

Advanced solid state physics

Nobel Prize winners 2007 Physics

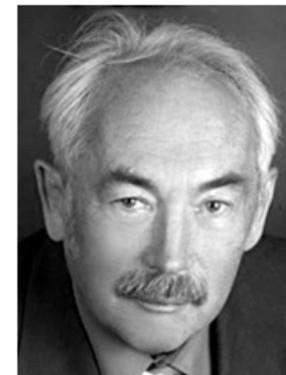
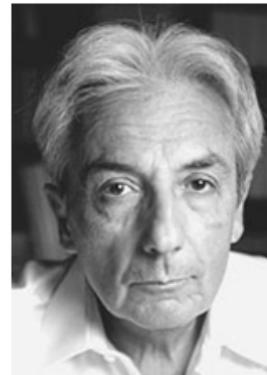
"for the discovery of Giant Magnetoresistance"

Peter Grünberg
Forschungszentrum Jülich
Jülich, Germany



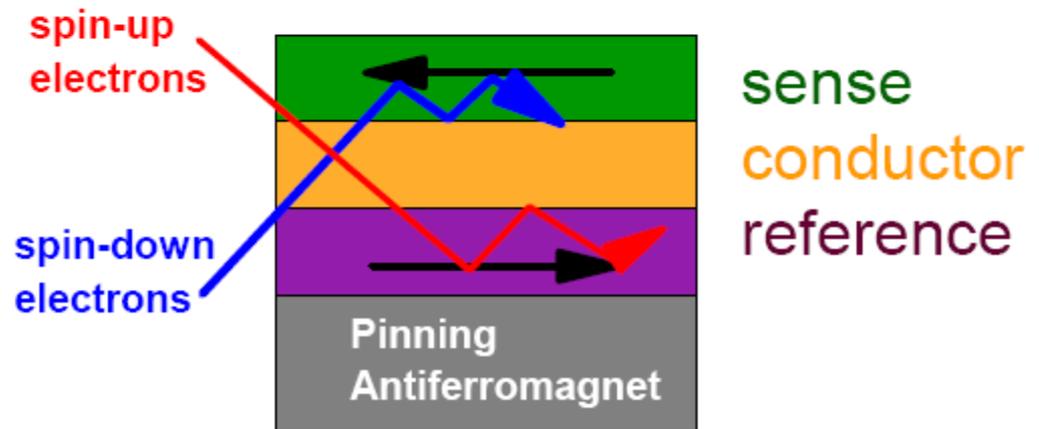
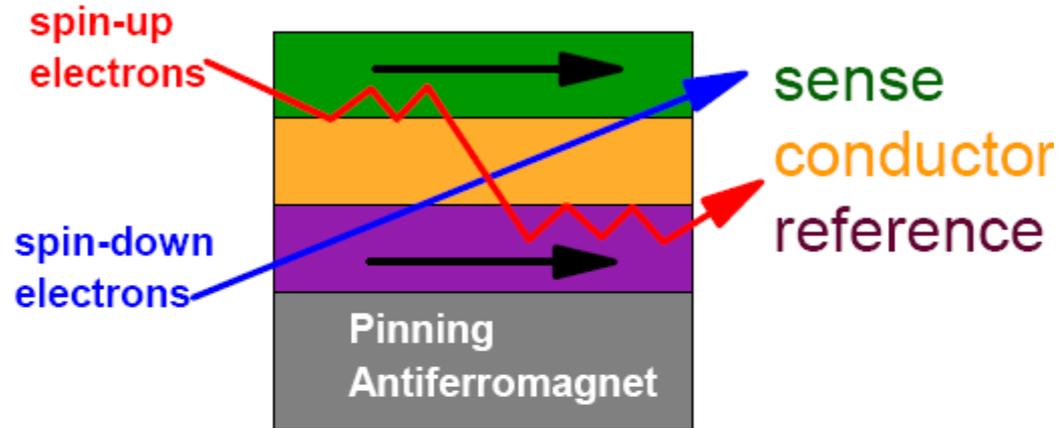
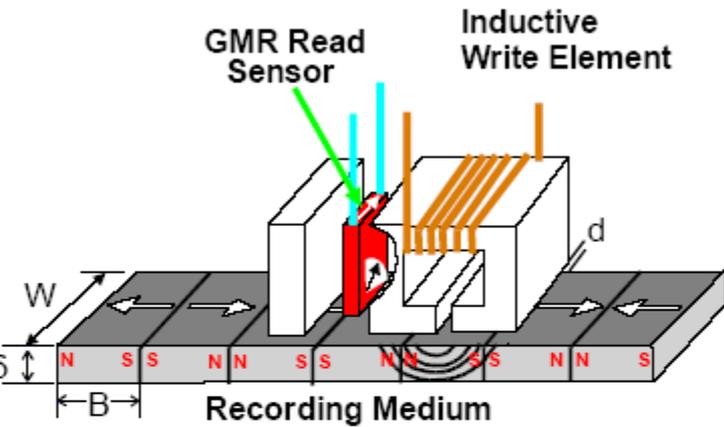
Albert Fert

Université Paris-Sud; Unité Mixte
de Physique CNRS/THALES
Orsay, France



Some pictures are taken from Ashcroft and Mermin from Kittel from Mizutani and from several sources on the web.

GMR sensor

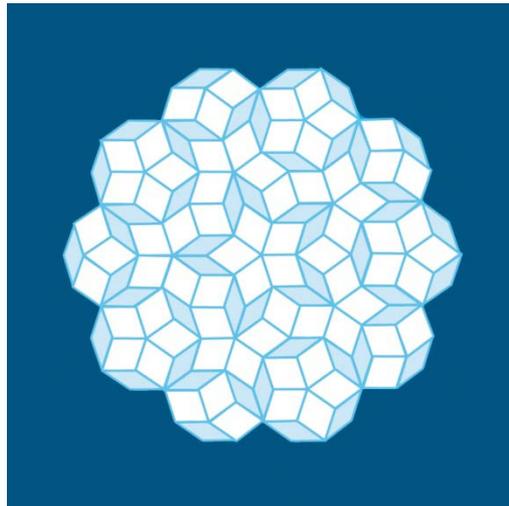


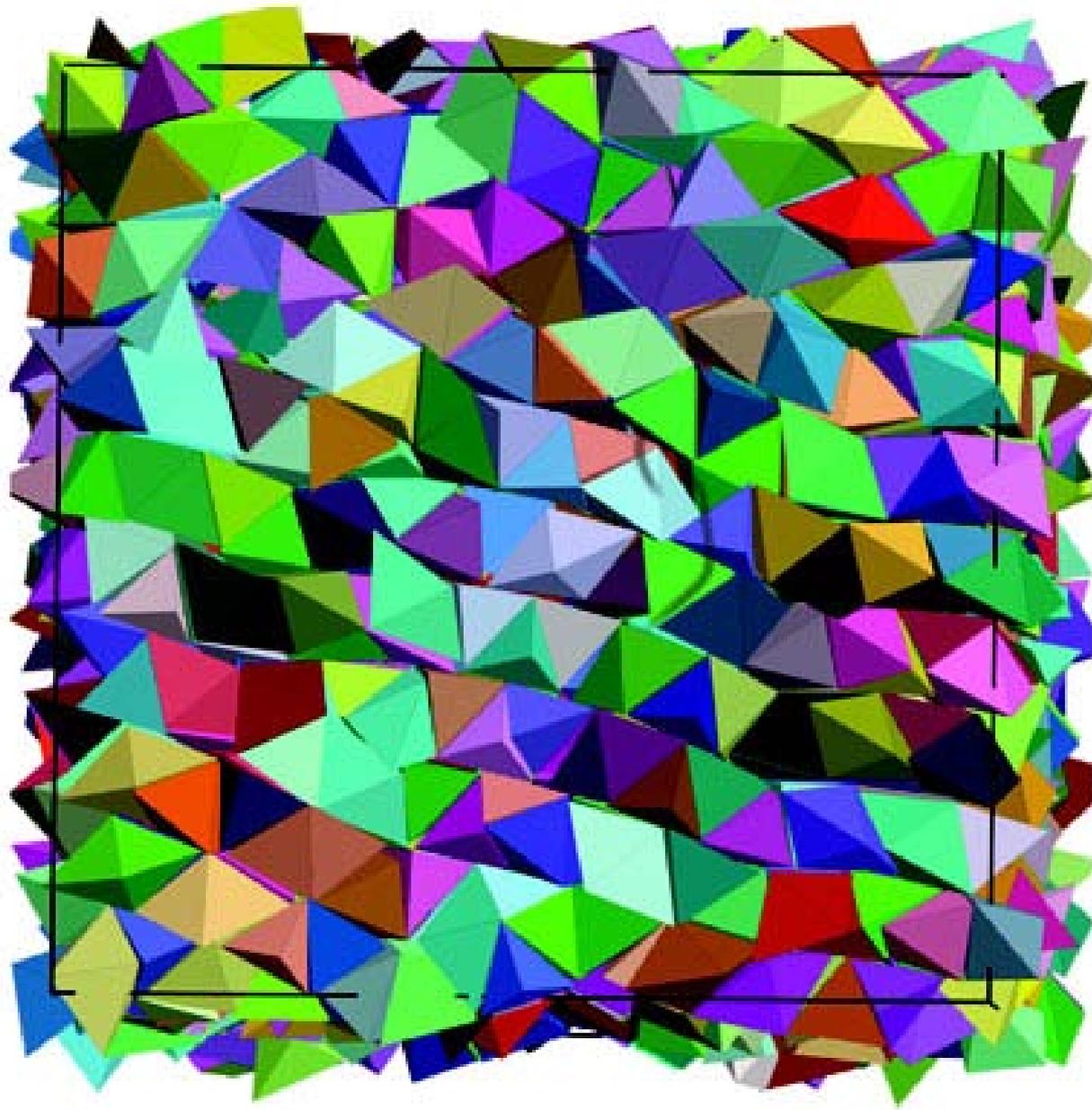




Quasicrystals – materials that have ordered but not periodic structures – were discovered by **Daniel Shechtman** in 1984 and won him the **2011** Nobel Prize for Chemistry.

Before Shechtman's discovery, it was thought that **long-range order** in physical systems was impossible **without periodicity**. Atoms were believed to be packed inside crystals in symmetrical patterns that were repeated periodically over and over again. But Shechtman found atoms in a crystal that were packed in a pattern that could not be repeated and yet had "10-fold" rotational symmetry. Since then, hundreds of different quasicrystals have been discovered, including icosahedral quasicrystals that have 2-fold, 3-fold and 5-fold rotational symmetry. There are also octagonal (8-fold), decagonal (10-fold) and dodecagonal (12-fold) quasicrystals that exhibit "forbidden" rotational symmetries within 2D atomic layers but that are periodic in the direction perpendicular to these layers.

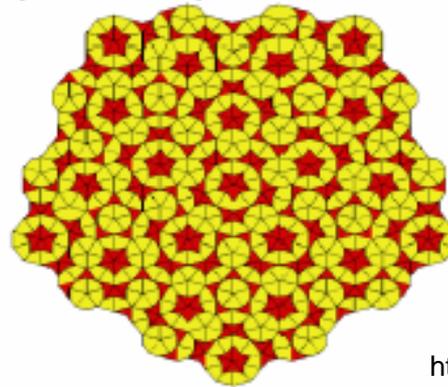
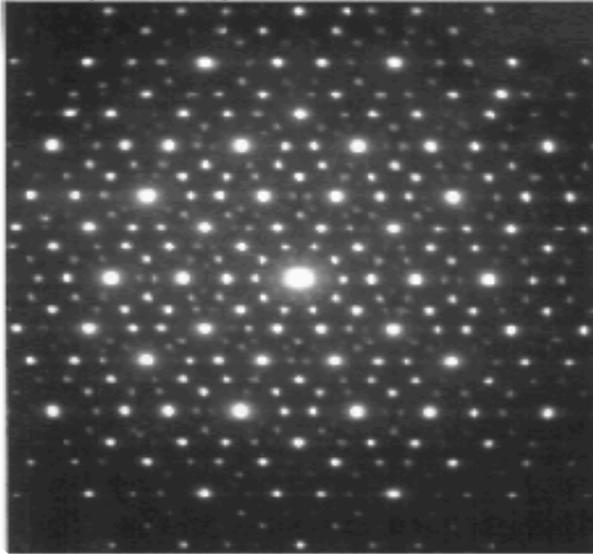




Assembly of triangular bipyramids forming a dodecagonal quasicrystal in Monte Carlo simulations. (Courtesy: Sharon C Glotzer *et al.*)

□ Among the most well known consequences of periodicity is the fact that the only rotational symmetries that are possible are 2-, 3-, 4-, and 6-fold rotations \Rightarrow Five-fold rotations (and any n -fold rotation for $n \neq 6$) are incompatible with periodicity.

