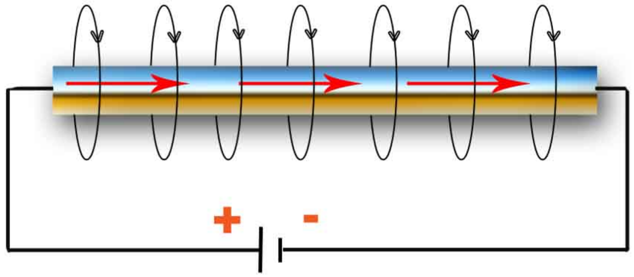
Current-carrying wire = magnet!

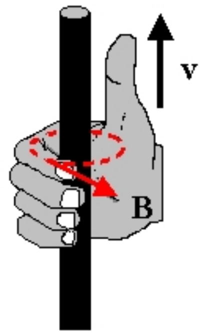
- Note similarity in flux lines between current in a ring (top) and a bar magnet (bottom)



Basic Electromagnetism

- A magnetic field is produced whenever there is electrical charge in motion
  - Conventional currents or "Ampèrian" currents are due to motion of electrons in a solid
- A current of **1 ampere** passing through **1 meter** of conductor generates a tangential magnetic field strength of $\frac{1}{4\pi}$ amps/m at a radial distance of **1 meter**





Calculations of magnetic field strength

- *Question:* How to calculate magnetic field strength generated by an electric current?

- *Answer*: the Biot-Savart law (1820) $\delta\vec{H} = \frac{1}{4\pi r^2} i\delta\vec{l} \times \hat{r}$

  – i = current flowing along an elemental length $\delta\vec{l}$ of conductor
  – $\hat{r}$ is a unit vector in the radial direction
  – $\delta\vec{H}$ is the contribution to the magnetic field at r due to the current element $i\delta\vec{l}$

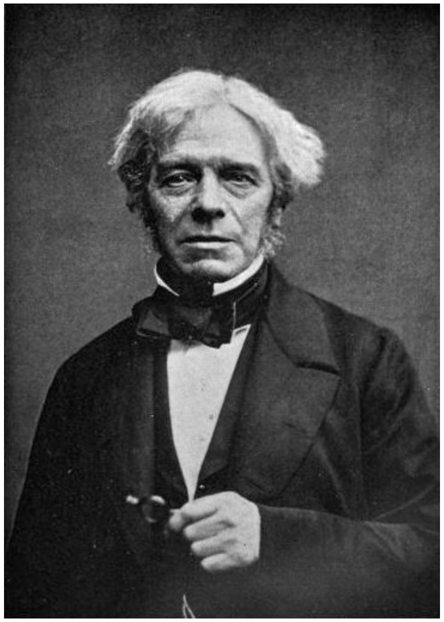
Question:

How are electric fields and magnetic fields related?

A: Faraday's Law & Ampère's Law

Andre-Marie Ampere (1775-1836)

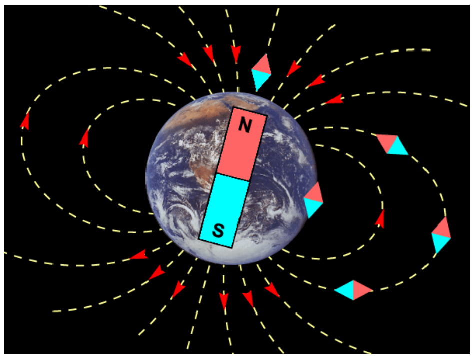
$$\nabla \times \vec{B} = \mu_0 \bar{J}$$

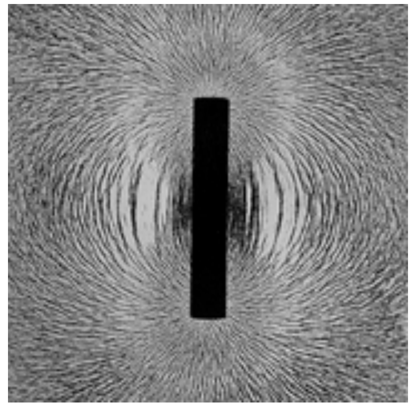


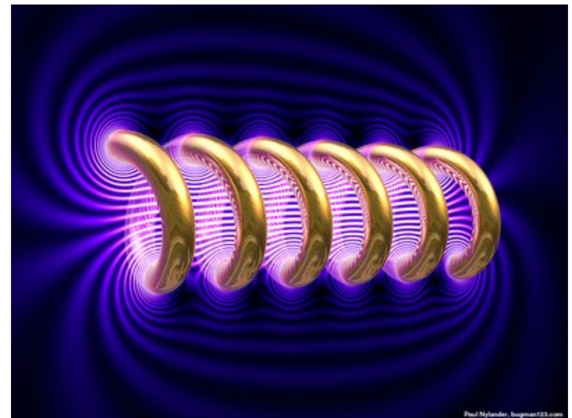
Michael Faraday, 1831

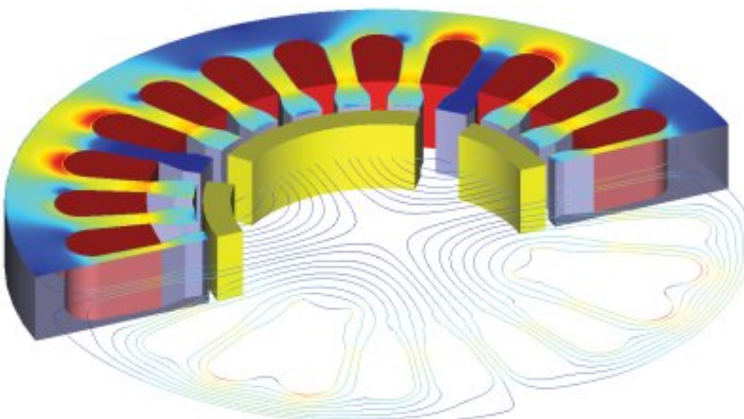
$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

What do magnetic field look like?

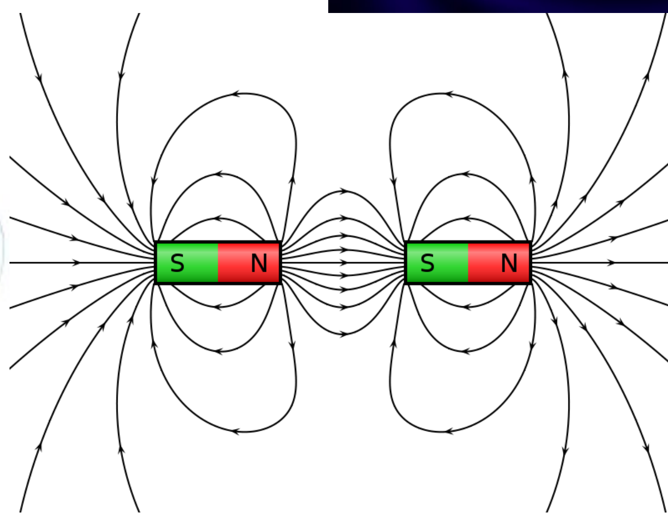








Flux distribution in a motor



Magnetic Induction *B* & Magnetic Field *H*

- *Question*: What is the relationship between ***B*** and ***H***?
- *Answer*: When a magnetic field has been generated in a medium by a current in accordance with Ampere's law, the medium will respond with a magnetic induction ***B*** ("magnetic flux density")
- The magnetic "flux density" is given in webers/m^2 = ***B***
- 1 weber per square meter = 1 Tesla

Magnetic Induction ***B*** & Magnetic Field ***H***

$$\vec{B} = \mu_0\left(\vec{H} + \vec{M}\right)$$

- SI units (Sommerfeld)

$$\vec{B} = \vec{H} + 4\pi\vec{M}$$

- EMU (Gaussian)

2 contributions to B: one from the field, one from the magnetization in a material

- 1 oersted = 1 Oe = $\left(\frac{1000}{4\pi}\right)\frac{A}{m} = 79.58\frac{A}{m}$
- 1 gauss = 1 G = $10^{-4}T$
- 1 $\frac{emu}{cm^3} = 1000\frac{A}{m}$

Units

- Can be extremely confusing!
- http://www.nist.gov/pml/electromagnetics/magnetics/upload/magnetic_units.pdf

Units for Magnetic Properties

Symbol	Quantity	Conversion from Gaussian and cgs emu to SI
Φ	magnetic flux	1 Mx → 10^{-8} Wb = 10^{-8} V·s
B	magnetic flux density, magnetic induction	1 G → 10^{-4} T = 10^{-4} Wb/m^2
H	magnetic field strength	1 Oe → $10^3/(4\pi)$ A/m
m	magnetic moment	1 erg/G = 1 emu → 10^{-3} A·m^2 = 10^{-3} J/T
M	magnetization	1 erg/(G·cm^3) = 1 emu/cm^3 → 10^3 A/m
$4\pi M$	magnetization	1 G → $10^3/(4\pi)$ A/m
σ	mass magnetization, specific magnetization	1 erg/(G·g) = 1 emu/g → 1 A·m^2/kg
j	magnetic dipole moment	1 erg/G = 1 emu → $4\pi \times 10^{-10}$ Wb·m
J	magnetic polarization	1 erg/(G·cm^3) = 1 emu/cm^3 → $4\pi \times 10^{-4}$ T
χ, κ	susceptibility	1 → 4π
χ_ρ	mass susceptibility	1 cm^3/g → $4\pi \times 10^{-3}$ m^3/kg
μ	permeability	1 → $4\pi \times 10^{-7}$ H/m = $4\pi \times 10^{-7}$ Wb/(A·m)
μ_r	relative permeability	$\mu \to \mu_r$
w, W	energy density	1 erg/cm^3 → 10^{-1} J/m^3
N, D	demagnetizing factor	1 → $1/(4\pi)$

Gaussian units are the same as cgs emu for magnetostatics; Mx = maxwell, G = gauss, Oe = oersted; Wb = weber, V = volt, s = second, T = tesla, m = meter, A = ampere, J = joule, kg = kilogram, H = henry.

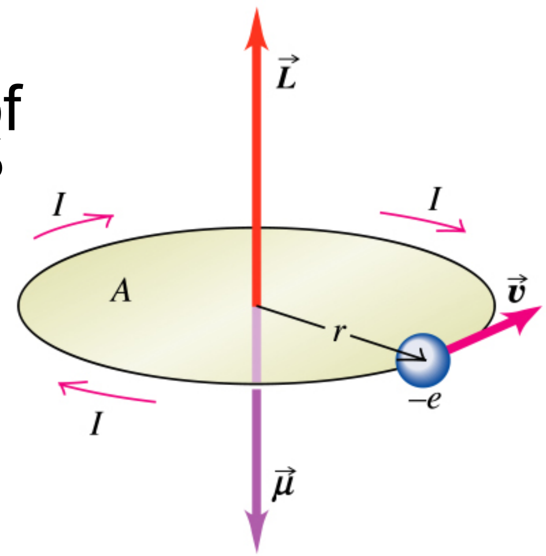
Developing intuition….

- What is the magnitude of the Earth's magnetic field?
  - *A*: Earth's magnetic field ***H*** = 56 A/m (0.7 Oe), ***B*** = 0.7 x 10^{-4} T
- *Q*: What is the saturation magnetization of iron?
  - *A*: Saturation magnetization M_S (T=0 K) of Fe = 1.7 x 10^6 A/m or 2.2 T

Magnetic moment and magnetization

- Magnetic moment μ of a current loop $\vec{\mu} = IA$

- The torque $\vec{\tau}$ on a dipole in the presence of a magnetic field in free space = $\vec{\tau} = \vec{\mu} \times \vec{B}$



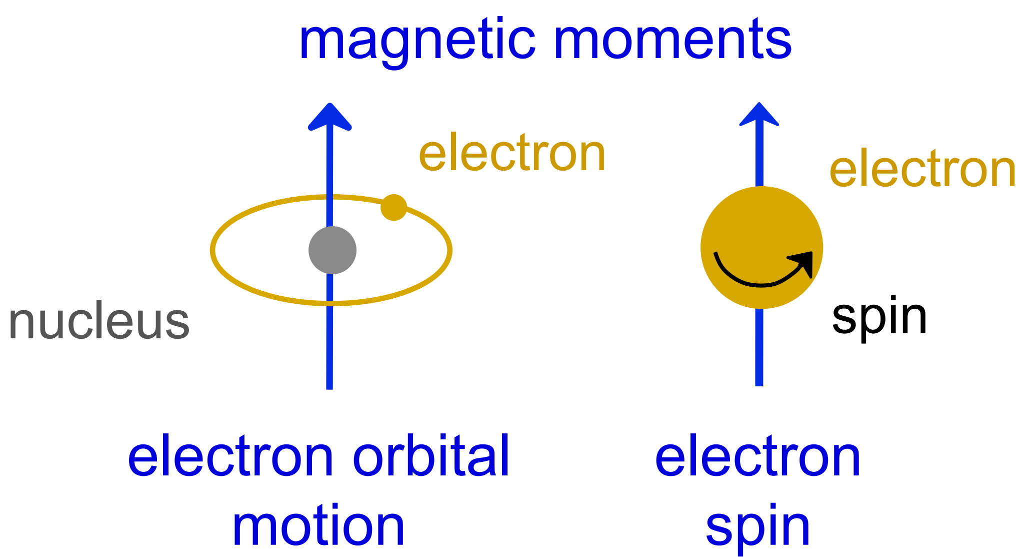
So in free space $\vec{m} = \dfrac{\tau_{\max}}{\mu_0 \vec{H}}$

Permeability: $\mu = \dfrac{\vec{B}}{\vec{H}}$; Susceptibility: $\chi = \dfrac{\vec{M}}{\vec{H}}$

Atomic origins of magnetism

Origins of Magnetic Moments: Simple View

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

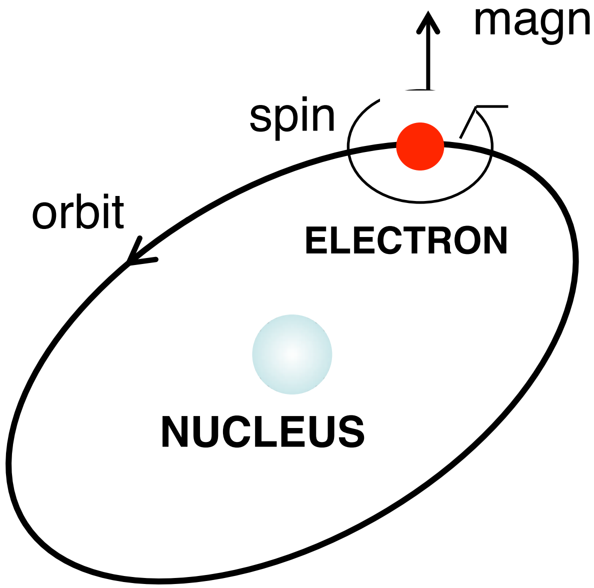


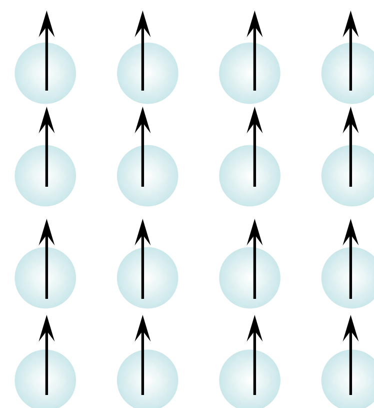
Adapted from Fig. 18.4, *Callister & Rethwisch 3e*.

Net atomic magnetic moment = sum of moments from all electrons.

magnetism: atomic origins

magnetic moment $\mu_B = \dfrac{e\hbar}{2m_e}$

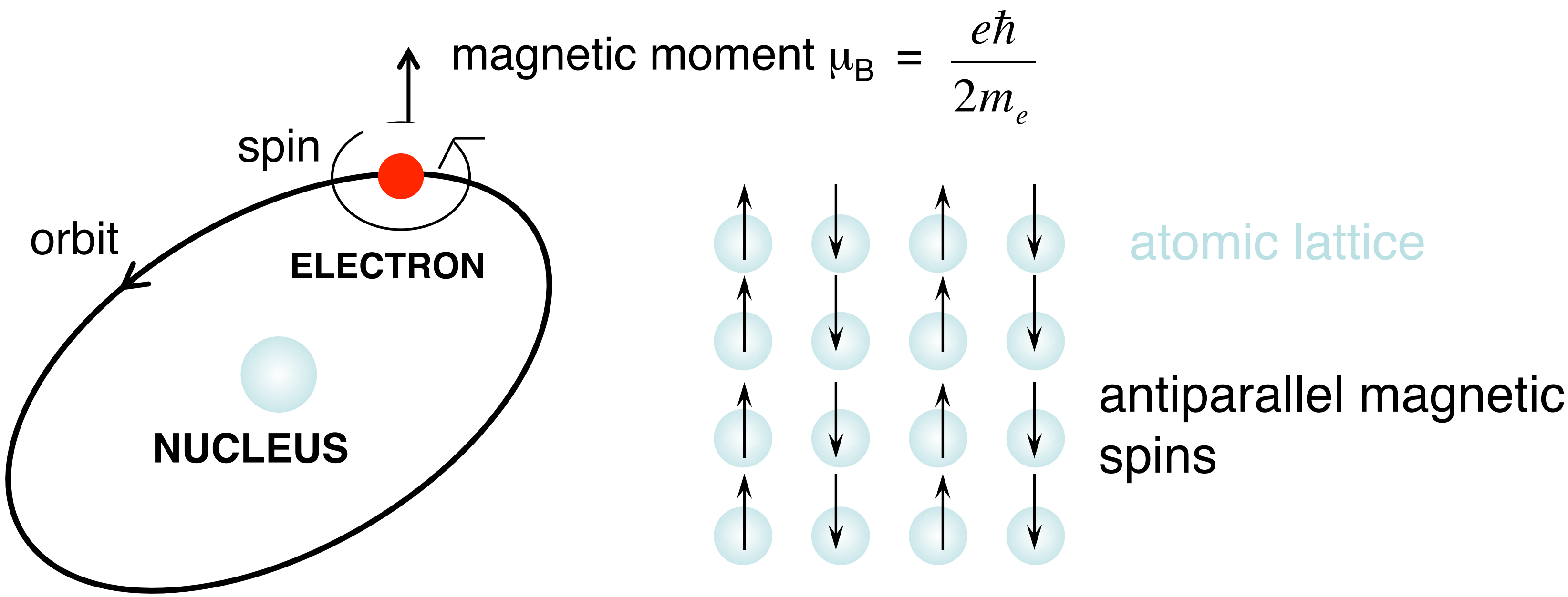




Parallel spins = "ferromagnetism"

- Feature: *Curie Temperature*
  - The temperature above which a ferromagnetic material loses its magnetism

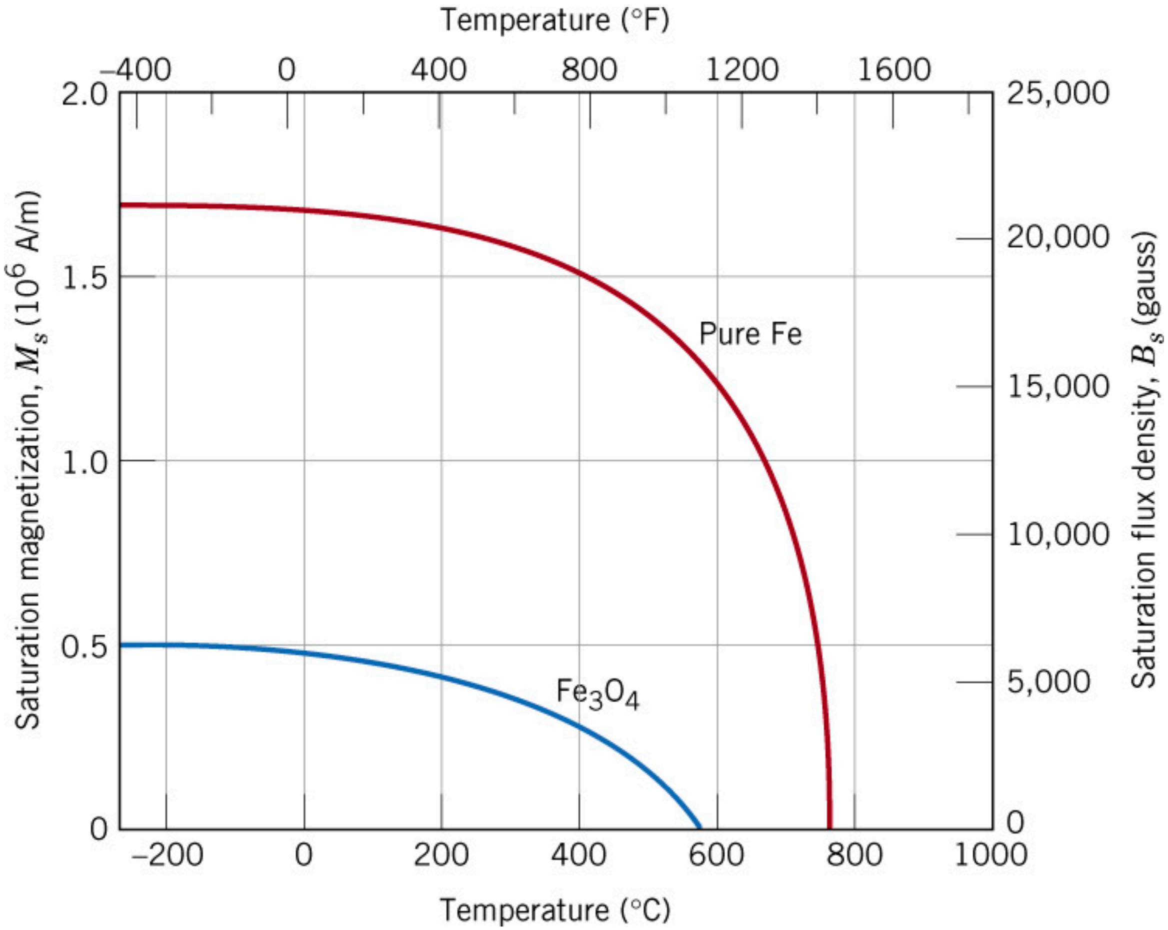
magnetism: atomic origins



antiparallel spins = “antiferromagnetism”

- Feature: *Néel Temperature*
  - The temperature above which an antiferromagnetic material loses its magnetism

Curie temperature comparisons



Categories of Magnetism

- Can utilize the susceptibility χ to categorize types of magnetism:
  - χ is small and negative ($\sim -10^{-5} - 10^{-6}$): **DIAMAGNETIC**
    - *examples*: gold, copper, silver, bismuth, silica, many molecules (and superconductors)
  - χ is small and positive ($\sim 10^{-3}$ or 10^{-6}): **PARAMAGNETIC**
    - *examples*: aluminum, platinum, manganese
  - χ is large and positive (>>1; 50 – 10,000): **FERROMAGNETIC**
    - *examples*: iron, cobalt, gadolinium

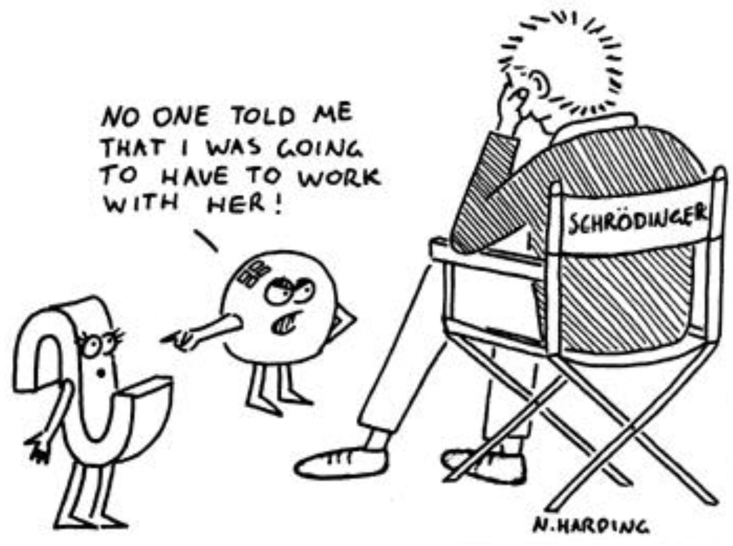
WILL BE REVISITED LATER IN THIS INTRODUCTION

The Quantum World of the Electron

Magnetism of Electrons

The magnetism of an electron is rooted in **quantum mechanics**

An electron is **both** a particle and a wave. In wave mechanics, the electron is represented by a complex **wave function** $\psi(r)$



http://stochastix.wordpress.com/2007/09/06/wave-particle-duality-a-cartoon/

$\psi^*(\vec{r})\psi(\vec{r})\delta^3 r$ is the probability (0 ➔ 1) of finding an electron in a volume $\delta^3 r$ at a position $\vec{r}$.

