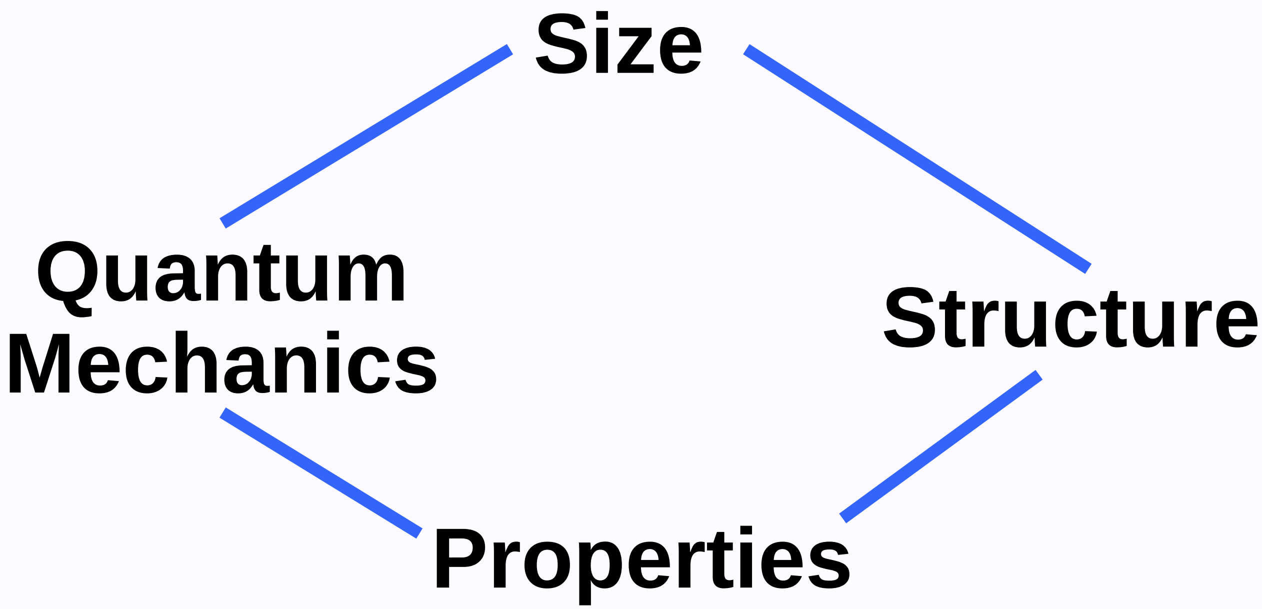
Lecture 26: Nanosystems

Superconducting, Magnetic, ….

What is nano?