□ **Quasicrystals = quasiperiodic crystals** [D. Shechtman, I. Blech, D. Gratias, and J.W. Cahn, "Metallic phase with with long-range orientational order and no translational symmetry," Phys. Rev. Lett. **53**, 1951 (1984)]: Translational order completely broken; rotational symmetry broken to 5-fold discrete subgroup.



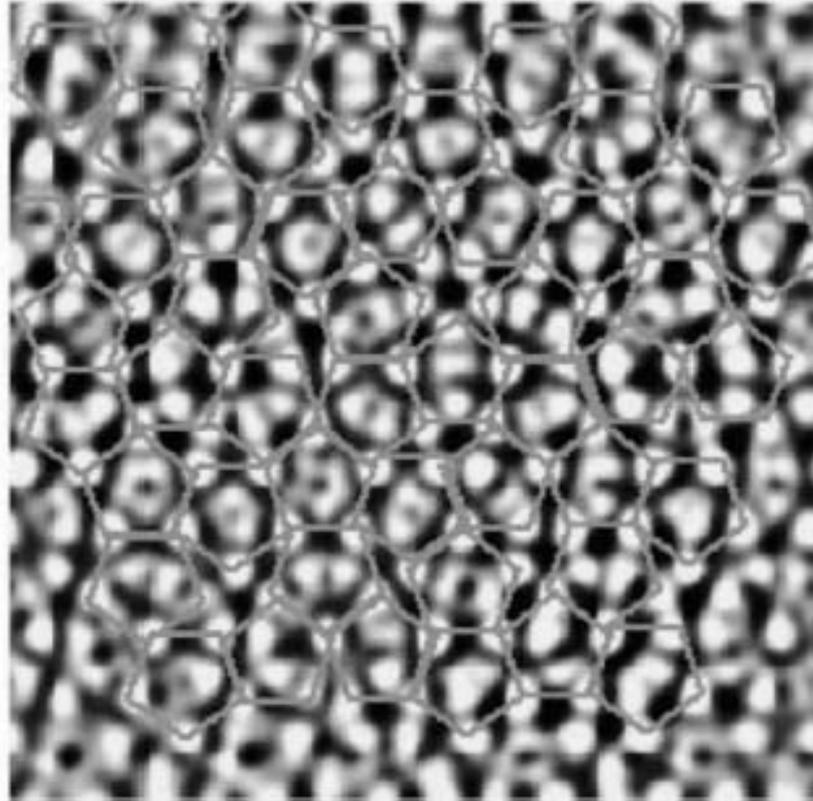
□ Penrose tile is a 2D example of a quasicrystal: **There is perfect long-range order and no periodicity in the normal sense.**

http://en.wikipedia.org/wiki/Penrose_tiling

□ **Quasicrystals** possess unique physical properties: even though they are all alloys of two or three metals they are **very poor** conductors of electricity and of heat.

<http://www.physics.udel.edu/~bnikolic/teaching/phys624/phys624.html>

see more: <http://jcrystal.com/steffenweber/qc.html>



Scanning tunneling microscope image of a 10 nm² quasicrystal of AlPdMn with a Penrose tiling overlaid [Ledieu et al., Phys. Rev. B **66**, 184207 (2002)]

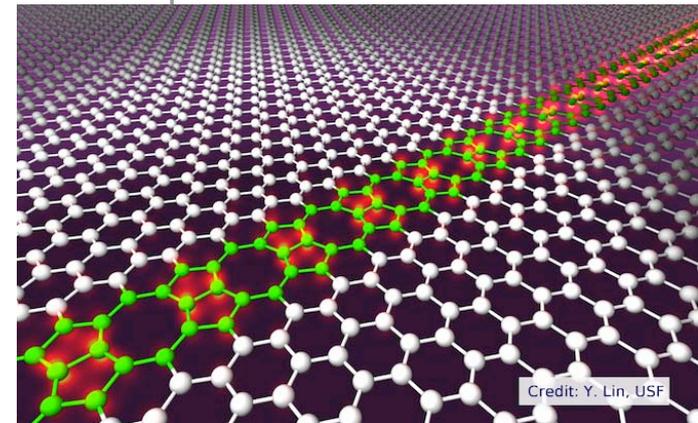
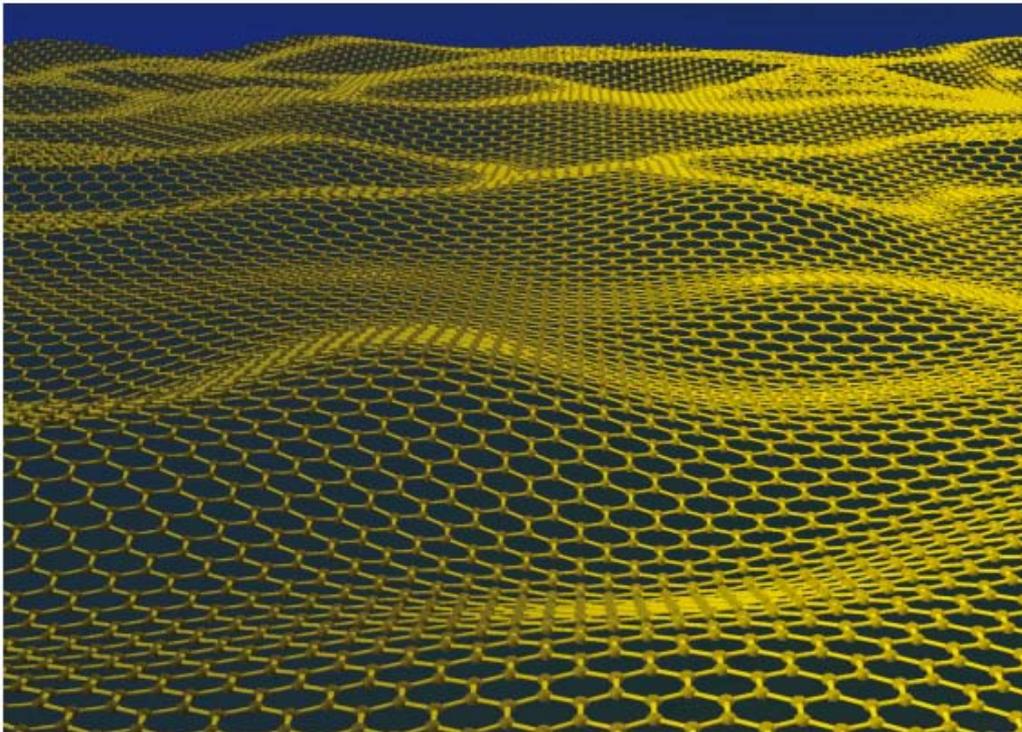
Graphene – the perfect atomic lattice

A thin flake of ordinary carbon, just one atom thick, lies behind this year's Nobel Prize in Physics. Andre Geim and Konstantin Novoselov have shown that carbon in such a flat form has exceptional properties that originate from the remarkable world of quantum physics.

Graphene is a form of carbon. As a material it is completely new – not only the thinnest ever but also the strongest. As a conductor of electricity it performs as well as copper. As a conductor of heat it outperforms all other known materials. It is almost completely transparent, yet so dense that not even helium, the smallest gas atom, can pass through it.

The Nobel Prize in Physics 2010 was awarded jointly to Andre Geim and Konstantin Novoselov "for groundbreaking experiments regarding the two-dimensional material graphene"

Jannik Meyer, Science vol. 324, 15 May 2009

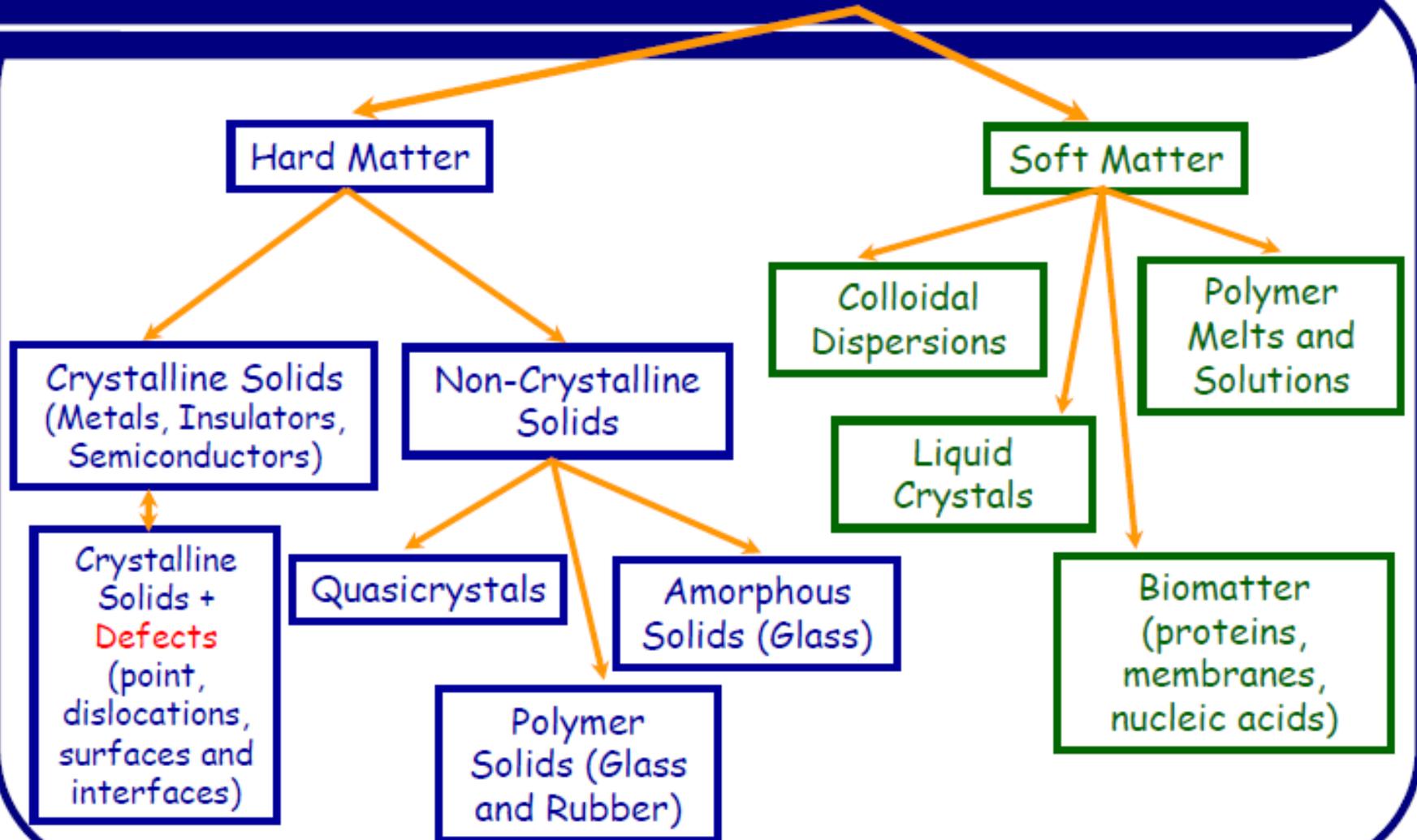


<http://www.wired.com/gadgetlab/2010/10/graphene/>



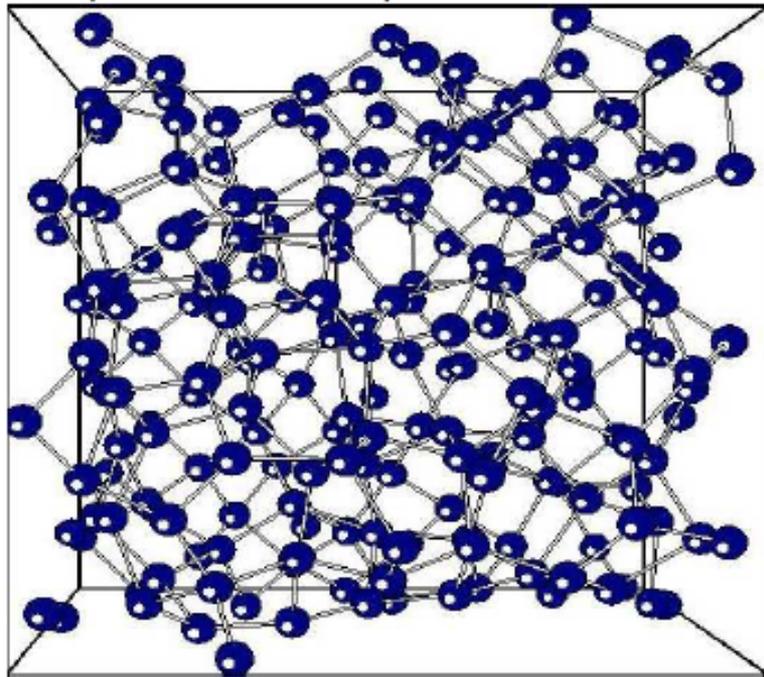
Figure 1. Graphene. The almost perfect web is only one atom thick. It consists of carbon atoms joined together in a hexagonal pattern similar to chicken wire.