The Schroedinger Equation

- One can solve for the motion of the electron in a particular potential by solving the Schroedinger Equation:

$$H\psi = E\psi$$

where *H* is the Hamiltonian Operator and *E* is energy.

For a single electron in a central potential:

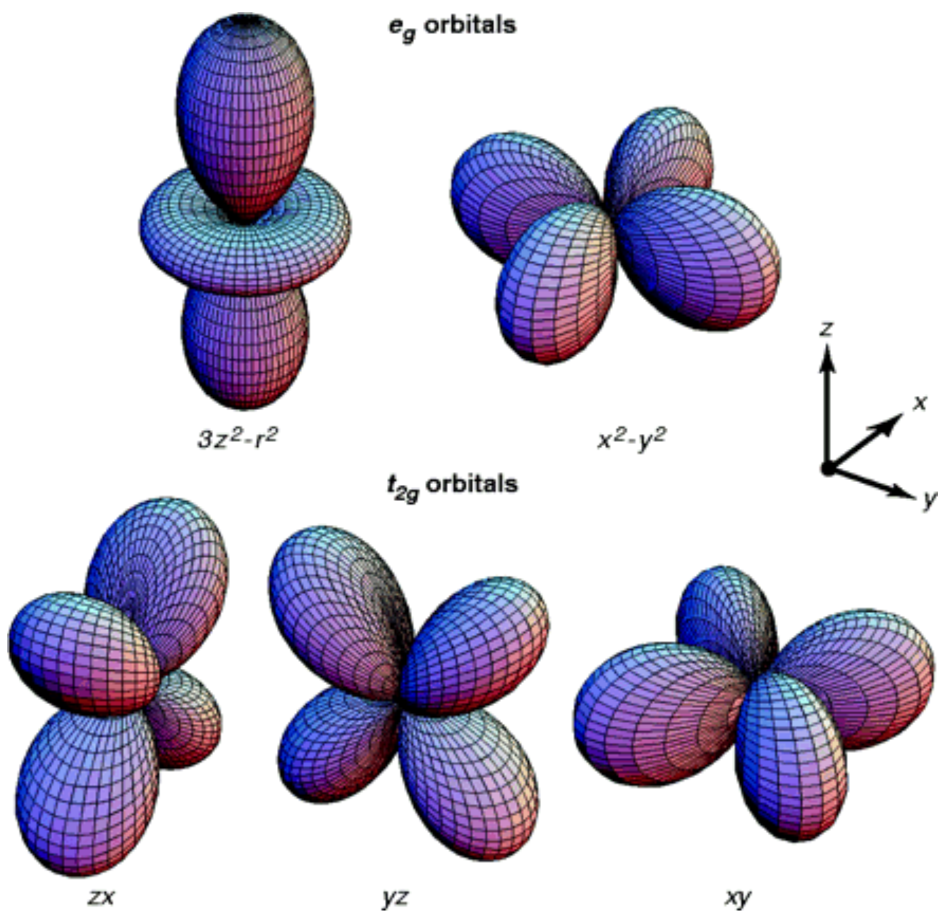
$$H = -\frac{\hbar^2}{2m_e}\nabla^2 - \frac{Ze^2}{4\pi e_0 r}$$

- $\hbar$ = Planck's constant
- m_e = mass of electron
- Z = atomic number
- *e* = charge of electron
- ε_0 = permittivity of free space
- r = radius

What do solutions to the Schroedinger Equation look like?

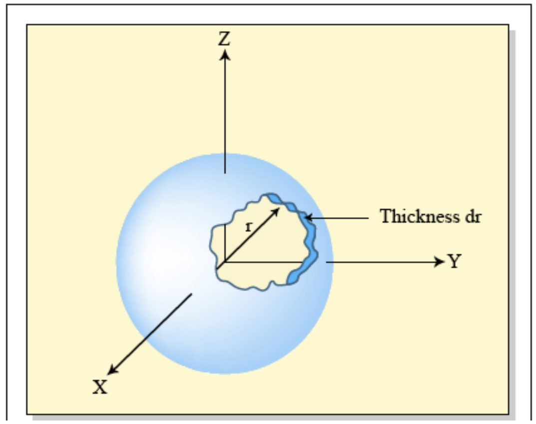
Solutions to the Heisenberg Equation

d orbitals!



How do we get those shapes? (<ψ*ψ>)

- Radial electron probability density:



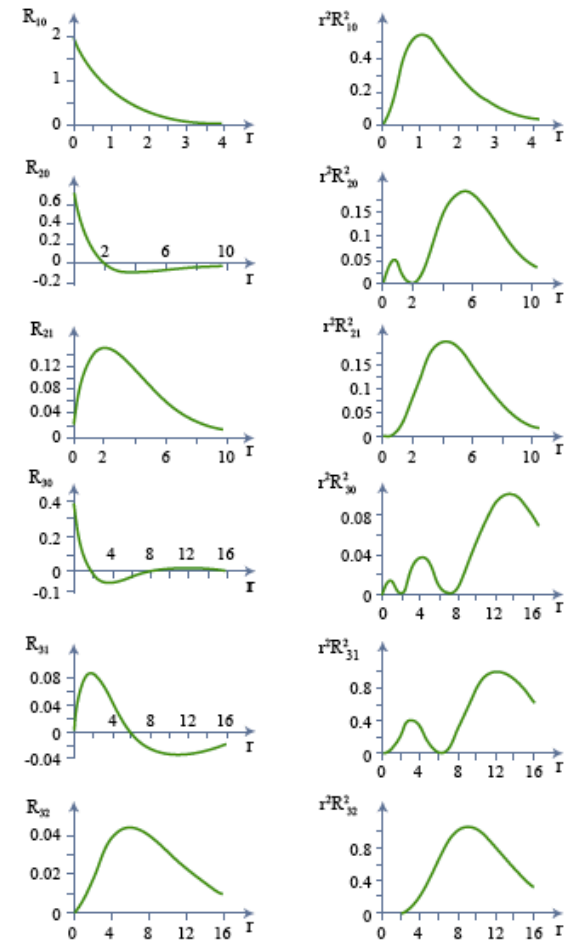
For a single particle in three dimensions:

$$i\hbar\frac{\partial}{\partial t}\psi = -\frac{\hbar^2}{2m}\nabla^2\psi + V(x,y,z)\psi$$

where

- ψ is the wavefunction, which is the amplitude for the particle
- m is the mass of the particle.
- $V(x,y,z)$ is the potential energy the particle has at each position.

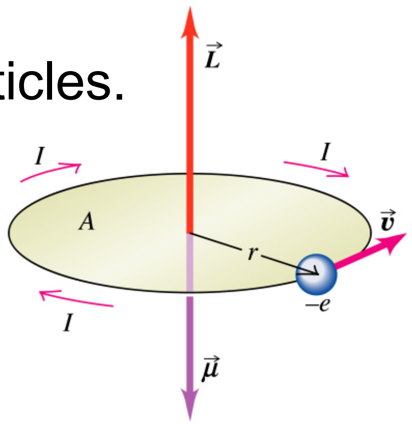
Solve the Schroedinger Eqn. in spherical coordinates



Radial functions $R_{nl}(r)$ and radial distribution functions $r^2R^2_{nl}(r)$ for atomic hydrogen. The unit of length is $a_\mu = (m/\mu)\ a_0$, where a_0 is the first Bohr radius.

Orbital and spin moments - *revisited*

- Quantum mechanics lead to understanding of the quantization of **angular momentum** of elementary particles.
- Electrons have angular momentum:
  - from **orbital motion** around the nucleus;
  - from **spin** of the electron



- Definition of angular momentum: $\vec{l} = m_e \vec{r} \times \vec{v}$
  - Application to magnetism:

    magnetic moment $m = -\frac{e}{2m_e}\vec{l}$; angular momentum is quantized:

    component of *m* in a particular direction: $m_z = -\frac{e}{2m_e} m_l \hbar$

    m_l = orbital magnetic quantum number

$$\frac{e\hbar}{2m_e} = \mu_B =$$ **Bohr Magneton**!!

Properties of Electrons

- Occur in discrete (quantized) energy levels or orbitals around the nucleus
- **Behave as particles with wave-like properties**
- Position of an electron in space around the nucleus is a probability function defined by 4 quantum numbers

n – principle quantum number (= 1, 2, 3, 4...)
defines the **energy level** of the primary electron shell

l – azimuthal quantum number (= *n* -1)
defines the type and number of electron **subshells** (s, p, d, f, ...)

m – magnetic quantum number (= +*l* to -*l*)
defines orientation and number of **orbitals** in each subshell

s – spin quantum number (= +1/2 or -1/2)
defines direction of **spin of the electron** in each orbital

Electron Shells, Subshells, and Orbitals

TABLE 3.4 Summary of the Three Quantum Numbers

Principal Quantum Number, *n* (Shell)	Azimuthal Quantum Number, *l* (Subshell)	Subshell Designation	Magnetic Quantum Number, *m* (Orbital)	Number of Orbitals in Subshell	Maximum Number of Electrons	
1 (K)	0	1*s*	0	1	2	2
2 (L)	0	2*s*	0	1	2	8
	1	2*p*	−1, 0, +1	3	6	
3 (M)	0	3*s*	0	1	2	18
	1	3*p*	−1, 0, +1	3	6	
	2	3*d*	−2, −1, 0, +1, +2	5	10	
4 (N)	0	4*s*	0	1	2	32
	1	4*p*	−1, 0, +1	3	6	
	2	4*d*	−2, −1, 0, +1, +2	5	10	
	3	4*f*	−3, −2, −1, 0, +1, +2, +3	7	14	

Recipe to build the Periodic Table

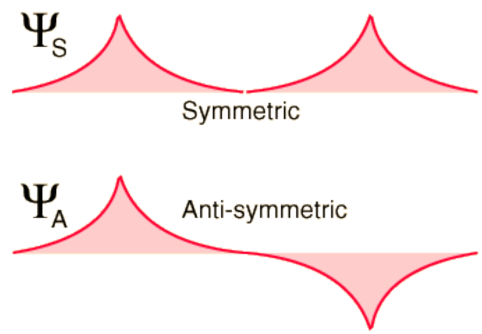
Quantum Mechanical Exchange: *J*

- Electrons interact via quantum mechanical rules:
  - *Pauli principle*: 1 electron per quantum state

Imagine 2 electrons that change places in an interaction.

Since electrons are indistinguishable:

$$|\psi(1,2)|^2 = |\psi(2,1)|^2$$



AND

Electrons are “fermions” thus $\psi(1,2) = -\psi(2,1)$

The Exchange Force

- Construct a system *f*(spin) & *f*(position):

$$\Psi_{tot} \approx \phi(r_{1-2})\psi(s_1,s_2) \pm \phi(r_{2-1})\psi(s_2,s_1)$$

- **Conclusion**: when one tries to put two electrons in the same place, there is **zero probability** of finding them there: it is as if a FORCE is keeping them apart.

This is the EXCHANGE FORCE: $\varepsilon = -2\left(\frac{J}{\hbar^2}\right)\vec{s}_1 \cdot \vec{s}_2$

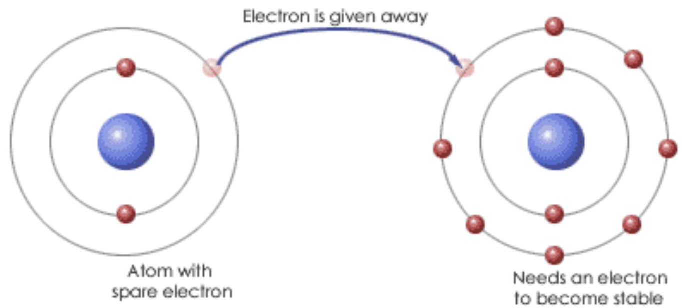
where *J* is the "exchange integral" that describes interelectronic interactions:

$$J = \int \psi_1^*(r')\psi_2^*(r)H(r,r')\psi_1(r)\psi_2(r')dr^3d^3r$$

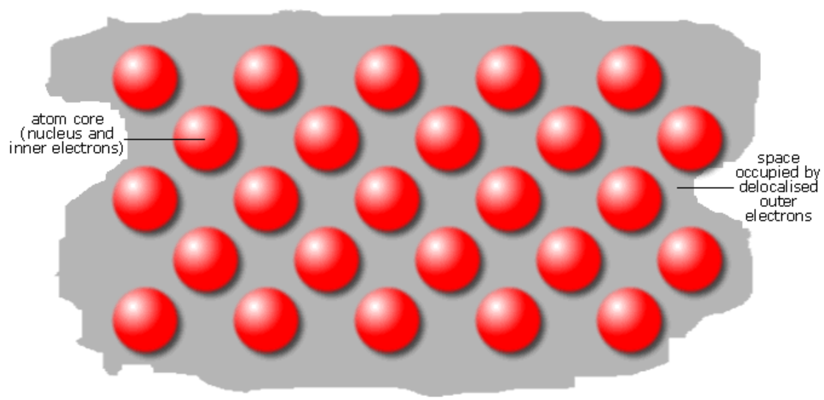
Localized *vs*. Itinerant Electrons

Magnetic behavior is derived from interactions between electrons

Approach depends on the system character



Localized electron system

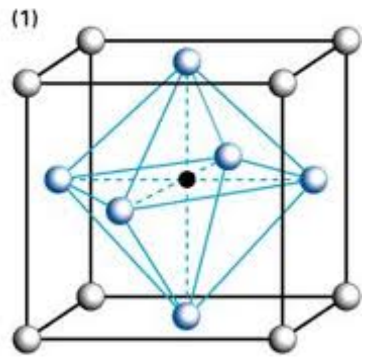


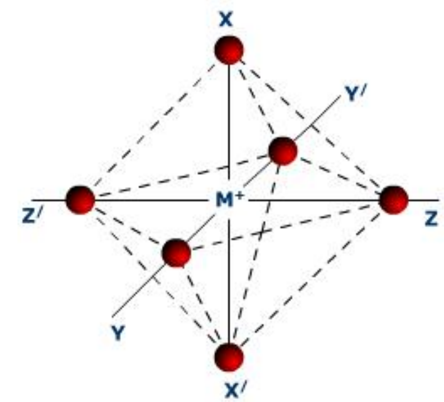
Itinerant electron system

- "Localized" systems: electrons are identified with a particular site or atom (oxides)
- "Itinerant" systems: electrons belong to the entire system; in a sea of electrons (metals)
- (what about in-between? = "Strongly correlated electron systems")

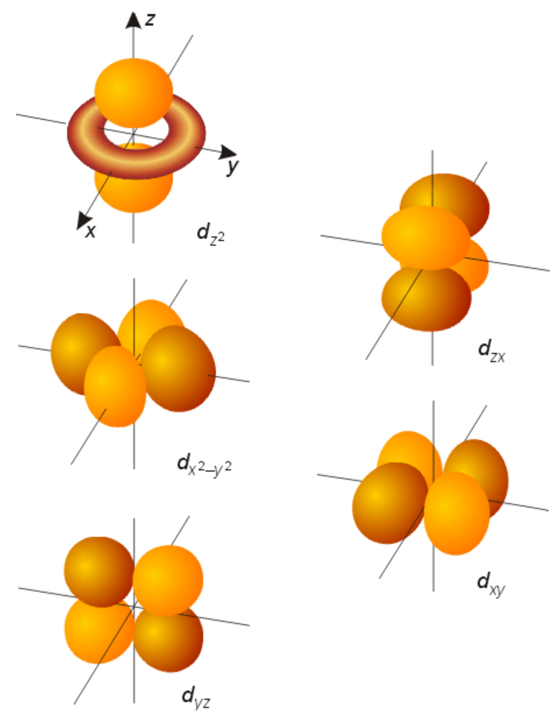
Localized electron magnetism: “crystal field theory”

Example = Perovskite ABO_3
($LaMnO_3$, etc)

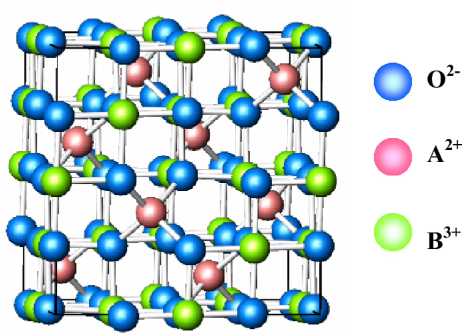


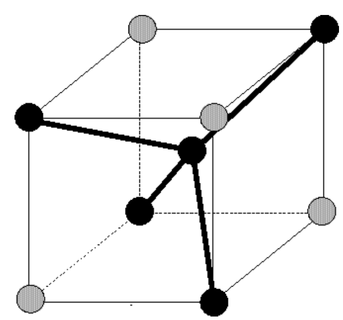


Octahedral interstice



Example = spinel ferrite AB_2O_4
(Fe_3O_4, $ZnFe_2O_4$, etc.…)





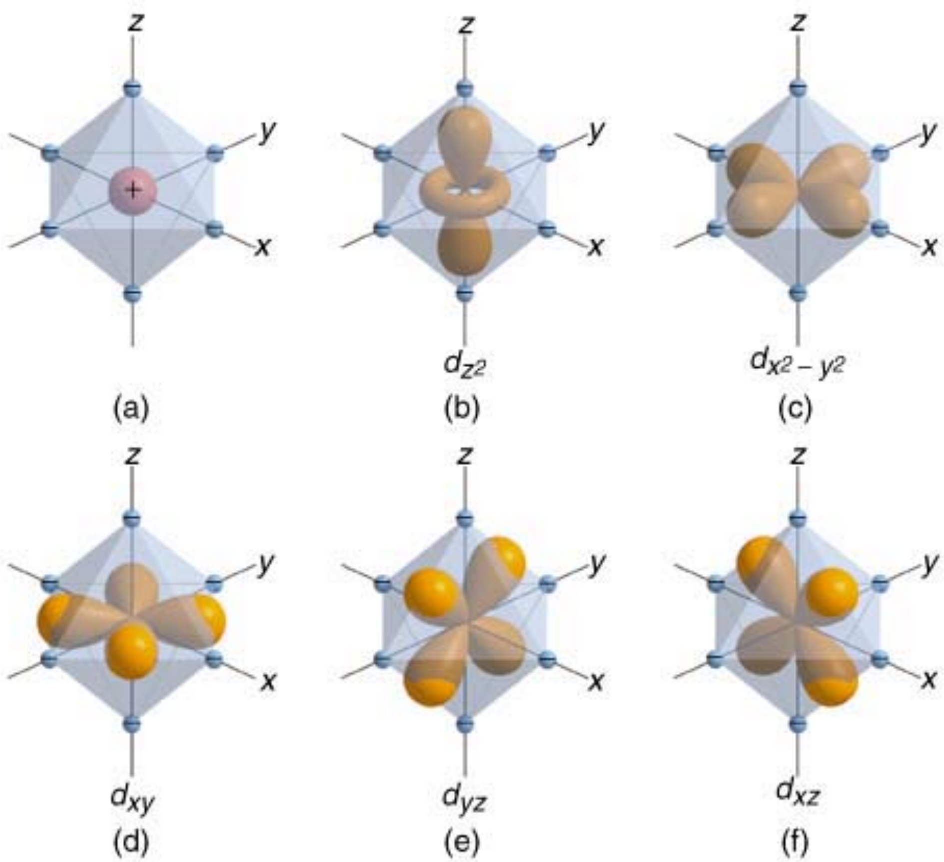
tetrahedral interstice

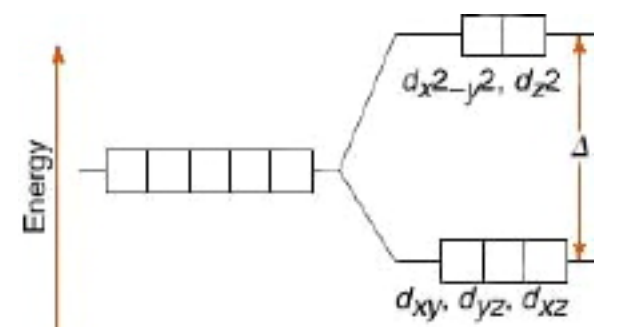
Transition-metal *d*-orbitals

The distribution of electrons in a “localized” solid is described using Crystal Field Theory

