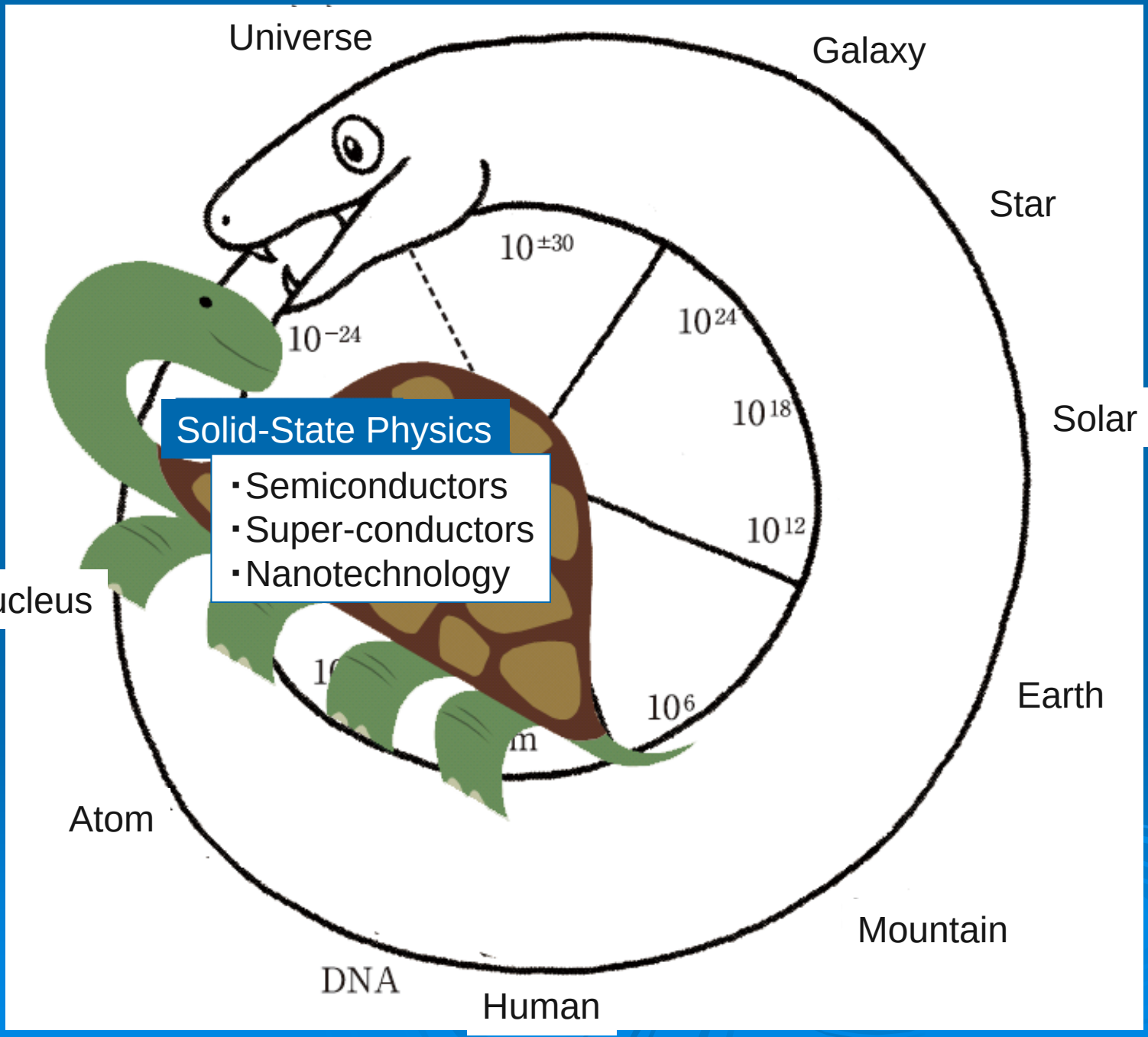

Universe
Galaxy
Star
Solar System
Earth
Mountain
Human
DNA
Atom
Nucleus
$10^{\pm 30}$
10^{24}
10^{18}
10^{12}
10^{6}
10^{-24}
Solid-State Physics
・Semiconductors
・Super-conductors
・Nanotechnology

A Synopsis on Science
A Journey through 13.7 billion years of "Matter"

from The Big Bang to a Green Earth

Lectures 4-6

The Properties of Matter

Tokyo University Institute for Solid State Physics

Yasuhiro Iye

Lecture Plan

Lectures 4-6: Yasuhiro Iye “The Properties of Matter”

Lecture 4: Modern Society and Material Science

What does the discipline of Solid-State Physics do

Lecture 5: From an Atom to a Solid Object

Diverse Matter, Varied Physicality

Lecture 6: Manipulating Atoms, Manipulating Quanta

High-Tech and Nano-Science

Today's Talk

- From an Atom to a Solid Object
  - Diamonds are hard, Gold is soft
- Electron States in Solid Objects-Metals and Insulators
  - Copper Wire and Plastic
- Magnetism
  - Why does Iron become a magnet?
- Super-conductors
  - Super!

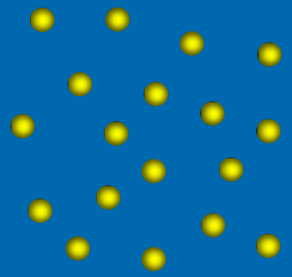
From an Atom to a Solid Object

Inter-atomic Forces and Crystal Structures

The Forces that Bind Atoms Together

Groups of atoms are scattered at high temperatures (Gas)
Below a certain temperature, they become Liquid, then Solid

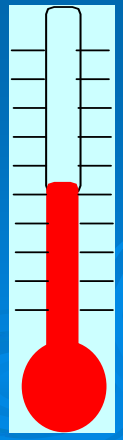
Disordered State

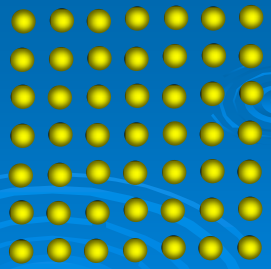


The state of cohesion (Solid, Liquid)
depends on the forces of attraction
at work between the atoms

Crystal structure and mechanical properties reflect the type of inter-atomic forces at work

Phase Transition





Ordered State

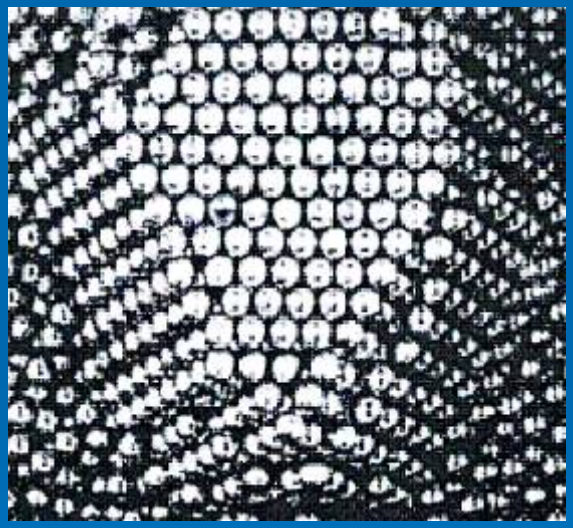
Diamonds are hard
Gold is soft

Crystal Structure

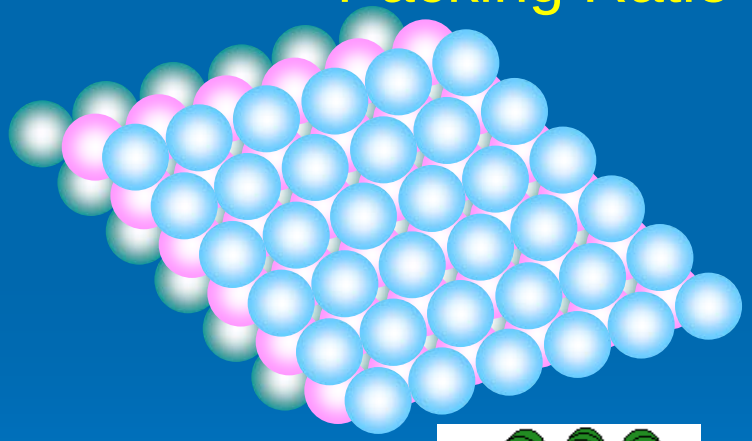
What arrangement do atoms take at the lowest amount of energy?

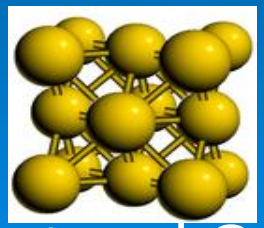
What if you fill a box with Pachinko balls (solid spheres)?

A Packing Problem



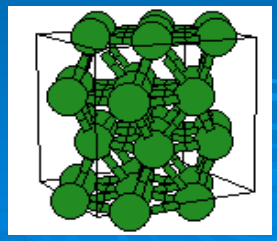
Close-Packing Structure
Packing Ratio of 74%





Face Centered Cubic lattice

fcc

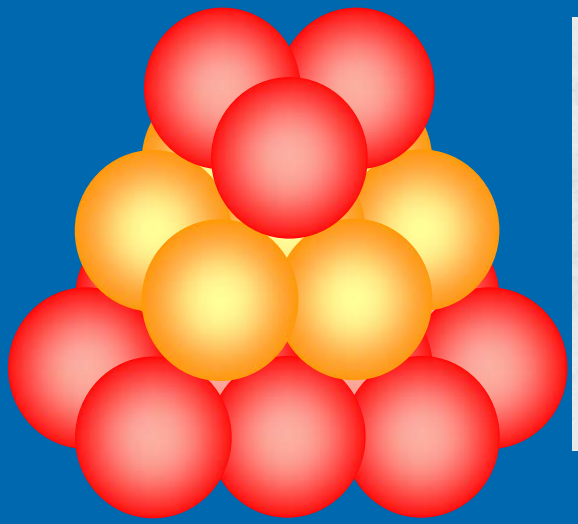


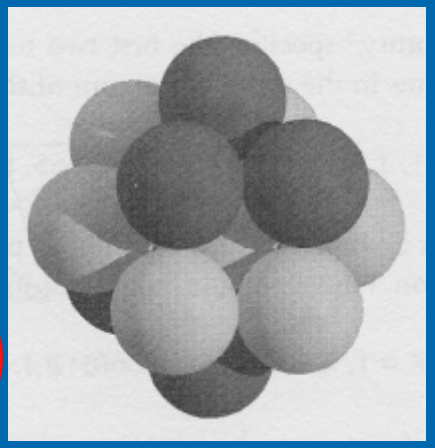
Hexagonal Close-Packing

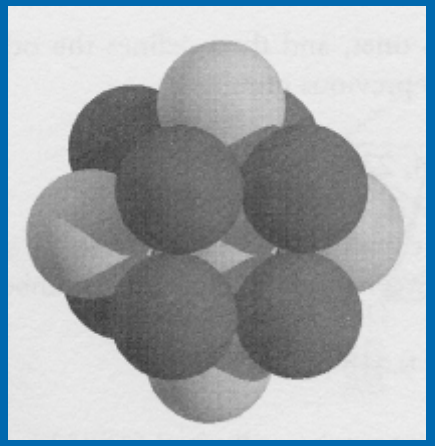
hcp

[Digression] Kepler's Conjecture

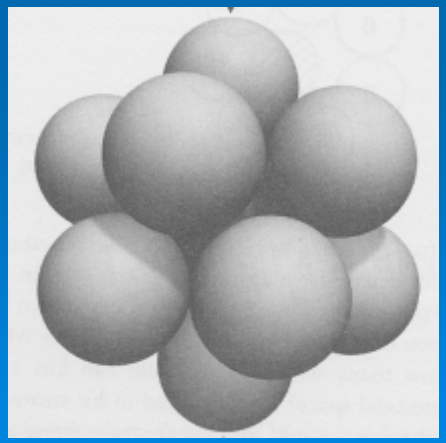
Packing spheres without spaces in-between :
3-D Packing







Johannes Kepler
(1571-1630)



Icosahedral arrangement

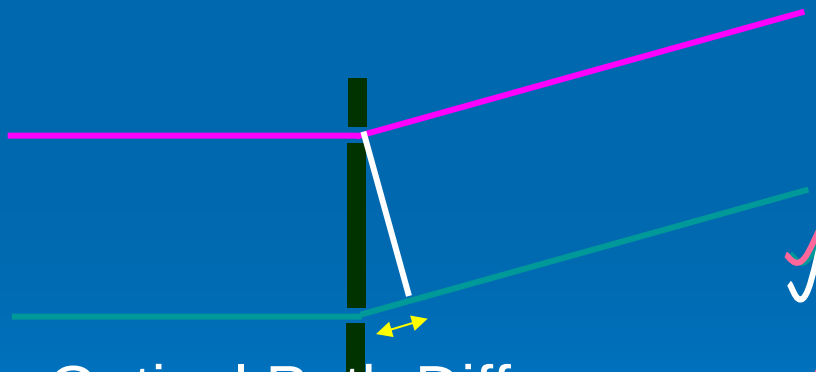
The greatest number of same-sized spheres that can be packed around a single sphere is 12…
Kepler's Conjecture

A mathematical rigorous proof of this was finally established in 1997

How do you investigate a crystal structure?

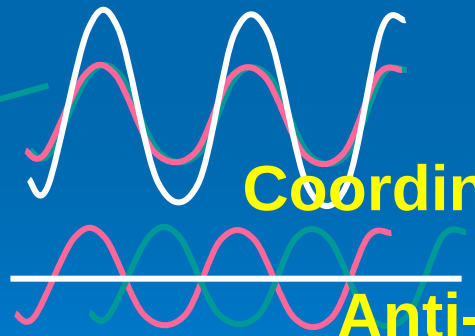
Diffraction of Light

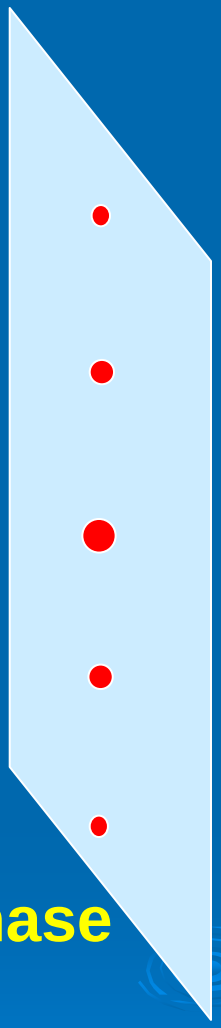
Diffraction



Optical Path Difference

$$d \sin\theta = n\lambda$$

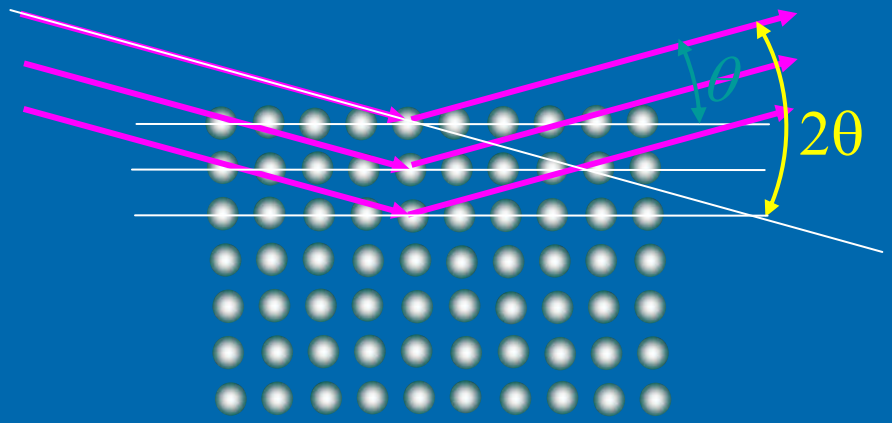


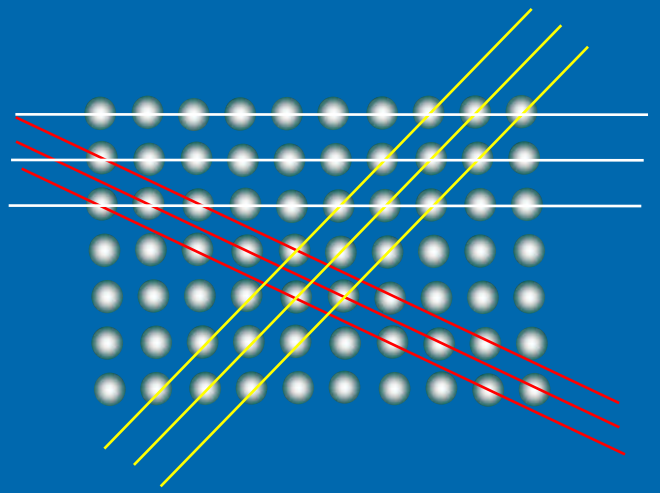


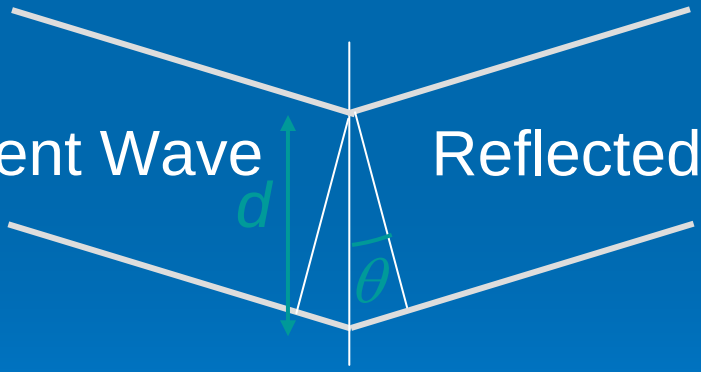
Inter-atomic Spacing ~0.3nm <=> ~Wavelength of X-Rays