Condensed Matter Systems



Non-Crystalline Hard CM Phases: Glasses

□ **Glasses:** rigid but random arrangement of atoms; in fact, they are "non-equilibrium phase" - effectively they look more like a frozen "snapshot" of a liquid.

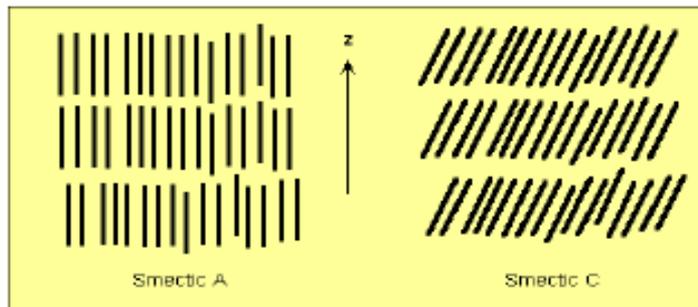
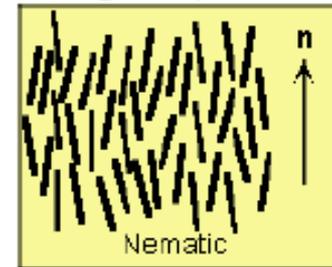
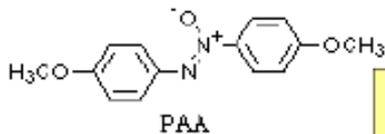


□ **Example:** Amorphous Silicon.

□ The structural glassy materials arise when a liquid is cooled to an amorphous solid fast enough to prevent crystallization, which would otherwise occur if the time had been sufficient for the sample to reach true equilibrium at each temperature. Thus, "frozen" supercooled liquids (which have enormous viscosity that prevents any large-scale flow on human time scales) form a glassy state of matter that is substantially different from crystals: it is disordered and only metastable thermodynamically. Moreover, the essential physics of nonequilibrium glassy state (leading to rapid increase in response time, and phenomena like aging, rejuvenation, memory effects, ...) is the prototype of a slow nonexponential relaxation found in diverse physical systems: spin glasses, disordered insulators (Coulomb glass), magnets, superconductors, proteins, colloidal suspensions, granular assemblies, ...

Soft Condensed Matter Phases

- ❑ **Liquids** (full translational and rotational group preserved) vs. **Solids** (preserve only a discrete subgroups).
- ❑ **Liquid crystalline phase** - translational and rotational symmetry is broken to a combination of discrete and continuous subgroups:



- ❑ **Polymers** - extremely long molecules that can exist in solution or a chemical reaction can take place which cross-links them, thereby forming a gel.

1. **Introduction.** Review of the basic solid state physics concepts.
2. **Electronic structure, density of states and the physical properties of solids.**
3. **Experimental techniques and principles of electronic structure-related phenomena.**
4. **Phonons and electrons in solid.**
5. **Dielectric properties of solids.**
6. **Defects in solids.**
7. **Introduction to superconductivity**

References

1. C. Kittel, Introduction to Solid State Physics (8ed., Wiley, 1996)
2. N. W. Ashcroft, N. D. Mermin, *Solid State Physics*, Saunders, 1976.
3. Ch. Enss, S. Hunklinger, Low-Temperature Physics, Springer-Verlag Berlin Heidelberg 2005.
4. U. Mizutani, Introduction to the Electron Theory of Metals, Cambridge University Press 2001.
5. H. Alloul, Introduction to the Physics of Electrons in Solids, Springer-Verlag Berlin Heidelberg 2011
6. H. Ibach, IH. Lüth, Solid-State Physics, Springer 2009
7. J. M. Ziman, Electrons and phonons, The Theory of Transport Phenomena in Solids, Oxford, Clarendon Press 1960.

Minimal Update of Solid State Physics

#1: Review of Solid State Physics

- Types of Solids \longleftrightarrow Crystalline Solids
 - Ionic, Covalent, and Metallic.
- Classical Theory of Conduction
 - Current density j , drift velocity v_d , resistivity ρ .
- Band Theory and Band Diagrams
 - Energy levels of separated atoms form energy "band" when brought close together in a crystal.
 - Fermi Function for how to "fill" bands.
 - Metal, Insulator, and Semiconductor band diagrams.
 - Donor and Acceptor dopants.

3 D

The 14 possible BRAVAIS LATTICES

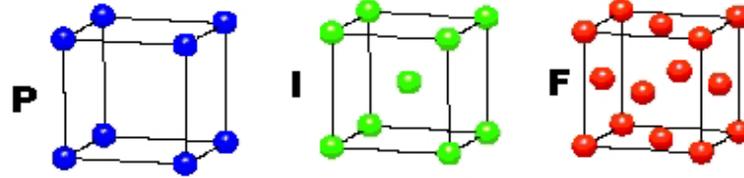
{note that spheres in this picture represent lattice points, not atoms!}

all the points are equivalent

CUBIC

$$a = b = c$$

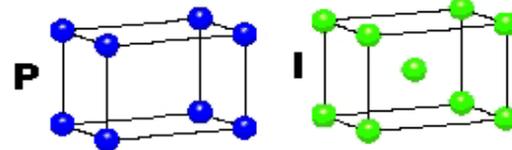
$$\alpha = \beta = \gamma = 90^\circ$$



TETRAGONAL

$$a = b \neq c$$

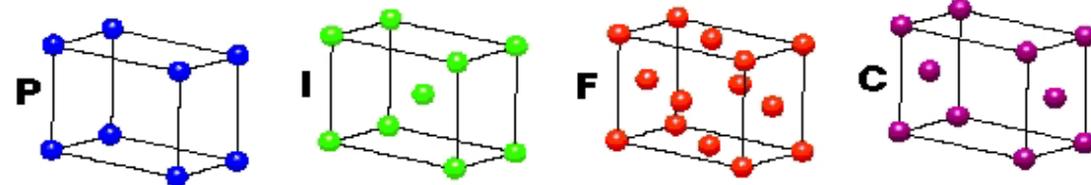
$$\alpha = \beta = \gamma = 90^\circ$$



ORTHORHOMBIC

$$a \neq b \neq c$$

$$\alpha = \beta = \gamma = 90^\circ$$

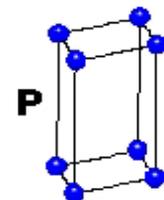


HEXAGONAL

$$a = b \neq c$$

$$\alpha = \beta = 90^\circ$$

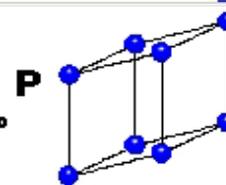
$$\gamma = 120^\circ$$



TRIGONAL

$$a = b = c$$

$$\alpha = \beta = \gamma \neq 90^\circ$$

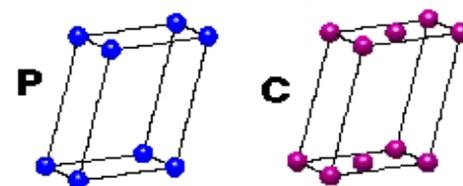


MONOCLINIC

$$a \neq b \neq c$$

$$\alpha = \gamma = 90^\circ$$

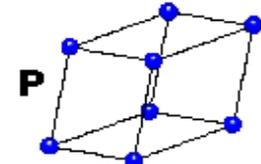
$$\beta \neq 120^\circ$$



TRICLINIC

$$a \neq b \neq c$$

$$\alpha \neq \beta \neq \gamma \neq 90^\circ$$



4 Types of Unit Cell
P = Primitive
I = Body-Centred
F = Face-Centred
C = Side-Centred
 +
7 Crystal Classes
 → **14 Bravais Lattices**

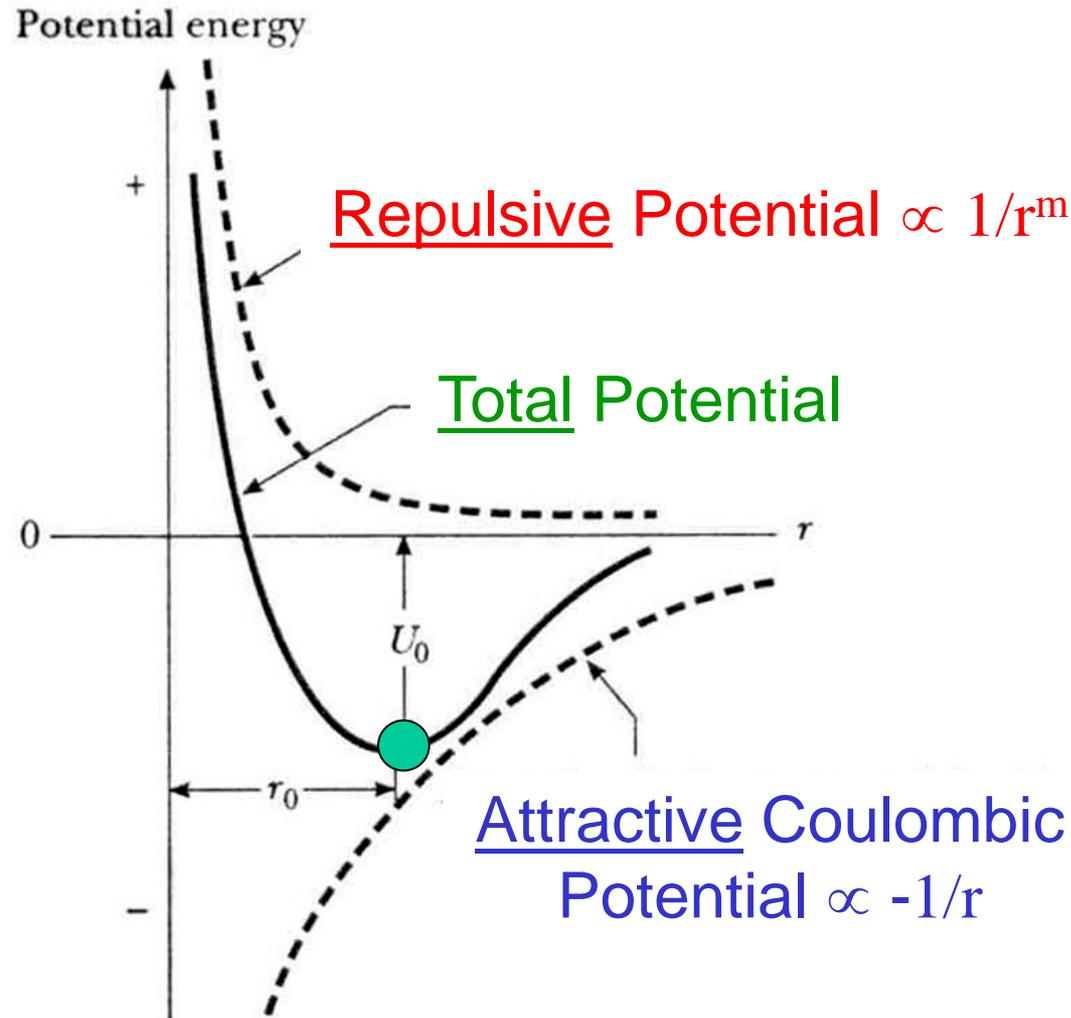
2D

5 systems
 (oblique,
 rectangular,
 centered
 rectangular
 (rhombic),
 hexagonal,
 square

Types of Solids: Ionic Solid, Properties

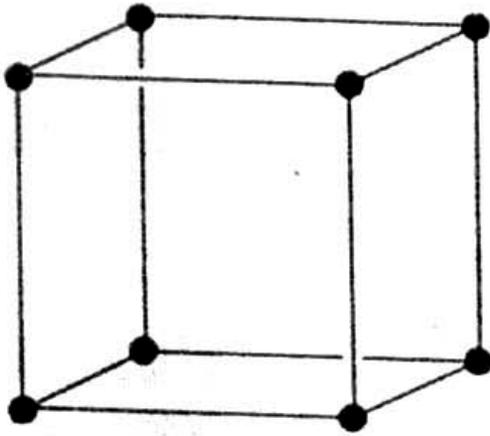
- Formed by Coulombic attraction between ions.
 - Examples include group I alkali cations paired with group VII halide anions, e.g. $\text{Na}^+ \text{Cl}^-$.
- Large cohesive energy (2-4 eV/ atom).
 - Leads to high melting and boiling points.
- Low electrical conductivity.
 - No “free” electrons to carry current.
- Transparent to visible light.
 - Photon energy too low to “free” electrons.
- Soluble in polar liquids like water.
 - Dipole of water attracts ions.