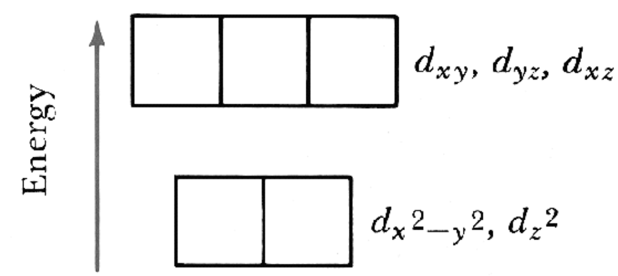
The effective field “felt” by an electron is called the Crystalline Electric Field or “CEF”

CEF and transition-metal oxide magnetism





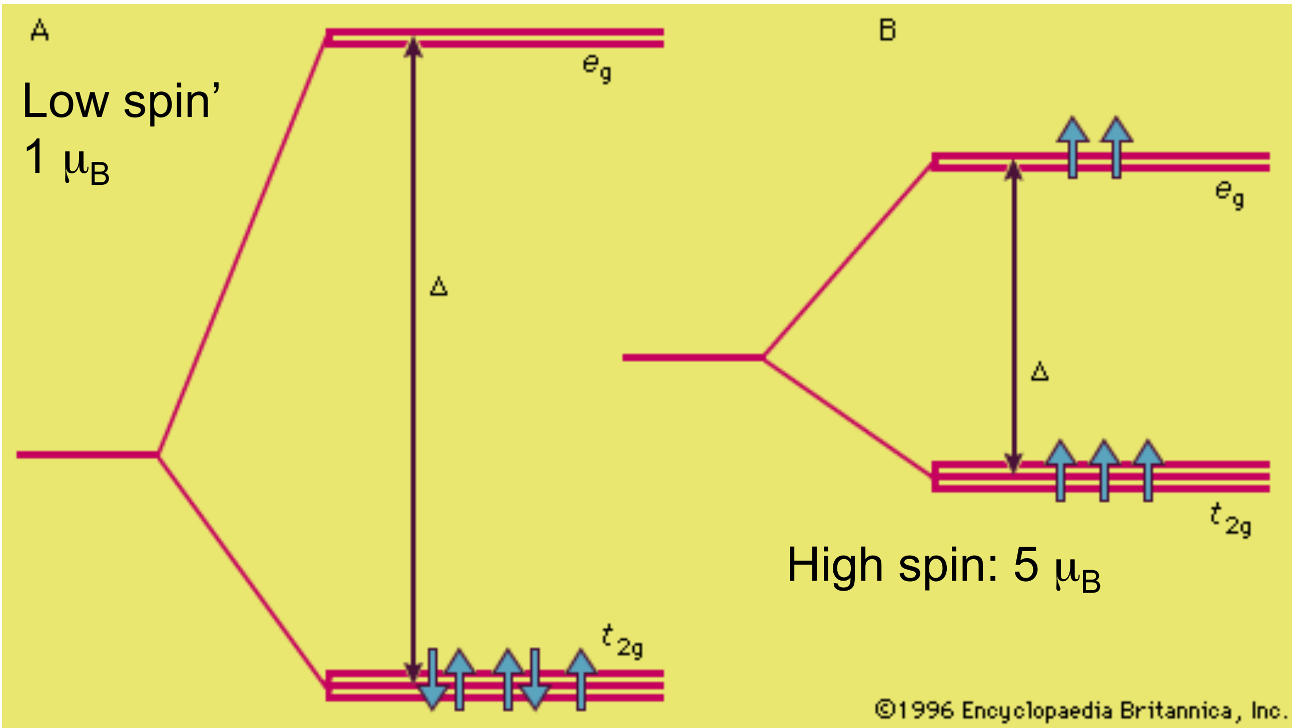
Octahedral configuration



Tetrahedral configuration

Magnetic moment: high-spin *vs* low-spin

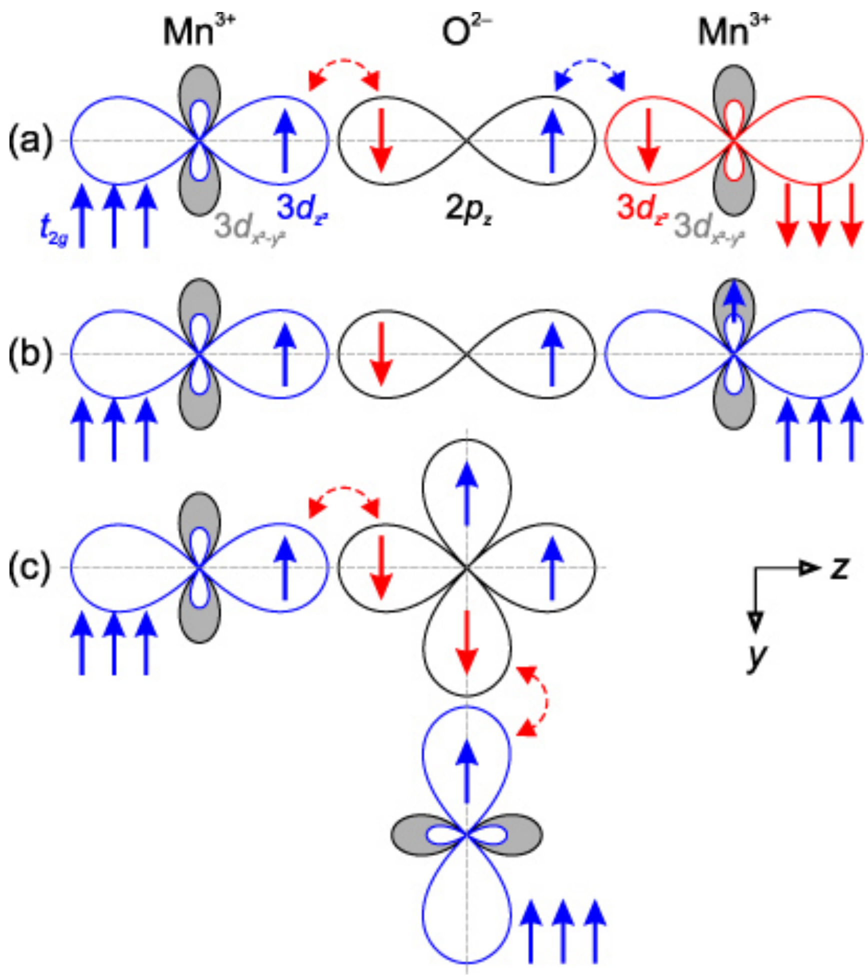
MnO = $Mn^{2+}O^{2-}$



Mn =$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^5\ 4s^2$

Mn^{2+} =$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^5$

Superexchange: TM-oxide-TM bonding & magnetism



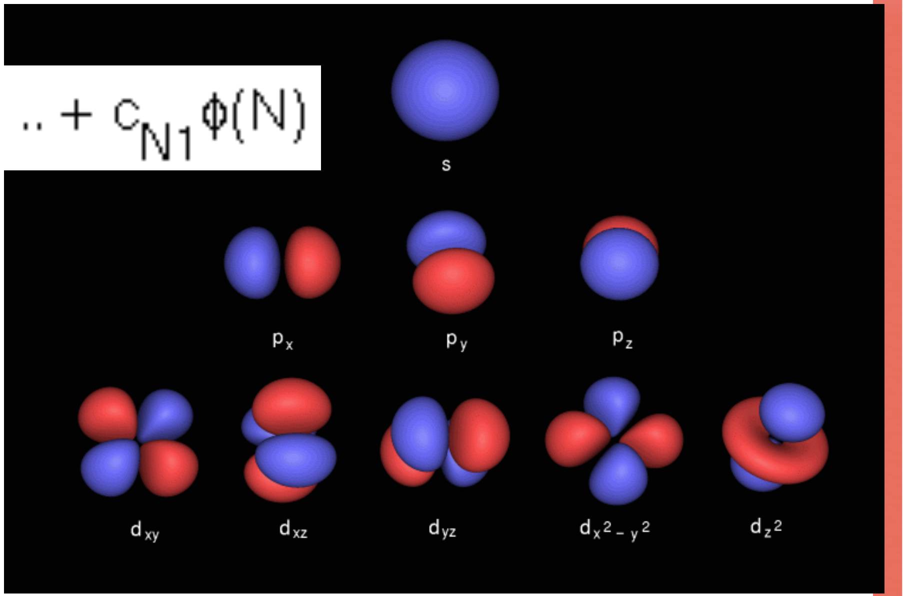
Note antiferromagnetic and ferromagnetic interactions here (Goodenough – Kanamori rules)

Journal of Physics D: Applied Physics
Volume 45 Number 3
Matthias Opel 2012

Itinerant magnetism: use Band Theory

- The band model, proposed by Bloch, is a molecular-orbital model of metallic crystals.
- Orbital characteristic of the whole crystal obtained as linear combinations of the atomic orbitals of the individual atoms.

$$\psi(1) = c_{11}\phi(1) + c_{21}\phi(2) + c_{31}\phi(3) + .. + c_{N1}\phi(N)$$



"LCAO" method: Linear Combination of Atomic Orbitals

How to build electronic energy bands

Building a crystal

- Consider the formation of a linear array of lithium atoms from individual lithium atoms:

Li   Li–Li   Li–Li–Li   Li–Li–Li–Li ...

(Li_2)   (Li_3)   (Li_4) ....

- Li_2: 2 Li atoms bound together by a pair of valence electrons:
  - each lithium atom supplies its 2s-electron which, through orbital overlap, forms a covalent molecular bond

- Li_3: 3 atomic valence electron clouds overlap to form one continuous distribution.

Building a crystal….

- As the length of the Li chain is increased, the number of electronic states into which the atomic 2s state splits also increases
  – the number of states = number of atoms.

- Finally obtain the symmetry and size of a lithium crystal

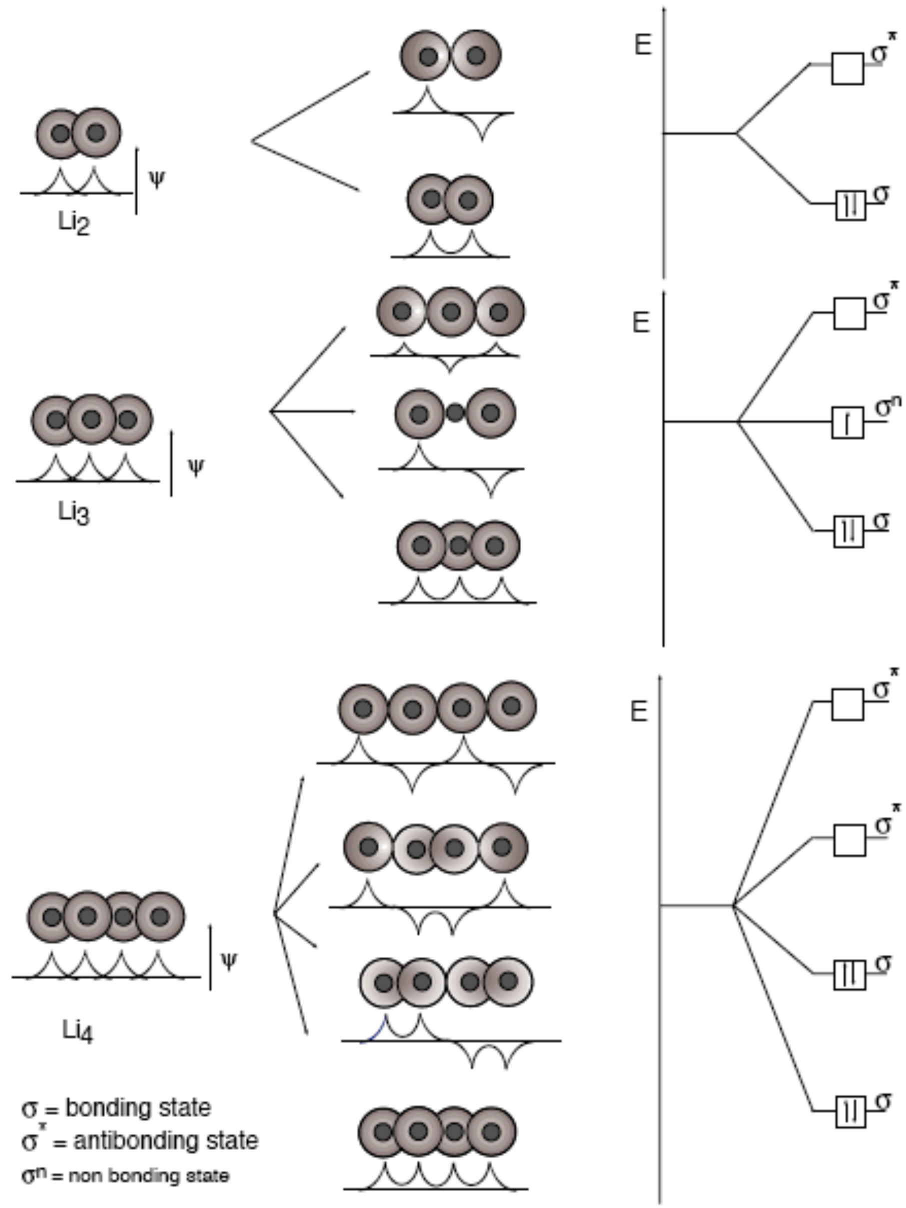


Figure 3 Formation of molecular chains of lithium atoms.

Result: The "manifold" of energy states

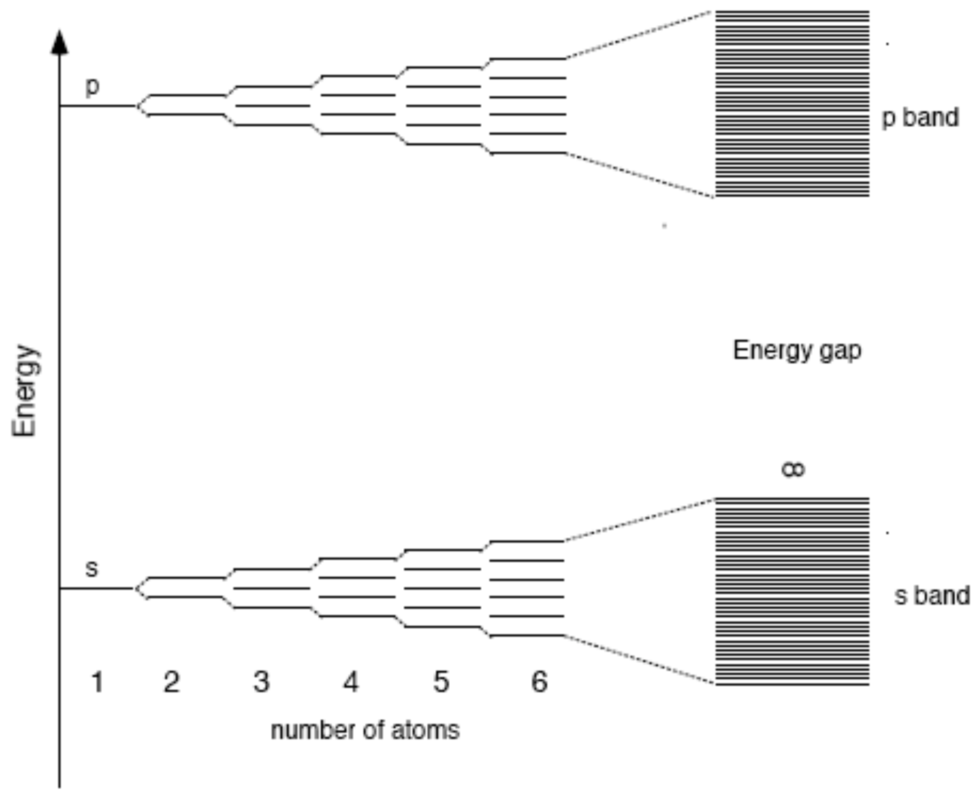


Figure 4 Formation of energy bands from energy levels of constituent atoms

Energy Bands! cont'd

- Bands of allowed electron energies ~ overlap of electron wave functions.
- The width of each energy band is a function of the crystal structure because it determines the number of nearest neighbors in the crystal.

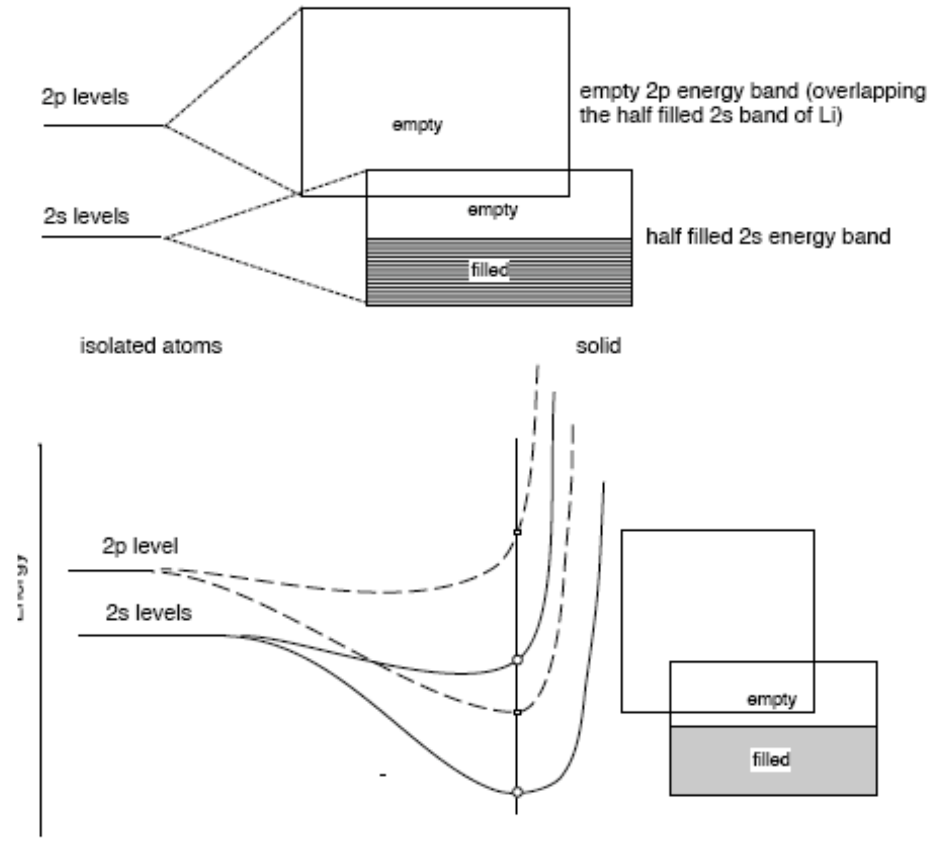
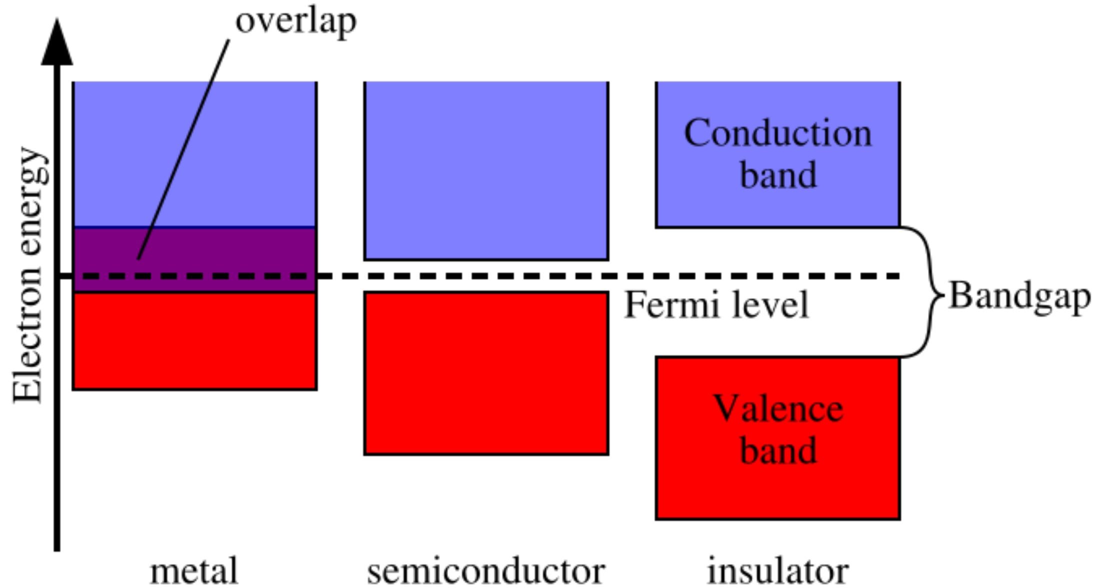


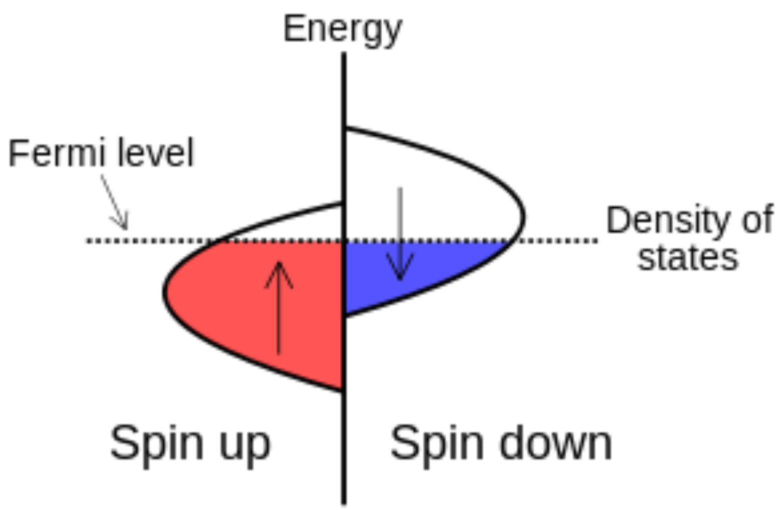
Fig. 5 Schematic energy band configuration for Li .