Diffraction of an Electron Beam or Neutron Beam can also be used

Crystal Structure Analysis







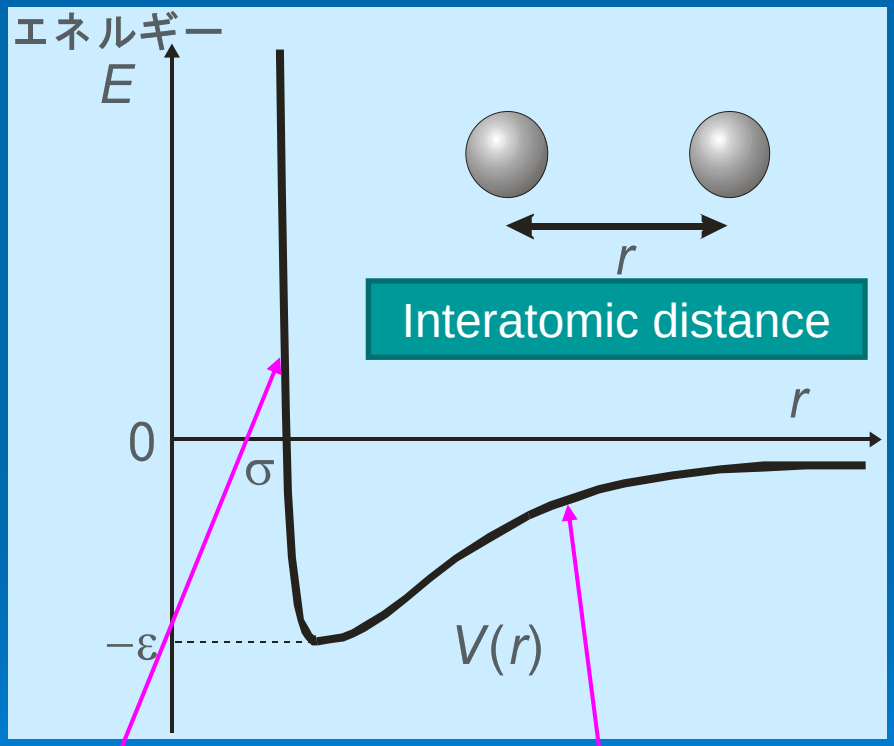
$$2d \sin\theta = n\lambda$$

Bragg's Condition

4-Axial X-ray Crystal Diffractometer

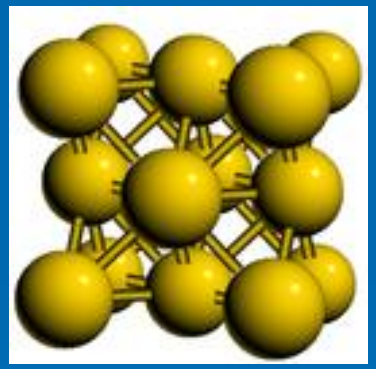
Nobel Gas Crystals

Inter-atomic Force Potential



Ne, Ar、Kr, Xe

Close - Packing Structure
Face centered cubic lattice (fcc)



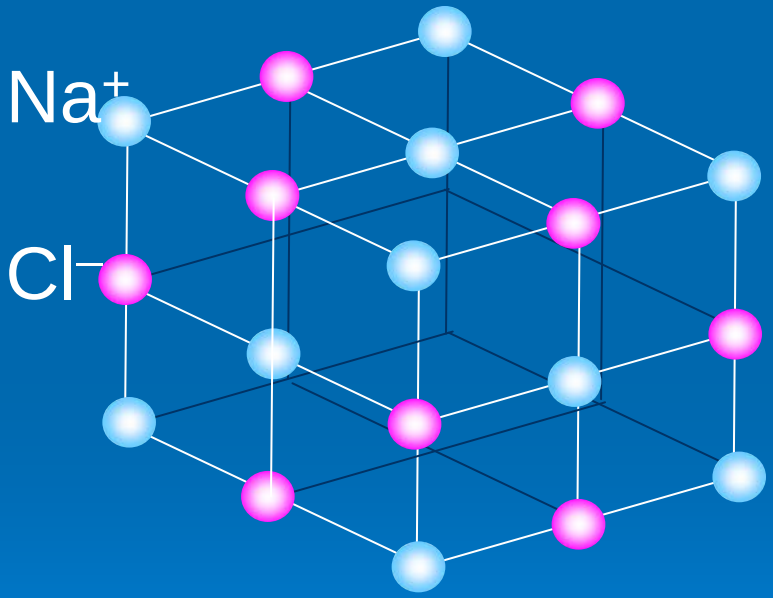
He is?
Quantum Liquid

Rigid Body
Central Repulsion Force

Van der Waals Attractive Forces

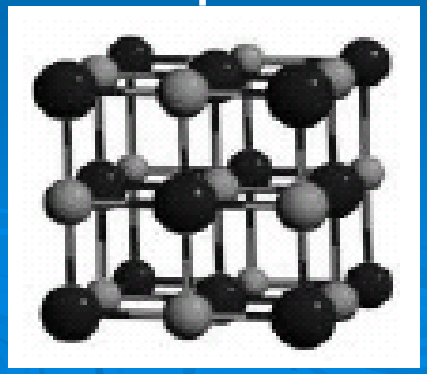
Ionic Bonding

Coulomb Forces acting between positive and negative ions

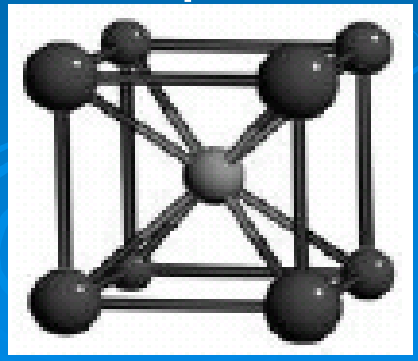


H							He
Li	Be	B	C	N	O	F	Ne
Na	Mg	Al	Si	P	S	Cl	Ar
K	Ca	Ga	Ge	As	Se	Br	Kr

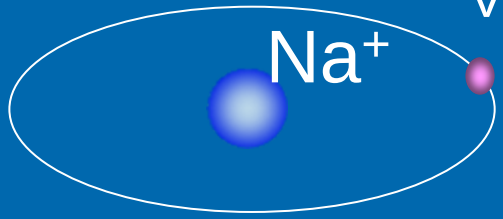
NaCl pattern



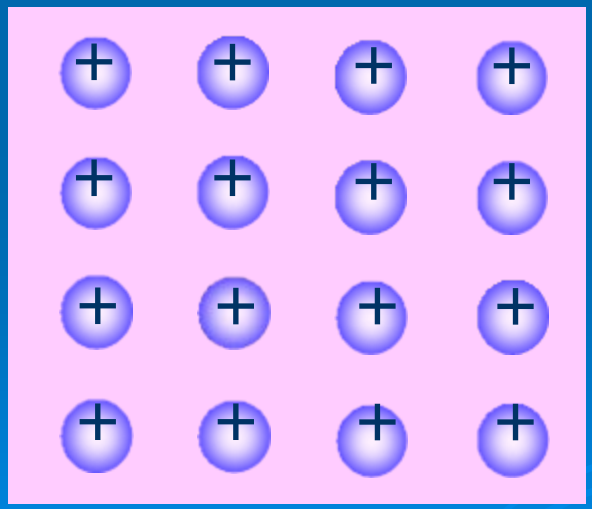
CsCl pattern



Ionic Bonding



$$Na : (1s)^2 (2s)^2 (2p)^6 (3s)^1$$

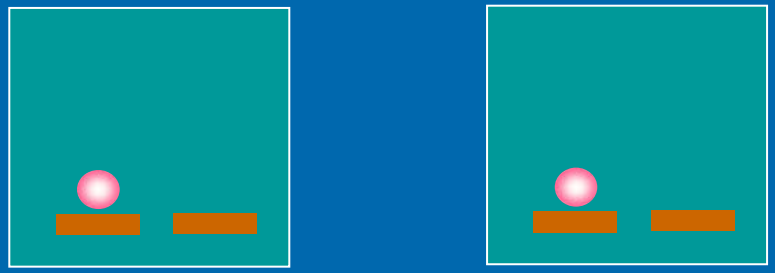


H							He
Li	Be	B	C	N	O	F	Ne
Na	Mg	Al	Si	P	S	Cl	Ar
K	Ca	Ga	Ge	As	Se	Br	Kr

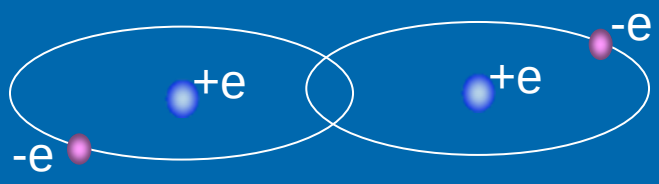
Positive-charged ions are embedded in a sea of negative electrical charge caused by the circulating electrons.

Covalent Bonding

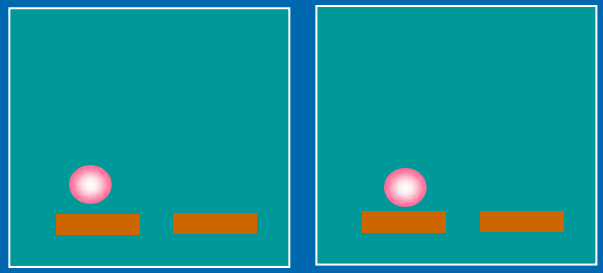
2 twin-bed rooms,
1 child each room



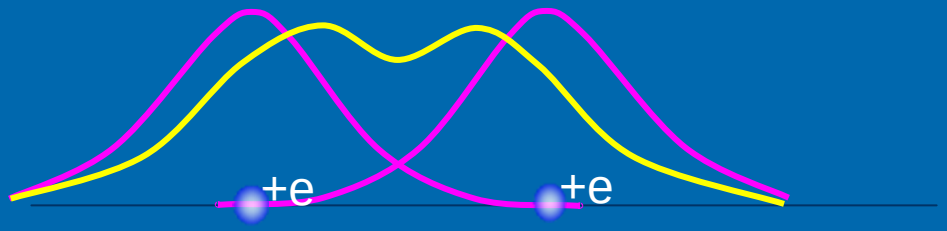
Hydrogen Molecule :H_2



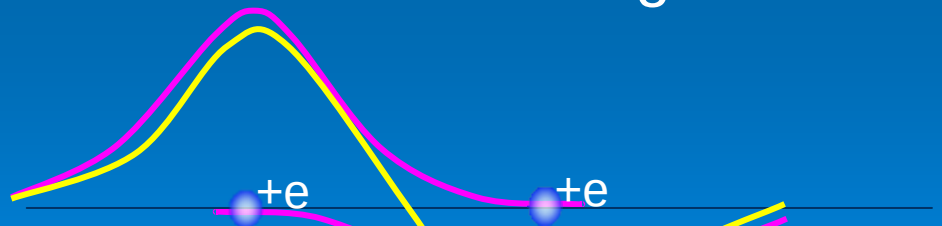
Visit next door



Molecular Orbit

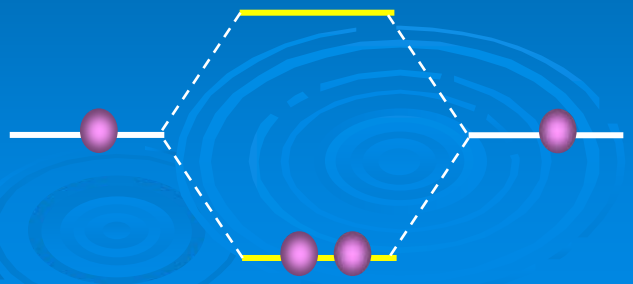


Bonding Orbital



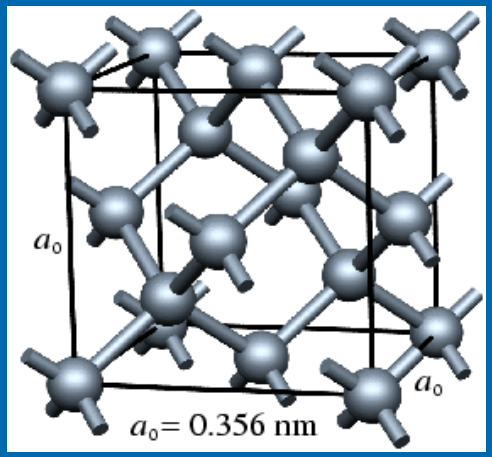
Anti-bonding Orbital

By broadening the area of activity,
the energy is reduced



Covalent Bonding

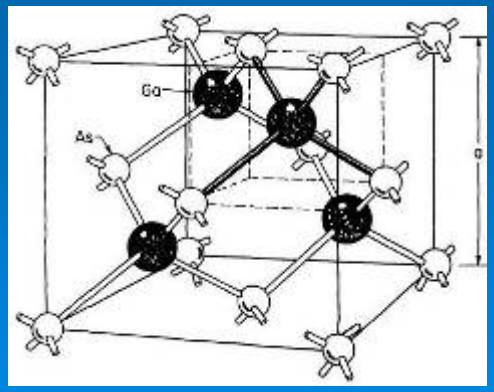
C, Si, Ge



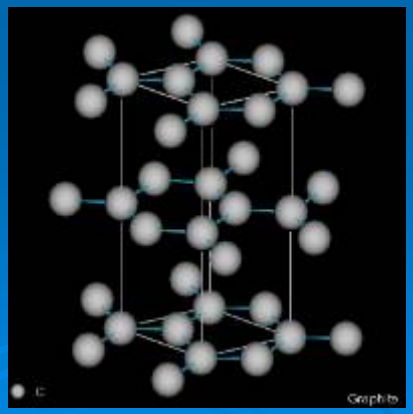
Diamond Structure

H							He
Li	Be	B	C	N	O	F	Ne
Na	Mg	Al	Si	P	S	Cl	Ar
K	Ca	Ga	Ge	As	Se	Br	Kr

GaAs, InP



Sphalerite Structure



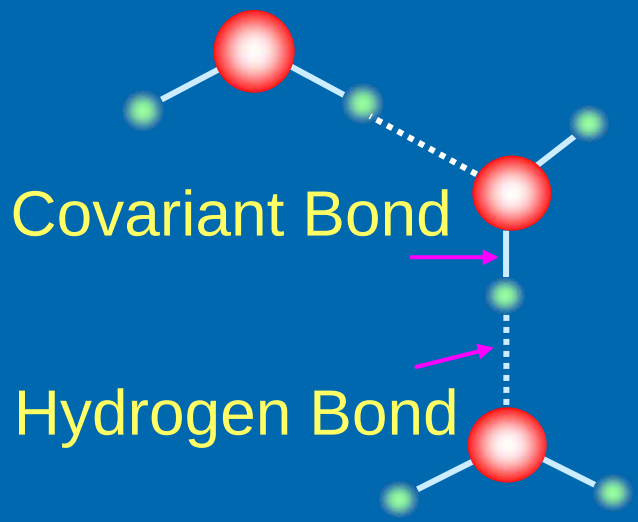
Black lead

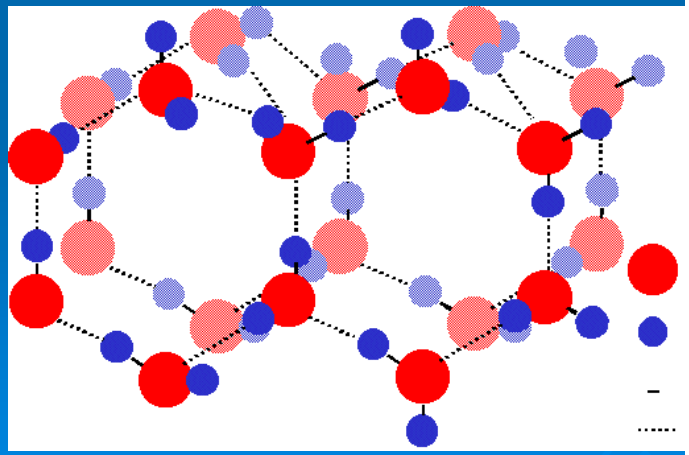
Layered Crystal

Within the layers there is strong covalent bonding,
between the layers there is weak Van der Waals Bonding
=> easy to cleave