Size

Quantum Mechanics

Structure

Properties

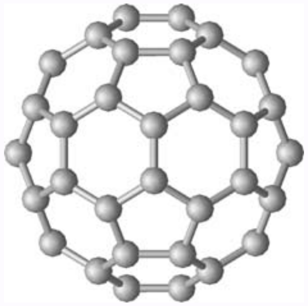
Recall discussion in Lecture 21

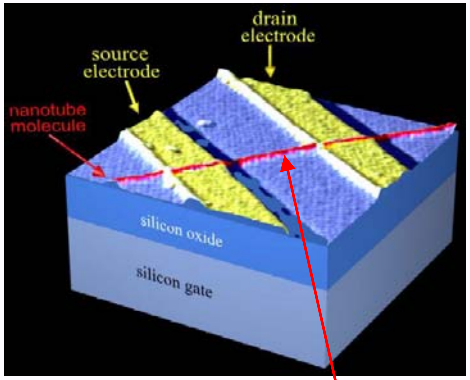
Add new ideas

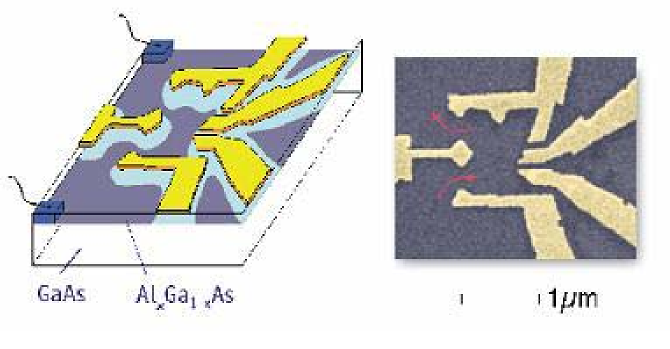
Outline

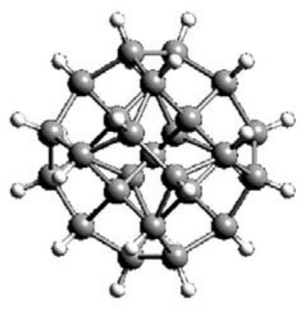
- Electron in a box (reminder)
- Examples of nanostructures
- Created by Applied Voltages
  - Patterned metal gates on semiconductors
  - Create "dots" that confine electrons
- Created by material structures
  - Clusters of atoms, e.g., $Si_{29}H_{36}$, CdSe clusters
  - Buckyballs, nanotubes, . . .
- Created by phases of matter
  - Sensitive to size effects
  - Length scales set by the nature of the phase
  - Magnets – length scale ~ magnetic domain
    - quantum fluctuations
  - Superconductors – length scales ~ pentration
    - depth – coherence length

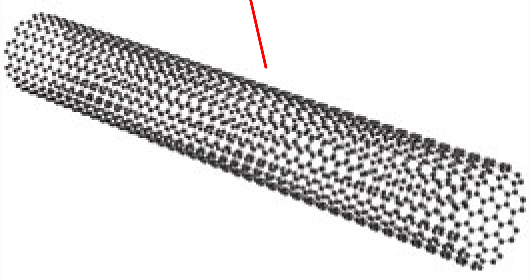
Lecture 21: Nanostructures
Kittel Ch 18
+ extra material in the class notes

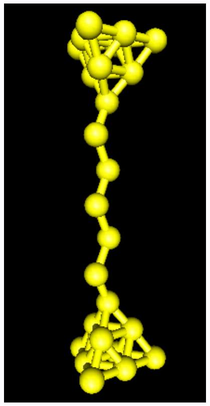












From Lect 21

How small – How large?

- “Nano” means size ~ nm
- Is this the relevant scale for “nano effects” ?
  - Important changes in chemistry, mechanical properties
  - Electronic and optical properties
  - Magnetism (later)
  - Superconductivity (later)
- Changes in chemistry, mechanical properties
  - Expect large changes if a large fraction of the atoms are on the surface
- Electronic and optical properties
  - Changes due to the importance of surface atoms
  - Quantum “size effects” – can be very large and significant

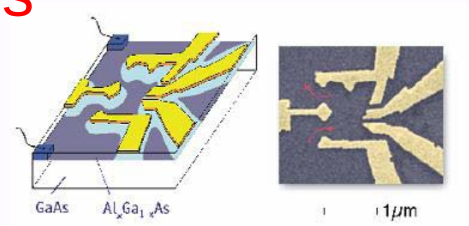
Aspects of Nanosystems (Lect 21)

- Chemistry changes if a large fraction of the atoms are on the surface - nanocluster of radius R
  - R = 3 nm ⇒ ~ 10^3 atoms - 10^2 on the surface – 10%
  - R = 1.2 nm ⇒ ~ 64 atoms - 16 on the surface – 25%
  - R = 0.9 nm ⇒ ~ 27 atoms - 9 on the surface – 33%

- Effects on electronic states due to confinement of electrons "Electron in a box" --

$$E = (h^2/4m L^2) (n_x^2 + n_y^2 + n_z^2)$$

  - For Si, R = 0.9 nm ⇒ ~ 27 atoms - Gap changes in ~ few eV
  - Si becomes a good light emitter - Prof. Nayfeh lecture
- For a semiconductor added electrons or holes have an effective mass m*
  - Quantum well ~ 1000 nm confines electrons – controls semiconductor properties