A Few Definitions…

- **Valence band**: highest energy band, at least partially occupied
- **Core band**: includes all the energy bands below valence band
- **Conduction band**: band with higher energy than valence band
- **Band gap**: Magnitude of "forbidden zone" between valence & conduction bands
- **Fermi Level:** the energy of the highest occupied quantum state at absolute zero temperature.



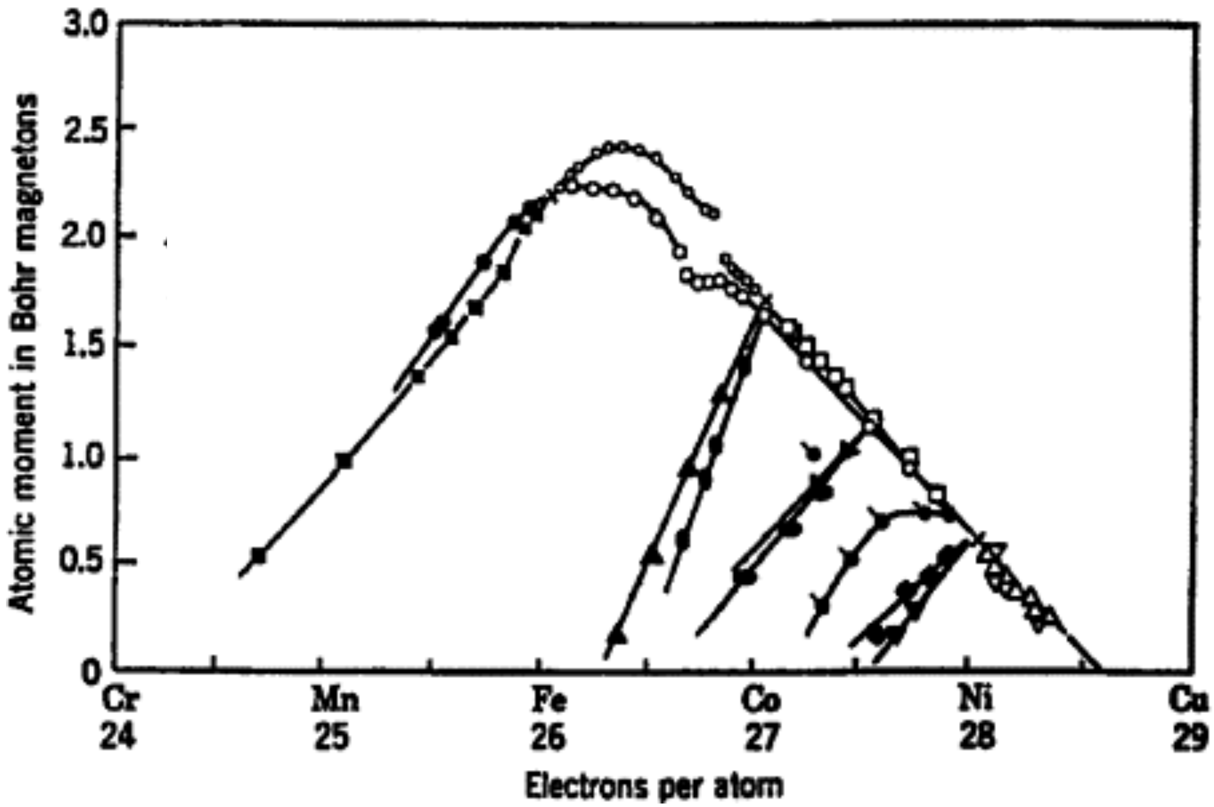
Band Magnetism



A schematic band structure for the Stoner model of ferromagnetism. An exchange interaction has split the energy of states with different spins, and states near the Fermi level are spin-polarized.

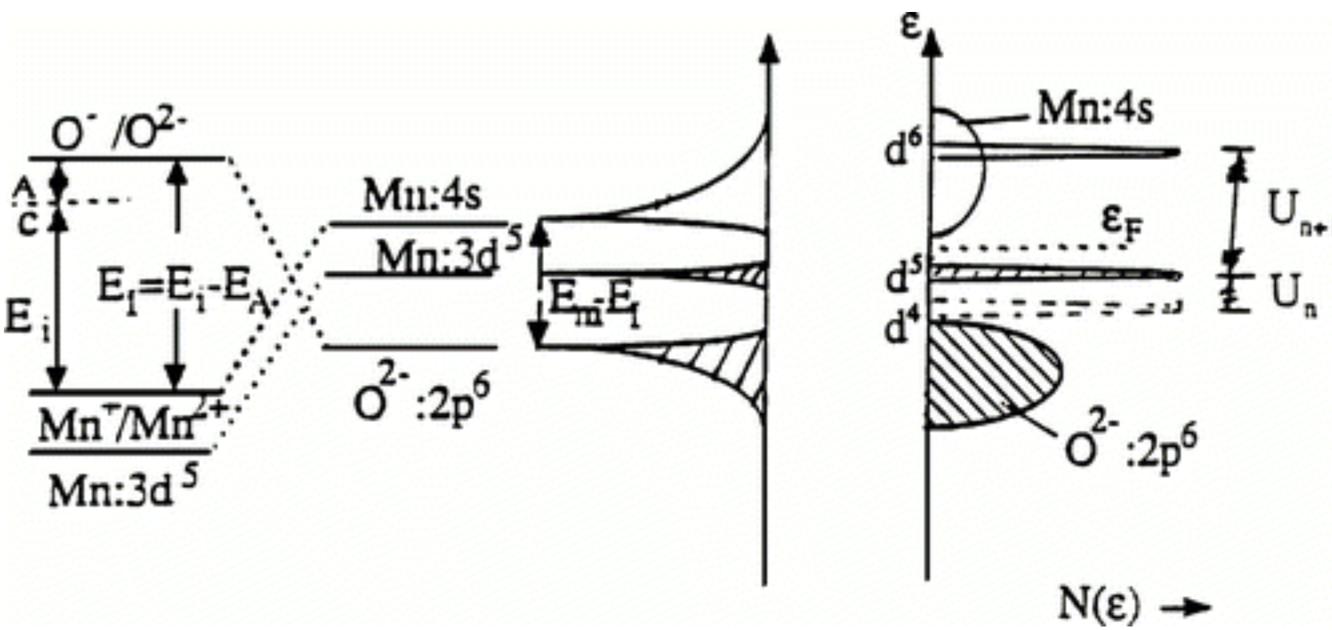
- Stoner Criterion: $\tilde{D}(E_F) \cdot I > 1$
  - $\tilde{D}(E_F)$ is the density of states at the Fermi Level;
  - ***I*** is the Stoner parameter which is a measure of the strength of the exchange correlation
  - Spin moments:
    - Ni ~ 0.6 μ_B/atom
    - Co ~ 1.6 μ_B/atom
    - Fe ~ 2.2 μ_B/atom

Slater-Pauling (-Bethe) Curve



$$\langle m_{3d} \rangle \sim \left(N_{3d}^{\uparrow} - N_{3d}^{\downarrow} \right) \mu_B$$

From bonds to bands



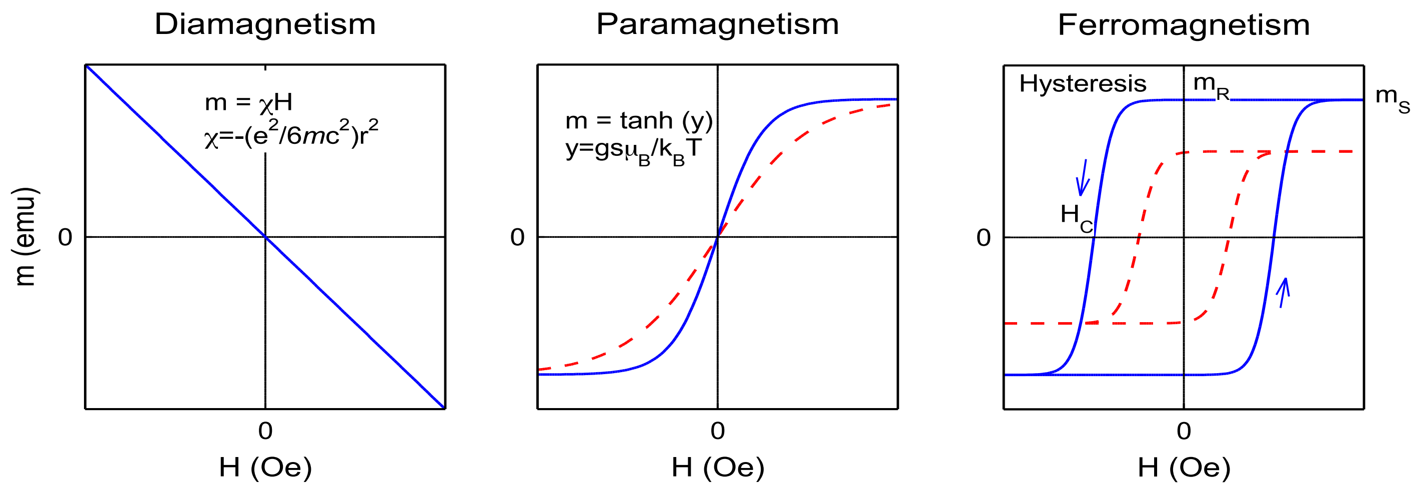
JAHN-TELLER PHENOMENA IN SOLIDS
Annual Review of Materials Science
Vol. 28: 1-27 (Volume publication date August 1998)
J. B. Goodenough

Categories of Magnetic Order

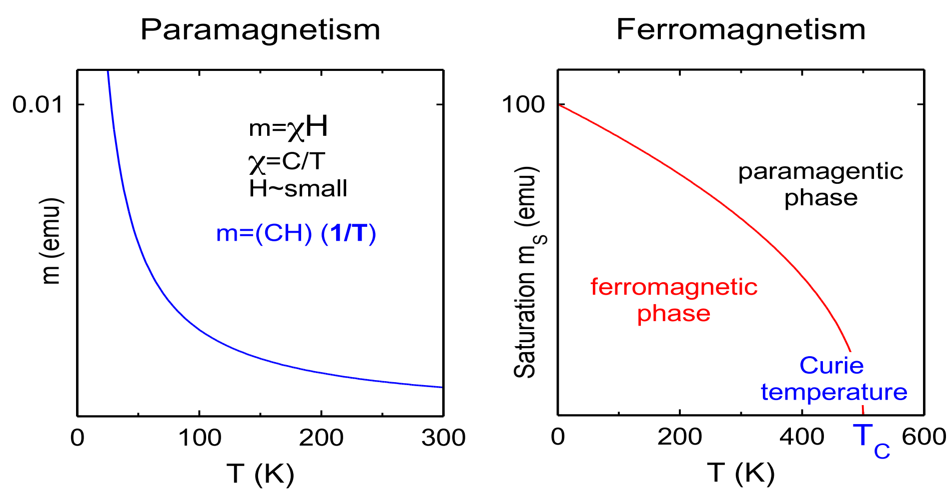
Paramagnetic
Ferromagnetic
Antiferromagnetic
Ferrimagnetic

Behavior of Magnetic Materials

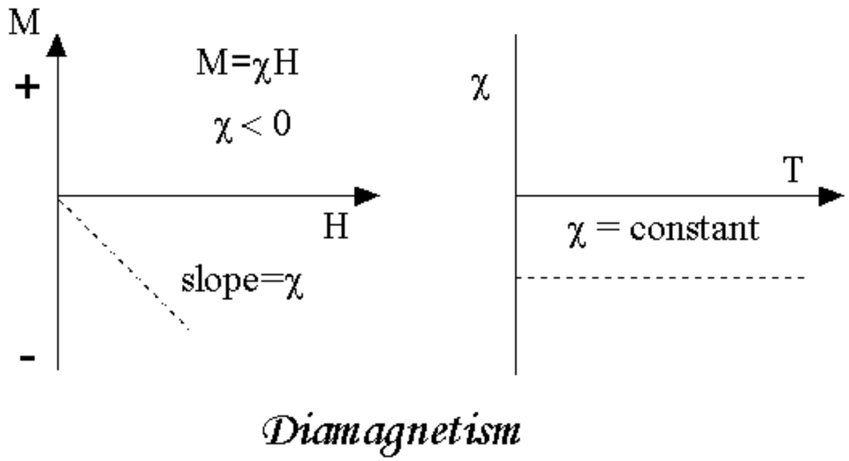
Field Dependence



Temperature Dependence

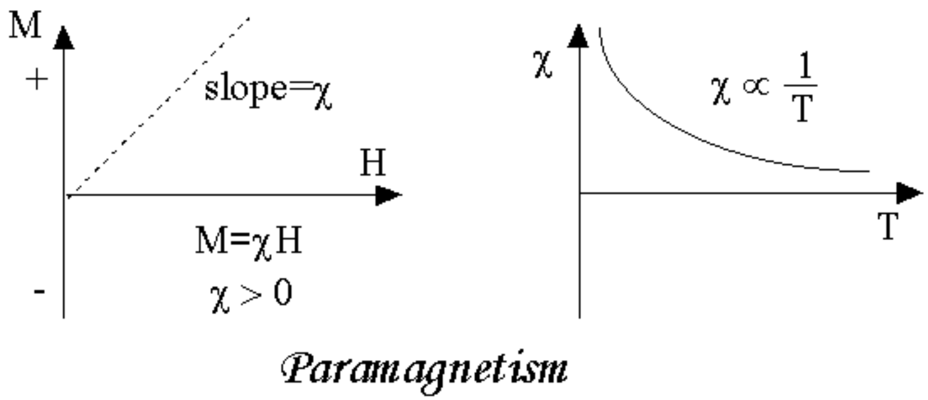


Diamagnetism vs. Paramagnetism



Appropriate for atoms/molecules with **closed-shell configuration**

Magnetically-levitated frog
http://www.ru.nl/hfml/research/levitation/diamagnetic/

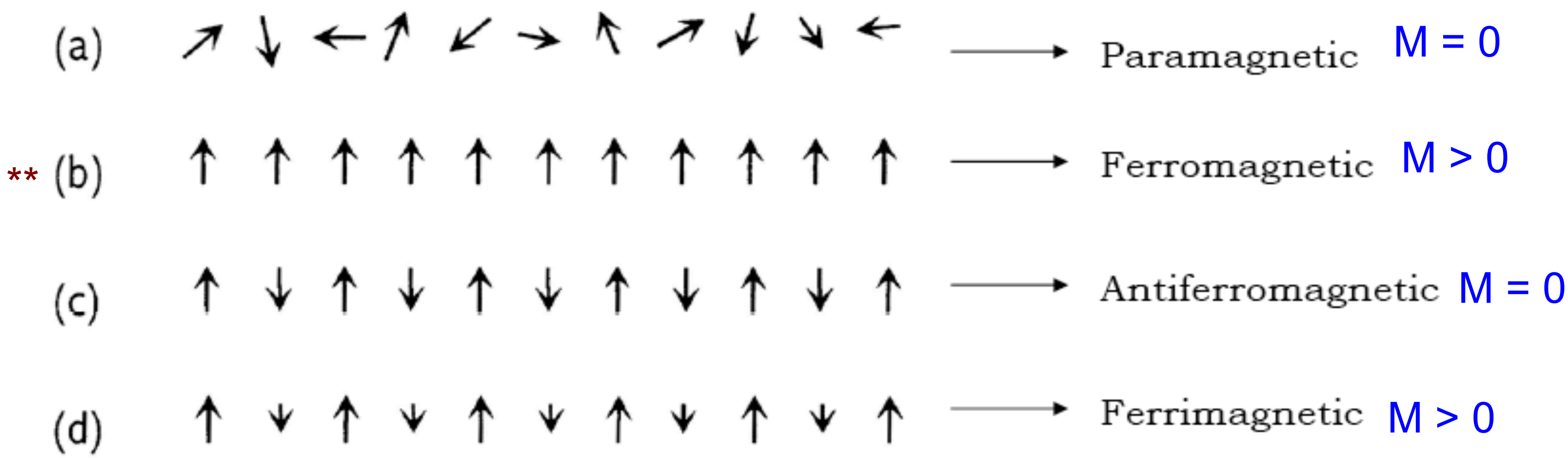


Appropriate for atoms/ molecules/materials with no interelectronic interaction (J = 0)

http://www.irm.umn.edu/hg2m/hg2m_b/hg2m_b.html

Schematic representation of magnetism types

All are technologically important



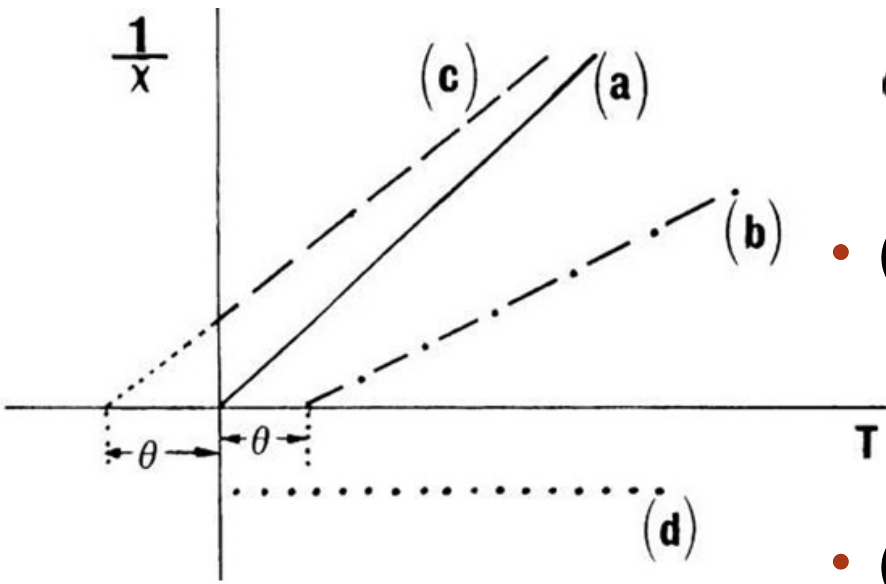
** The simplest model to describe ferromagnetism is the **Ising Model**, where the spins are either "up" or "down"

Classes of Magnetic Materials

Class	Critical Temperature	Magnitude χ	χ Temperature Variation	Structure
Diamagnetic (Al, other metals)	none	weak ~10^{-6} – 10^{-5}	Negative Constant	No permanent dipole moment - See A
Paramagnetic (Cu doped with Fe)	none	moderate ~10^{-5} – 10^{-3}	$\chi = C/T$	No permanent dipole moment Dipoles do not interact - See A
Ferromagnetic (Fe, Ni, Co)	Curie T_C	strong > 10^{-3}	Above T_C, $\chi = C/(T\text{-}Q)$ $Q \sim T_C$	Permanent dipole moment (parallel) - See B
Antiferromagnetic (MnF_2)	Neel T_N	moderate ~10^{-5} – 10^{-3}	Above T_N, $\chi = C/(T \pm Q)$ $Q = T_N$	Permanent dipole moment (antiparallel) - See C
Ferrimagnetic (Fe_3O_4)	Curie T_C	strong > 10^{-3}	Above T_C, $\chi = C/(T \pm Q)$ $Q \sim T_C$	Permanent dipole moment (unequal antiparallel) - See D
Superparamagnetic (nanoparticles)	Blocking T_B	strong > 10^{-3}	Above T_C, $\chi = C/T$	Permanent dipole moment below T_B

Temperature-dependent magnetism for T > $T_{ordering}$

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



- (a) Paramagnetism: $\chi = \frac{C}{T}$
  - $J = 0$
  - C = Curie Constant =

$$C = \frac{\mu_0 \mu_B^2}{3k_B} N g^2 J(J+1) \text{ or } C = \frac{1}{k_B} N \mu^2$$

- (b) Ferromagnetism: $\chi = \frac{C}{T - \theta}$
  - $J > 0$
  - θ = Paramagnetic ordering temperature
- (c) Antiferromagnetism: $\chi = \frac{C}{T + \theta_N}$
  - $J < 0$

(note: $\mathcal{J}$ (total angular momentum) ≠ J (exchange constant))

Review and Self Test: Categories of Magnetism

- χ is small and negative ($-10^{-5} \sim -10^{-6}$)?

  DIAMAGNETISM

  – *examples*: Au, Cu, Ag, Bi, silica, molecules (& superconductors)

- χ is small and positive ($\sim 10^{-6} \sim 10^{-4}$)?

  PARAMAGNETISM

  – *examples*: aluminum, platinum, manganese

- χ is large and positive (>>1; 50 – 10,000)?