Hydrogen Bonding

Water Molecule

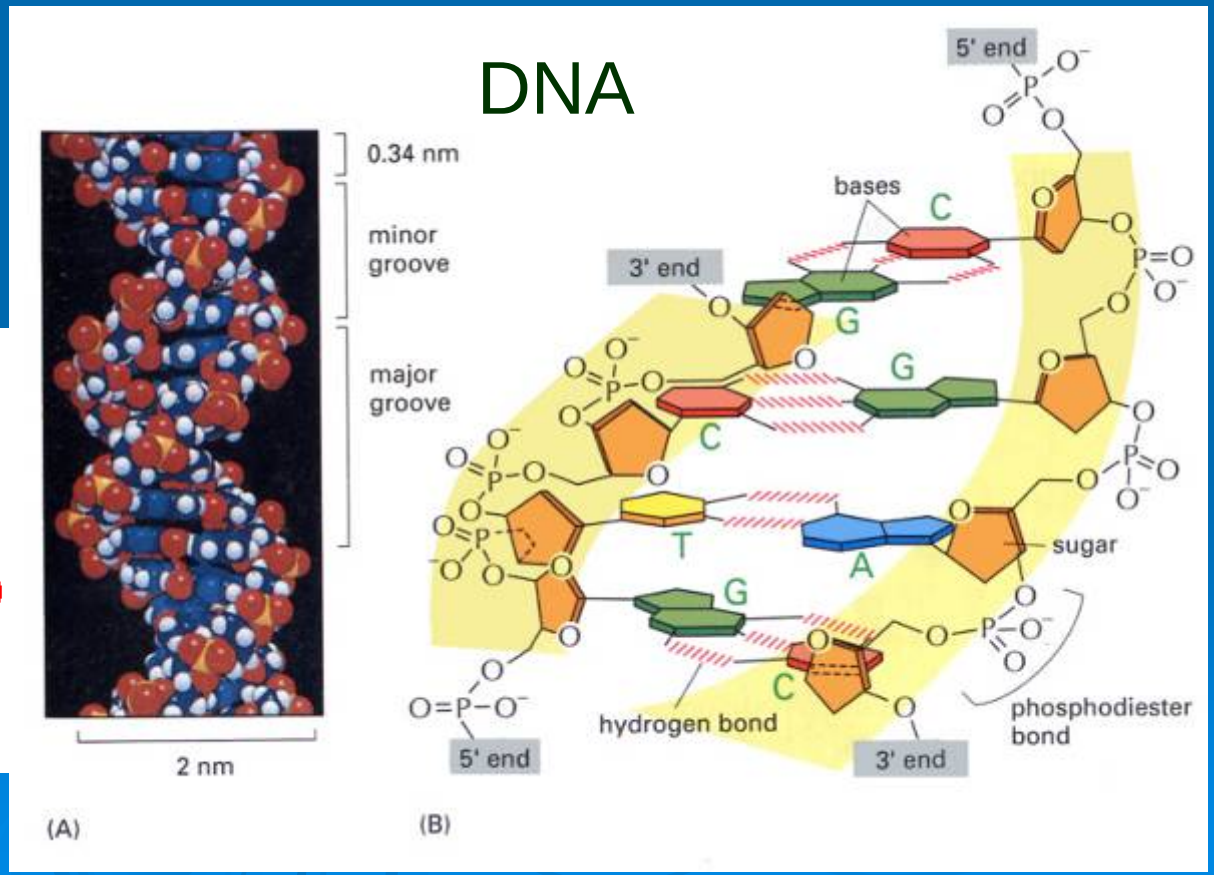




Ice Crystal

Hydrogen Bonding plays an important role in bio-molecules

DNA



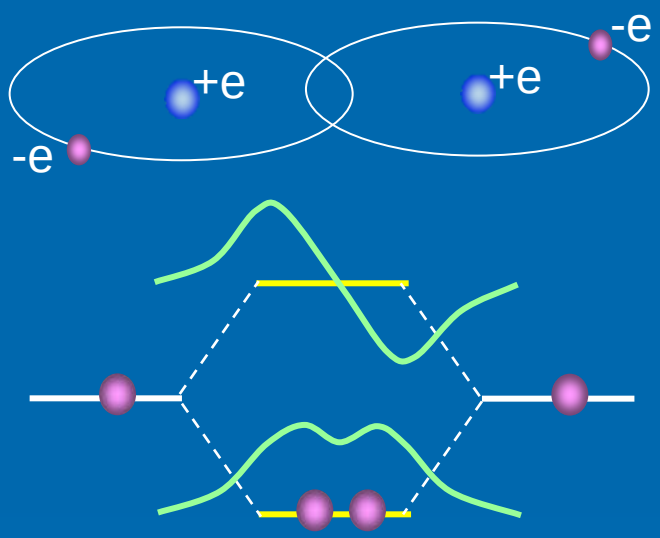
Electron State within Solids (Band Structure)

Electron State within Solids

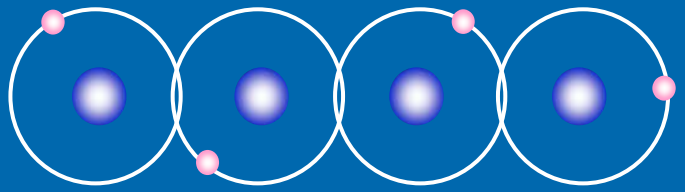
- Quantum mechanics deals with electrons' movement within the potential that makes atoms periodically line up
- There are two schools of thought
  - Atoms line up ⇒ tight-binding model
  - Depart from free space and bring in periodic potentials ⇒ nearly free electron model

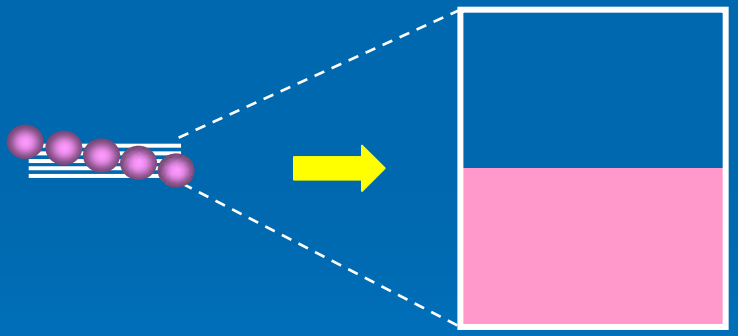
Lining Up Atoms

Hydrogen molecule : H_2



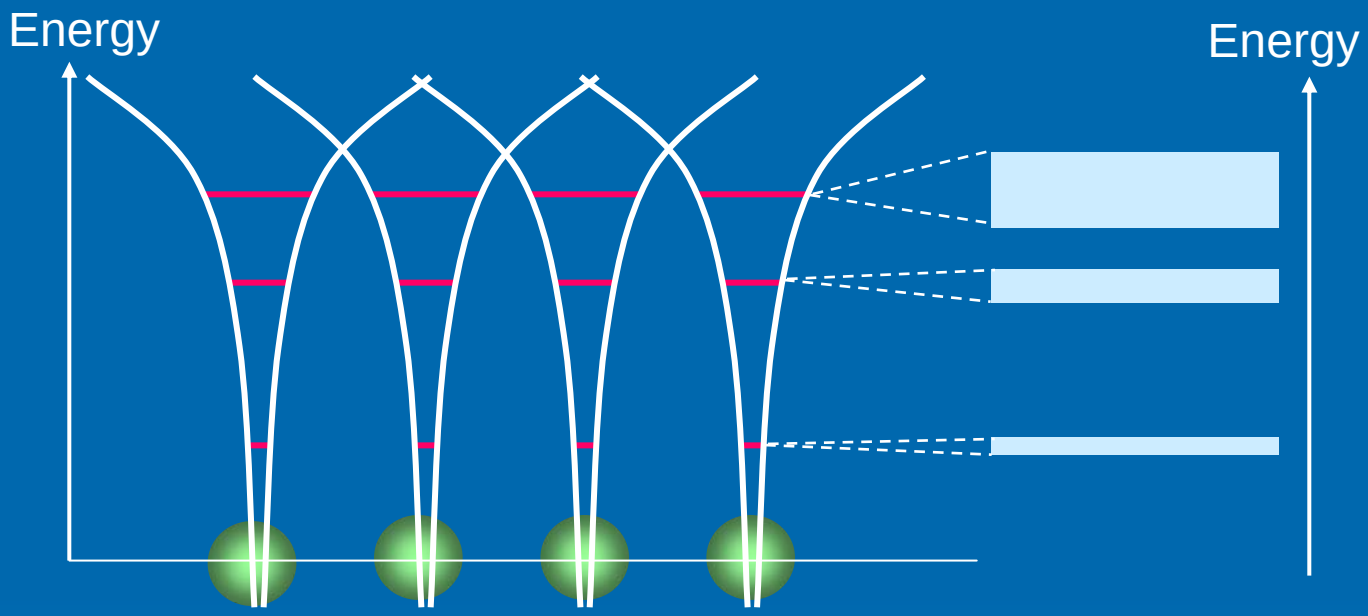
Hydrogen molecules periodically line up





The oscillation of electrons depends on the overlap of electron clouds of adjacent molecules, and electrons move around the entire crystal structure

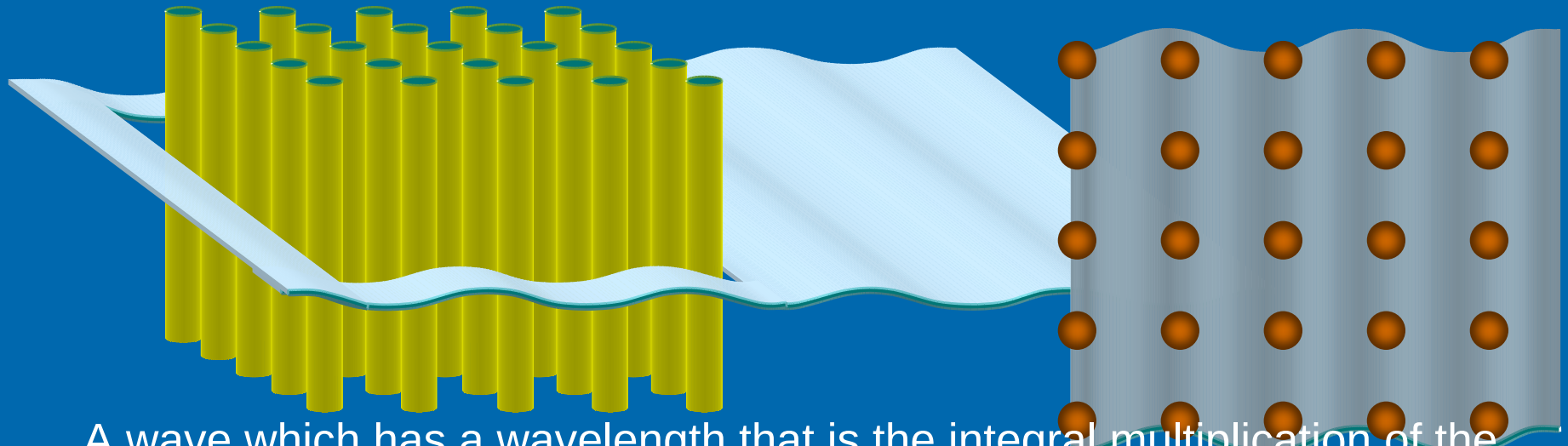
Broadening of Energy Width due to Oscillation



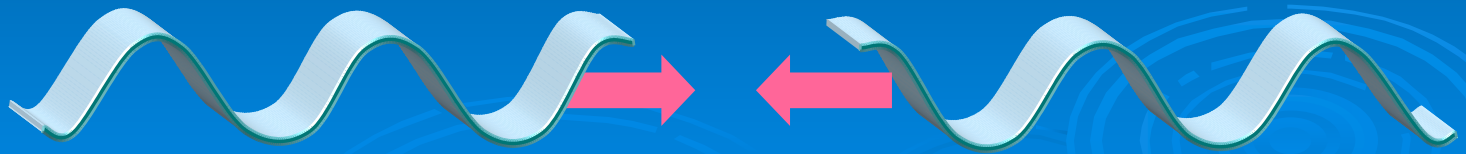
Depending on the oscillation of electrons, each electron energy level of a molecule expands and forms a band

Wave Dispersion due to Periodic Structure

Waves breaking onto lines of stakes standing in a pond

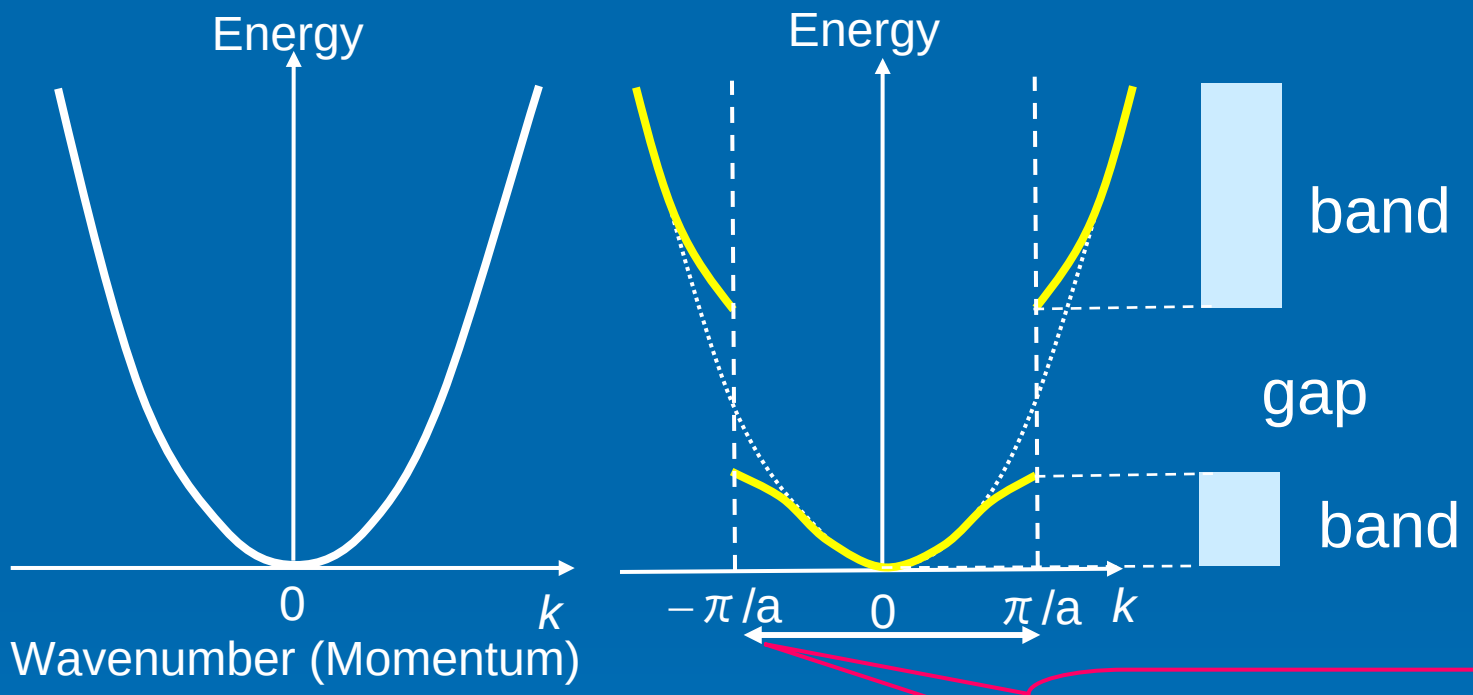


A wave which has a wavelength that is the integral multiplication of the arrangement period of the scattering body is strongly reflected (Bragg Reflection), and a standing wave is made by the interference between the incidence wave and reflected wave. => at a specific wavelength a travelling wave is unable to be formed.



$$e^{i(kx-\omega t)} + e^{i(-kx-\omega t)} = 2e^{-i\omega t}\cos(kx)$$

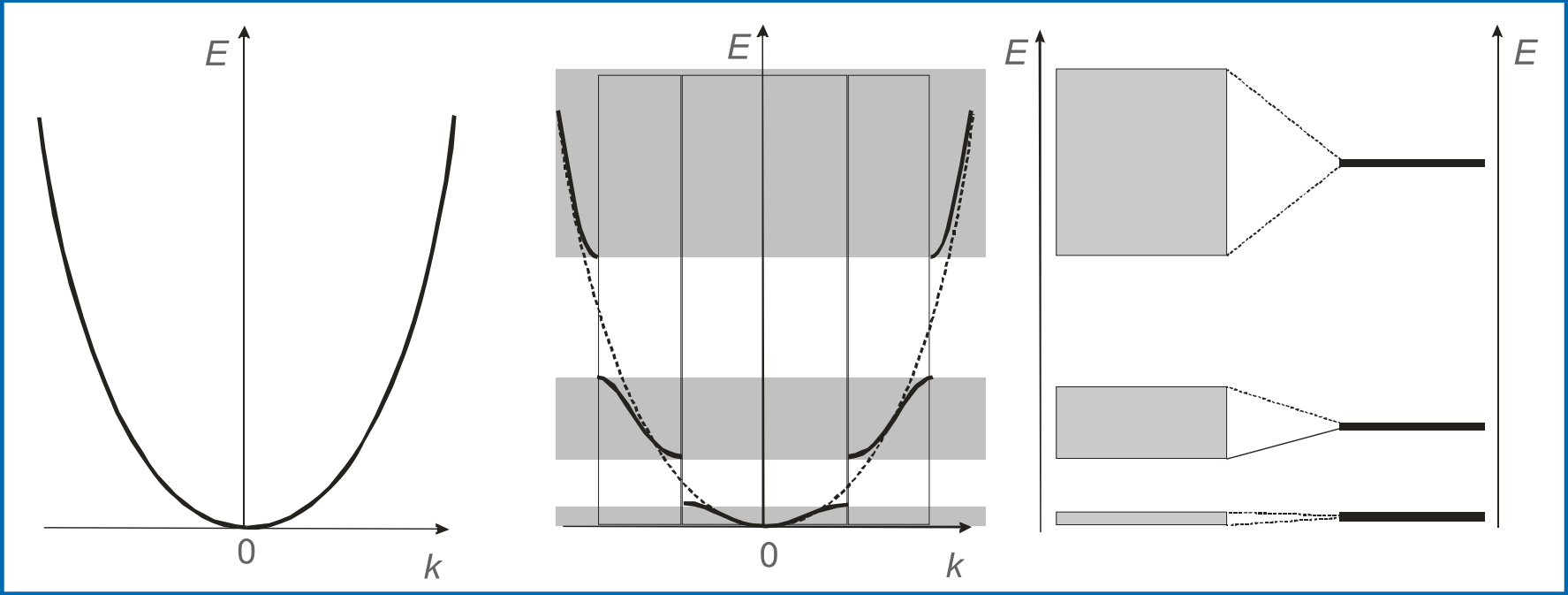
Formation of Bands and Gaps due to Bragg Reflection



Energy range taken (Band) and not taken (Gap) by an electron

Role of periodic potential => Change the relationship (Dispersion Relationship) of an electron's energy and momentum (Bloch Electron)