Types of Solids: Ionic Solid, Crystal Spacing

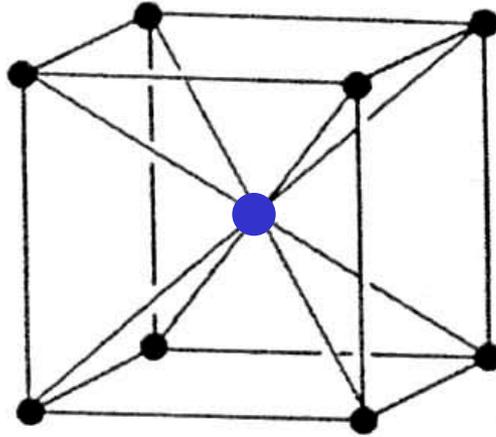


- Potential Energy: $U_{\text{tot}} = U_{\text{attract}} (+,-) + U_{\text{repulse}} (-,-)$

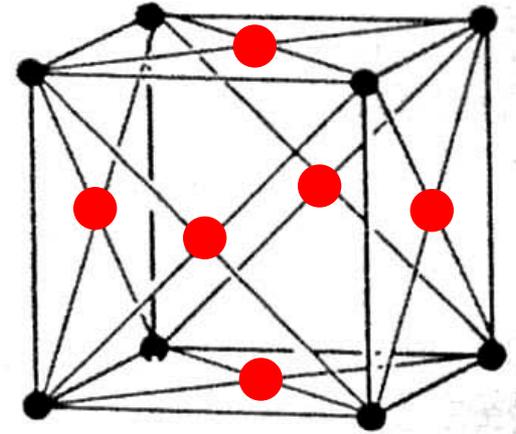
Types of Solids: Example Crystalline Structures



Simple Cubic

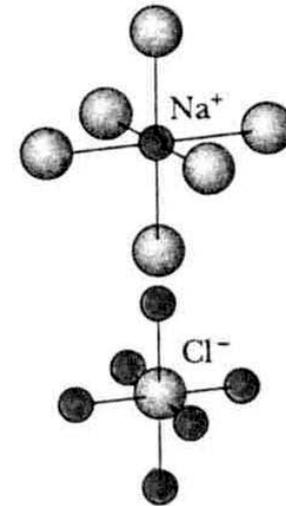
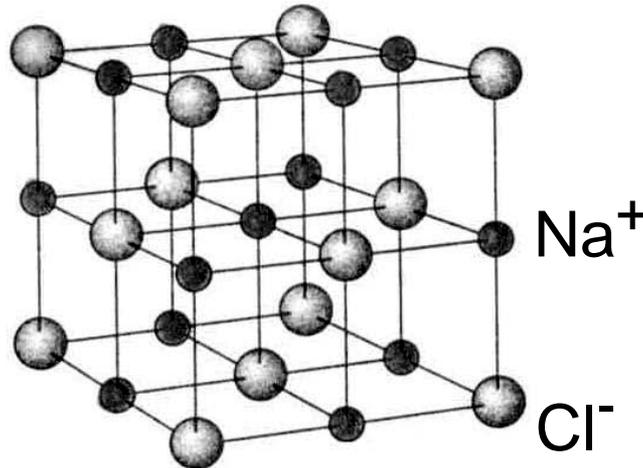


Body-Centered Cubic



Face-Centered Cubic

FCC
structure:
NaCl



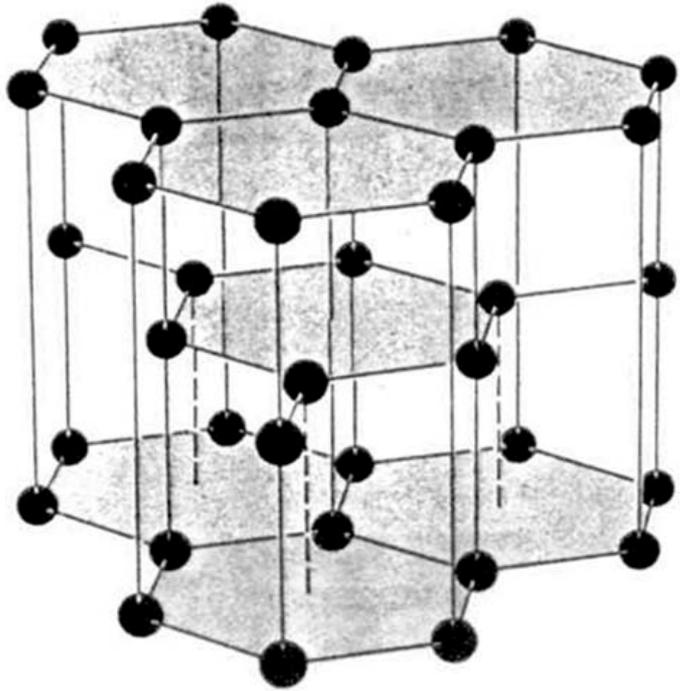
Types of Solids: Covalent Solid

- Examples include group IV elements (C, Si) and III-V elements (GaAs, InSb).
- Formed by strong, localized bonds with stable, closed-shell structures.
- Larger cohesive energies than for ionic solids (4-7 eV/atom).
 - Leads to higher melting and boiling points.
- Low electrical conductivity.
 - Due to energy band gap that charged carriers must overcome in order to conduct.

Types of Solids: Example Crystalline Structures

Graphite

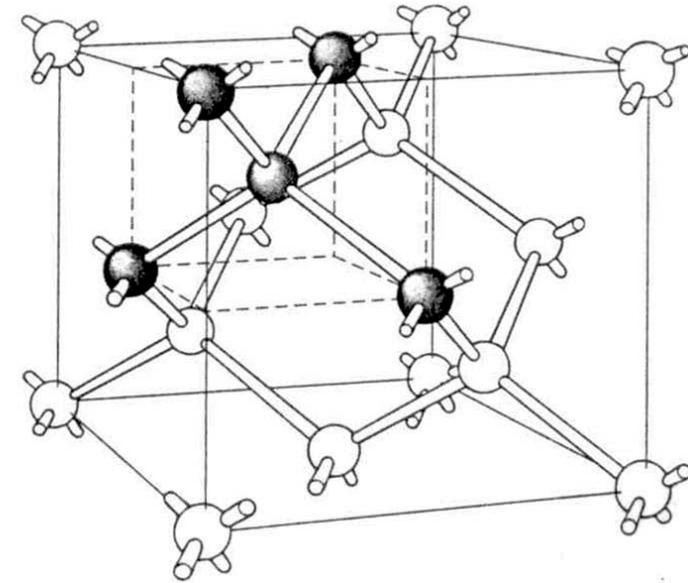
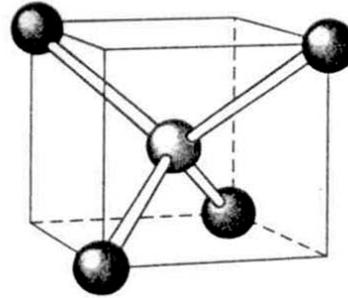
Planar sp^2 bonding
(good lubricant)



Vertical π -bonds

Diamond

Tetrahedral sp^3 bonding
(very hard!)



Bond angle = 109.5°

Escher loved two dimensional structures too (Dutch graphic artist)



Types of Solids: Metal

- Formed by **Coulombic attraction** between (+) lattice ions and (–) electron “gas.”
- Metallic bonds allows electrons to move freely through lattice.
- Smaller cohesive energy (1-4 eV).
- High electrical conductivity.
- Absorbs visible light (non-transparent, “shiny” due to re-emission).
- Good alloy formation (due to non-directional metallic bonds).

Classical Theory of Conduction

Macroscopic

Current: $i = \frac{dq}{dt}$ (Amps)

$$q = \int i dt$$

$$i = \frac{V}{R}$$

$$R = \frac{\rho L}{A}$$

Microscopic

Current Density: $\vec{J} = \frac{di}{d\vec{A}}$ (A/m²)

$$i = \int \vec{J} \cdot d\vec{A}$$

$$\vec{J} = \frac{\vec{E}}{\rho} = \sigma \vec{E} \quad \text{where } \rho = \text{resistivity}$$

$\sigma = \text{conductivity}$

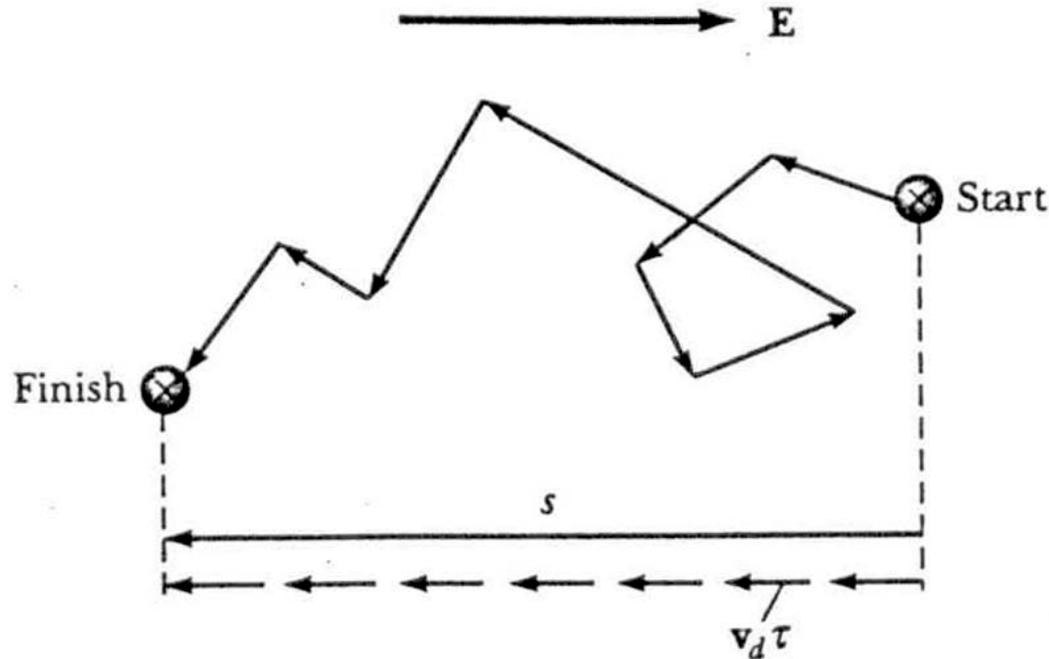
$$\vec{J} = n e \vec{v}_d \quad \text{where } n = \text{carrier density}$$

$v_d = \text{drift velocity}$

$$\rho = \frac{m}{ne^2 \tau} \quad \text{where } \tau = \text{scattering time}$$

- Drift velocity v_d is net motion of electrons (0.1 to 10^{-7} m/s).
- Scattering time τ is time between electron-lattice collisions.