More possibilities for Nanosystems

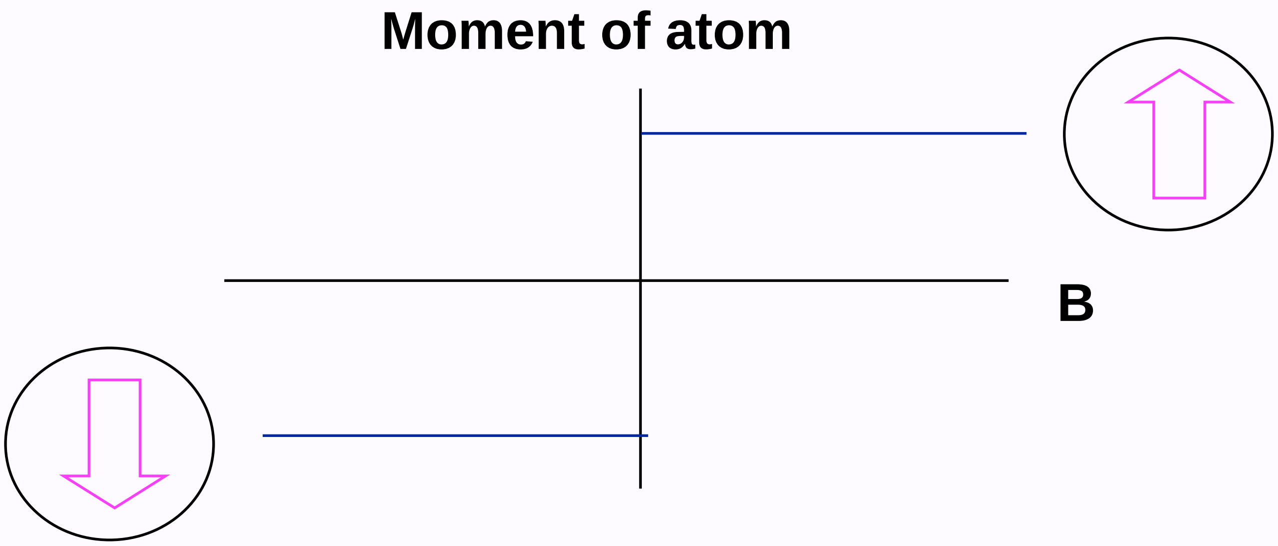
- If a material has a phase transition to an ordered state, the size can affect the properties
- Sensitive to size effects
  Length scales set by the nature of the phase

- Magnets – length scale ~ magnetic domain
  quantum fluctuations

- Superconductors – length scales ~ penetration
  depth – coherence length

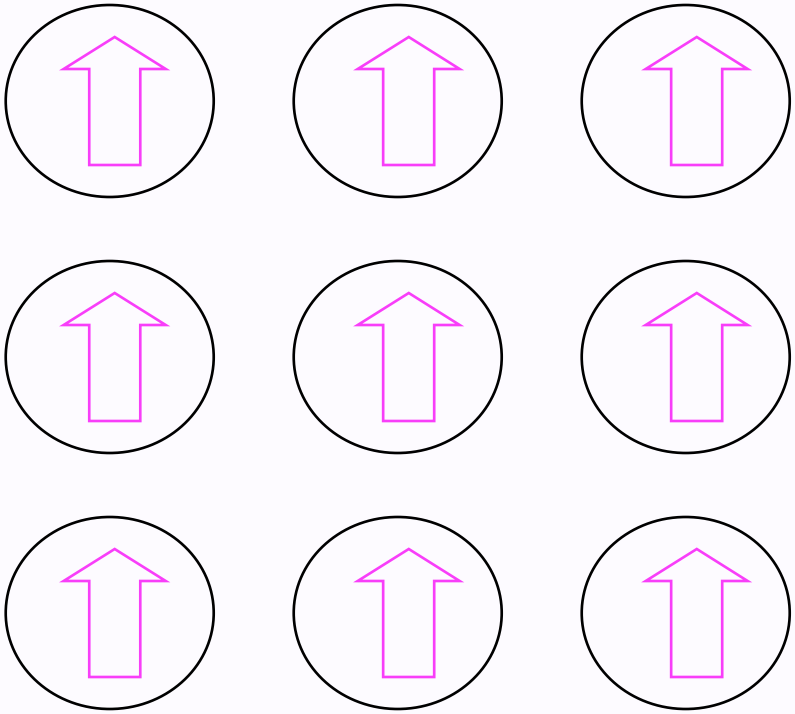
Magnetic systems (Lect 24)