Electron Band Structure



Free Electron → Electron within a Crystal (Bloch Electron) ← Isolated Atom

Nearly-Free Electron Model

Roaming Electron

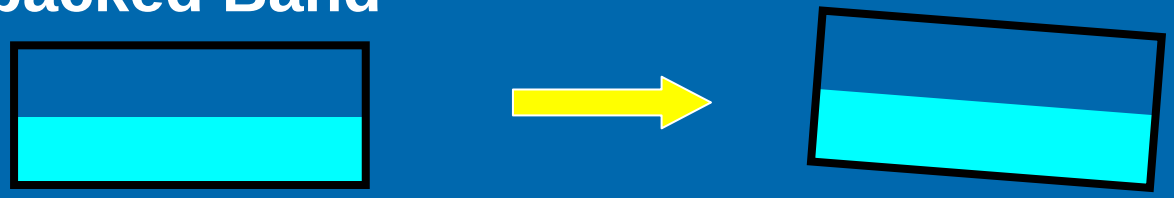
Tight-Binding Model

Localized Electron

Metals, Insulators, Semiconductors

Metals and Insulators

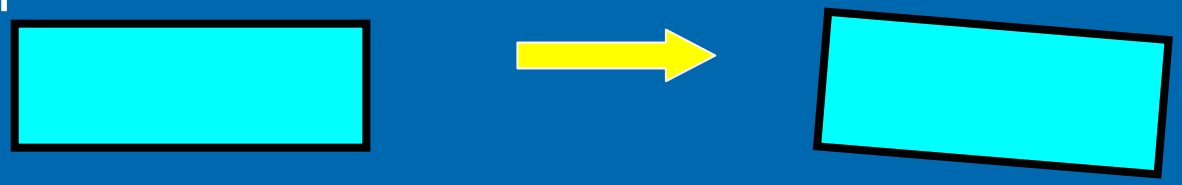
Half-packed Band



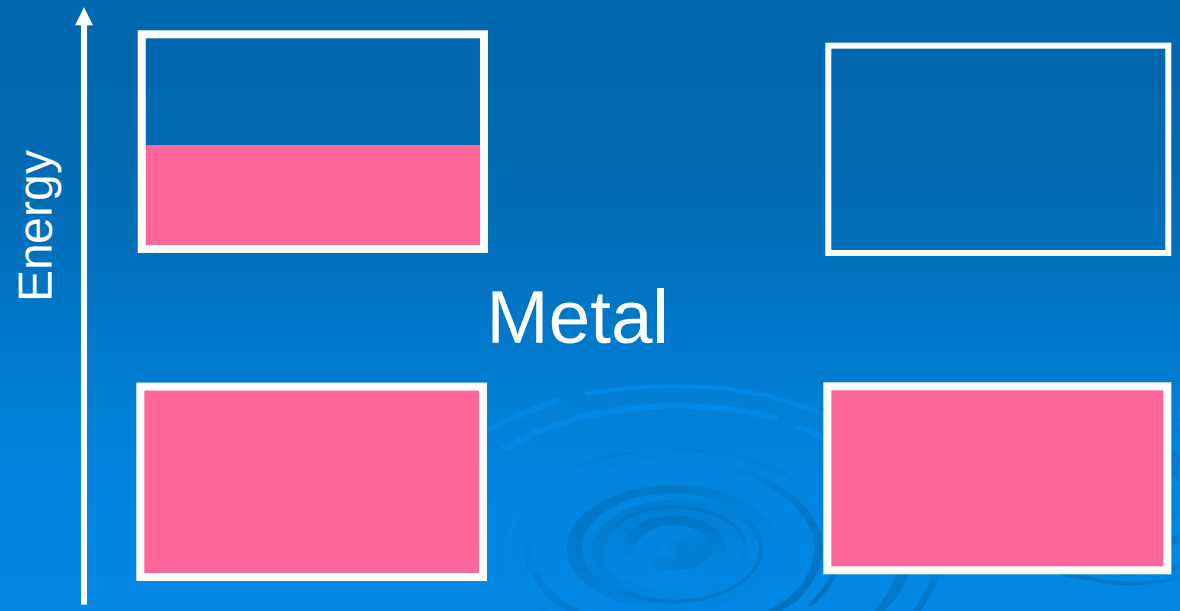
Electrical current can flow

Apply an Electrical Field

Fully-packed Band



Electrical current can't flow



Metal

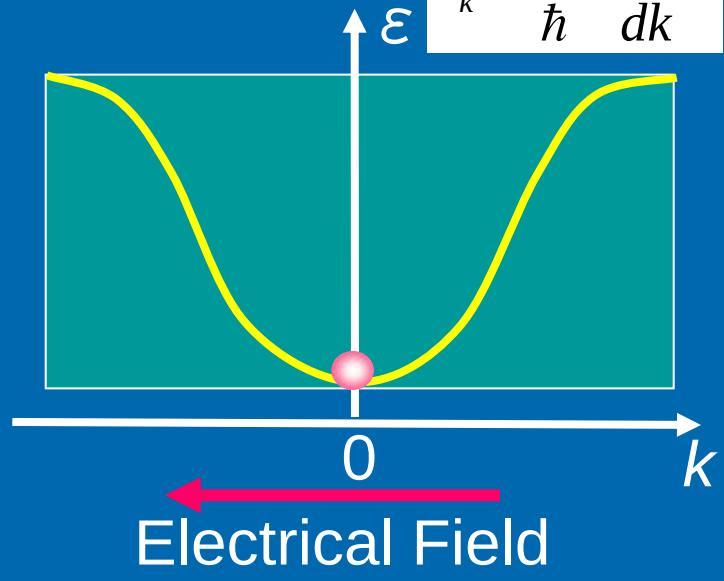
Insulator (Band Insulator)

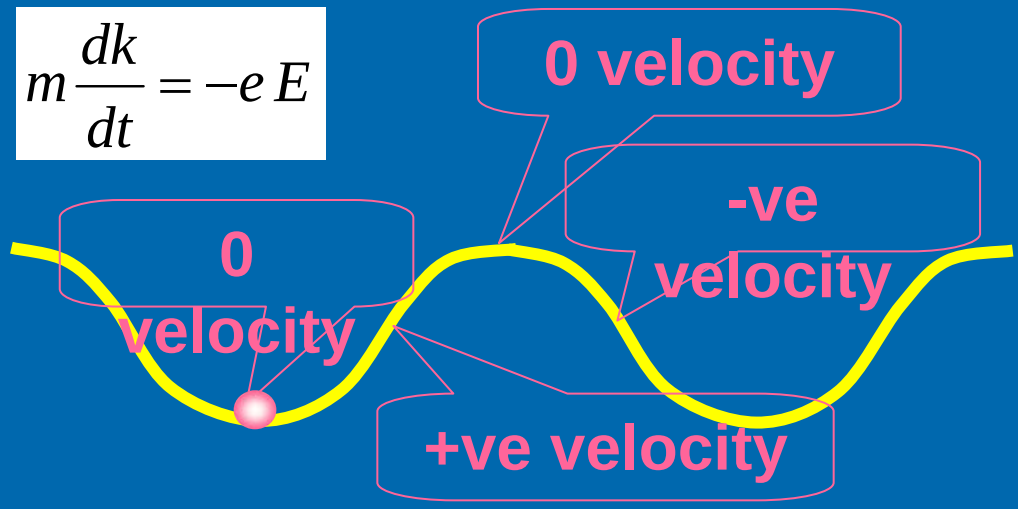
Movement of Bloch Electrons

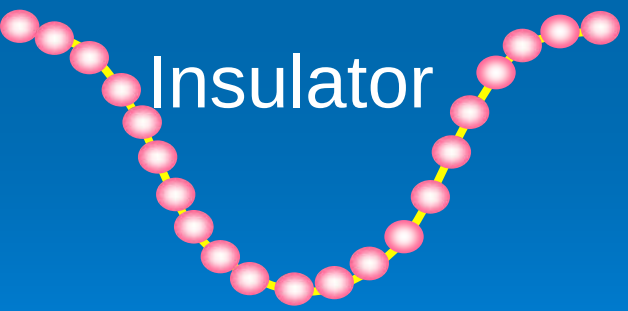
Momentum Space

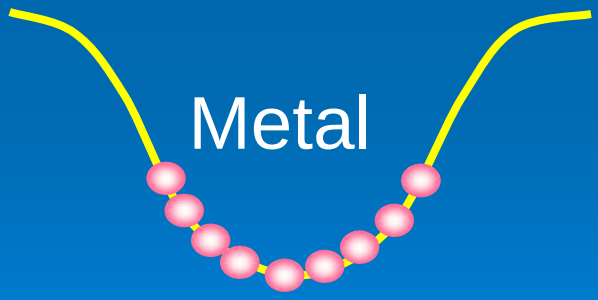
$$v_k = \frac{1}{\hbar}\frac{d\varepsilon(k)}{dk}$$

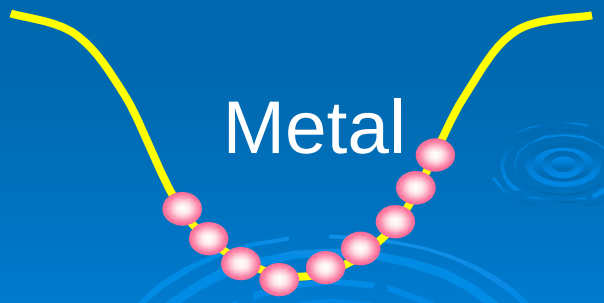
$$m\frac{dk}{dt} = -eE$$









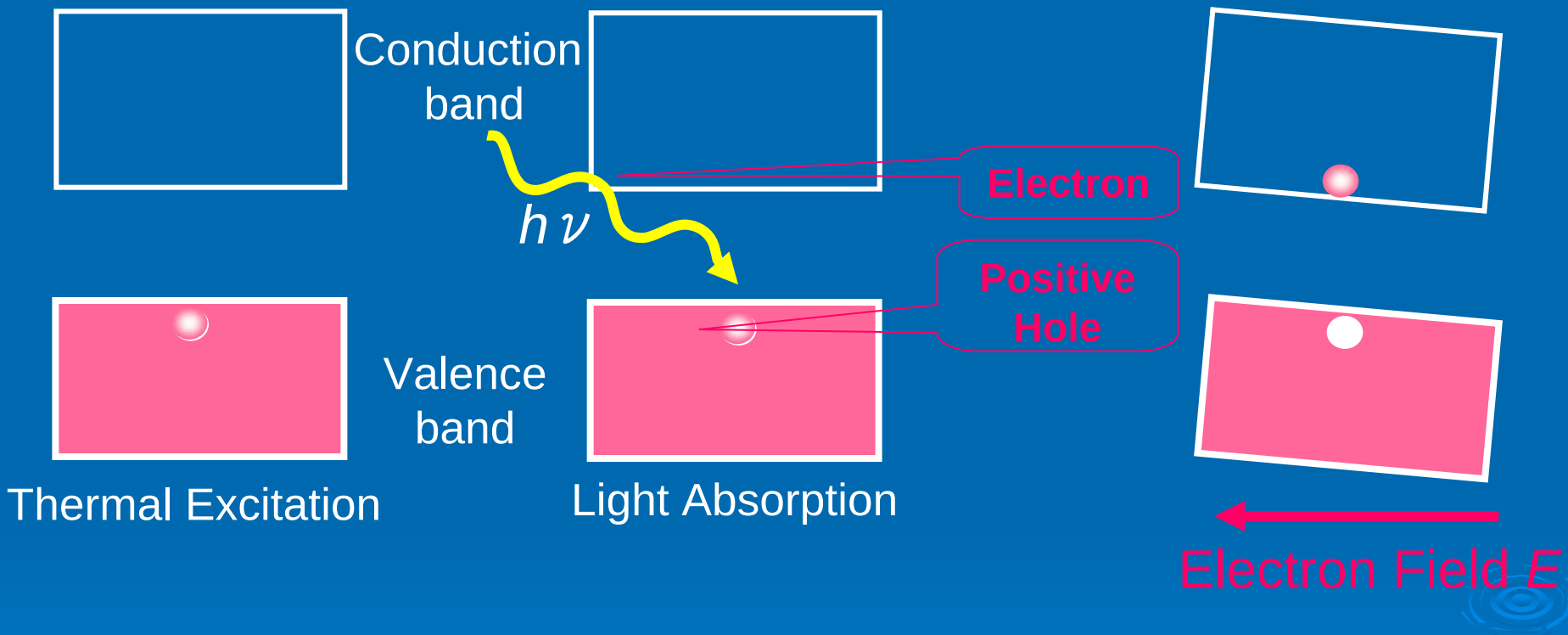


Even if you apply and electric field, the packing of electrons doesn't change

If there's absolutely no dispersion, do electrons just go and come back?

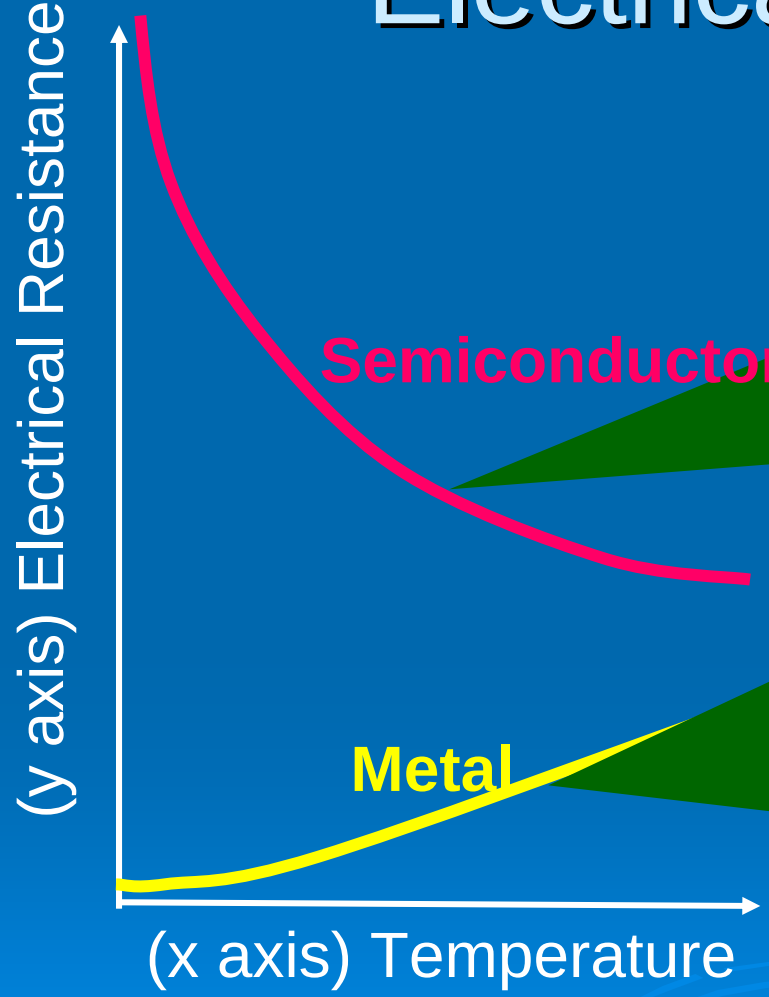
In real substances, the dispersion of electrons is usually slightly spaced-out to allow scattering.

The Electrons and '(Positive) Holes' of Semiconductors



In semiconductors, the few carriers that are formed (Conduction Band Electron, Valence Band Hole) carry electrical conduction due to thermal excitation or light absorption

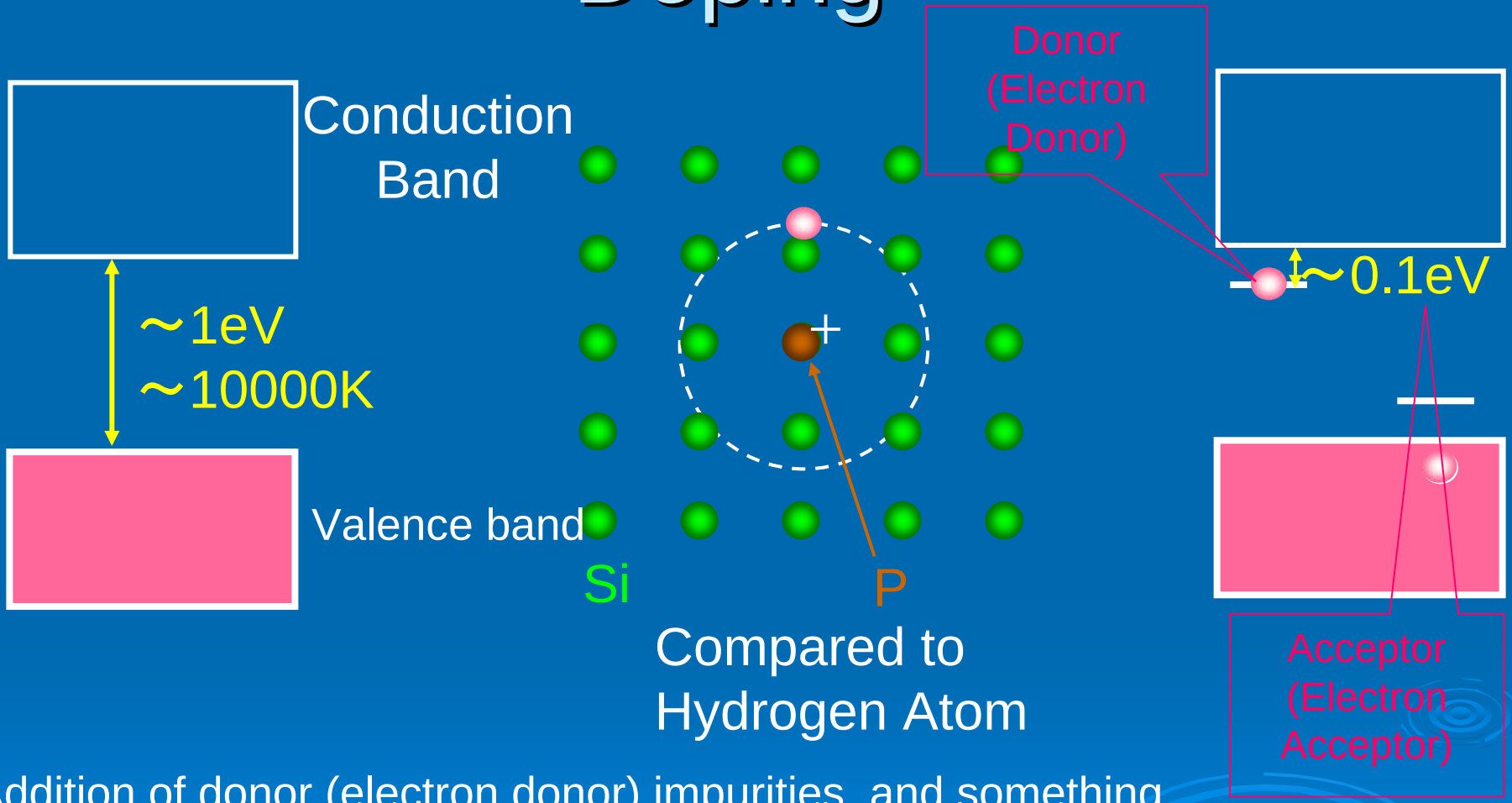
Temperature Change of Electrical Resistance



In semiconductors (insulators), resistance decreases as thermal excitation increases due to rising temperature, to allow the multiple formation of (carier) electrons and holes

In metals, the number of electrons doesn't change according to temperature. At high temperatures, lattice vibration works through the dispersion of electrons. Electron dispersion at extremely low temperatures is decided by impurities and defects etc.