Classical Theory of Conduction: Electron Motion



- Electron travels at fast velocities for a time τ and then “collides” with the crystal lattice.
- Results in a net motion opposite to the E field with drift velocity v_d .
- Scatter time τ decreases with increasing temperature T , i.e. more scattering at higher temperatures (leads to higher resistivity).

Classical Theory of Conduction: Resistivity vs. Temp.

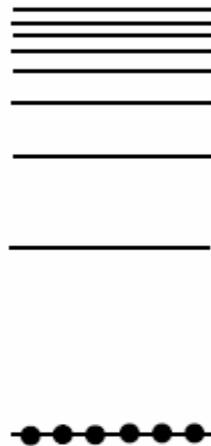
$$\rho = \frac{E}{J} = \frac{F_E / e}{ne v_d} = \frac{ma / e}{ne (a\tau)} = \frac{m}{ne^2 \tau} \propto \frac{1}{n\tau}$$

- Metal: Resistance increases with Temperature.
- Why? $\uparrow \text{Temp} \Rightarrow \downarrow \tau$, n same (same numb. conduction electrons) $\Rightarrow \uparrow \rho$
- Semiconductor: Resistance decreases with Temperature.
 - Why? $\uparrow \text{Temp} \Rightarrow \downarrow \tau$, $\uparrow n$ (“free-up” carriers to conduct) $\Rightarrow \downarrow \rho$

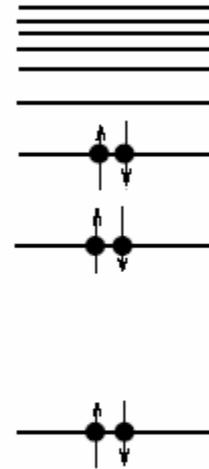
Band Theory: Two Approaches

- There are two approaches to finding the electron energies associated with atoms in a periodic lattice.
- Approach #1: "Bound" Electron Approach (single atom energies!)
 - Isolated atoms brought close together to form a solid.
- Approach #2: "Unbound" or Free Electron Approach ($E = p^2/2m$)
 - Free electrons modified by a periodic potential (i.e. lattice ions).
- Both approaches result in grouped energy levels with allowed and forbidden energy regions.
 - Energy bands overlap for metals.
 - Energy bands do not overlap (or have a "gap") for semiconductors.

Pauli Exclusion Principle for Atoms



Carbon without
Exclusion principle

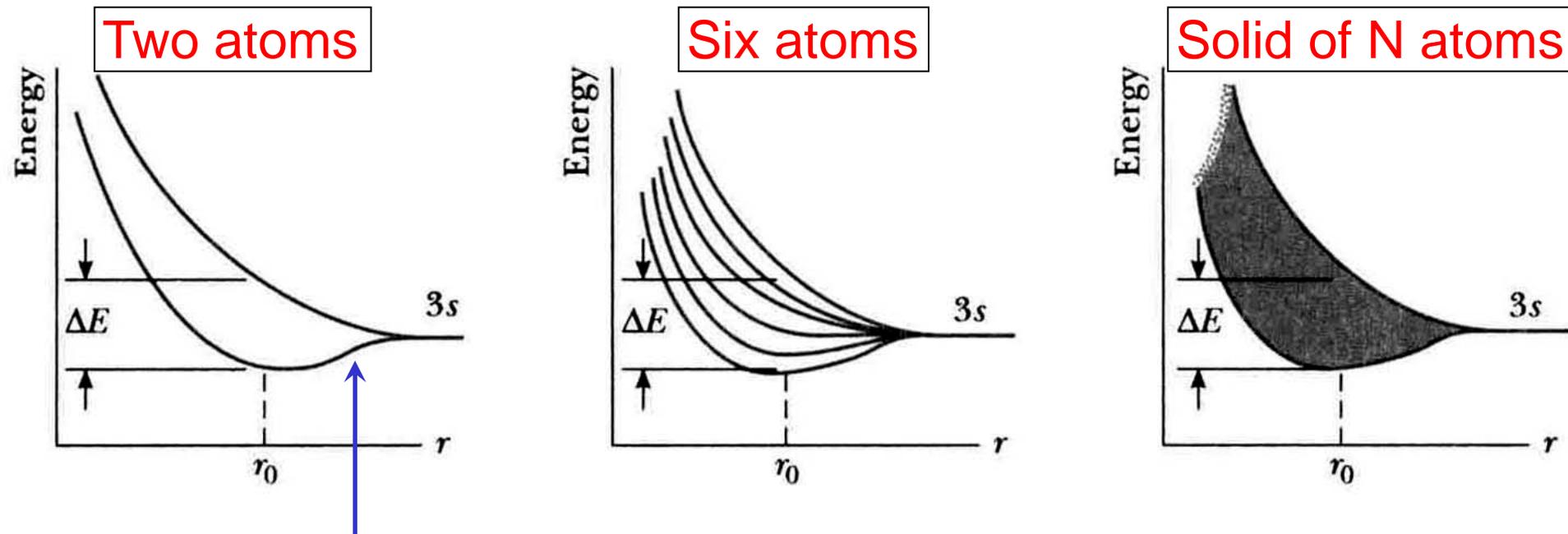


Carbon with
Exclusion principle

Without the exclusion principle all electrons would occupy the same atomic orbital.
There would be no chemistry, no life!

Band Theory: “Bound” Electron Approach

- For the total number N of atoms in a solid (10^{23} cm^{-3}), N energy levels split apart within a width ΔE .
 - Leads to a band of energies for each initial atomic energy level (e.g. 1s energy band for 1s energy level).



Electrons must occupy different energies due to Pauli Exclusion principle.

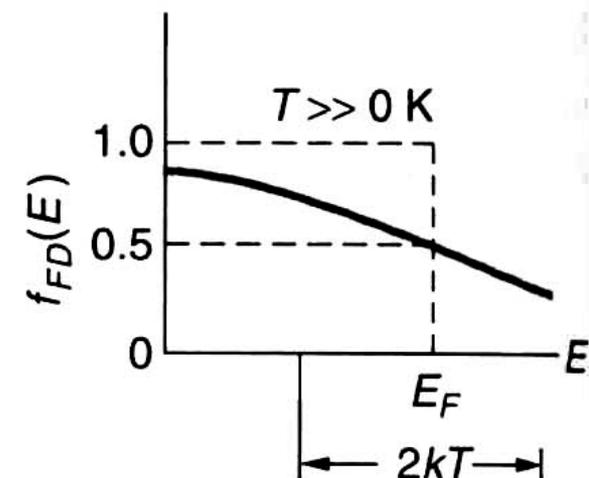
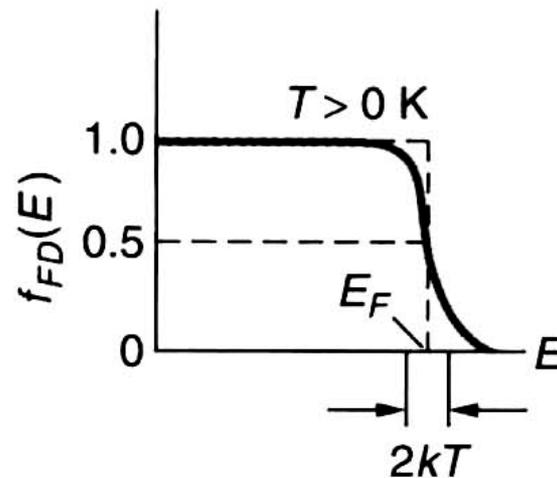
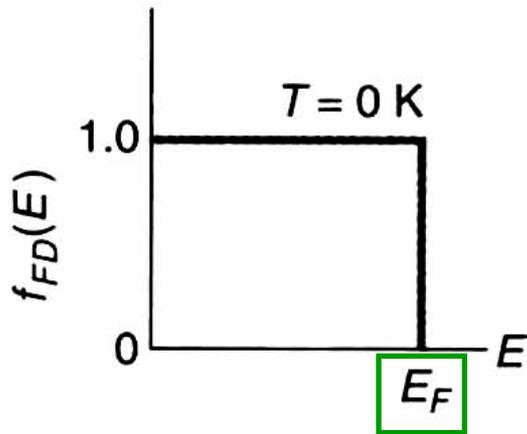
Band Diagram: Fermi-Dirac “Filling” Function

- Probability of electrons (fermions) to be found at various energy levels.

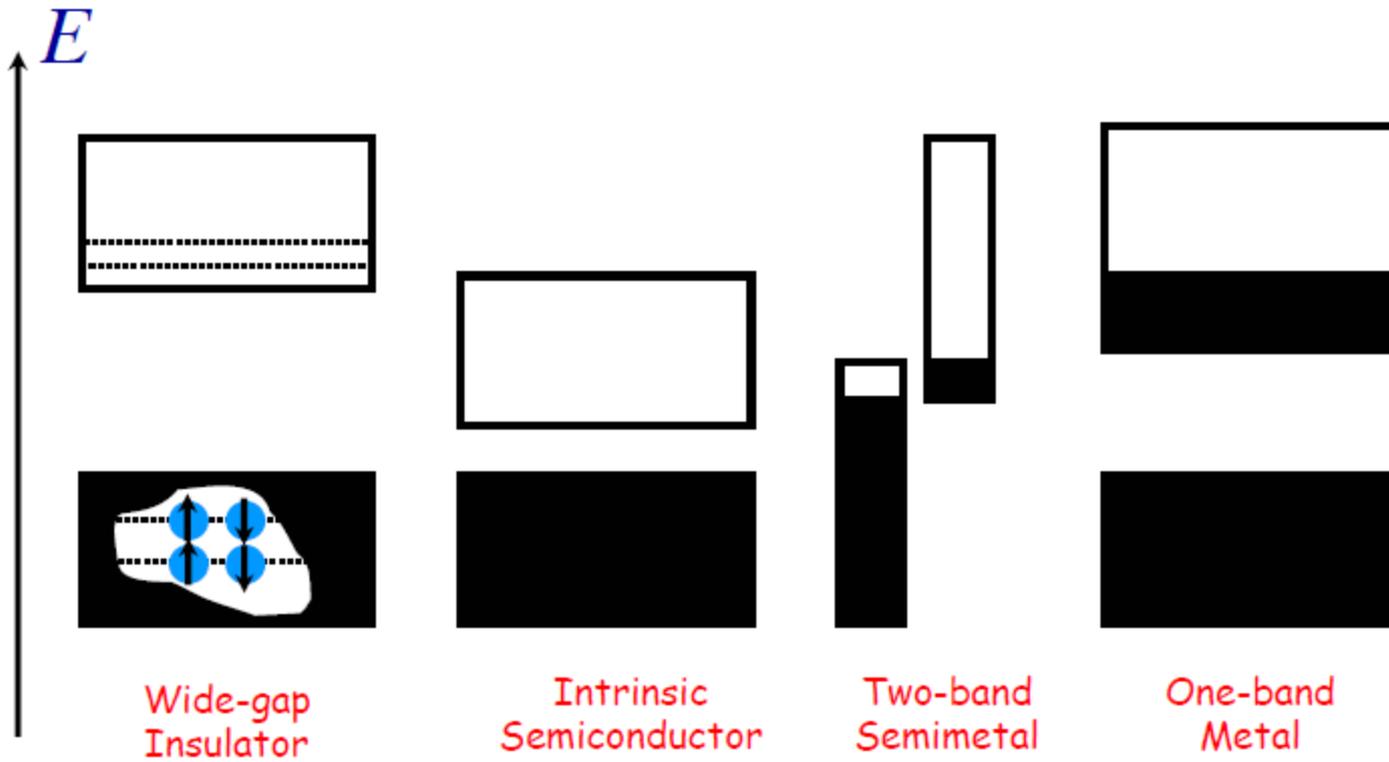
$$f_{FD}(E) = \frac{1}{e^{\frac{E - E_F}{kT}} + 1}$$

- At RT, $E - E_F = 0.05 \text{ eV} \Rightarrow f(E) = 0.12$
 $E - E_F = 7.5 \text{ eV} \Rightarrow f(E) = 10^{-129}$
- Exponential dependence has HUGE effect!