- Effect of Size
- In free space a single atom can have a moment – rotates easily – easily changed by magnetic field
  Curie Law (Kittel p 305)



Ferromagnetic solid

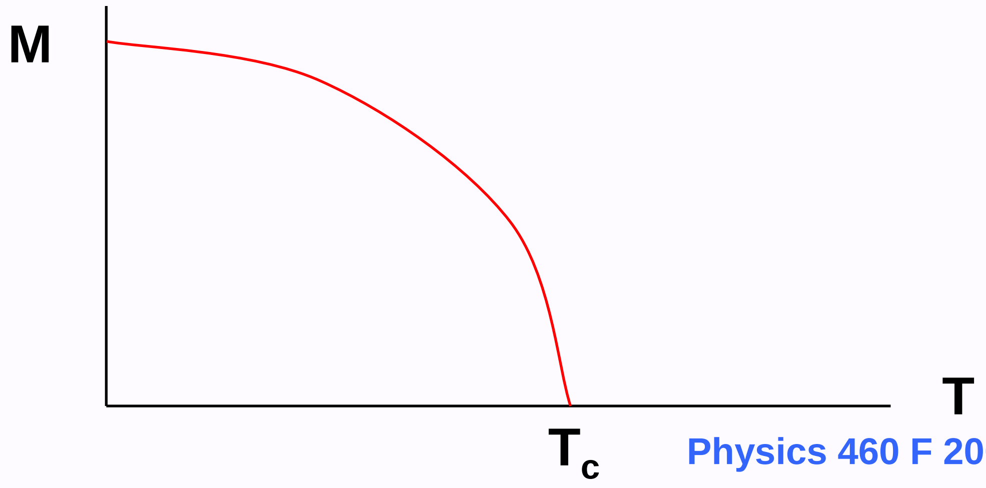
- “Localized” magnetic moments on the atoms aligned together to give a net magnetic moment



- Although there is some thermal disorder, there is a net moment at finite temperature.

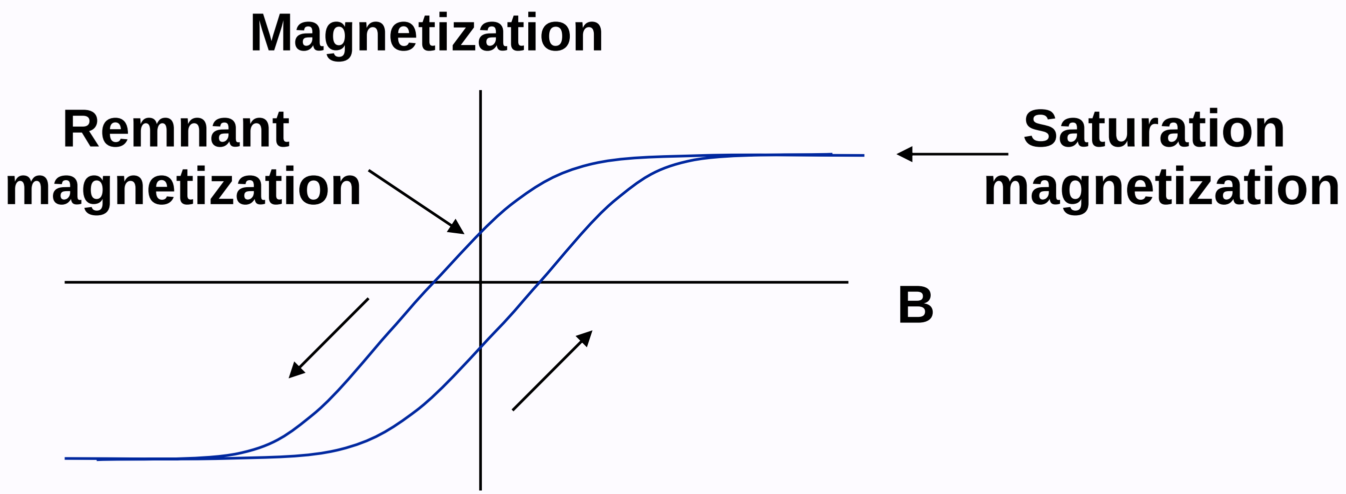
Example of a phase transition to a state of new order