Doping



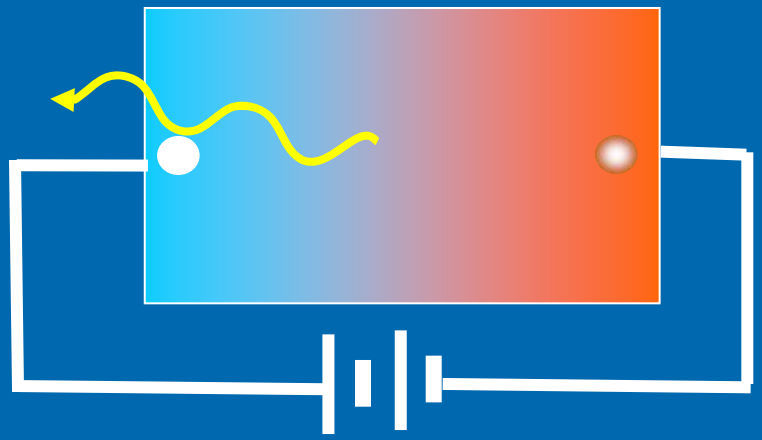
Compared to Hydrogen Atom

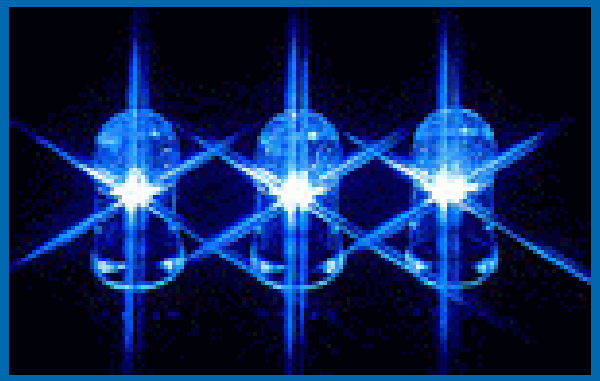
Addition of donor (electron donor) impurities, and something that supplies and electron to a conduction band is called an n-type semiconductor

Addition of acceptor (electron acceptor) impurities, and something that makes a positive hole in a valence band is called a p-type semiconductor

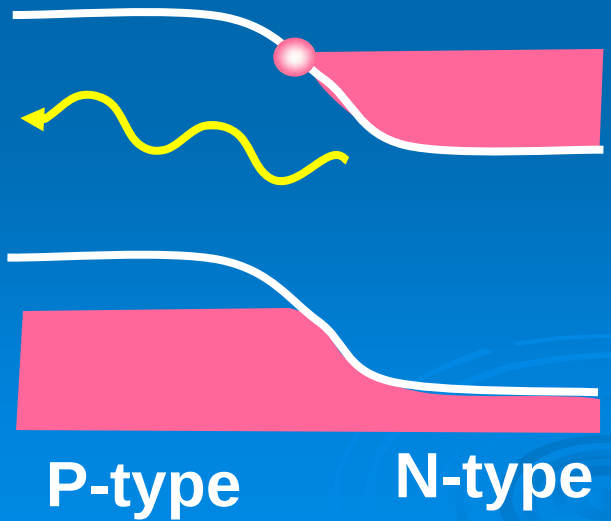
Light-Emitting Diode

p-n union





Light-Emitting Diode

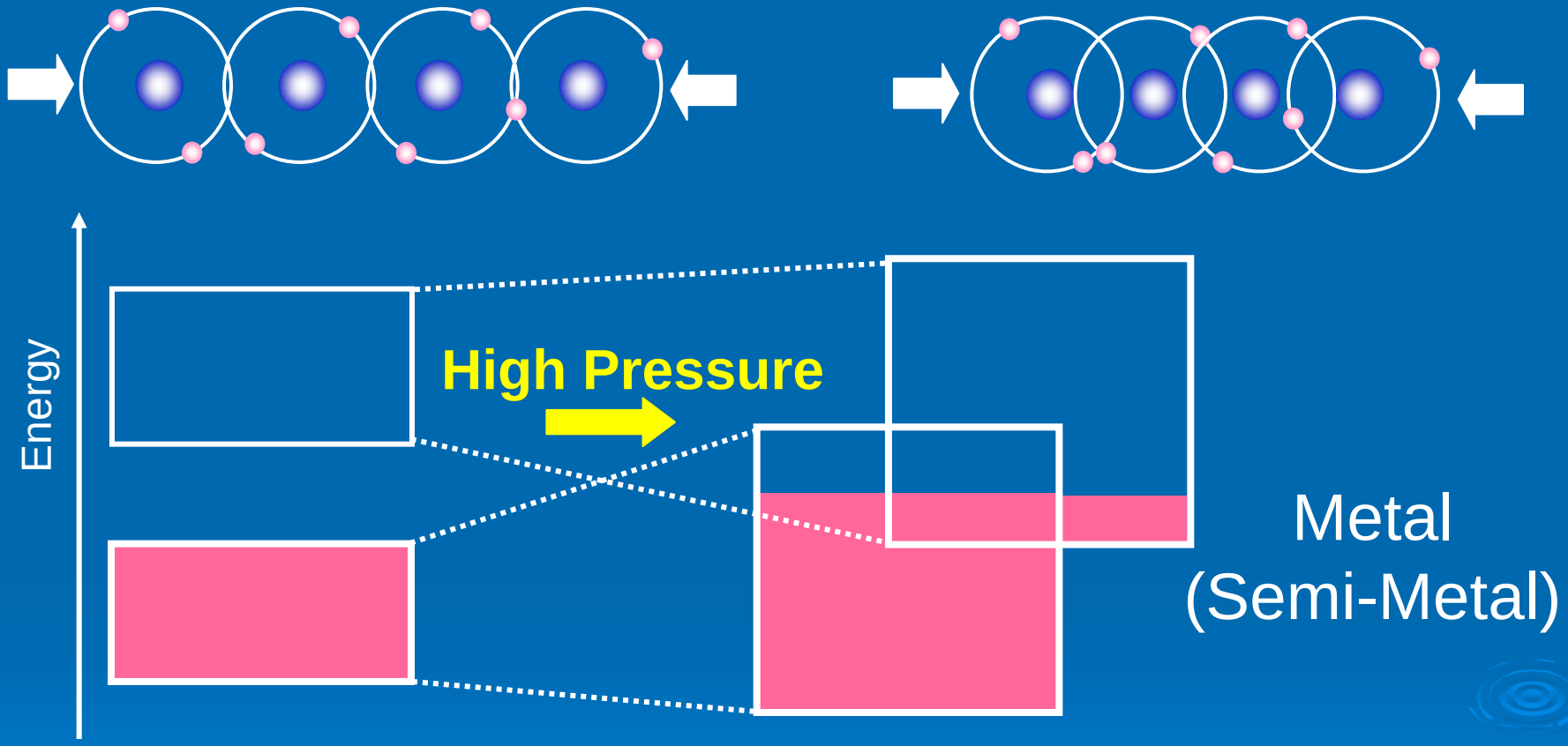


The color of the emanating light is determined by the band-gap of the semiconductor

1eV~3eV

Infra-red ~ Blue

(Simple) Metal-Insulator Transition

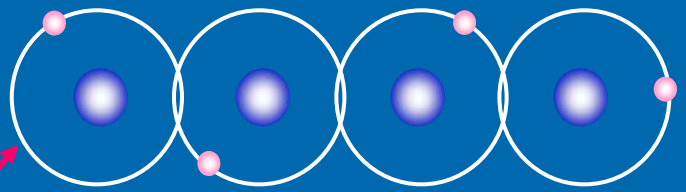


Insulator
(Band Insulator)

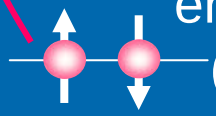
Metal
(Semi-Metal)

Width of the Band broadens as the lattice is squeezed under high pressures, and the Valence Band and Conduction Band subsequently overlaps (Closing the Energy Gap).

Mott Insulator

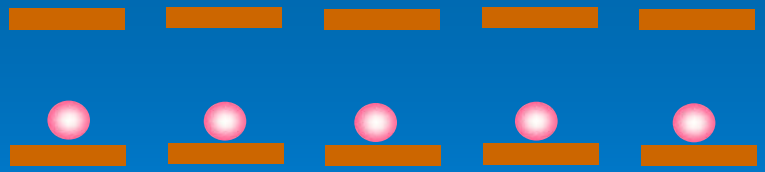


In a situation where there are two electrons in the same orbit, the energy becomes higher by U (the inter-electron Coulomb energy



When the number of beds and number of children is the same

⇒no room for movement

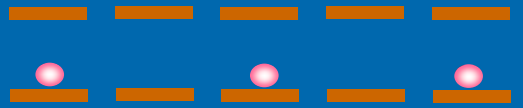


To move they must climb unto the neighboring bed

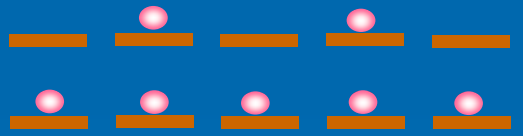
Children Playing in Bunk-Beds

Children who come later have to get into the upper bed

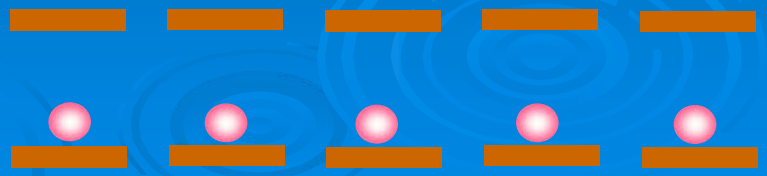
When there are more beds than children



When there are more children than beds



Mott Insulator



Strongly Correlated Electron System

- Like a Mott Insulator, a system where the strong coulomb interaction between electrons controls electron behavior is called a 'Strongly Correlated Electron System'.
- Many remarkable phenomenon such as High Temperature Superconductors and the Supergiant Magnetoresistance Effect etc act as a stage for Strongly Correlated Electron Systems
- The behavior of Strongly Correlated Electron Systems is an essentially difficult multifaceted problem, and presently many researchers are concentrating their efforts into the elucidation of this quintessential physics.

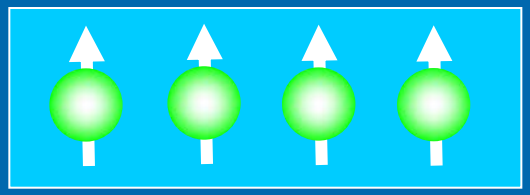
Magnetism

Ferromagnetism

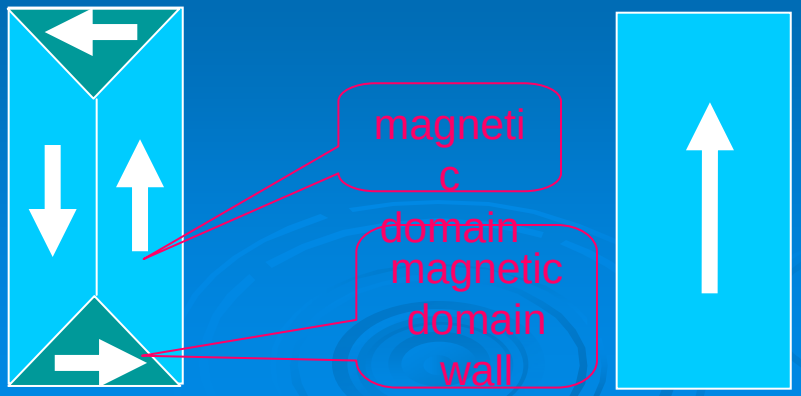
For a certain substance to be magnetic (ferromagnetic)

1) atoms (or molecules) must have magnetic moments (micro magnet)

2) these magnetic moments must align in the same direction

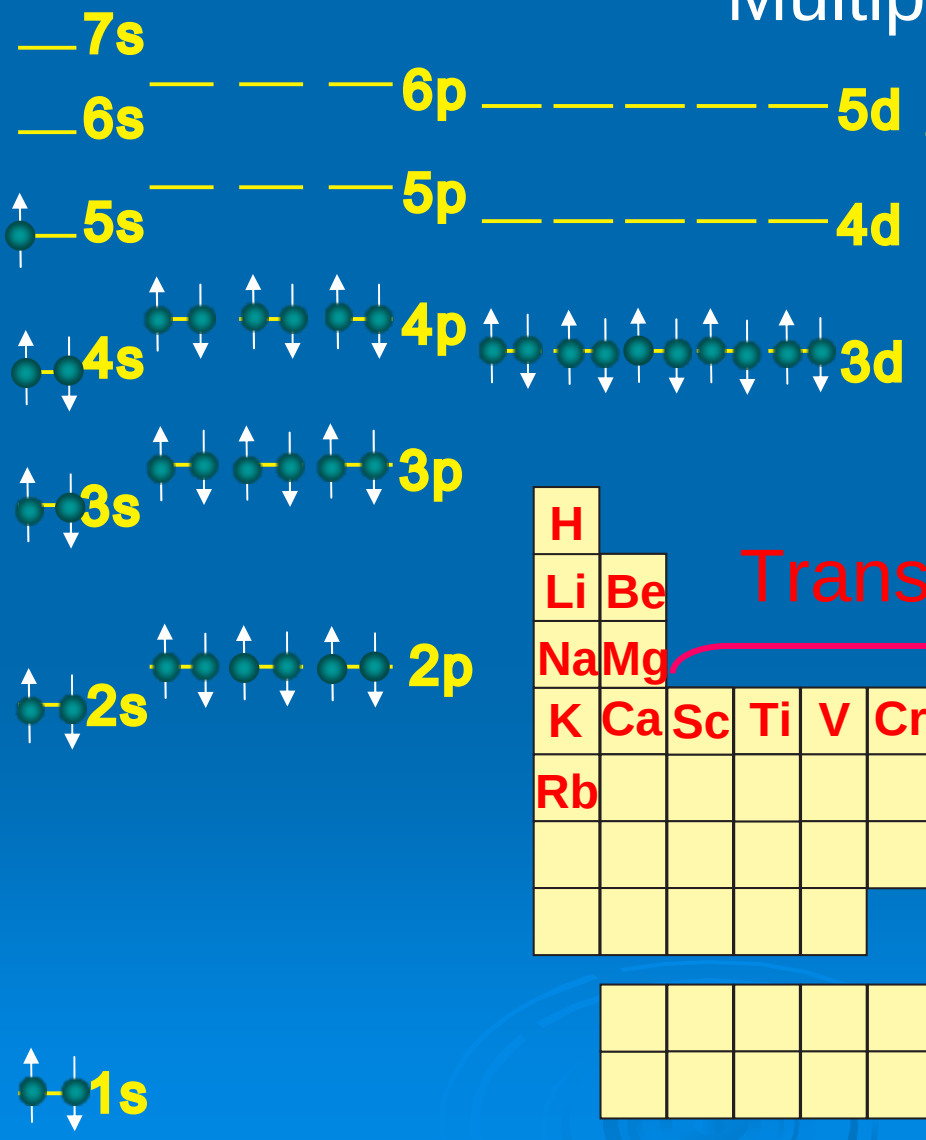


3) the macro specimen must have overall magnetization



The Filling of Electron Energy Levels

Multiple-electron atoms

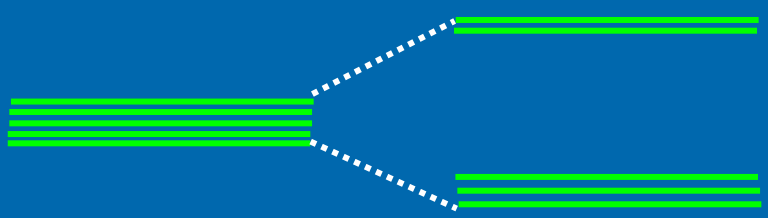


H																He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb																	

Transition Metals

Electron Moment of Atoms (Ions, Molecules)

d-Orbit of atom
5 positions each
of ↑ Spin, ↓ Spin

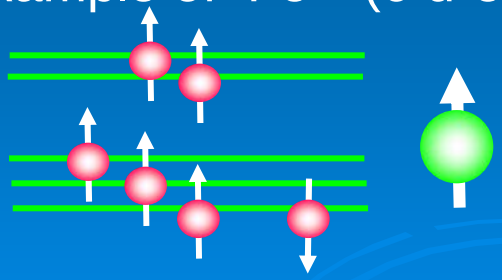


The 5 Energy Levels divide up depending on the environment (Crystal Field) that atom is placed in

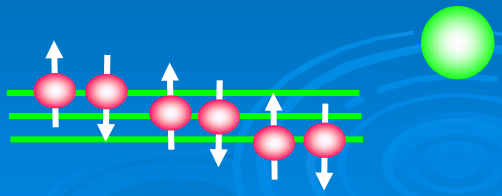
How do electrons fill here?

In avoiding as much as possible the repulsion coulombs between electrons, each orbital is occupied by single electrons of parallel spin before double occupation occurs. (Hund's Rule)

Fe^{2+}The example of Fe^{2+}(6 d-electrons)



When division is small



When division is large

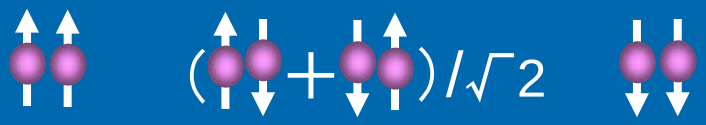
Arranging the Magnetic Moments of Atoms

What is the force that arranges the magnetic moments of atoms?