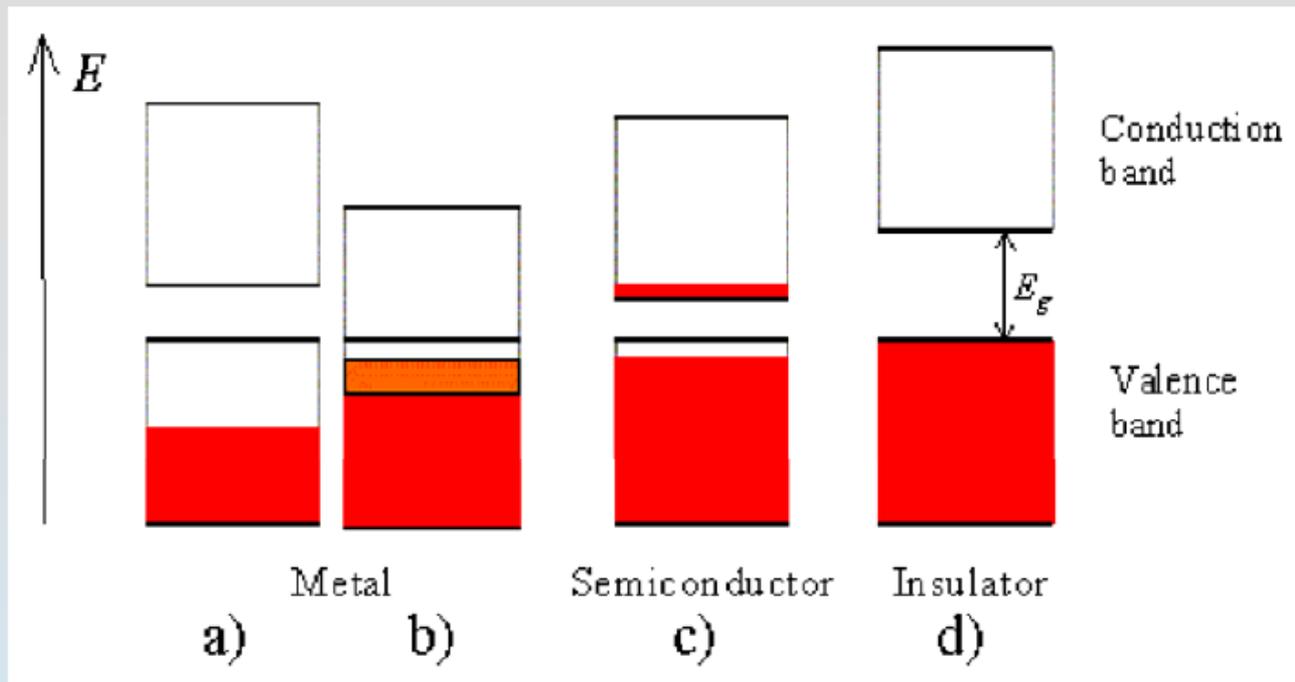
- Temperature dependence of Fermi-Dirac function shown as follows:



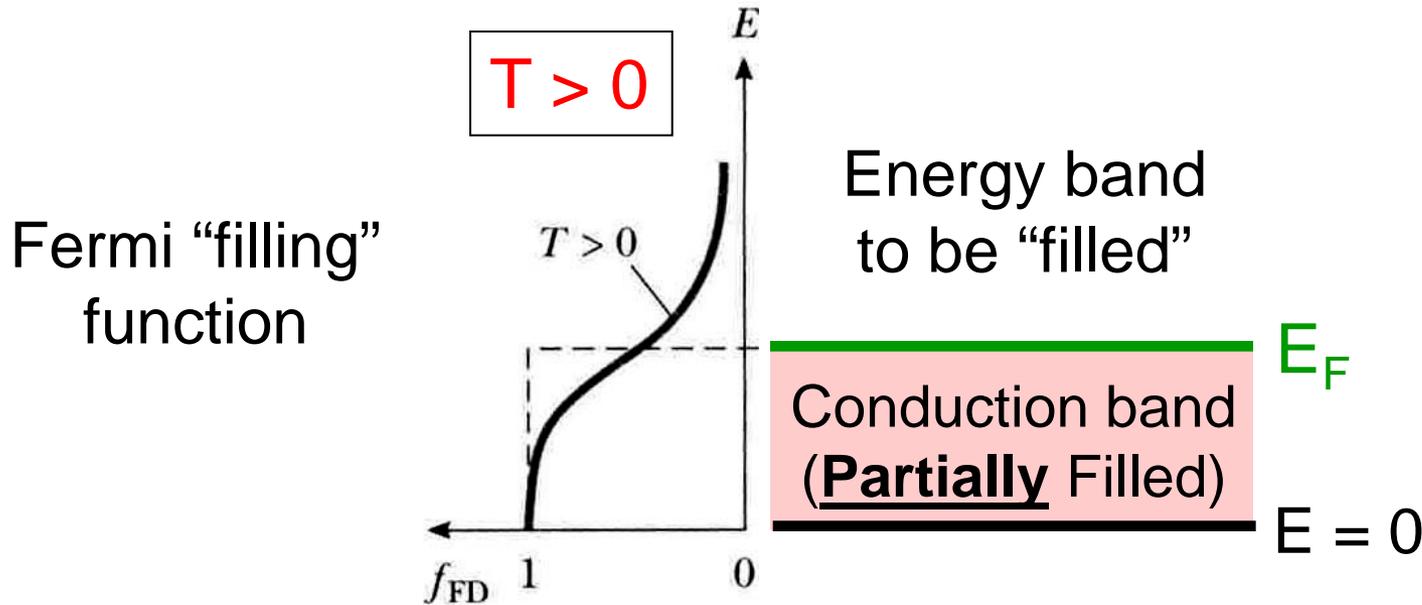
→ Step function behavior “smears” out at higher temperatures.



Occupation of energy bands



Band Diagram: Metal



- At $T = 0$, all levels in conduction band below the Fermi energy E_F are filled with electrons, while all levels above E_F are empty.
- Electrons are free to move into “empty” states of conduction band with only a small electric field E , leading to high electrical conductivity!
- At $T > 0$, electrons have a probability to be thermally “excited” from below the Fermi energy to above it.

The **Fermi energy** (E_F) is the energy of the highest occupied state at zero temperature.

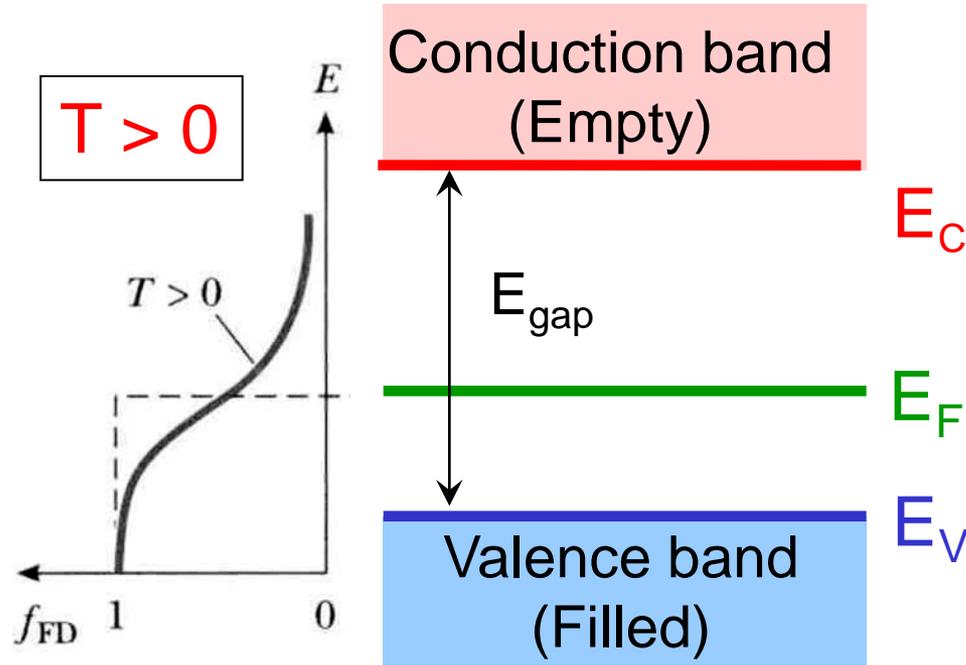
(Actually, it is the difference between the energy of the highest and the lowest occupied energy level).

Fermi level is a measure of the energy of the least tightly held electrons within a solid.

- it changes as the solid is warmed and as electrons are added to or withdrawn from the solid.
- it is also called the chemical potential that is temperature dependent
- $f(E_F(T)) = 1/2$

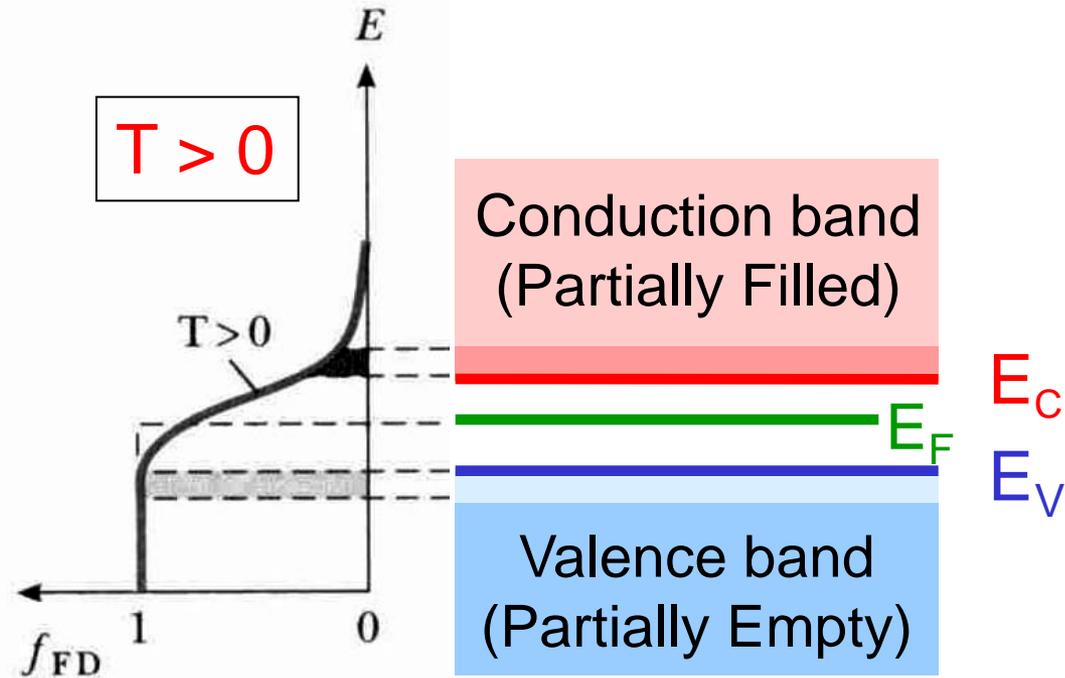
The internal chemical potential at zero temperature is equal to the Fermi energy.

Band Diagram: Insulator



- At $T = 0$, lower valence band is filled with electrons and upper conduction band is empty, leading to zero conductivity.
 - Fermi level E_F is at midpoint of large energy gap (2-10 eV) between conduction and valence bands.
- At $T > 0$, electrons are usually NOT thermally “excited” from valence to conduction band, leading to zero conductivity.