- At high temperature, the material is paramagnetic
  Magnetic moments on each atom are disordered
- At a critical temperature T_c the moments order
  Total magnetization M is an "Order Parameter"
- Transition temperatures:
  T_c = 1043 K in Fe, 627 K in Ni, 292 K in Gd



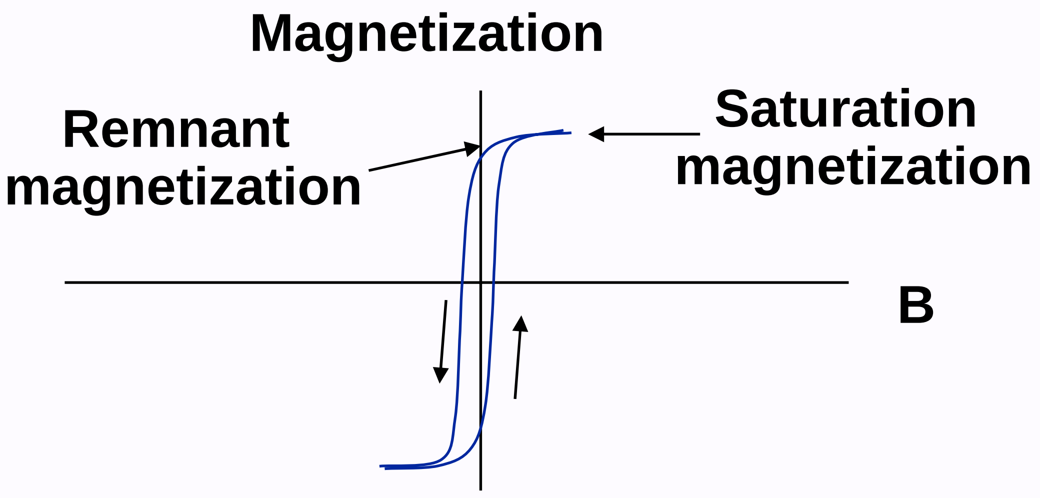
Magnetic materials –large magnets

- Domains and Hysteresis
- A magnet usual breaks up into domains unless it is “poled” - an external field applied to allign the domains
- A real magnet has “hysteresis” - it does not change the direction of its magnetization unless a large enough field is applied - irreversibility



Magnetic materials – Nano size

- Single Domains - changed Hysteresis
- Always a single domain - an external field applied can reorient the domains
- Hysteresis reduced – magnet less stable – easily changed – good/bad – depends on application



Two length scales in superconductivity

- London Penetration depth
  $\lambda_L^2 = \varepsilon_0 mc^2/nq^2$ (particles of mass m, charge q)
- (Understood from the BCS theory that m and q are for an electron pair)
- Coherence length – size of pair