  FERROMAGNETISM

  – *examples*: iron, cobalt, gadolinium

Sources of Magnetic Anisotropy

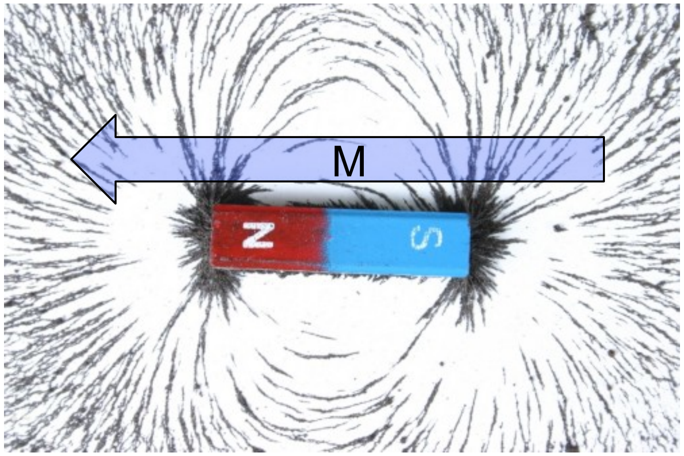
Magnetic Anisotropy = moment alignment

Magnetic anisotropy = directional -dependent magnetic properties

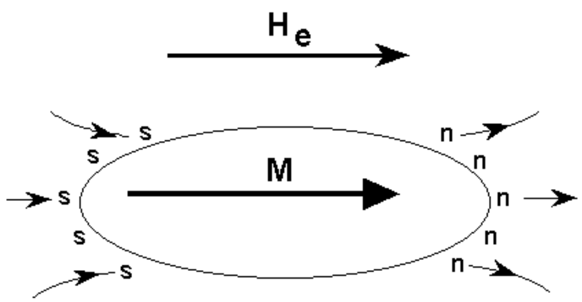
A magnetically *anisotropic* material aligns moment to an "easy axis"

Sources of Anisotropy:

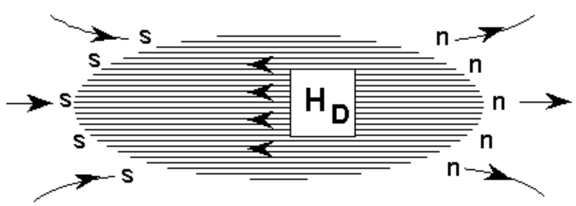
- Shape anisotropy
- Magnetocrystalline anisotropy
- Stress anisotropy
- Exchange anisotropy



Shape anisotropy and Demagnetizing Factor



Magnetization Produces Apparent
Suface Pole Distribution



Demagnetizing Field Due to
Apparent Surface Pole Distribution

$H_i = H_e - H_D$

$H_D = NM$

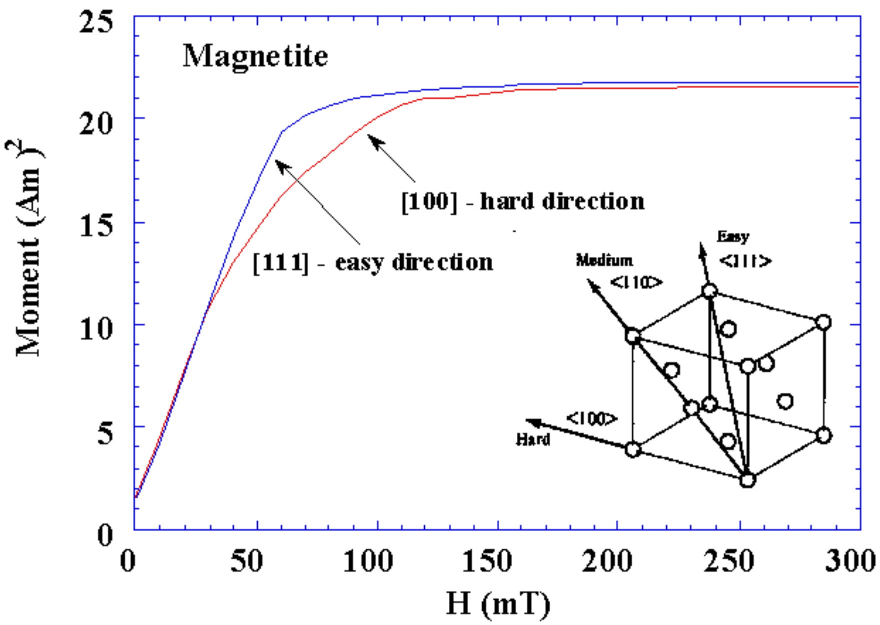
N= demagnetizing factor

- Geometric effect; **always present**
- *N* = "demagnetizing factor"
  - *N* = 0: needle, thin film
  - *N* = 1: infinite plate
  - $0 \leq N \leq 1$: everything else
    - (sphere: *N* = 1/3)

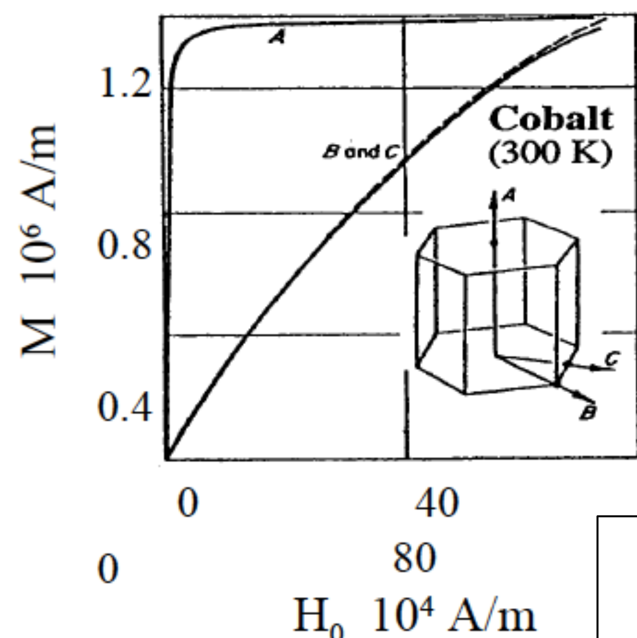
$$H_{\text{int}} = H_{appl} - NM$$

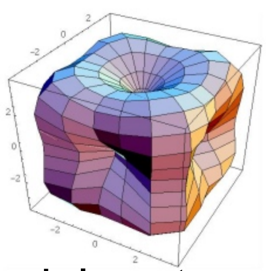
http://www.irm.umn.edu/hg2m/hg2m_c/hg2m_c.html

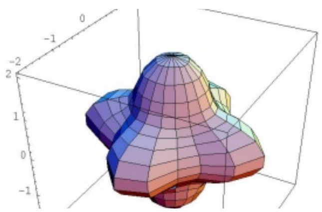
Magnetocrystalline anisotropy



Moments have different energies in different directions in a crystal



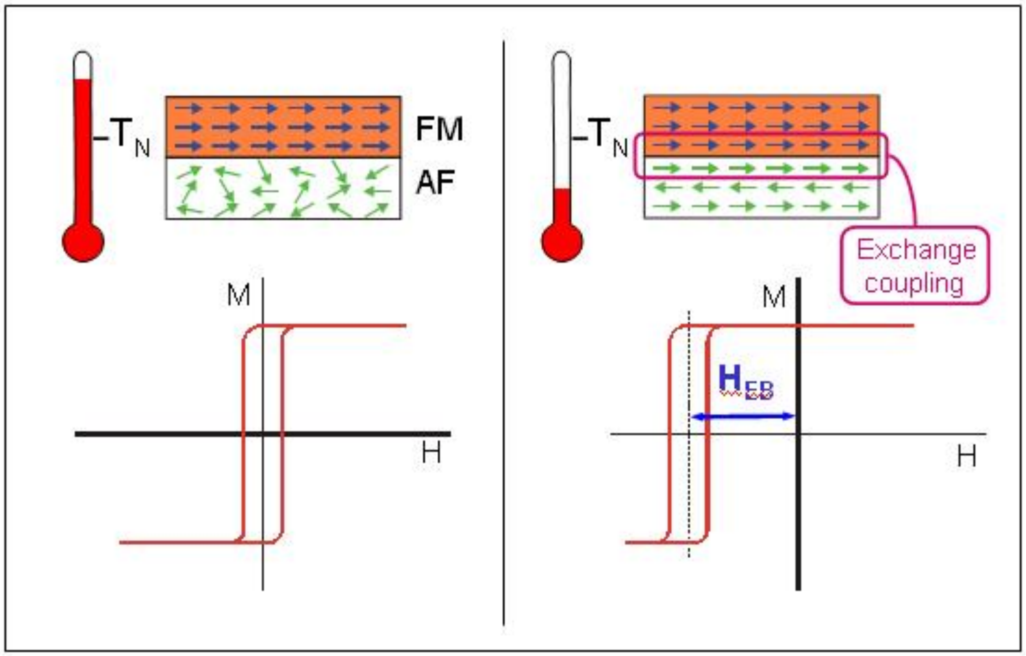




Uniaxial system: $$E_a(\theta,\phi) = K_1 \sin^2\theta + K_2 \sin^4\theta + \cdots$$

http://www.irm.umn.edu/hg2m/hg2m_c/hg2m_c.html http://www.physics.montana.edu/magnetism/Research/Nanoparticles.html

Exchange anisotropy

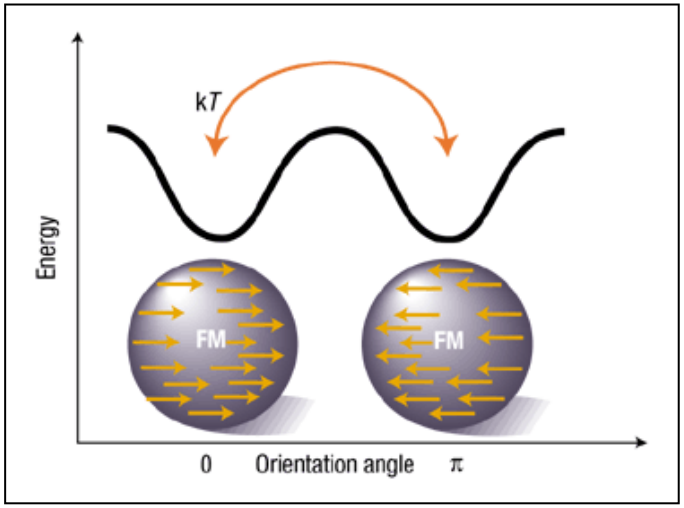


- Found in AF/F systems, under appropriate conditions
- Relevance to magnetic recording media

Superparamagnetism: no anisotropy ($T>T_B$)

SUPERPARAMAGNETIC NANOPARTICLES!

Magnetic particles can be so small that thermal energy rapidly flips the magnetic moment from one orientation to another.



Nèel Relaxation

$$\tau = \tau_o \exp(E_B/k_BT)$$

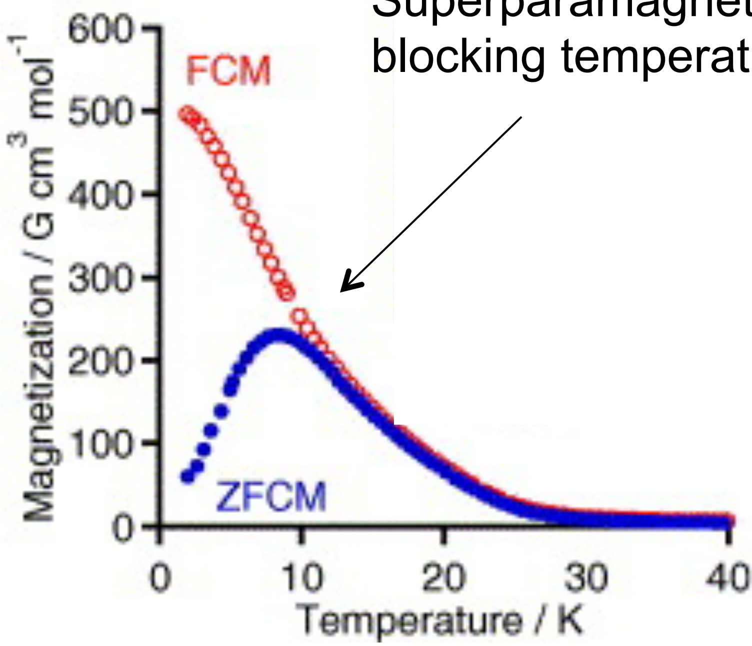
$$\tau_o = 10^{-9}\text{ sec}$$

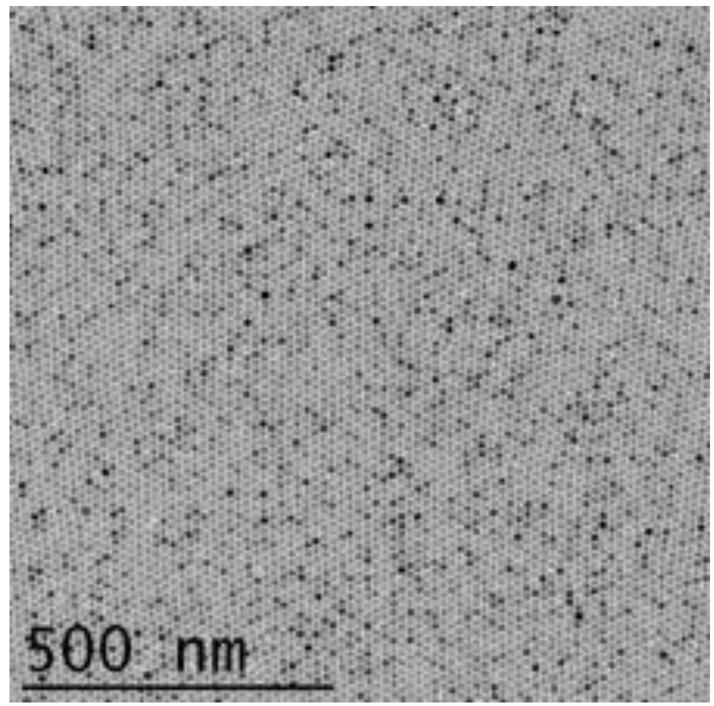
Blocking Temperature (T_B)

For $\tau=10^2$ sec, $E_B/k_BT_B = 25$

Superparamagnetism

Superparamagnetic blocking temperature T $_B$





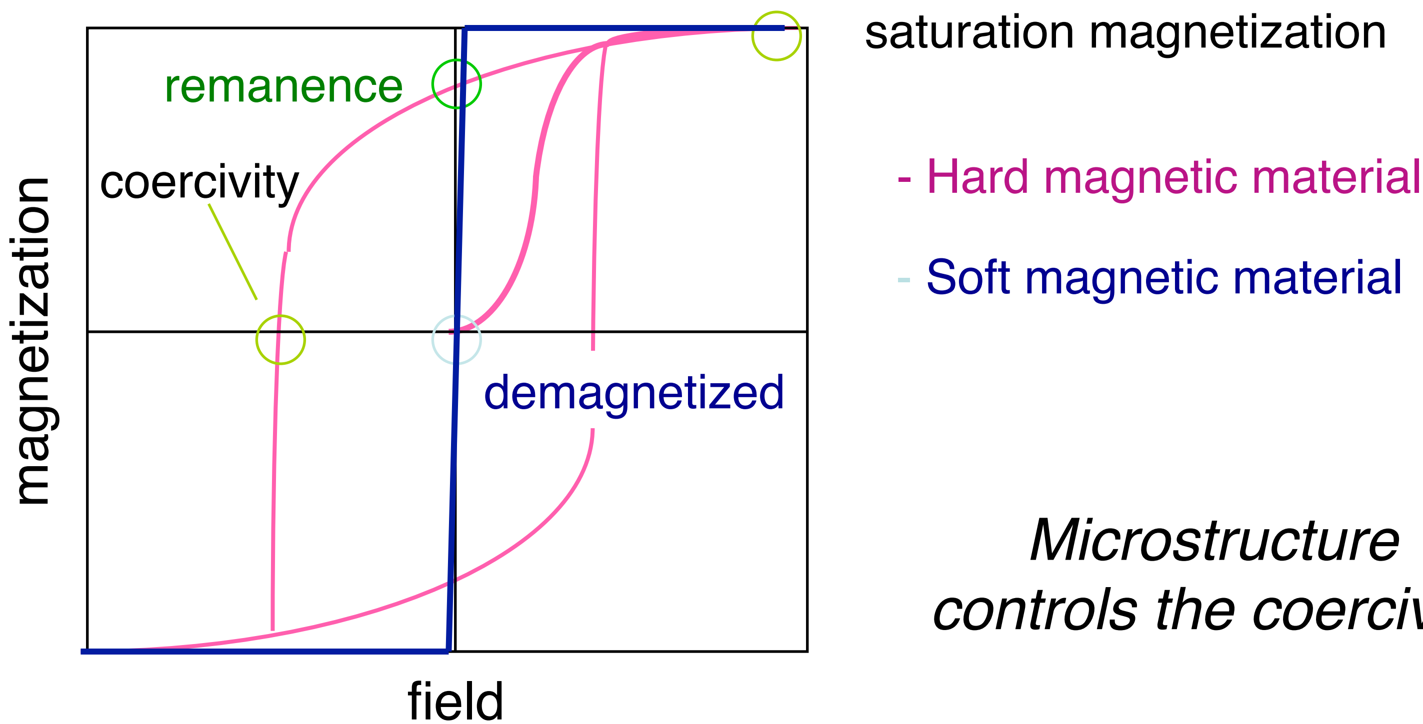
http://nano.phys.cmu.edu/

$$T_B = \frac{KV}{k_B \ln\left(\frac{\tau_m}{\tau_0}\right)} \sim \frac{KV}{k_B \ln(20)}$$

Hysteresis and Magnetic Domains

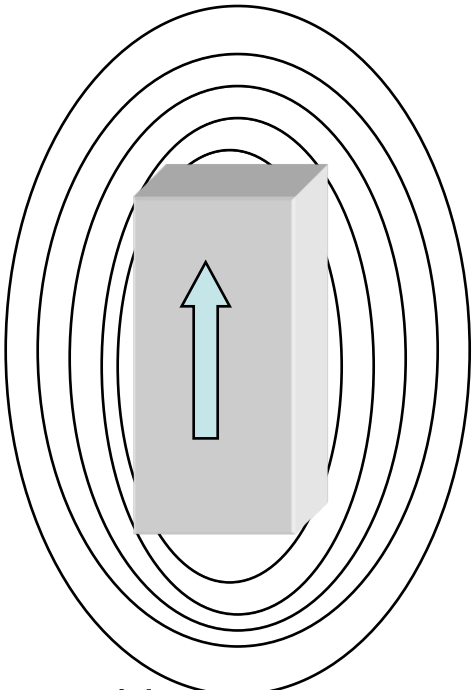
Hard and **Soft** magnets

- The application must be matched to the *coercivity* (magnetic hardness) of the material.

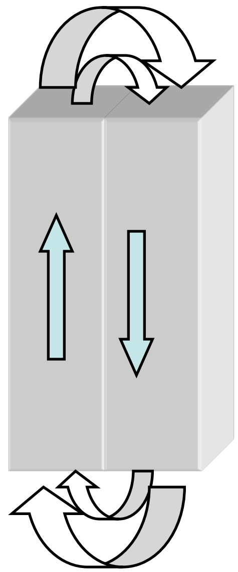


Microstructure controls the coercivity

Magnetic domains

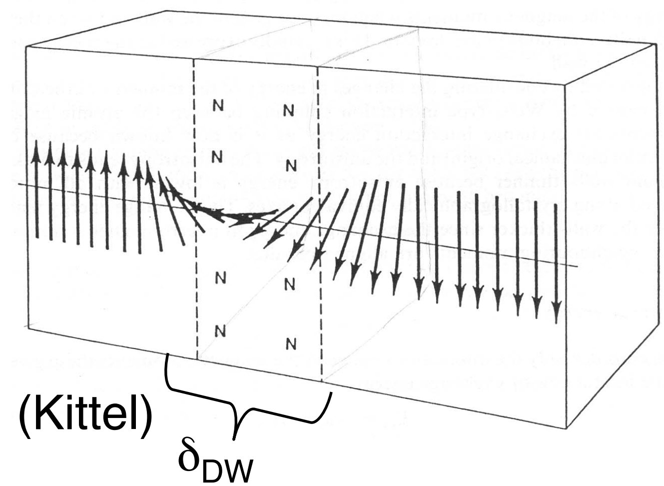


unfavorable



more favorable

Domain wall separates regions of uniform magnetic polarization

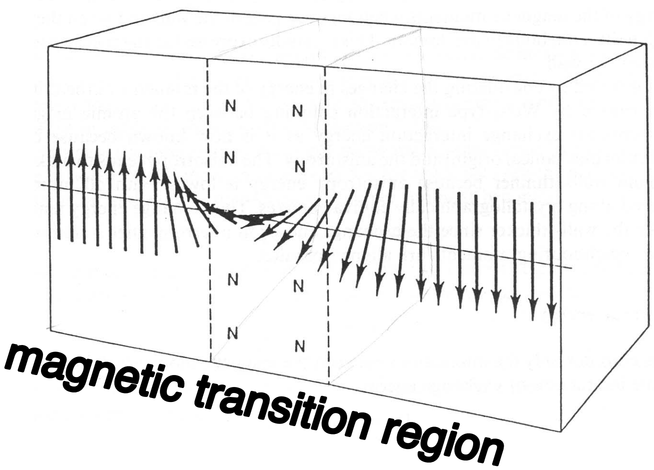


Domain wall behavior connects structure to magnetic properties:

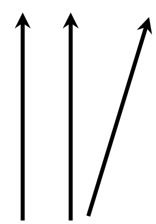
- **Easy** vs. **difficult** domain wall movement
- Control by microstructural design

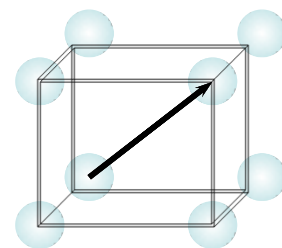
Domain walls

- Scale of magnetic interaction determined by the domain wall thickness.
- Key = "Magnetic Exchange Length" L_{ex}



L_{ex} = thickness of magnetic transition near interface $\approx \sqrt{\frac{A}{K}}$





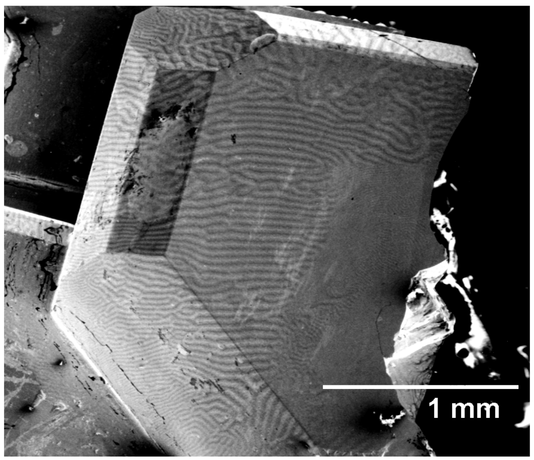
Materials properties:

A = "exchange constant"
Describes spin stiffness

K = "magnetic anisotropy"
Describes moment direction preference

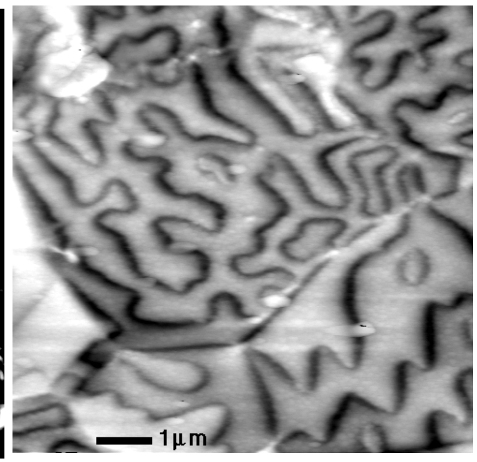
Magnetic Domain Images: $Nd_2Fe_{14}B$

Single crystal



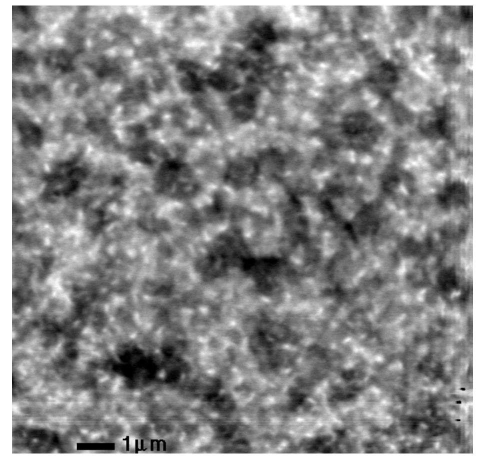
(J.-Y. Wang, BNL)

Sintered (polycrystalline)
Grain size ~ 10 μm

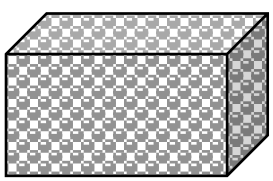


(S. M. Collins, ERULF)

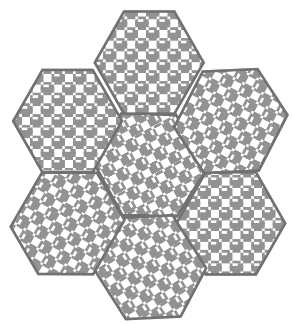
nanocrystalline
Grain size ~ 20 nm



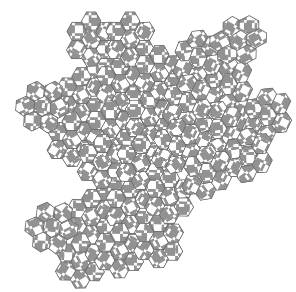
(D. C. Crew, BNL)



0.1 ~ 1 mm

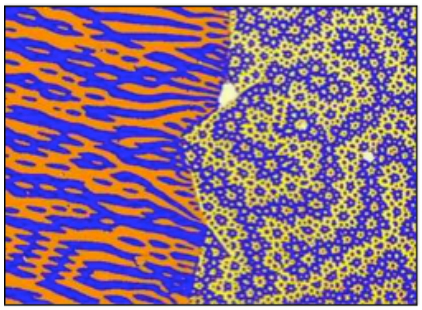


10 μm



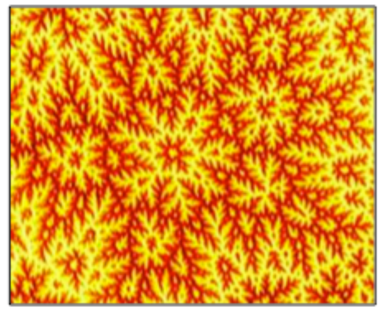
100 nm

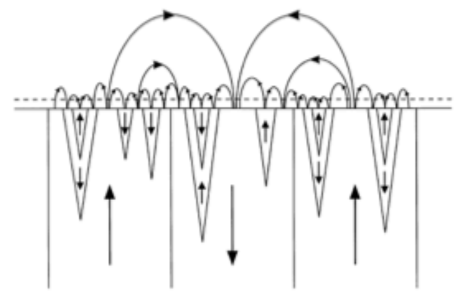
Magnetic domains



Flower patterns from out-of-plane uniaxial anisotropy

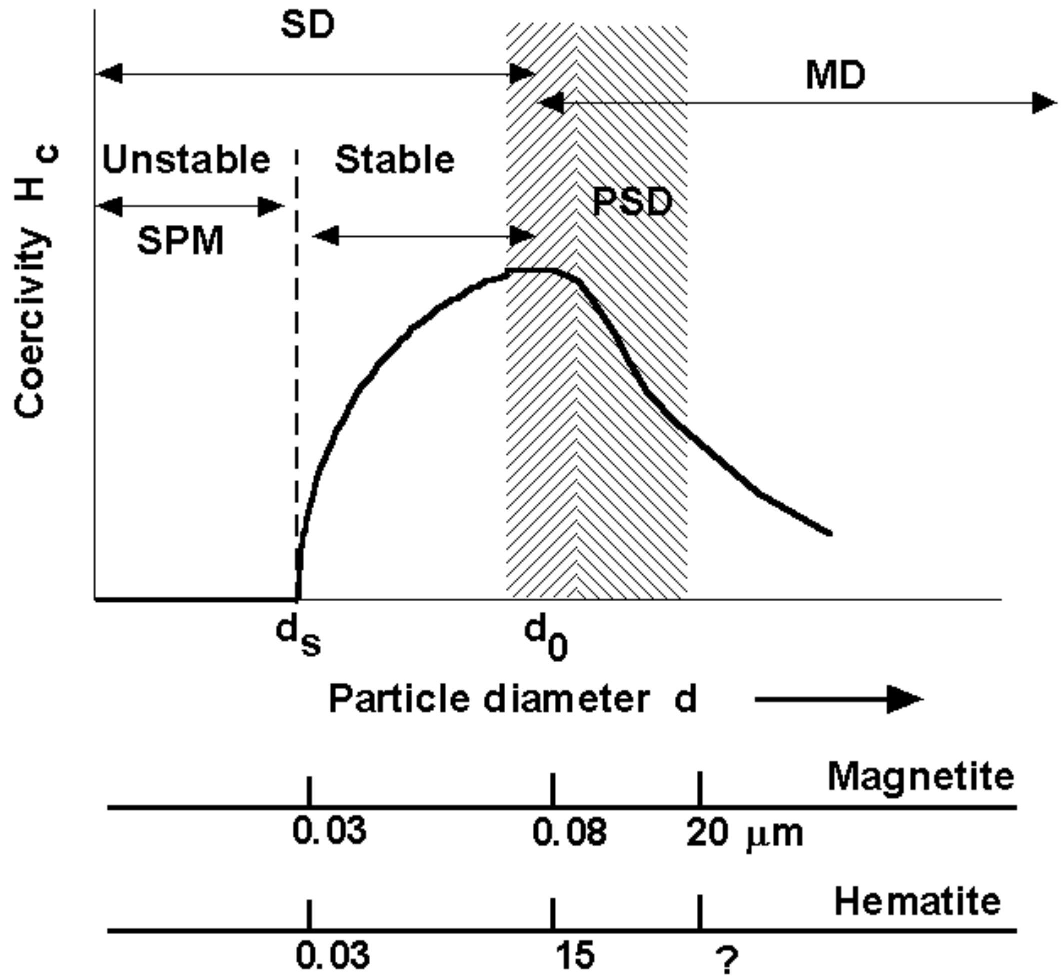
Branching pattern from misorientation of magnetization to sample surface





Example magnetic domains in uniaxial materials: NdFeB and Co [5]

Relationship between magnetism & particle size

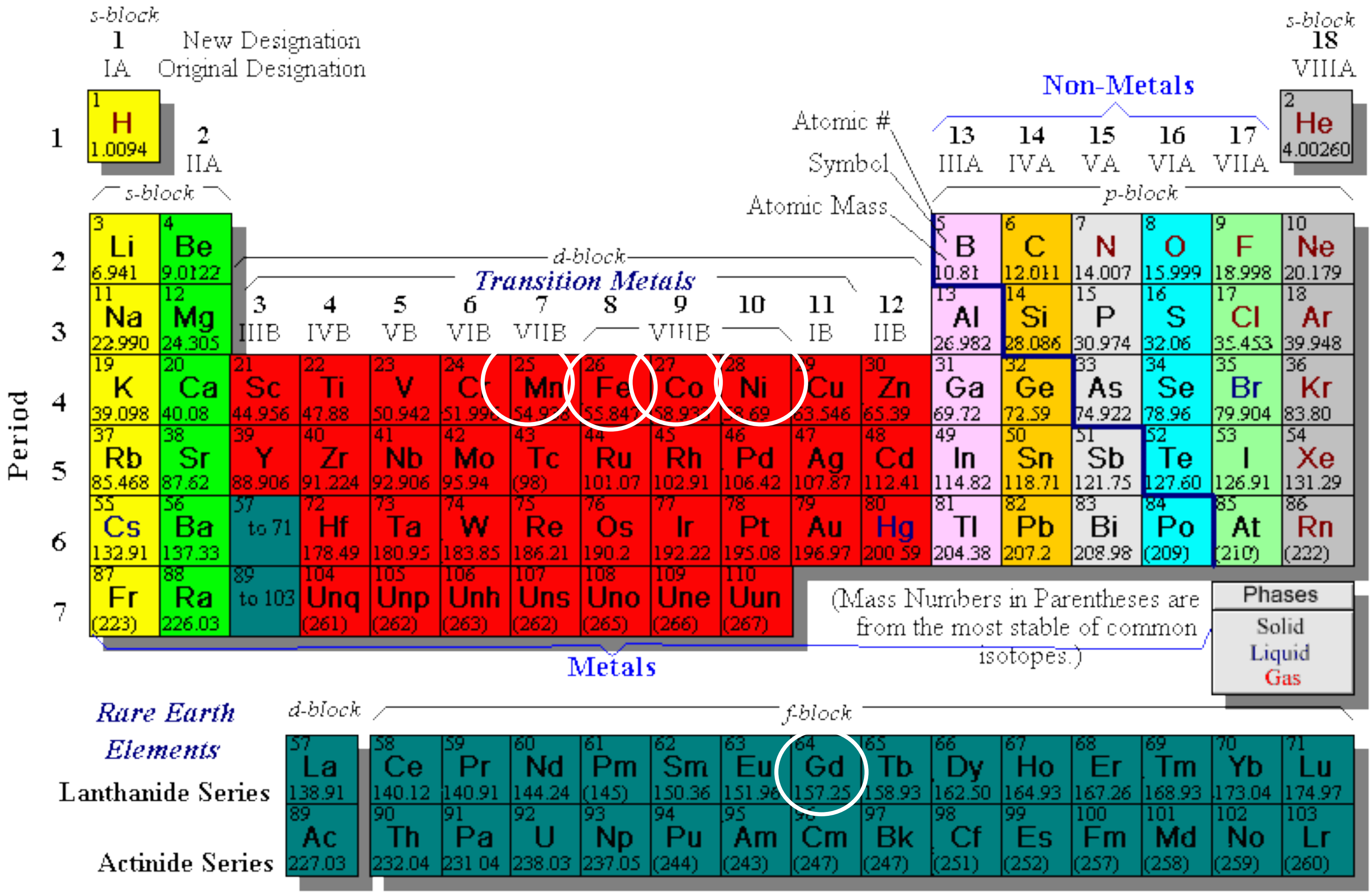


- SPM = superparamgnetic
- SD = single domain
- MD = multidomain
- PSD = pseudo-single domain

http://www.irm.umn.edu/hg2m/hg2m_d/hg2m_d.html

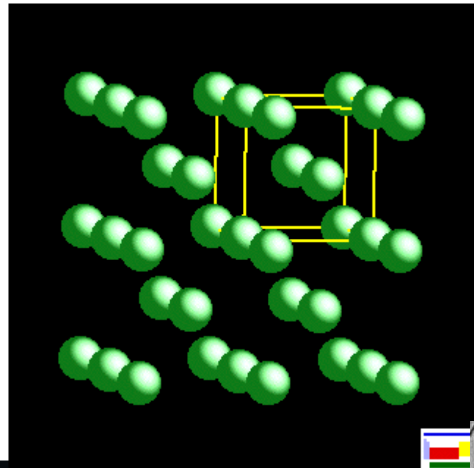
Magnetic Materials & Characterization Techniques

The Periodic Table & Magnetism

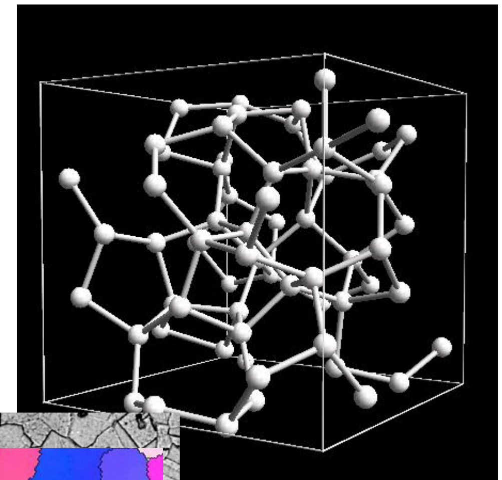


Forms of Materials: technical magnetic properties

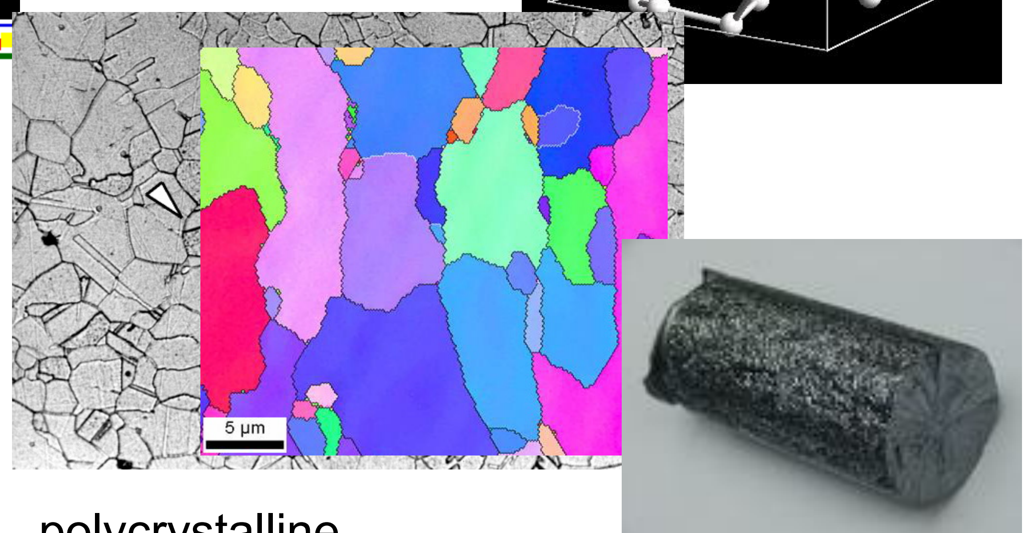
crystalline



amorphous



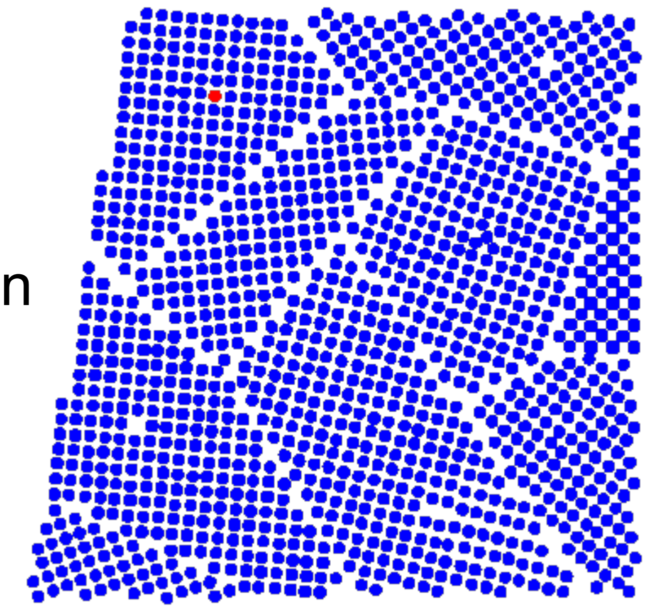
single crystal



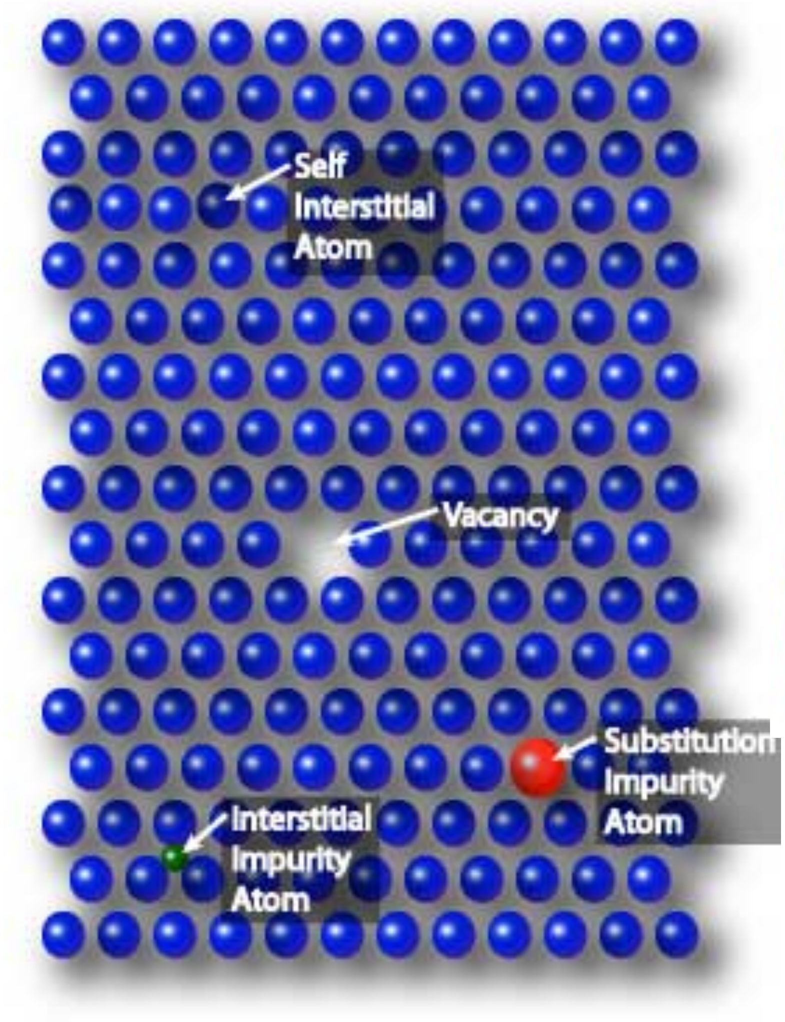
polycrystalline

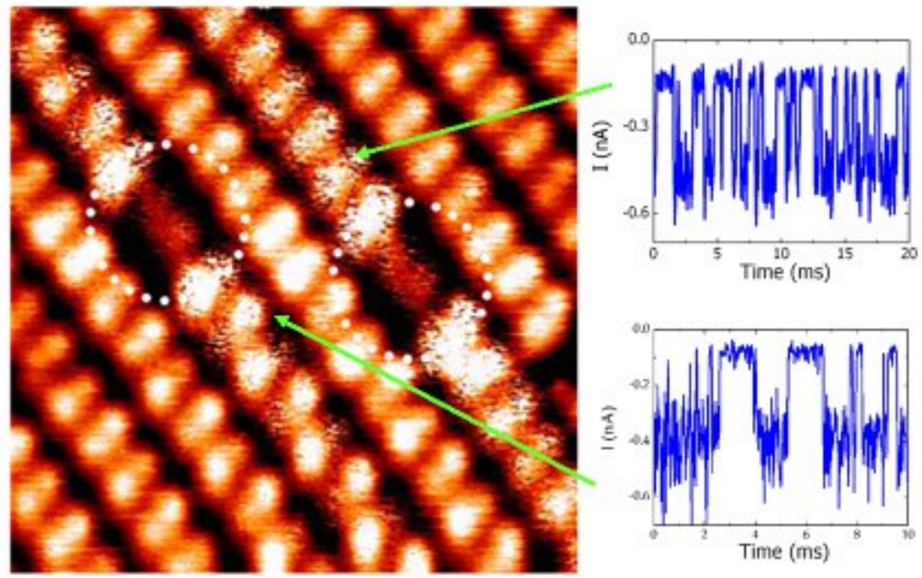
Materials defects impact magnetic properties

- 0-D: **point defects**, places where an atom is missing or irregularly placed in the lattice structure.
  - lattice vacancies, self-interstitial atoms, substitution & interstitial impurity atoms
- 1-D linear defects: **dislocations =** groups of atoms in irregular positions
- 2-D: **planar defects** =interfaces between homogeneous region of material.
  - grain boundaries
  - stacking faults
  - external surfaces



Point defects





Functional magnetic effects

- **Magnetocaloric**: temperature change on application of ***H***
- **Magnetostrictive**: shape change upon application of ***H***
- **Magnetoresistive**: resistivity change upon application of ***H***
  - ***Can you think of applications?***

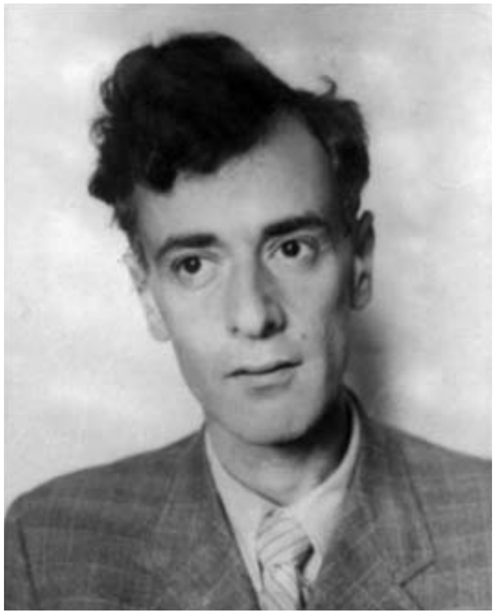
Question: How to describe magnetofunctional ("multifunctional") effects?

Answer: "Order parameters" and Landau Theory of phase transitions

Landau Theory of Phase Transitions*

- Order parameters and a general theory of phase transitions
- Based on idea of "critical point" that marks the transition from one state to another.
- The trend of the parameter change is described by the "critical exponent"

Critical Point	Order Parameter	Example	T_{cr} (K)
Ferromagnetic	Magnetic moment	Fe	1044.0
Antiferromagnetic	Sublattice magnetic moment	FeF_2	78.26
Chemical order	Fraction of atomic species on one sublattice	Cu-Zn alloy	739
Symmetry distortion	1-(c/a)	FePd	933
Ferroelectric	Electric dipole moment	Triglycine sulfate	322.5



Lev Landau, (1908-1968)
Nobel Prize 1962

* *acknowledgement:* Dr. Radhika Barua & Dr. Nina Bordeaux

Review of thermodynamics….