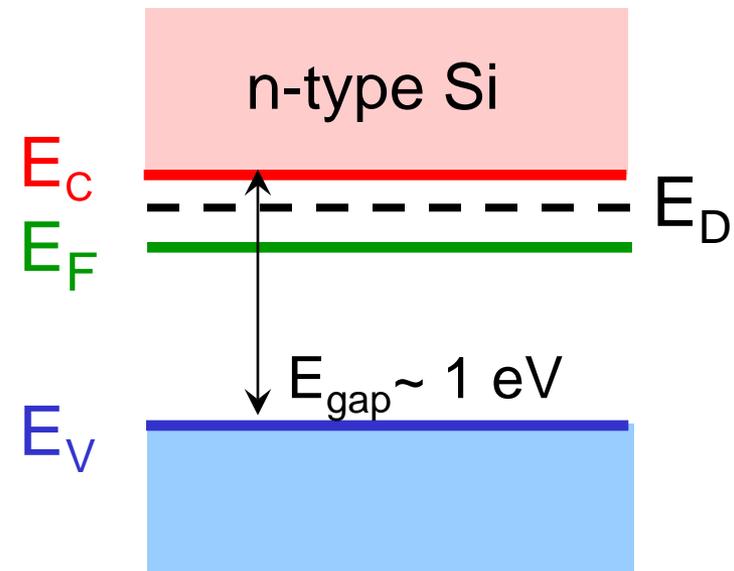
Band Diagram: Semiconductor with No Doping



- At $T = 0$, lower valence band is filled with electrons and upper conduction band is empty, leading to zero conductivity.
 - Fermi level E_F is at midpoint of small energy gap (< 1 eV) between conduction and valence bands.
- At $T > 0$, electrons thermally “excited” from valence to conduction band, leading to measurable conductivity.

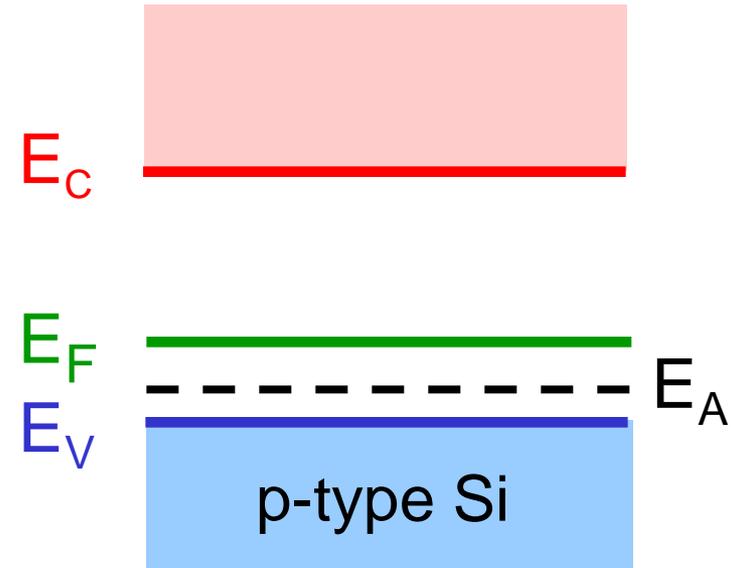
Band Diagram: Donor Dopant in Semiconductor

- Increase the conductivity of a semiconductor by adding a small amount of another material called a dopant (instead of heating it!)
- For group IV Si, add a group V element to “donate” an electron and make n-type Si (more negative electrons!).
- “Extra” electron is weakly bound, with donor energy level E_D just below conduction band E_C .
 - Dopant electrons easily promoted to conduction band, increasing electrical conductivity by increasing carrier density n .
- Fermi level E_F moves up towards E_C .



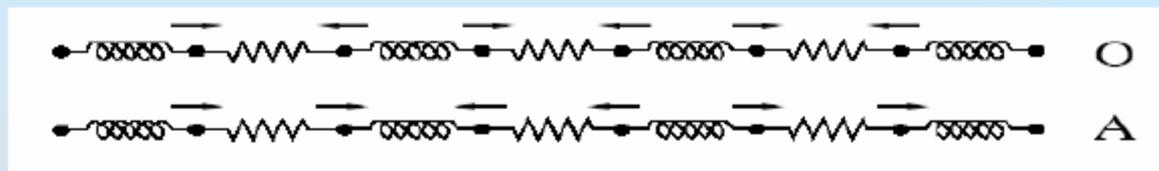
Band Diagram: Acceptor Dopant in Semiconductor

- For Si, add a group III element to “accept” an electron and make p-type Si (more positive “holes”).
- “Missing” electron results in an extra “hole”, with an acceptor energy level E_A just above the valence band E_V .
 - Holes easily formed in valence band, greatly increasing the electrical conductivity.
- Fermi level E_F moves down towards E_V .



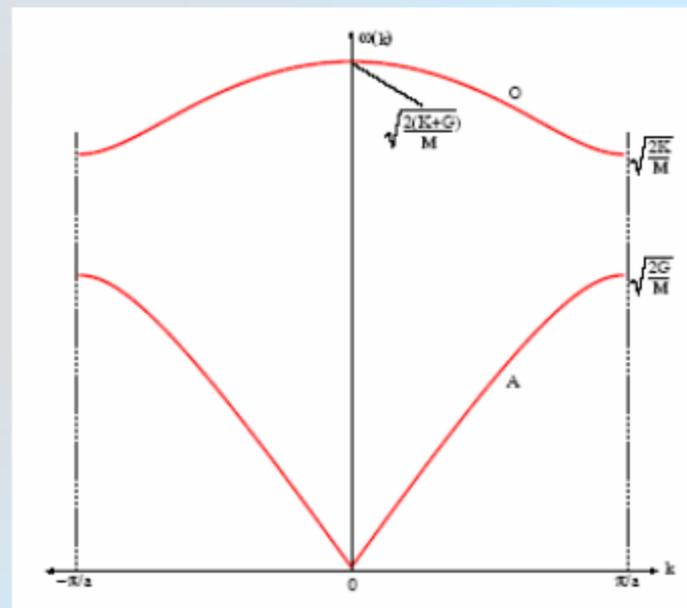
Lattice vibrations: *acoustical* and *optical* modes

For 1D chain:



According to quantum mechanics, lattice vibrations can be regarded as quasi-particles - phonons - with (quasi) momentum $\hbar\vec{k}$ and energy $\hbar\omega_{\vec{k}}$.

The dependence $\omega_{\vec{k}} = \omega(\vec{k})$ is called the *dispersion law*, or energy spectrum of phonons.

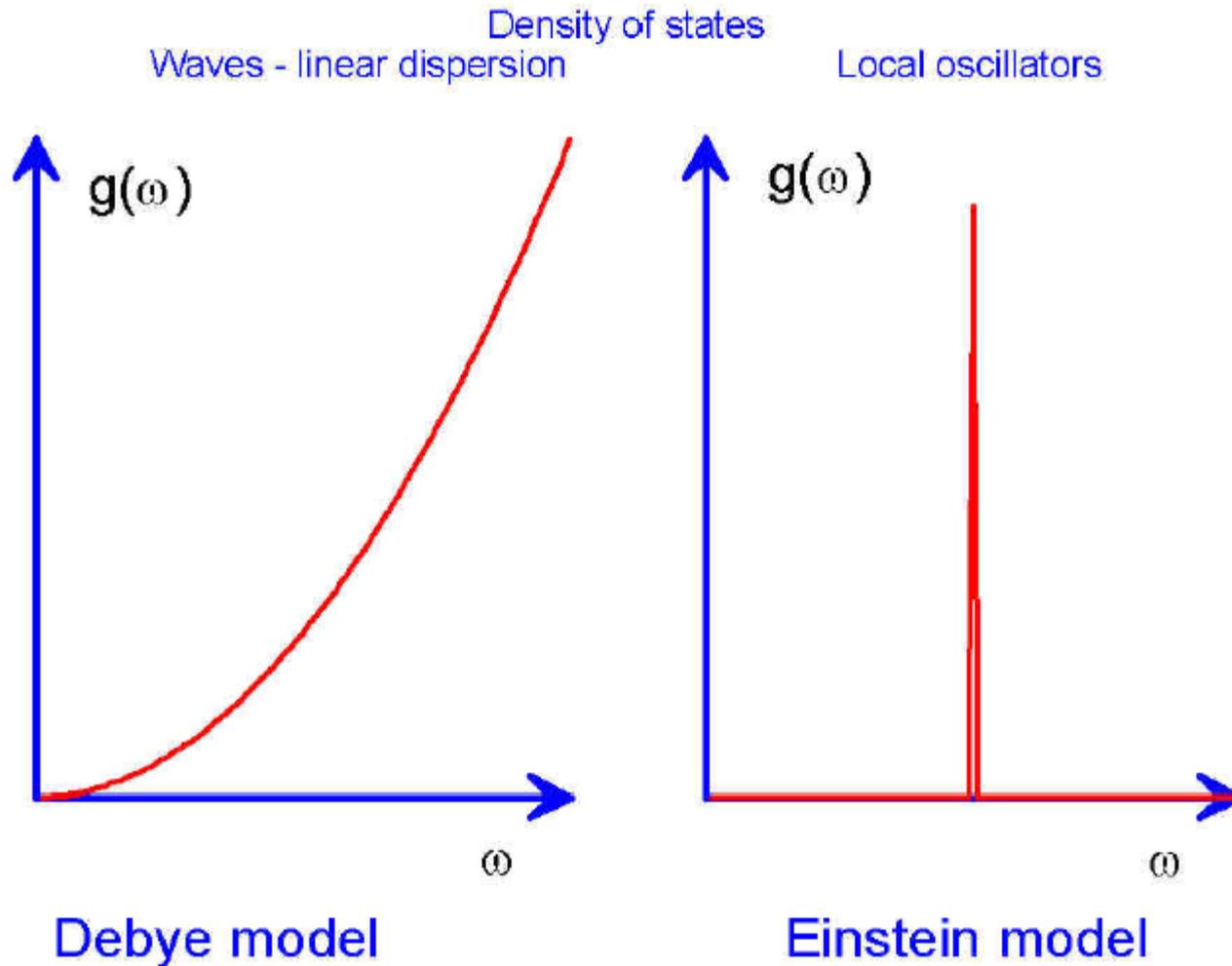


For 1D chain

- **Lattice vibrations, in the harmonic approximation, described as normal modes of the crystal;**
- **Each normal mode has the same Hamiltonian as a harmonic oscillator;**

1

Calculate the specific heat, by adding the contributions of all the modes.



N.B. Einstein model can be used as model of narrow optical branch of phonon spectrum.