~~The magnetic dipole interaction of classical electrodynamics?~~

Interaction is too weak
(Energy < 1K)

2 spin in parallel (spin triplet)

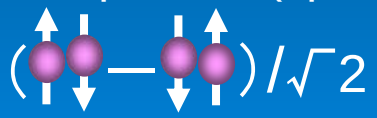


$/\sqrt{2}$

Difference in Coulomb Interaction Energy (Exchange Interaction)

Quantum Mechanical Effect
Exchange Interaction
(Difference in Coulomb interaction according to direction of spin)

2 spin in anti-parallel (spin singlet)



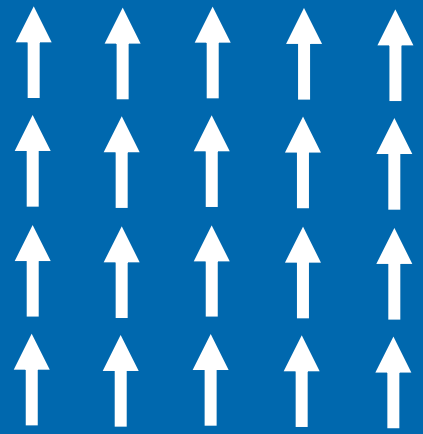
$/\sqrt{2}$

Ferromagnetic
$J > 0$

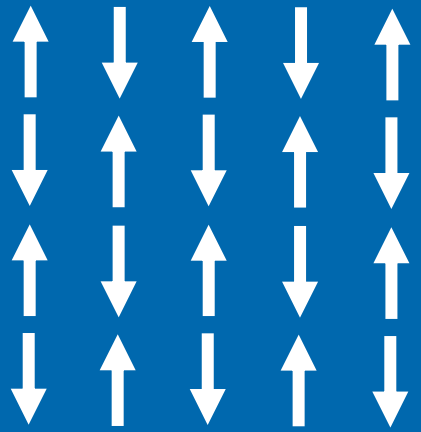
Antiferromagnetic
$J < 0$

$$\text{Energy} = -J\,\mathbf{s}_1 \cdot \mathbf{s}_2$$

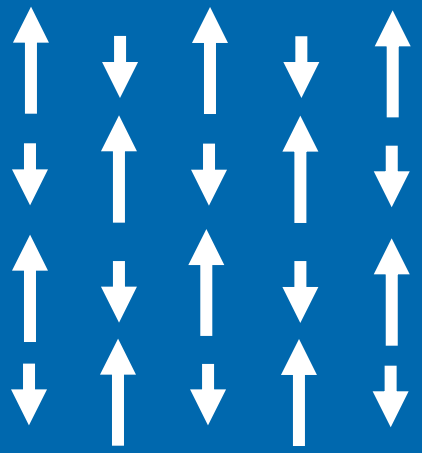
About Magnetic Bodies



Ferromagnetism
(Marco-magnetization)

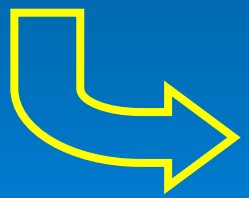


Antiferromagnetism
(No macro-magnetization)

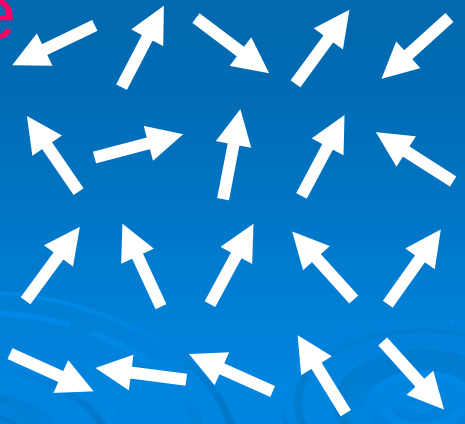


Ferrimagnetism
(Macro-magnetization)

Ordered State



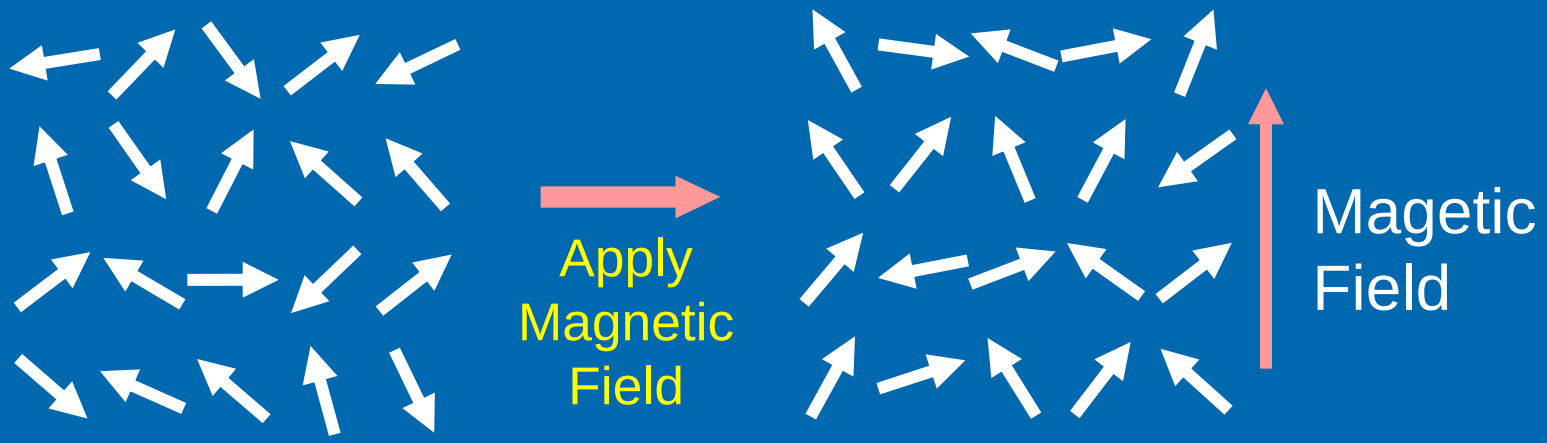
High Temp



Chaotic State

Paramagnetism(No macro-magnetization)

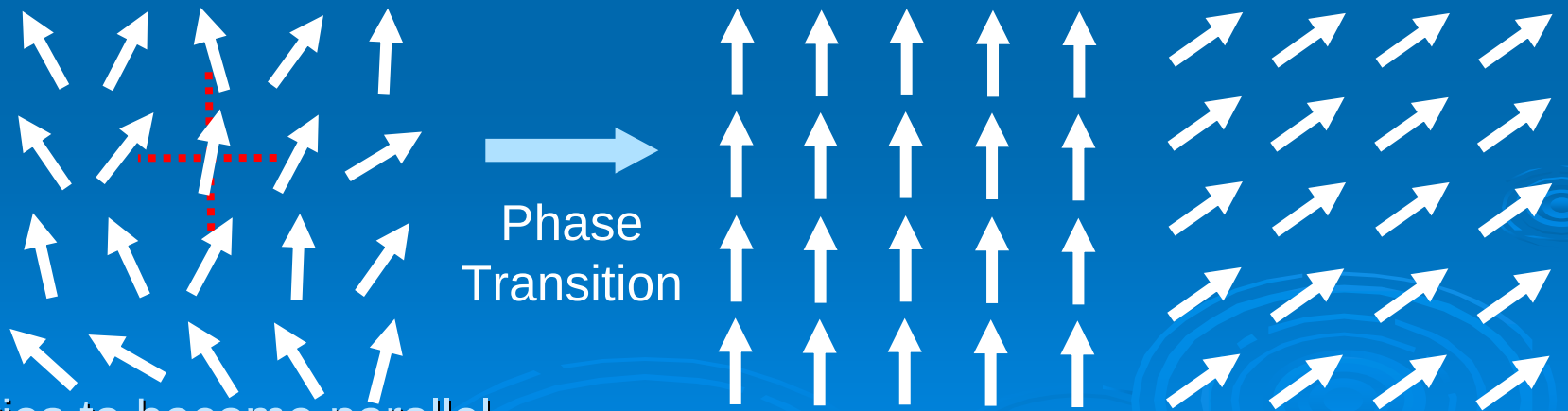
Magnetic Order (Cooperative Phenomenon and Phase Transition)



Chaotic State of High Temp

Low Temp

In terms of magnetic domain, the power arranging spin by changing-interaction is several hundreds tesra

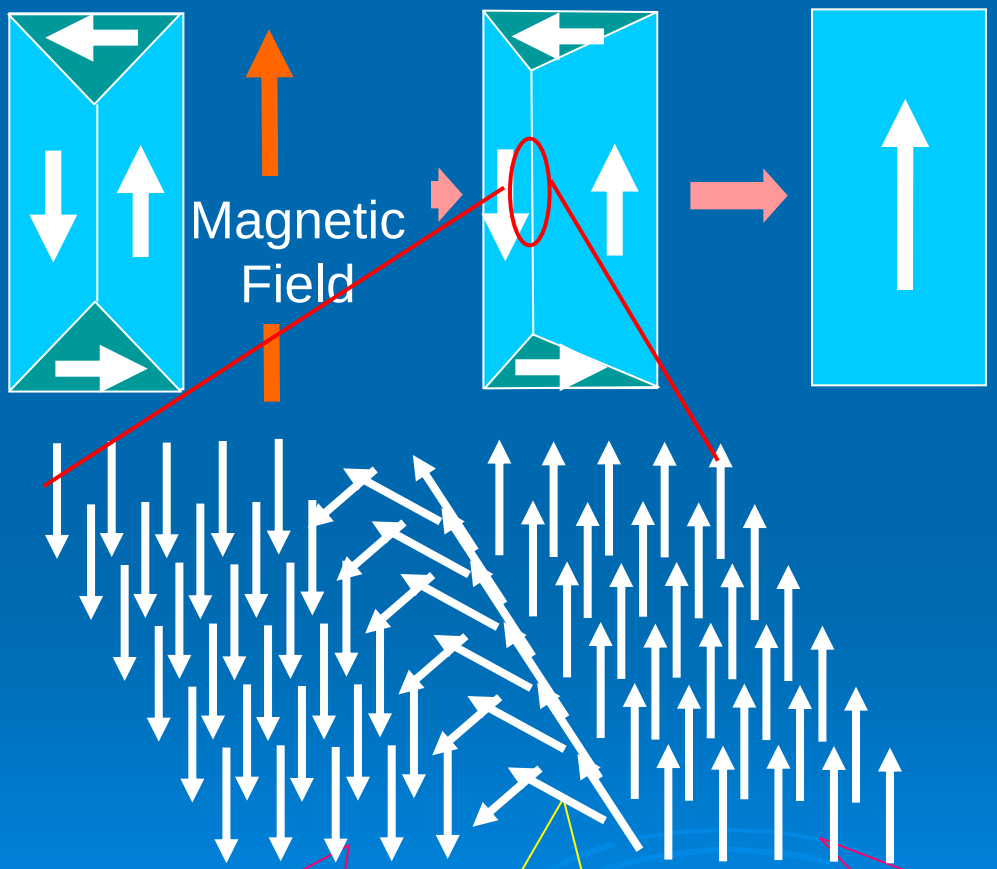


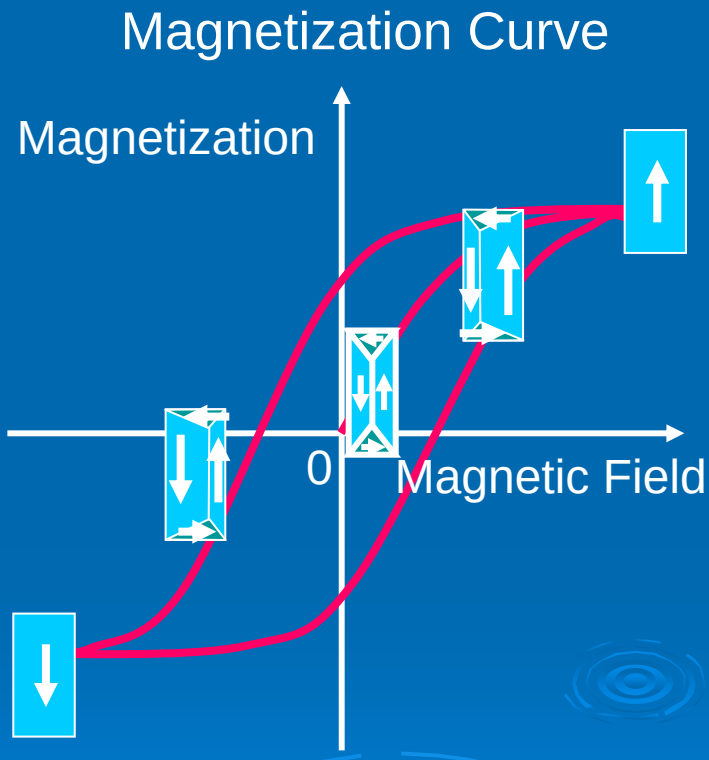
Tries to become parallel
With the spin of their
neighbor

Ordered State of Ferromagnetism

Magnetic Domains and Magnetic Domain Walls

Magnetization Process of Ferromagnetic Bodies





Magnetic Domain

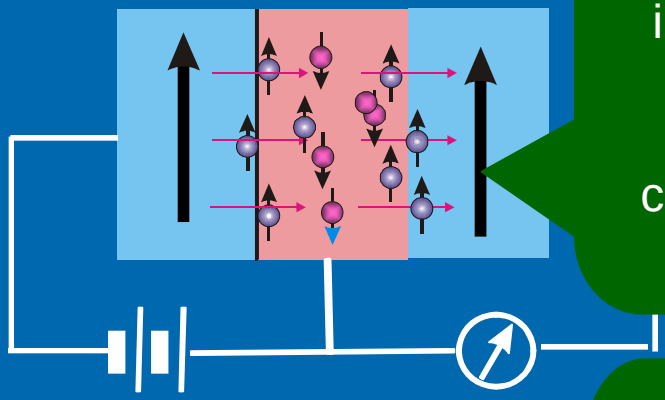
Magnetic Wall

Magnetic Domain

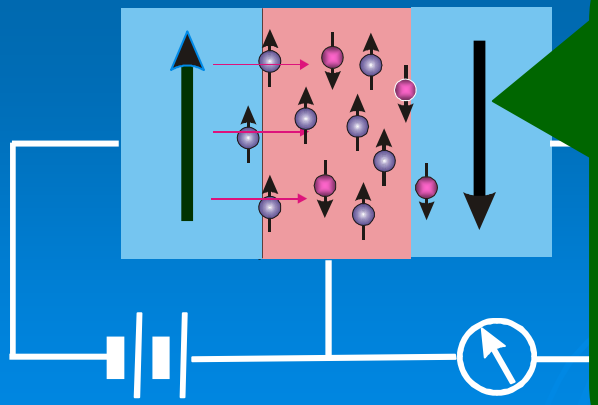
Spintronics

Electronics: uses the degree of freedom of electron's charge
Spintronics: uses the degree of freedom of electron's charge and spin

Spin Valve Device

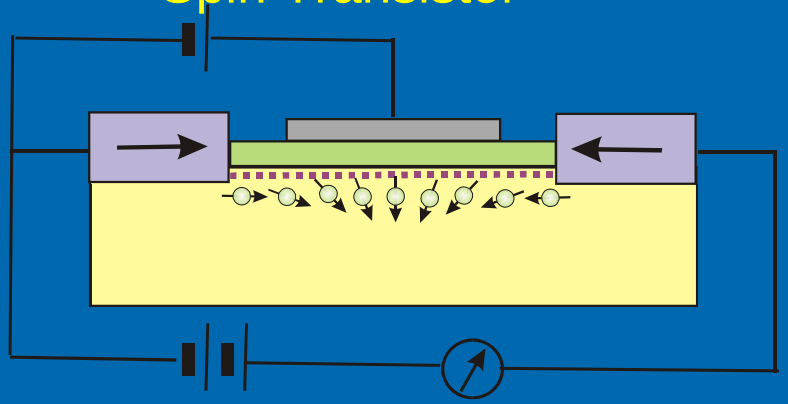


When magnetized is in the same direction, electrical current flows easily

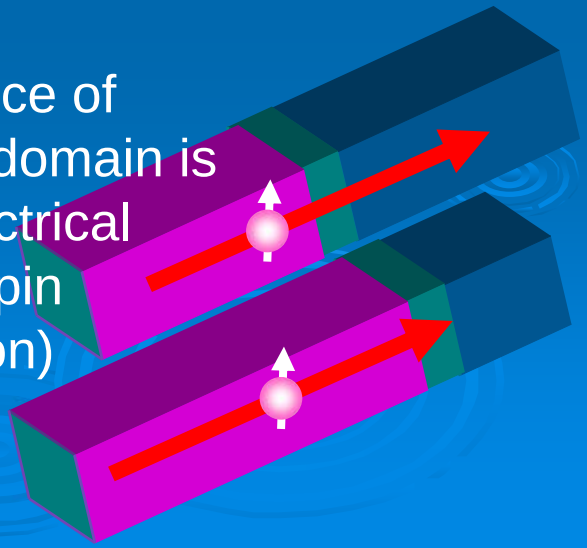


When magnetized is in the opposite direction, flow of electrical current is more difficult