A system is stable at a given (T, P) when the Gibbs free energy G(T,P) is minimized. **3 criteria for stability**:

$$\left(\frac{\partial^2 G}{\partial T^2}\right)_P < 0$$

1

$$\left(\frac{\partial^2 G}{\partial P^2}\right)_T < 0$$

2

$$\left(\frac{\partial^2 G}{\partial T^2}\right)_P \left(\frac{\partial^2 G}{\partial P^2}\right)_T - \left(\frac{\partial^2 G}{\partial T \partial P}\right)^2 < 0$$

3

Phase transitions are singularities in a derivative (1st, 2nd, 3rd, etc) of the free energy

Thermodynamics continued….

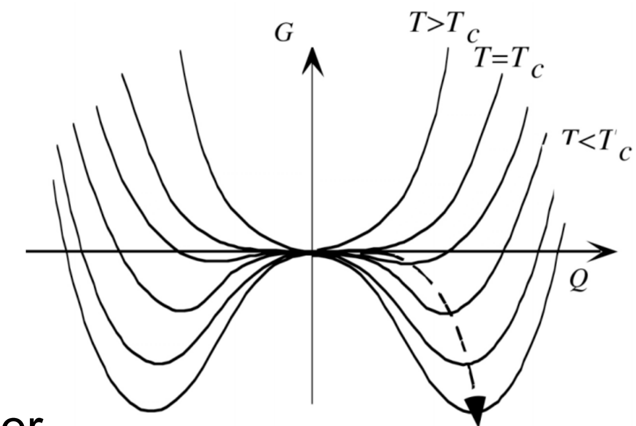
- G varies with T (minimum in free energy also varies w/T)

- Write the free energy as a power series of order parameter

$$G = G_0 + G_1 Q + G_2 Q^2 + G_3 Q^3 + \cdots$$

- The condition $G(-Q) = G(Q)$ requires power series to only have even powers

Free energy for a second-order phase transition

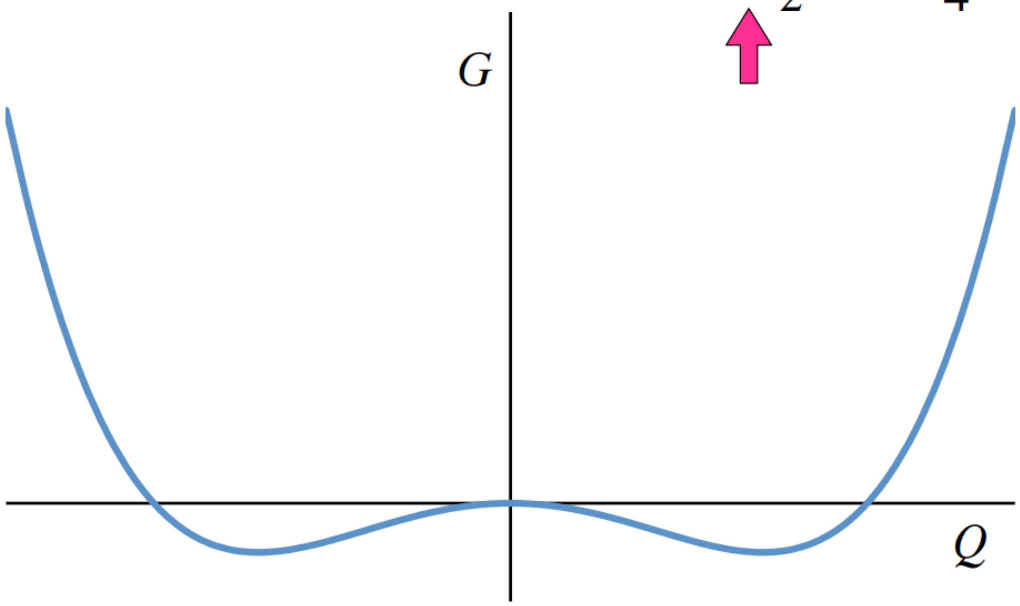


Q = order parameter

Examine the behavior of the expression

Low temperature

$$G = G_0 - \frac{1}{2}aQ^2 + \frac{1}{4}bQ^4$$

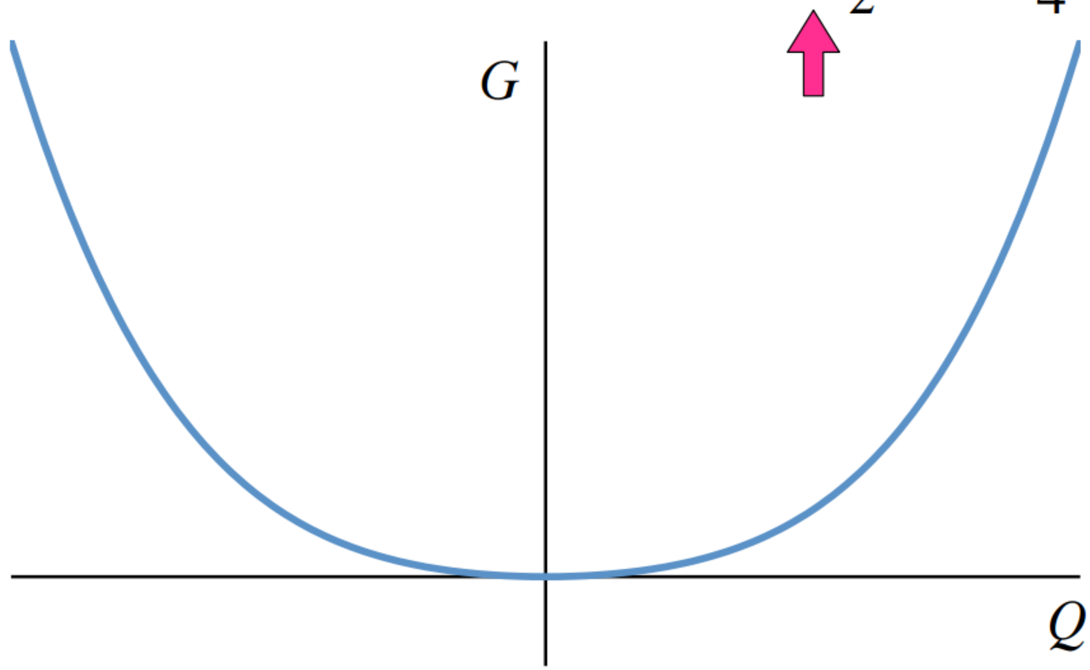


$T < T_C$

Examine the behavior of the expression

High temperature

$$G = G_0 + \frac{1}{2}aQ^2 + \frac{1}{4}bQ^4$$



$T > T_C$

Solve for the extrema of the expression

Let $a(T) = a(T - T_C)$

Then $G = G_0 + \frac{1}{2}a(T - T_C)Q^2 + \frac{1}{4}bQ^4$

where *a*, *b* are temperature-independent coefficients

$$\frac{\partial G}{\partial Q} = a(T - T_C)Q + bQ^3 = 0$$

$$bQ^3 = a(T_C - T)Q$$

Get two solutions:

$$1.\ Q = 0$$

$$2.\ Q = \left[\frac{a}{b}(T_C - T)\right]^{1/2}$$

Match up terms with thermodynamic expressions

$$G = G_0 + \frac{1}{2}a(T - T_C)Q^2 + \frac{1}{4}bQ^4 = G_0 + \Delta H - T\Delta S$$

$$\Delta H = -\frac{1}{2}aT_C Q^2 + \frac{1}{4}bQ^4$$

Terms without T

$$-T\Delta S = \frac{1}{2}aTQ^2$$

Temperature terms

$$Q^2 = a(T_C - T)/b$$

Substitute Q^2 back in

$$\Delta S = -\frac{1}{2}aQ^2 = -\frac{1}{2}a^2(T_C - T)/b$$

$$\Delta C = T\frac{\partial \Delta S}{\partial T} = \begin{cases} 0 & \text{for } T > T_C \\ \frac{a^2}{b}T & \text{for } T < T_C \end{cases}$$

for T > T_C

for T < T_C

This is the change in heat capacity across the transition (measurable)

Classic Example: the Ising Magnet

- The order parameter is $M = \left\langle \sum m_i \right\rangle$; spins can only be up or down

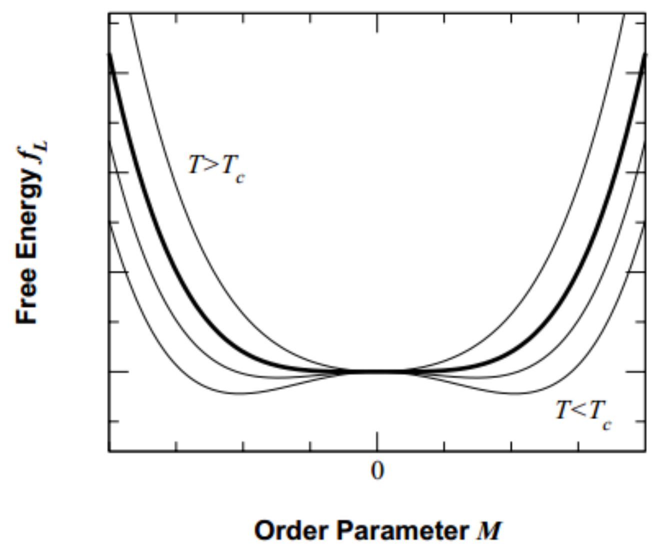
$$G = G_0 + \frac{1}{2}a(T - T_C)M^2 + \frac{1}{4}bM^4$$

- Spin up and spin down are identical states; *G* is minimized when:

$$M = \begin{cases} 0 & (T > T_c) \\ \pm\left[\dfrac{a(T_c - T)}{b}\right]^{1/2} & (T < T_c) \end{cases}$$

$$G = \begin{cases} G_0(T) & (T > T_c) \\ G_0(T) - \frac{1}{2}\dfrac{a^2(T_c - T)^2}{b} & (T < T_c) \end{cases}$$

$$\Delta C_V = T\left(\frac{\partial S}{\partial T}\right)_V = -T\frac{\partial^2 G}{\partial T^2}\bigg|_V = -T\frac{a^2}{b}$$



Parameters *a* and *b* determined from *M*(*T*), C_V

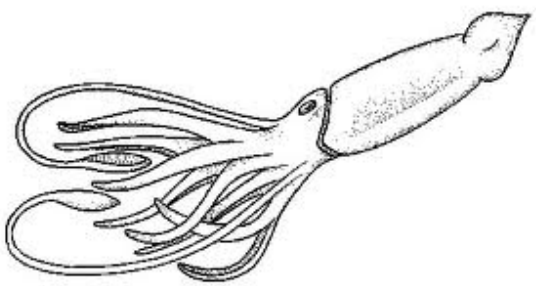
How to measure magnetism?

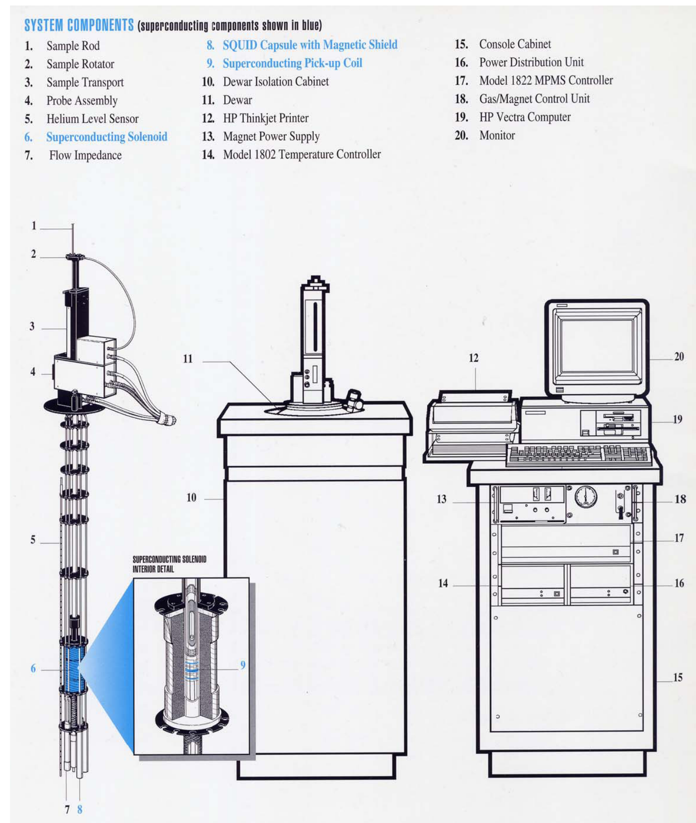
SQUID Magnetometer: high sensitivity, slow measurement

Superconducting **Qu**antum **I**nterference **D**evice Magnetometer

SQUID Magnetometer

Quantum Design, Inc.
www.qdusa.com

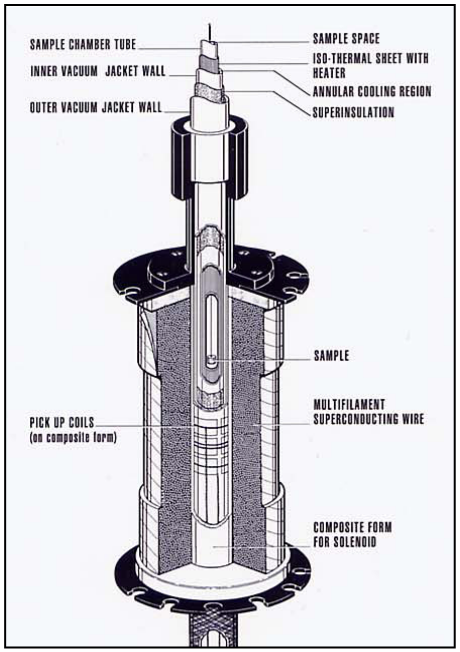


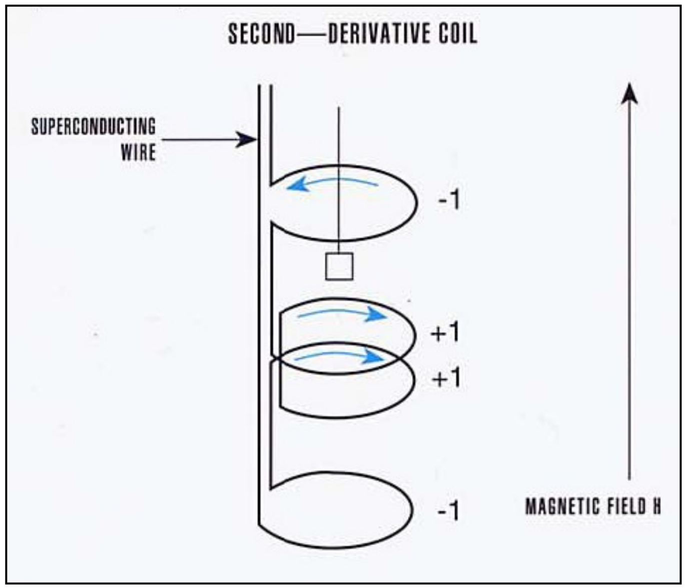


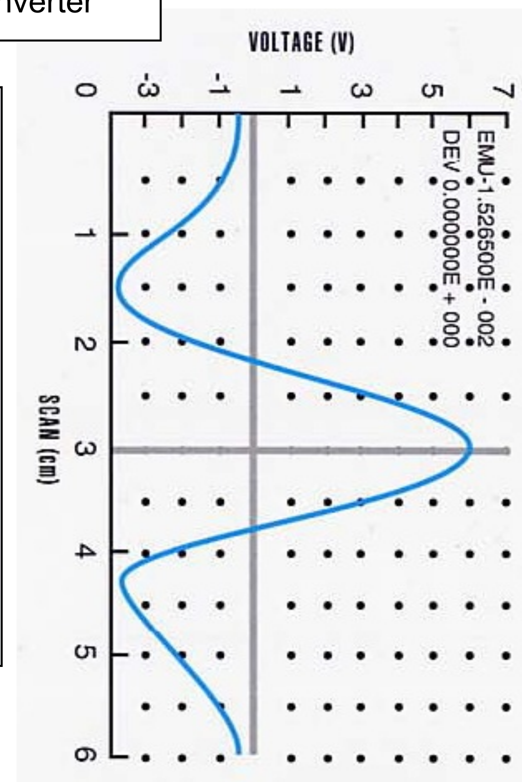
SQUID Magnetometer: How it works

SQUID
Superconducting QUantum Interference Device

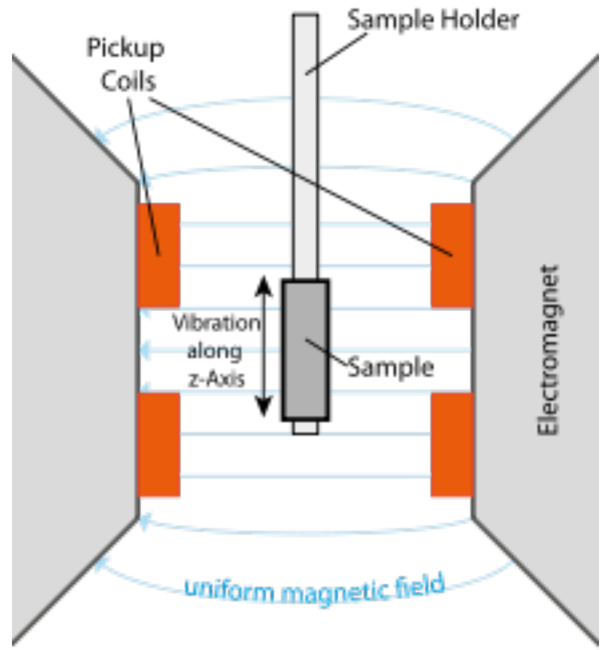
= an extremely sensitive current-to-voltage converter







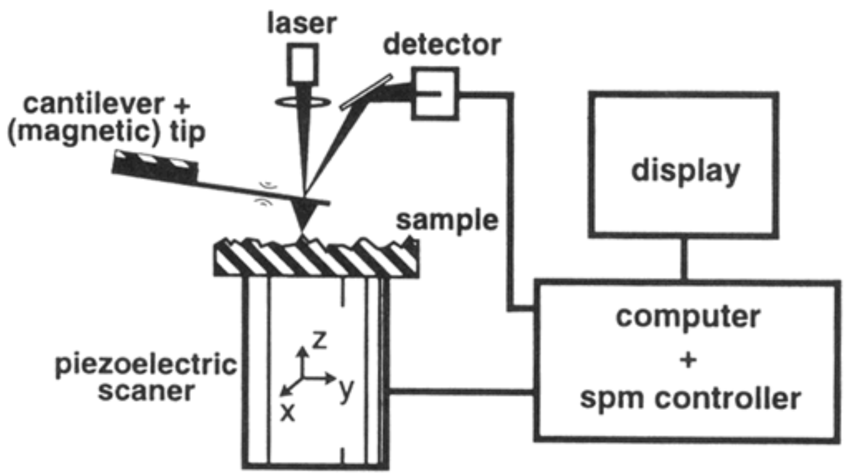
Vibrating Sample Magnetometer (VSM): lower sensitivity, fast measurement



Induction method: moving magnetic moment produces current

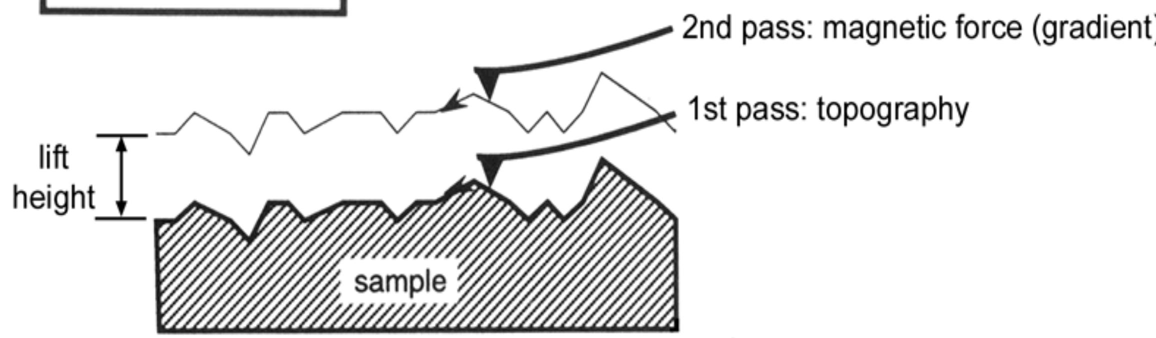
Magnetic Force Microscopy (MFM)

- Scanning Probe Technique: sharp tip probes surface forces using resonance technique



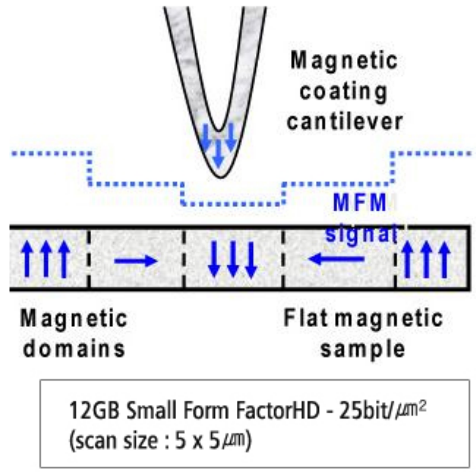
- Deceptively simple
- Magnetic tip
- Operates in air

- Magnetic signal = total signal — topographic signal

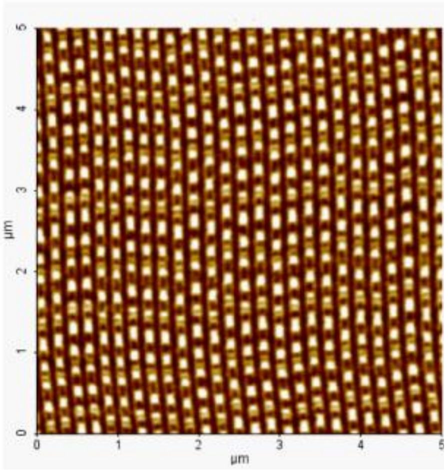


(Atomic) Magnetic Force Microscopy (SPM)