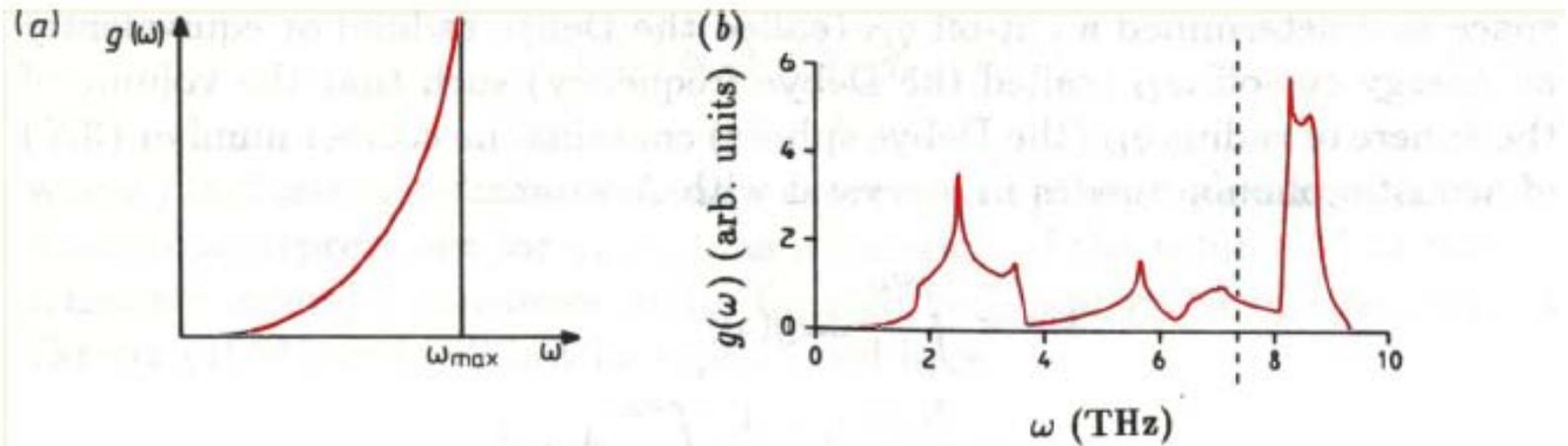
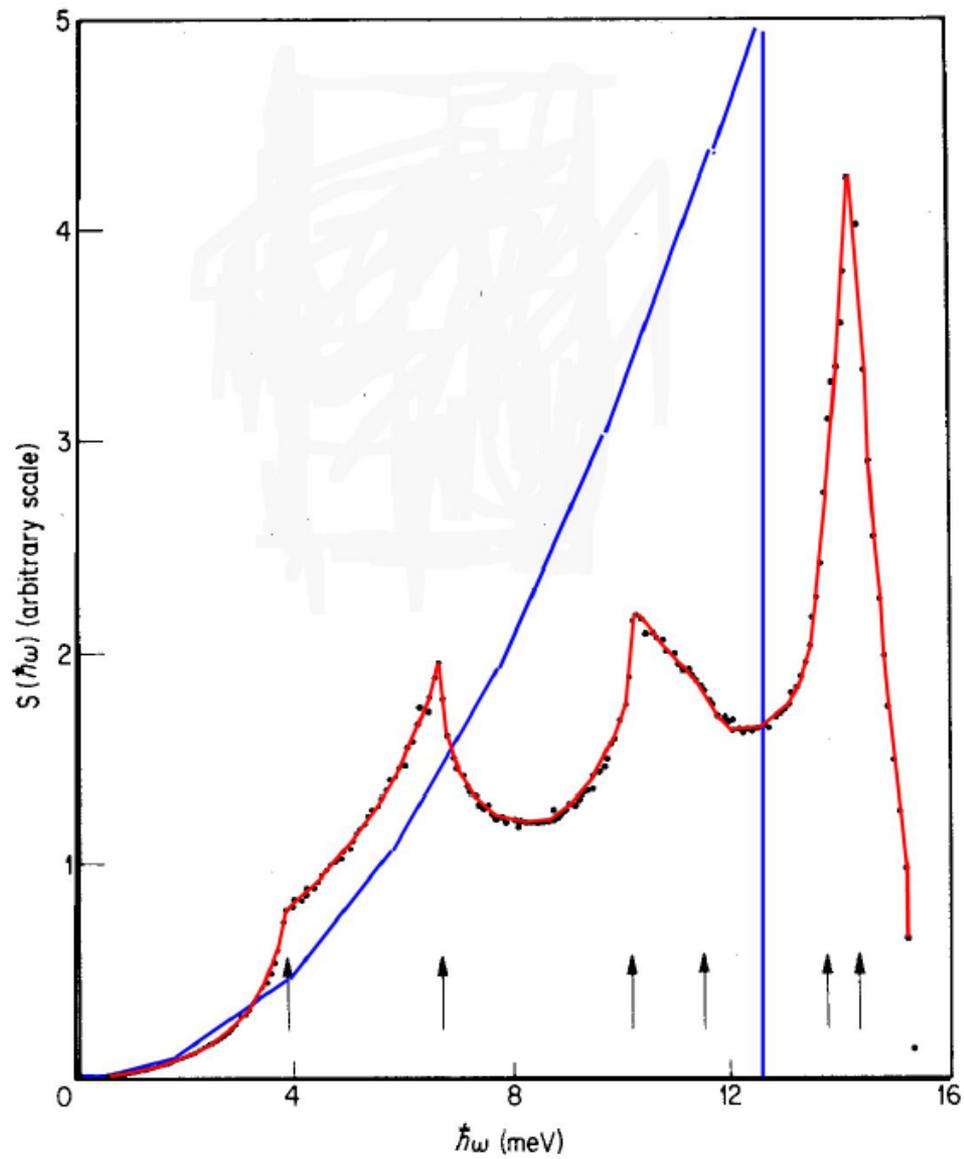
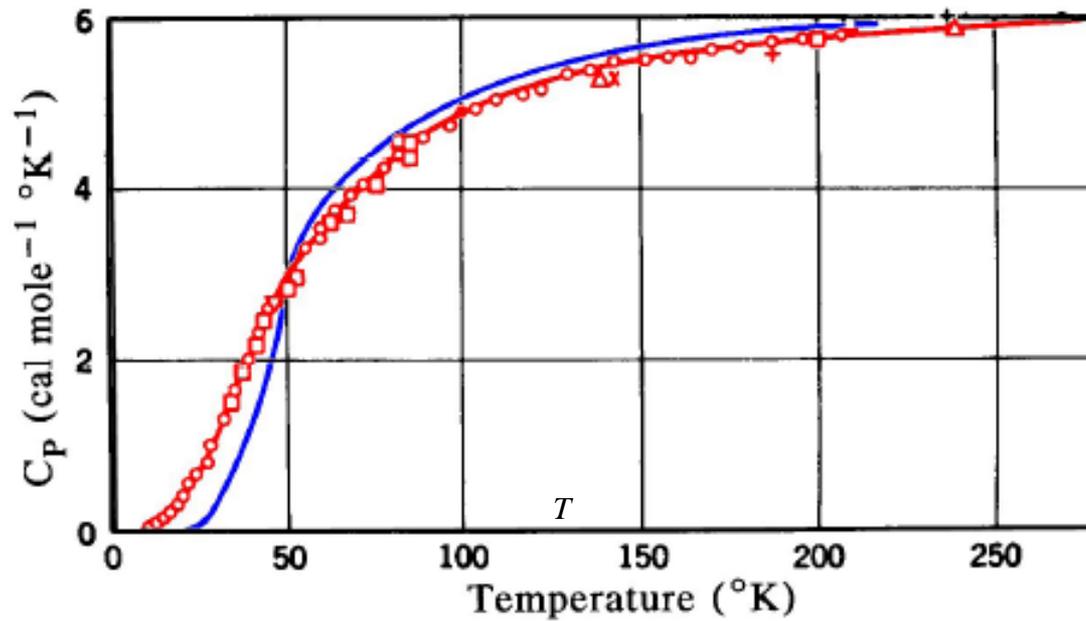


Figure The density of normal modes in a three-dimensional crystal. (a) The Debye model, (b) The density of states for Ge, as calculated with the adiabatic bond charge model (Weber 1977).



Density of modes in Na (after A. E. Dixon *et al.*,
Proc. Phys. Soc. **81**, 973 (1963)).



Specific heat data (points) for silver. The lines are the fits from the Einstein and Debye results. The Debye curve goes through the data points.

$$C_V = A \cdot T^3 \quad T \ll \theta_D$$

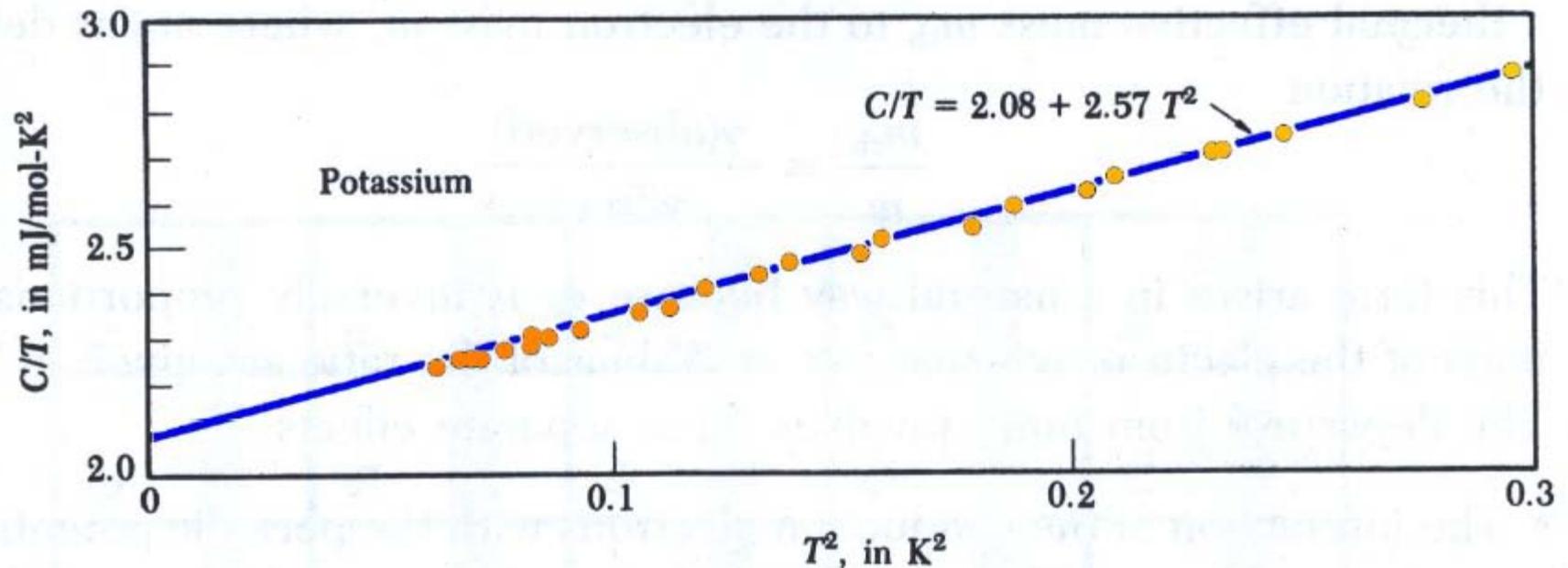
Electronic specific heat

$$C_v = \frac{\pi^2}{3} g(E_F) k_B^2 T,$$

At low temperatures, though, the vibrational contribution falls off as T^3 , so the vibrational and electronic parts become comparable. Conventionally write

$$C_v = \gamma T + AT^3$$

at low T , and so a plot of C_v/T against T^2 should give a straight line.



Superconductors

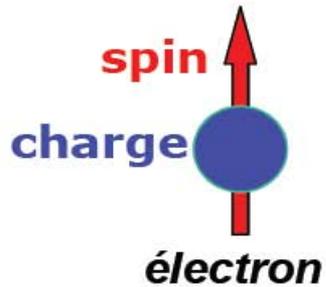
$$T < T_c \Rightarrow \sigma \rightarrow \infty$$

+ Meissner effect



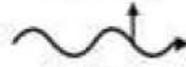
Above a critical temperature, T_c , superconductors are typically normal metals, but not very good conductors. Below T_c , resistivity is zero and the material is a perfect diamagnet. Pure metals, like Pb, Ta, Sn are superconductors, while Cu, Ag, or Au are not.

| Material | T_c (K) | Year |
|--|-----------|------|
| Hg | 4.1 | 1911 |
| Pb | 7.2 | 1913 |
| Nb | 9.2 | 1930 |
| NbN _{0.96} | 15.2 | 1950 |
| Nb ₃ Sn | 18.1 | 1954 |
| Nb ₃ (Al _{3/4} Ge _{1/4}) | 20-21 | 1966 |
| Nb ₃ Ga | 20.3 | 1971 |
| Nb ₃ Ge | 23.2 | 1973 |
| Ba _x La _{5-x} Cu ₅ O _y | 30-35 | 1986 |
| YBa ₂ Cu ₃ O _{7-δ} | 95 | 1987 |
| Bi ₂ Sr ₂ Ca ₂ Cu ₃ O ₁₀ | 110 | 1988 |
| Tl ₂ Ba ₂ Ca ₂ Cu ₃ O ₁₀ | 125 | 1988 |
| HgBa ₂ Ca ₂ Cu ₃ O _{8+δ} | 133 | 1993 |
| HgBa ₂ Ca ₂ Cu ₃ O _{8+δ} at 25 GPa | 155 | 1993 |
| HgBa ₂ Ca ₂ Cu ₃ O _{8+δ} at 30 GPa | 164 | 1994 |



Influence of spin on conduction

Spin up electron

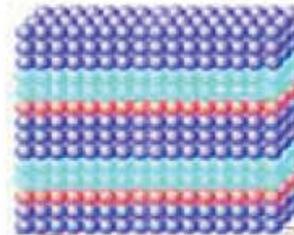


Spin down electron



+

Magnetic nanostructures



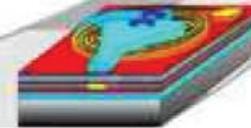
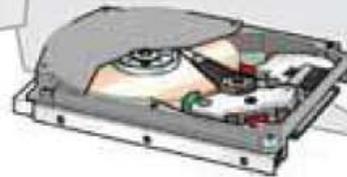
→ Spintronics



GMR, TMR, etc...

Magnetic switching and microwave generation by spin transfer, spintronics with semiconductors, molecular spintronics, etc

Memory (M-RAM)



Read heads, sensors, etc.