Spin Transistor

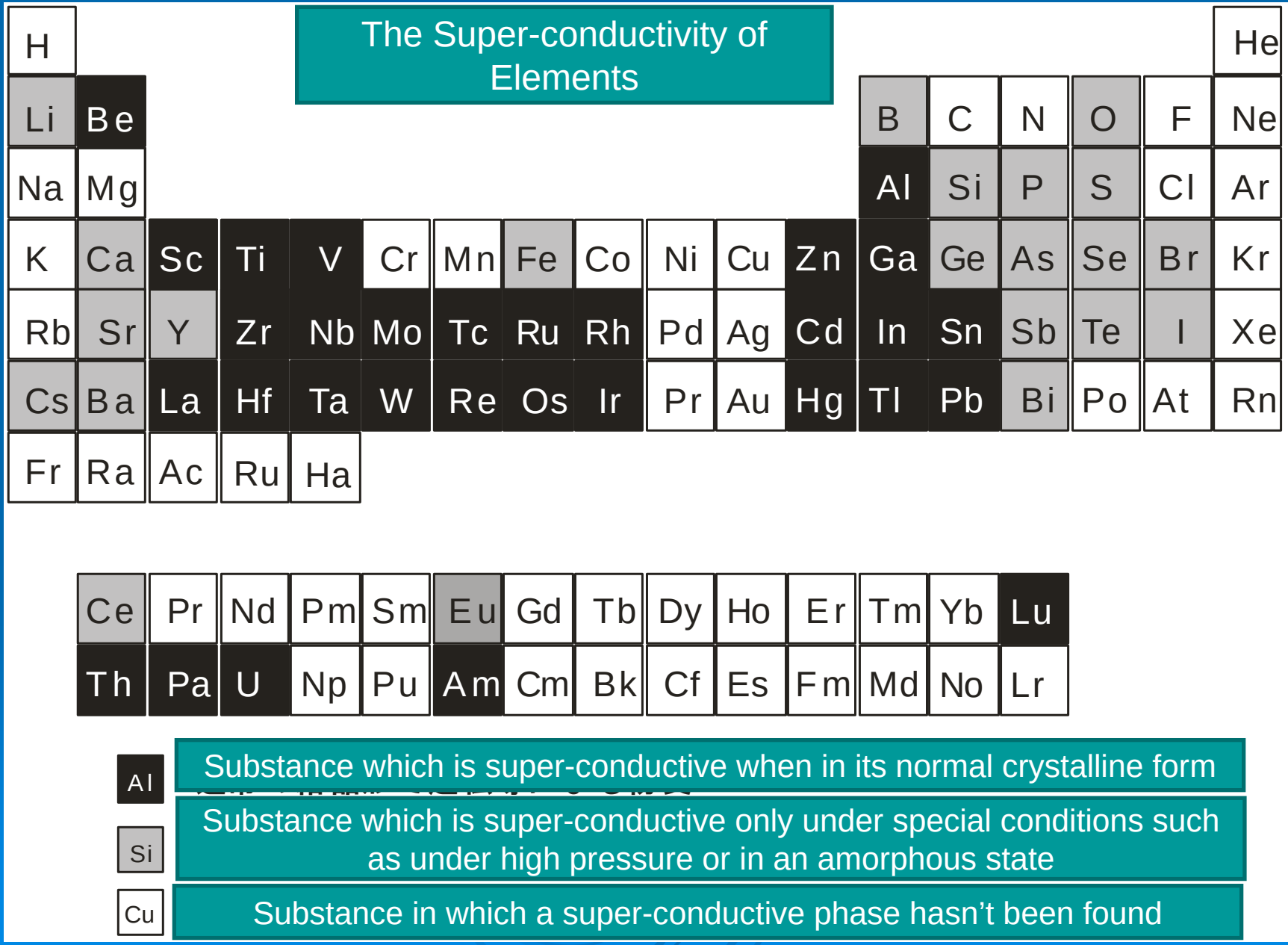


Driving force of magnetic domain is due to electrical current (Spin Polarization)

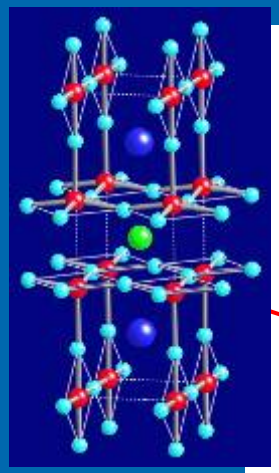


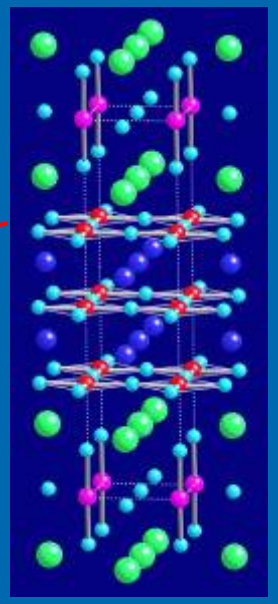
Super Conduction

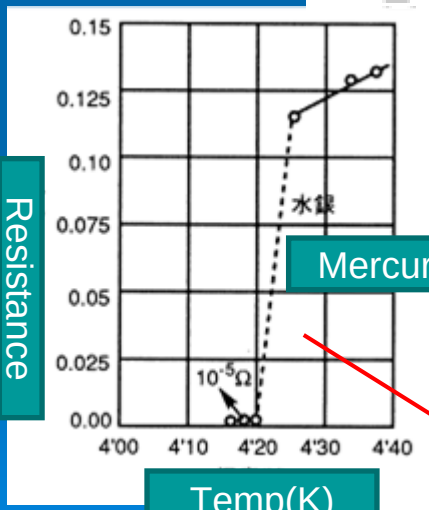
The Super-conductivity of Elements

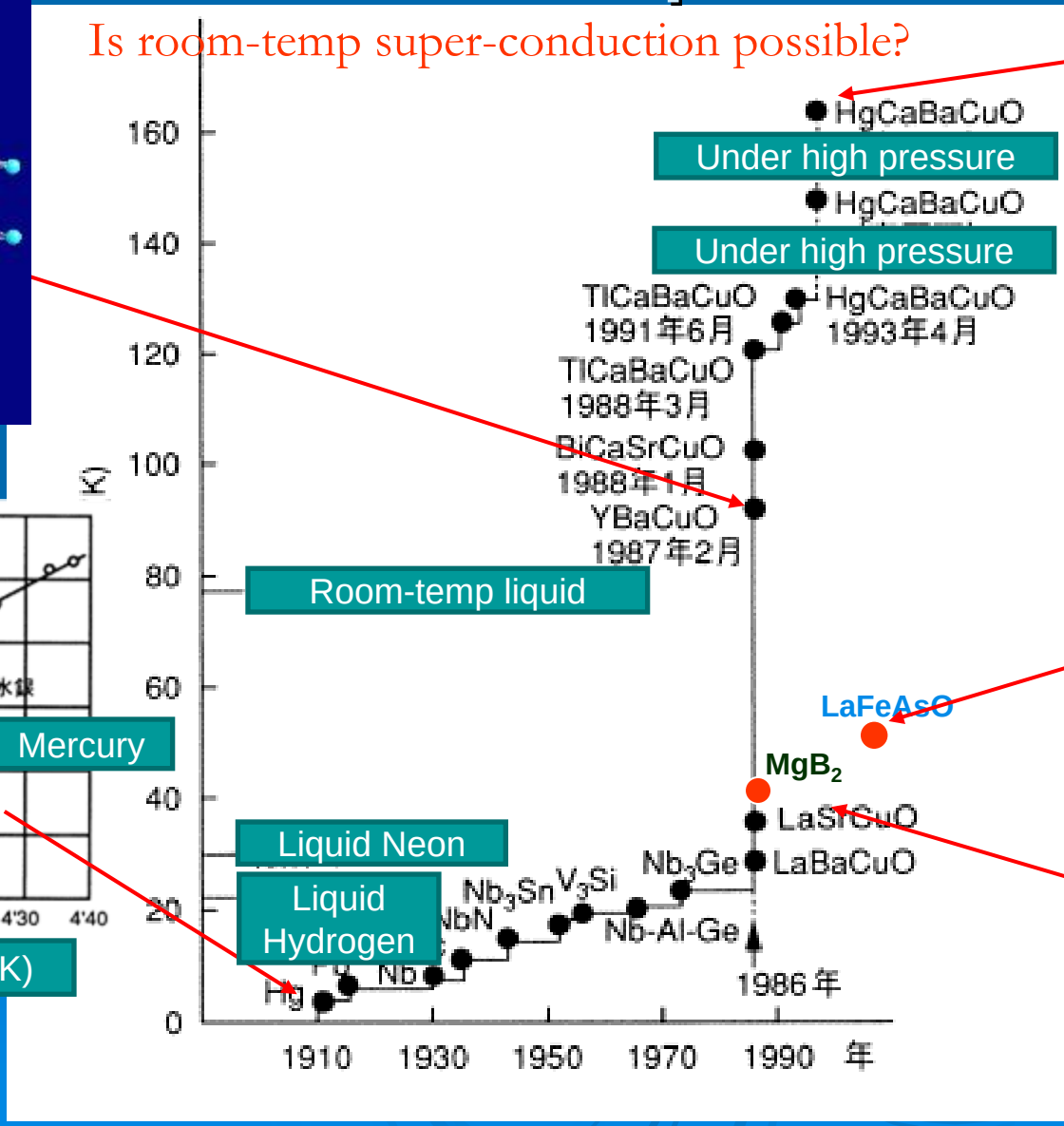


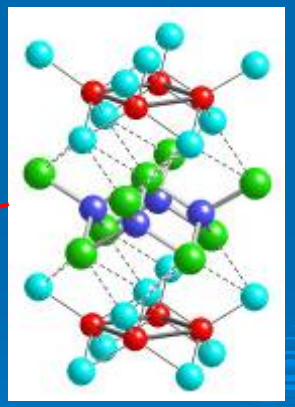
Vicissitude of Superconduction Transition Temperature

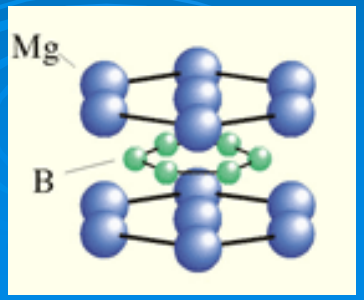






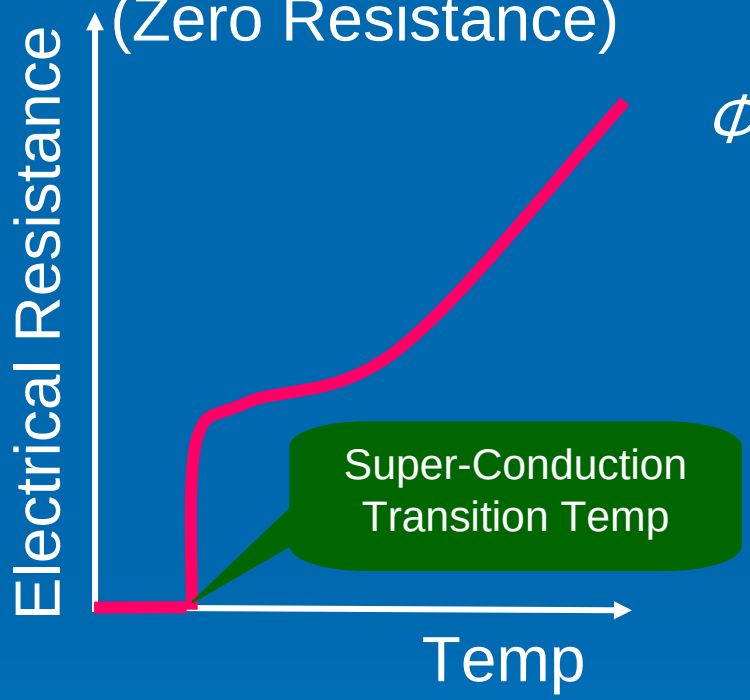




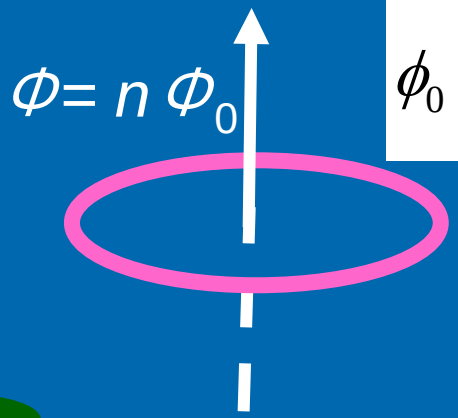


Basic Properties of Super-Conduction

Perfect Conductor
(Zero Resistance)



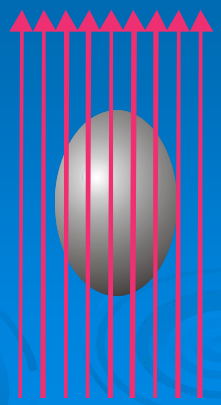
Quantization of Magnetic Flux

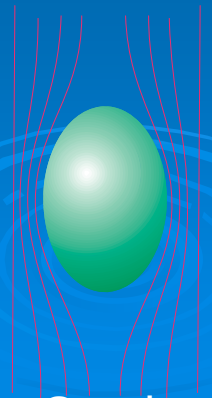


$$\phi_0 = \frac{h}{2e} = 2.07 \times 10^{-15}\ \mathrm{Wb}$$

Same as quantization of rotation (swirl) in superfluidity

Meissner Effect (Perfect Diamagnetism)

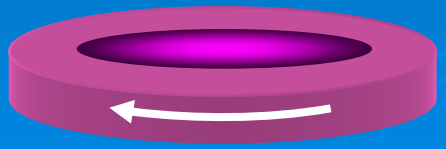




Normal Conductive State

Super-Conductive State

Permanent Electrical Current

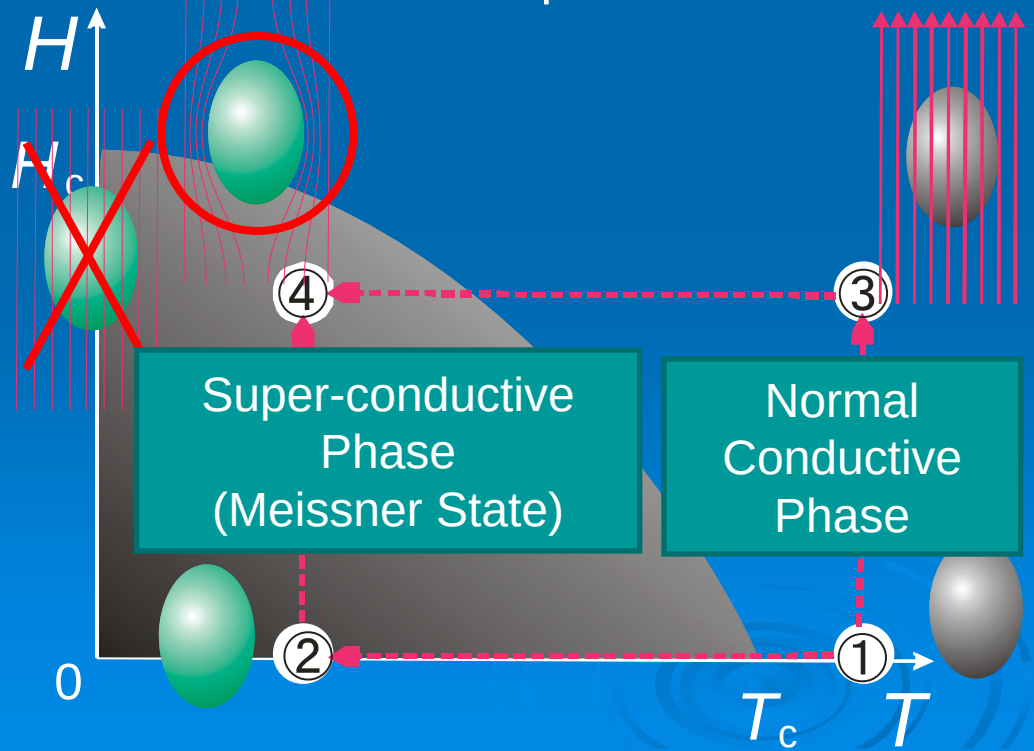


Super-Conduction ≠ Perfect Conduction

If you apply a magnetic field to a conductor,
a shield current will flow (Lenz's Law),
but it will soon decay due to resistance

In a perfect conductor, shield current continues to flow without any decay

However, in that case,
the situation is dependent on how the magnetic field is applied

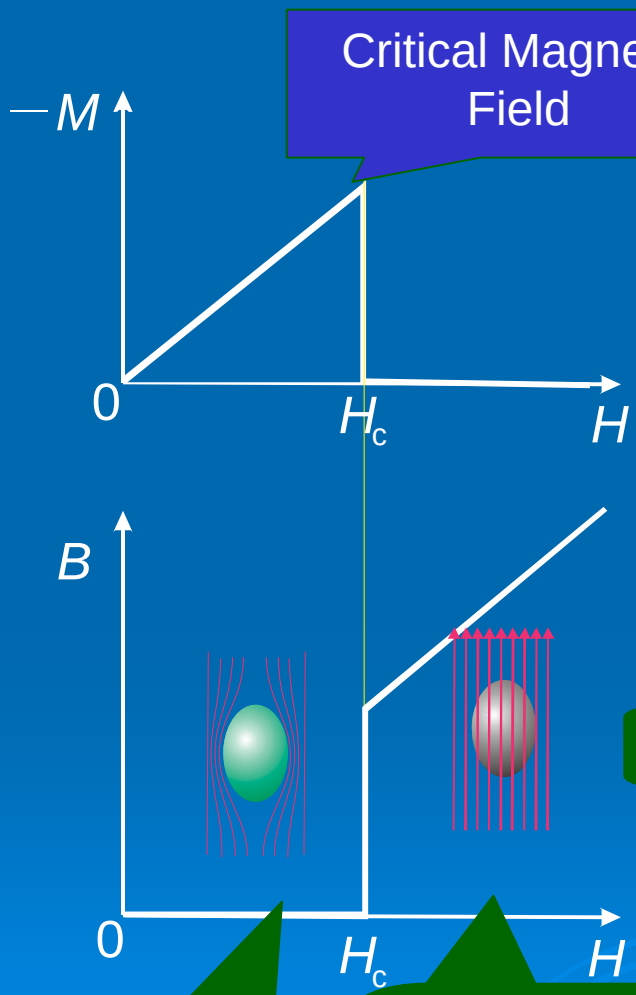


Meissner Effect (Perfect Diamagnetism)
With a super-conductor, magnetic fields are completely eliminated