Typical values

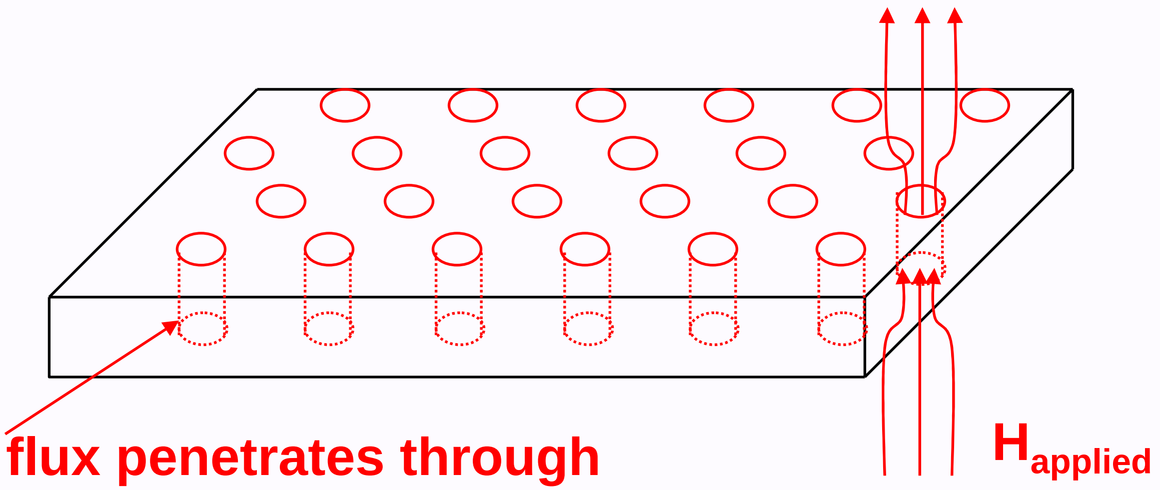
Al	$T_c = 1.19$K	$\xi = 1{,}600$ nm	$\lambda_L = 160$ nm	$\xi/\lambda_L = 0.01$
Pb	$T_c = 7.18$K	$\xi = 83$ nm	$\lambda_L = 370$ nm	$\xi/\lambda_L = 0.45$

The ratio determines type I ($\xi/\lambda_L \ll 1$) and
type II ($\xi/\lambda_L > \sim 1$) superconductors
see later

Sizes of this range affect superconductivity

Type II – already show a quantum “nano” effect

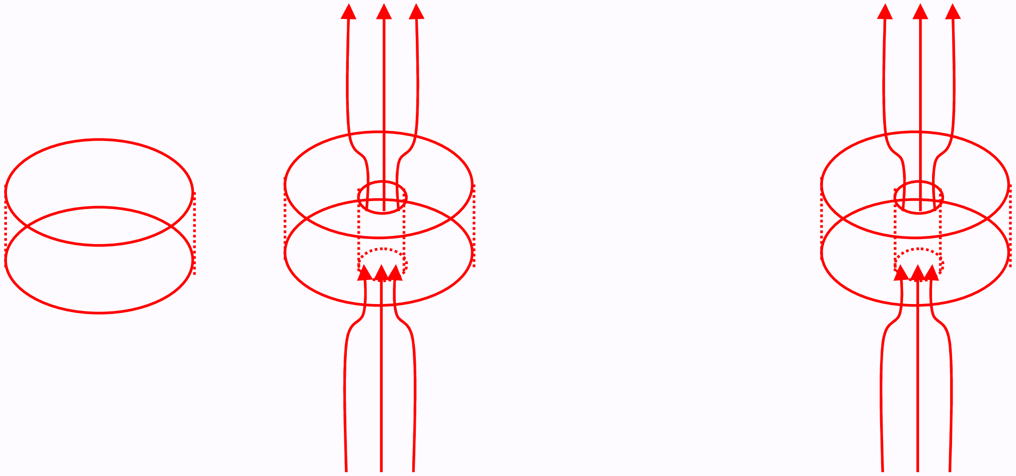
- Type II superconductors form flux quanta in “vorticers” for $H_{c1} < H < H_{c2}$
- Lattice of quantized flux units in a large sample



Magnetic flux penetrates through the superconductor by creating small regions normal metal

Type II – already show a quantum “nano” effect

- **Can have single quantum that can move in a nano sample – many other quantum effects**
- **Microscopic size “SQUIDS” to detect magnetic fields**



Applied field

Nanosize system with
a hole - applied field
Goes through hole –
Sets up currrents

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