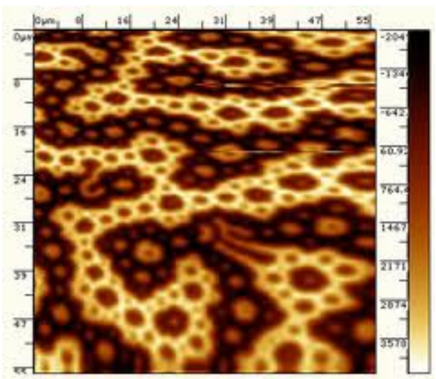
phys.sci.hokudai.ac.jp

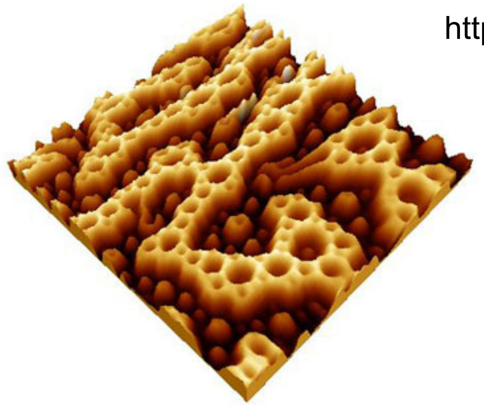


MFM Image of Hard Disk Drive

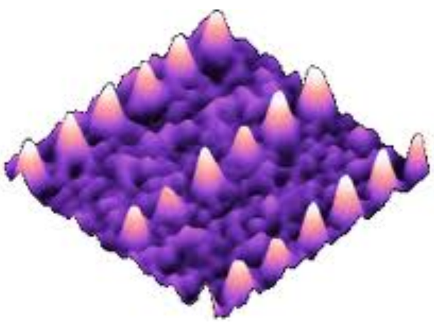


http://www.parkafm.com/



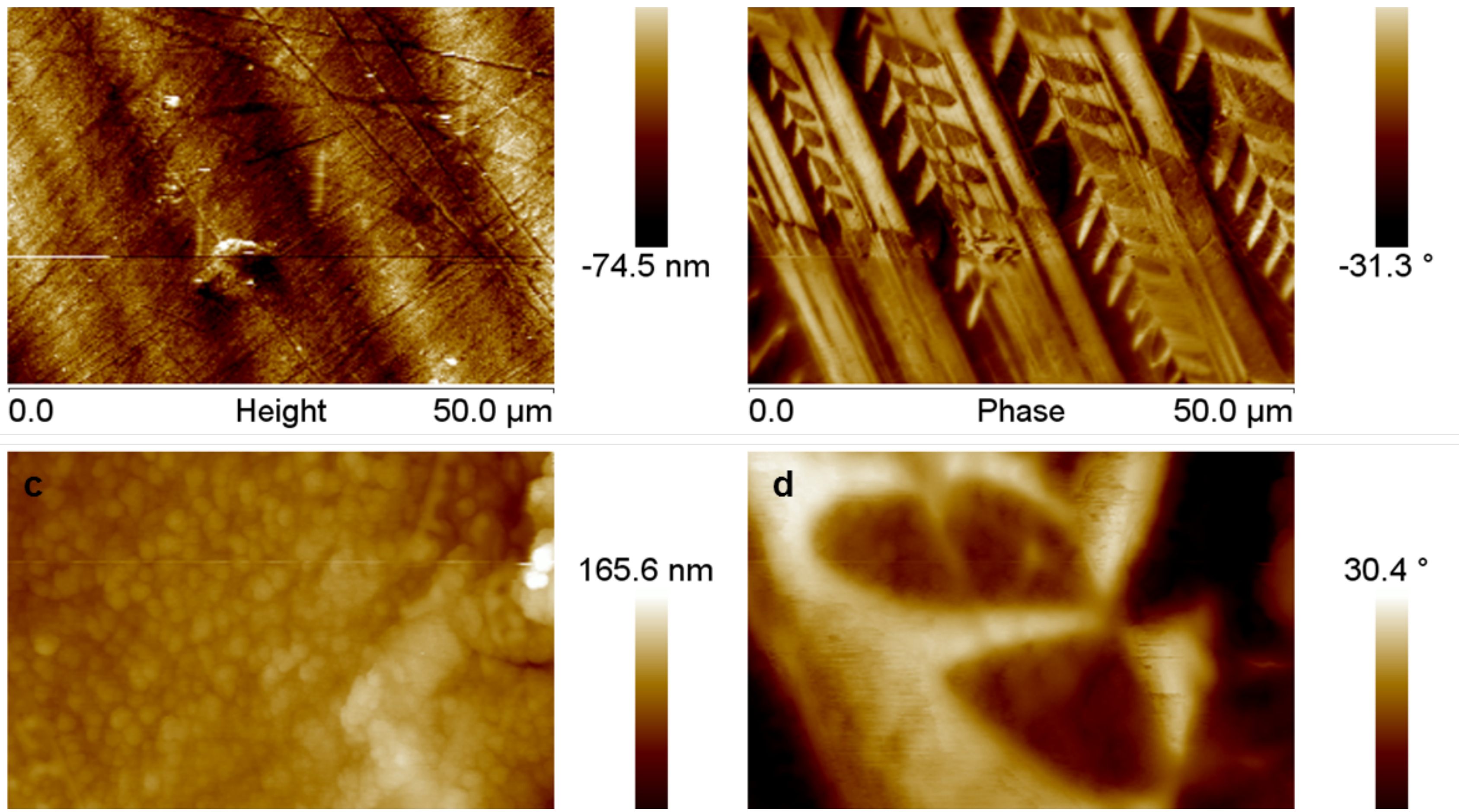


http://www.physics.wayne.edu/~nadgorny/research2.html

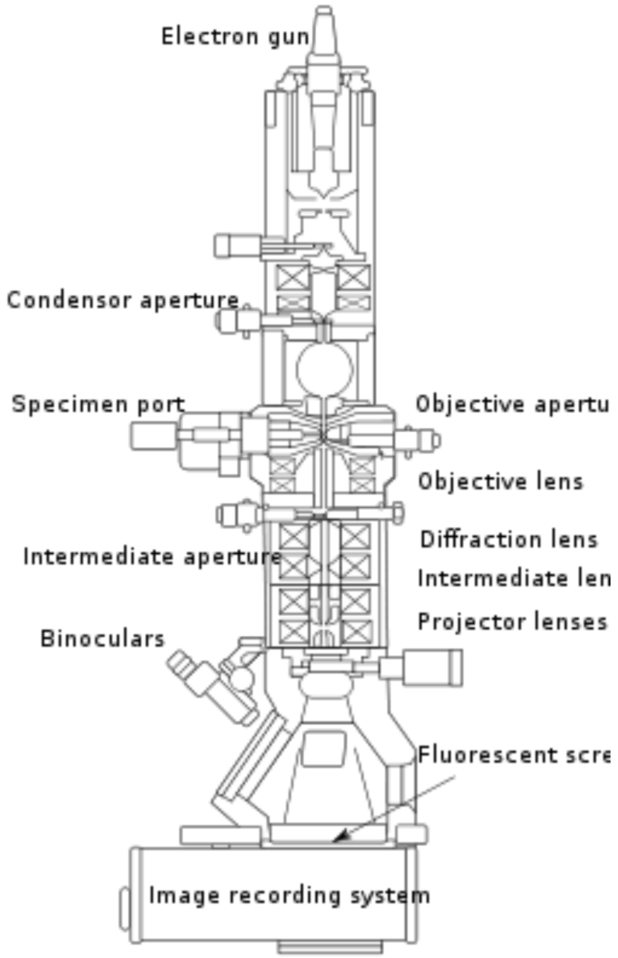


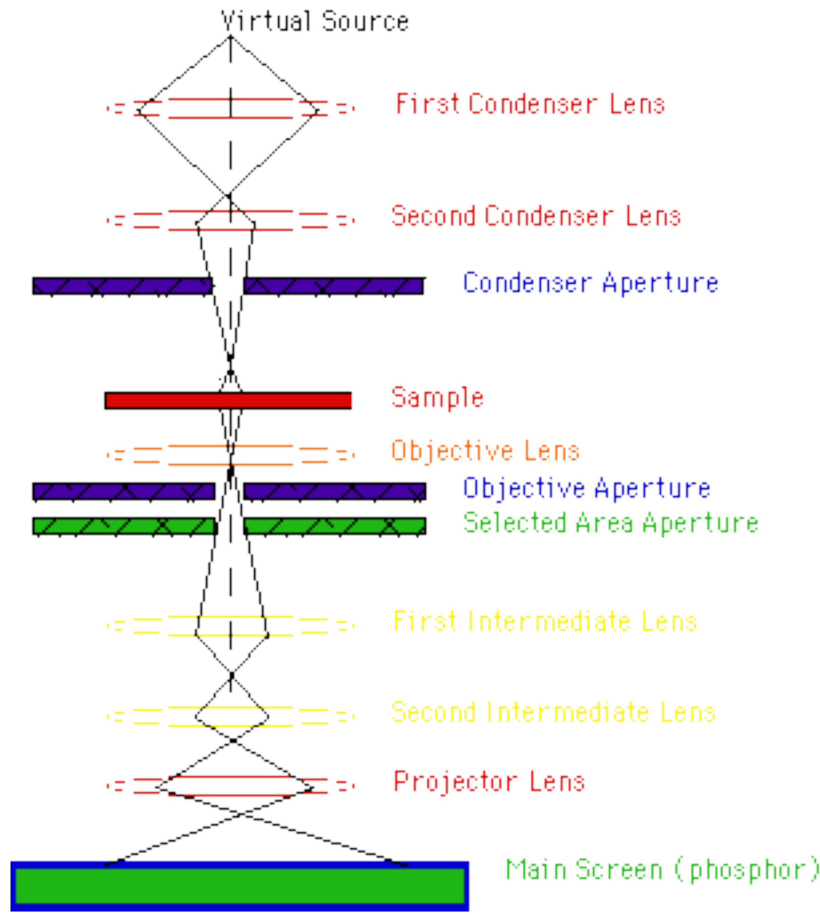
http://www.chem.orst.edu

Example: domains in FePd



Transmission electron microscopy (TEM)

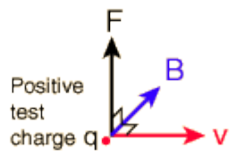


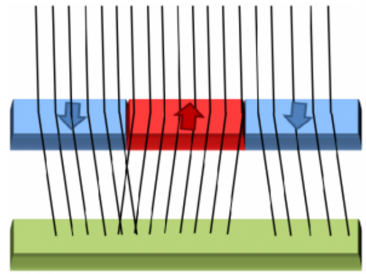


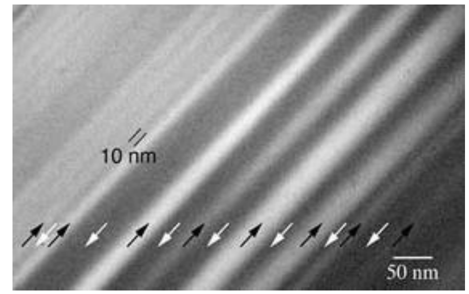
Magnetic TEM

- Lorentz Microscopy

$$\vec{F} = q\vec{v} \times \vec{B}$$

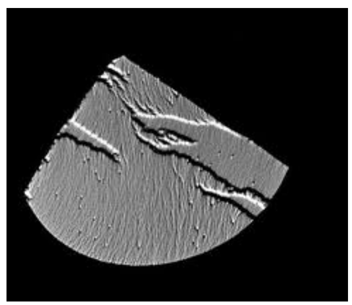






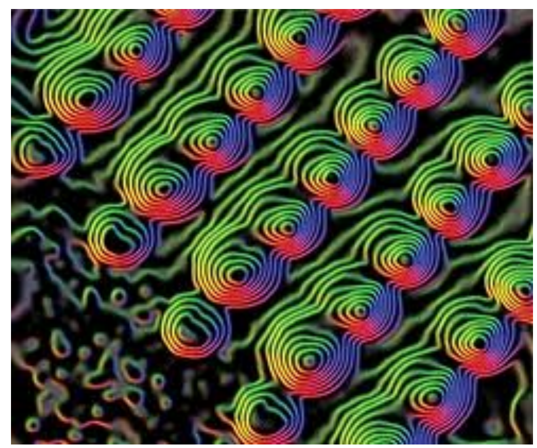
http://www.nims.go.jp/AEMG/research_E.html

- Foucault Microscopy



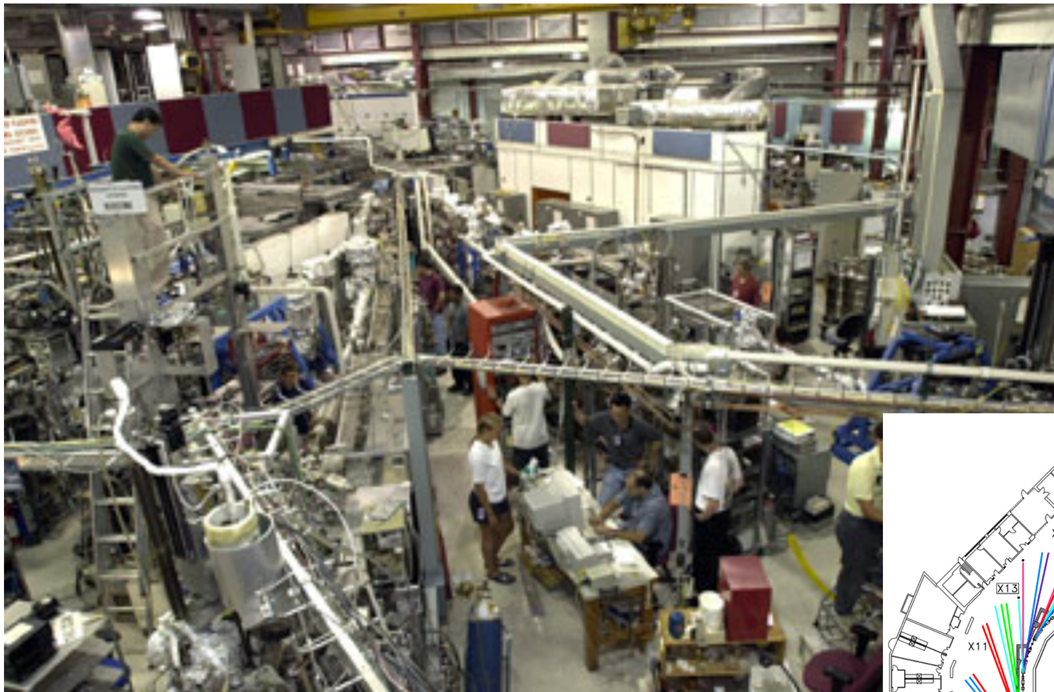
phy.cuhk.edu.hk

- Holographic Microscopy

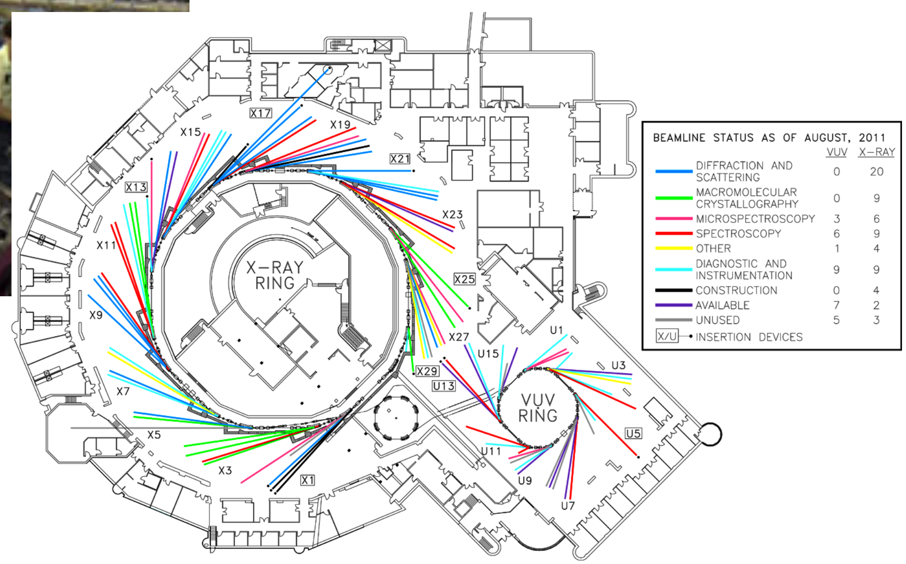


http://scienceblogs.com/brookhaven/2010/07

Synchrotrons:
element-specific magnetometry & structure

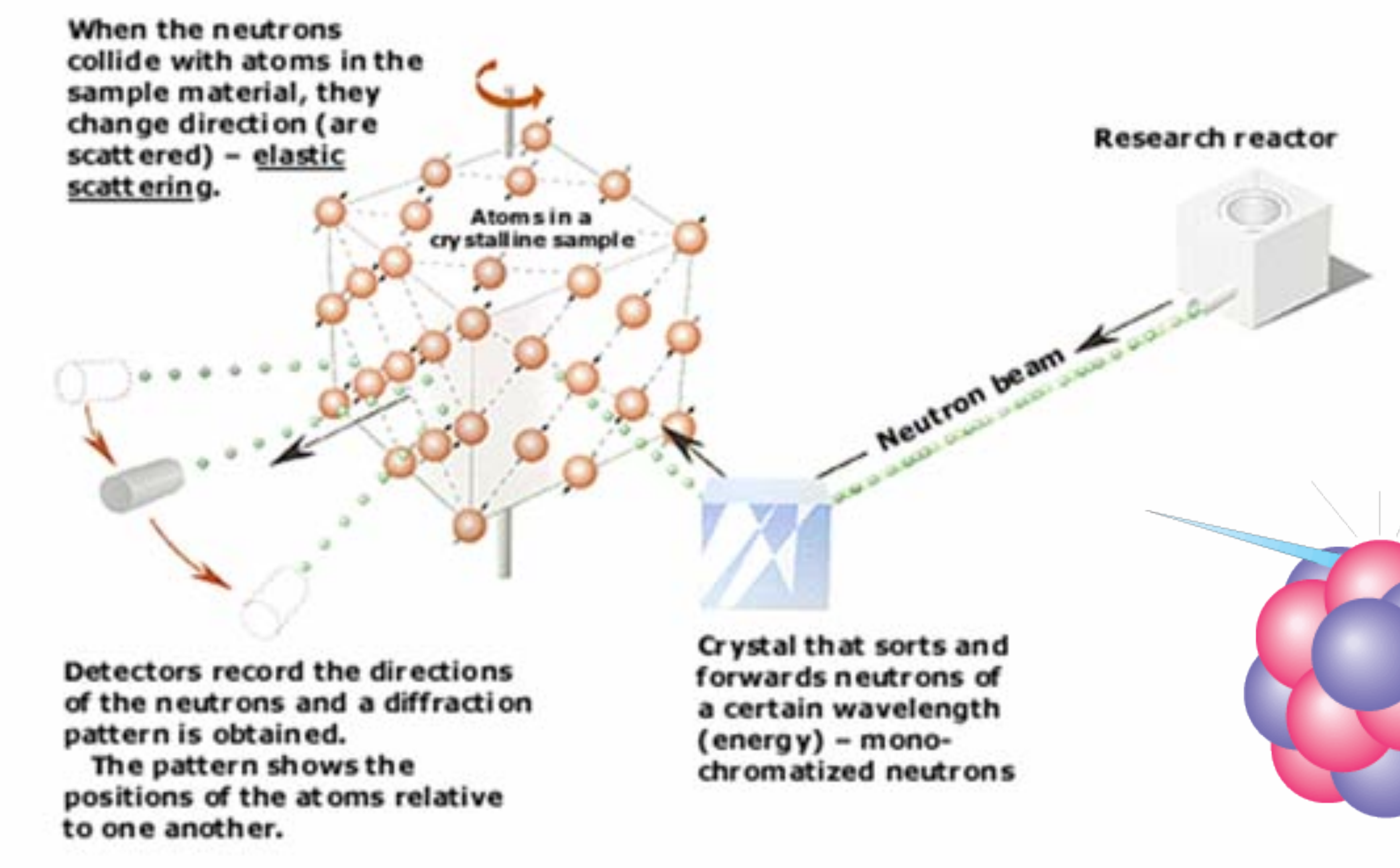


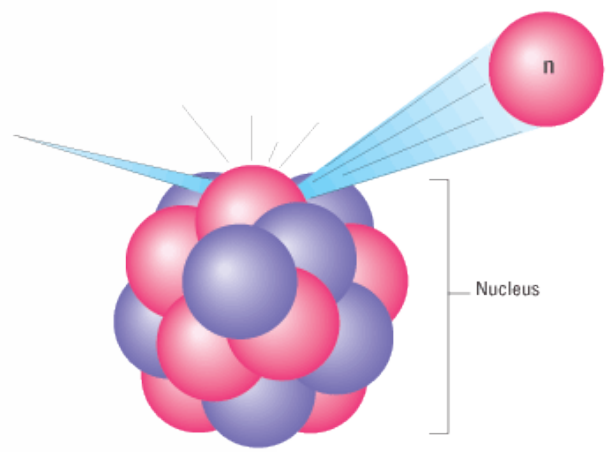
NSLS @ Brookhaven Lab



Tune radiation wavelength to examine magnetic phenomena

Neutron Scattering





http://neutron.magnet.fsu.edu/neutron_scattering.html

Recommended Textbooks

- David C. Jiles, "Introduction to Magnetism and Magnetic Materials, Second Edition"
- B. D. Cullity, "Introduction to Magnetic Materials"
- R. C. O'Handley, "Modern Magnetic Materials: Principles and Applications"
- Richard M. Bozorth, "Ferromagnetism"
- J. M. D. Coey, "Magnetism and Magnetic Materials"
- S. Chikazumi, C. D. Graham, "Physics of Ferromagnetim"

Review of concepts

Students should now know something about…..

- How magnetism benefits society;
- Basic electromagnetism;
- Magnetic exchange;
- paramagnetism, ferromagnetism, antiferromagnetism;
- magnetic domains; magnetic anisotropy, order parameters
- How to match magnetic materials to particular applications;
- Magnetism units;
- Resource for textbooks.

Thank you for your attention!