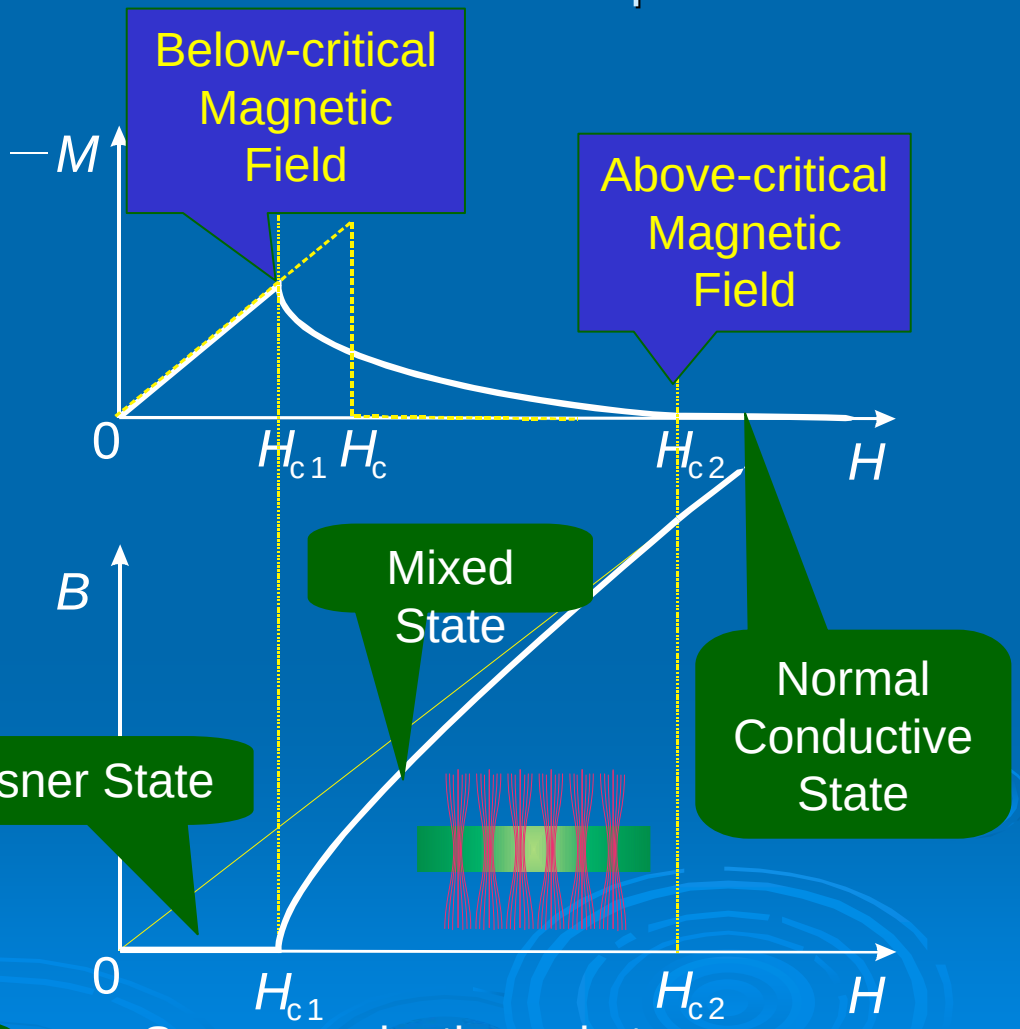
Super-conduction shield current is an electrical current that is flowing in a heat-balanced state

First and Second Generation Super-Conductors

First Generation Super Conductor



Second Generation Super Conductor

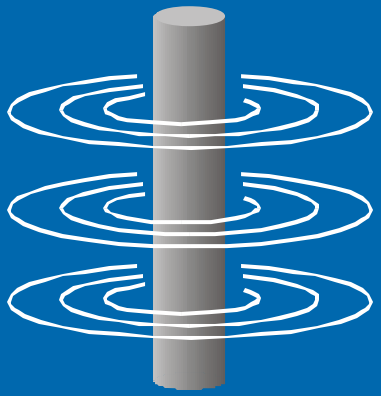


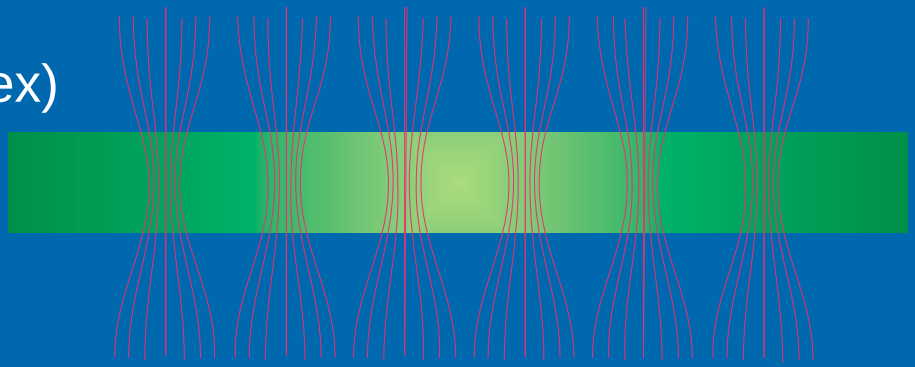
Super-conductive substances that are use as practical materials are 2nd Gen Superconductors

Quantum Magnetic Flux (Vortex)

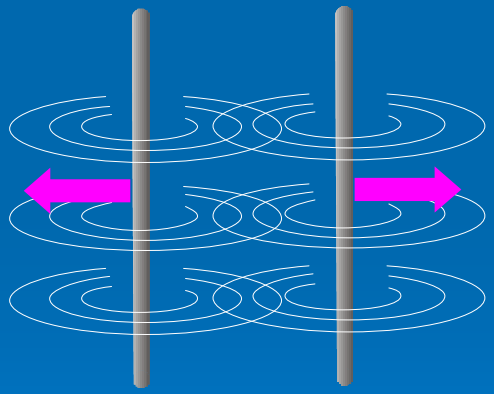
Mixed State of 2nd Gen Superconductors

Quantum Magnetic Flux (Vortex)

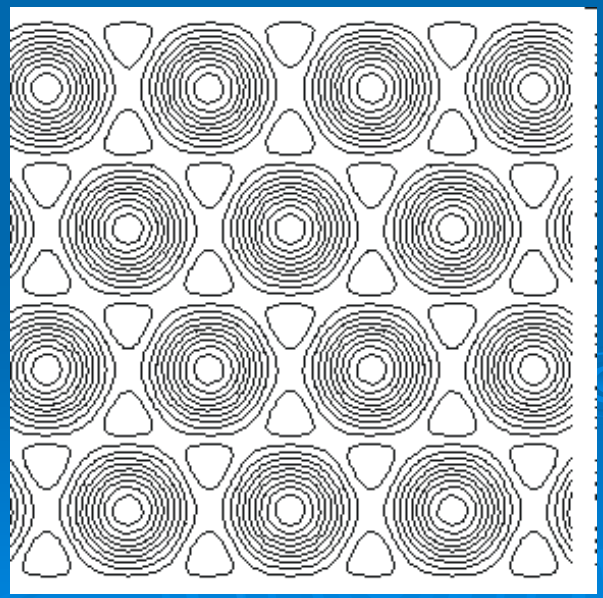




$$\phi_0 = \frac{h}{2e} = 2.07 \times 10^{-15}\,\mathrm{Wb}$$



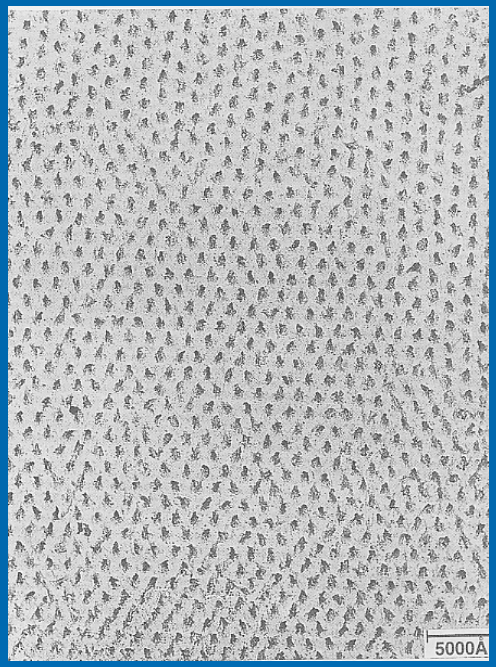
Repulsive Force at work between Vortices



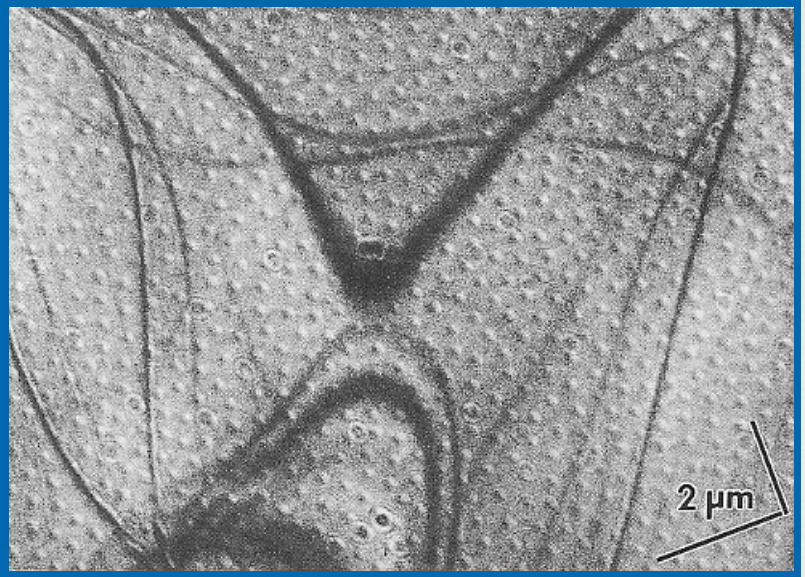
Triangular Lattice

Magnetic Flux Lattice
(Abrikosov Lattice)

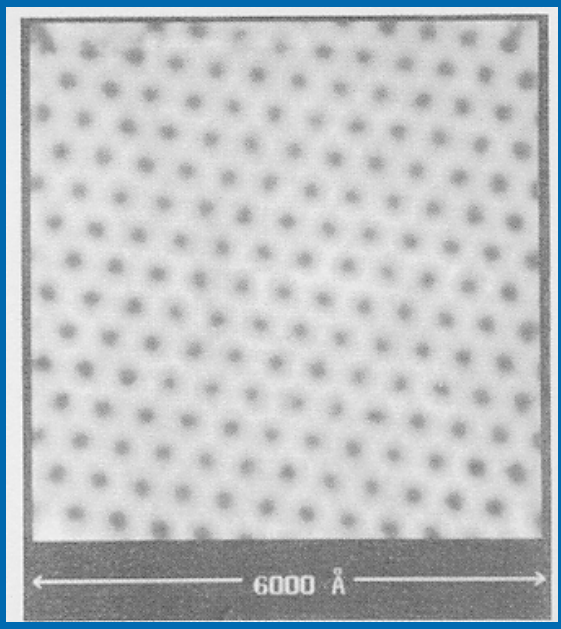
Observation of Magnetic Flux Lattice



Bitter Method
(Essmann & Traueble,1968)

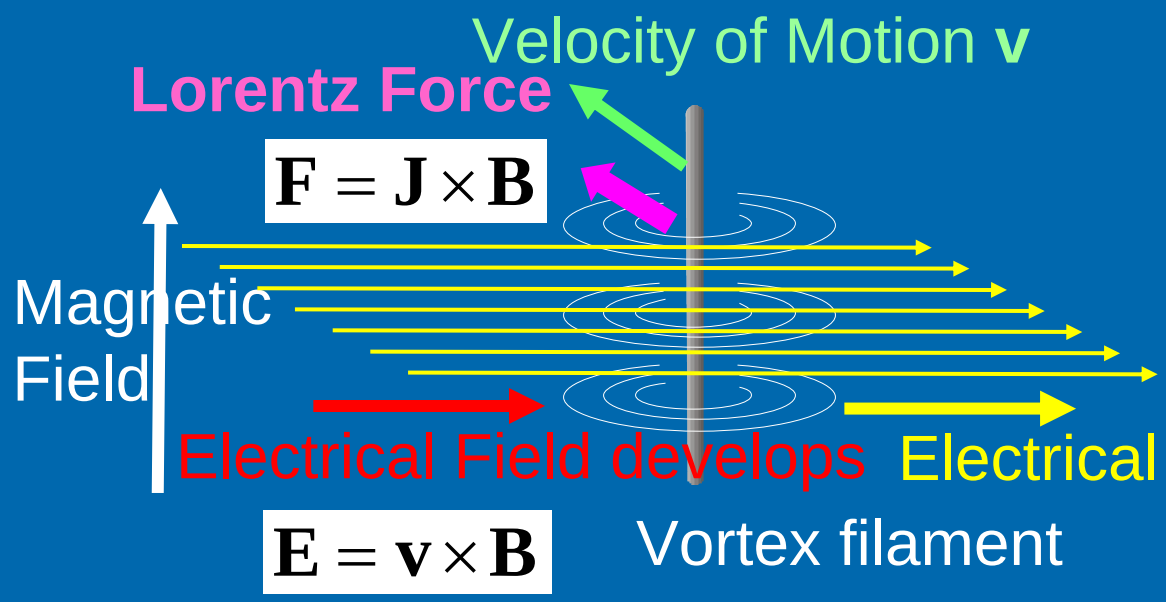


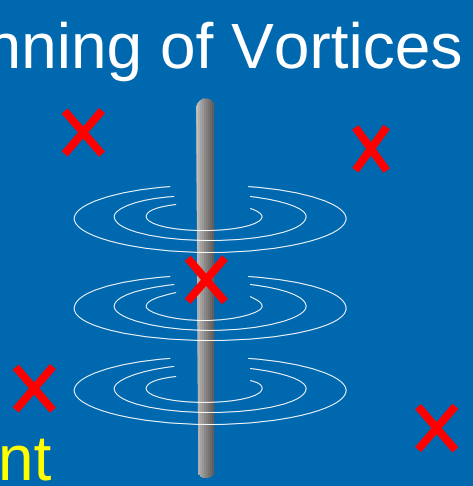
Lorentz Microscope
（Tonomura Akira, 1992）



Scanning Tunnel Microscope
（Hess, 1989）

Lorentz Force and Pinning of Vortices





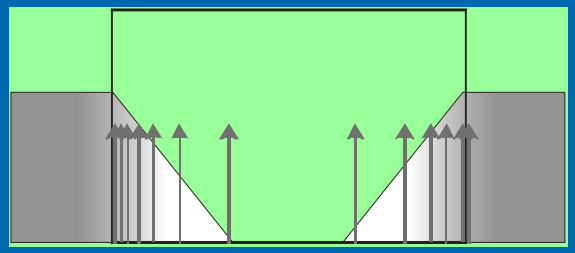
If a vortex is pinned and can't move, energy dissipation doesn't eventuate

Electrical field develops when a vortex moves. The creation of an electrical field in the direction of electrical current flow is the development of non-zero electrical resistance (energy dissipation)

Lorentz Force vs Pinning
Current density that starts to move a vortex
⇒ Critical Current Density

“Hard” Superconductor

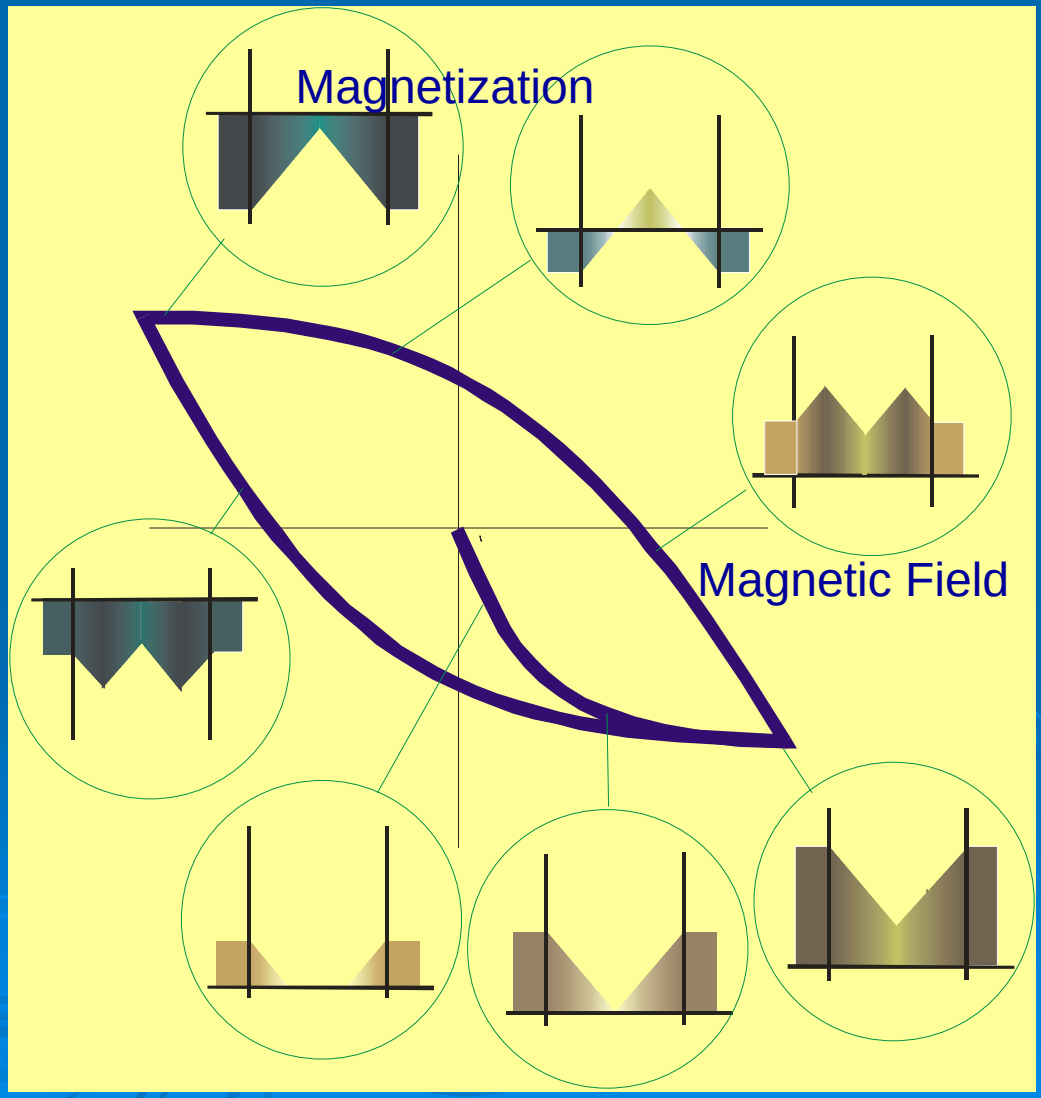
Strong Superconductor
Pinning Vortices



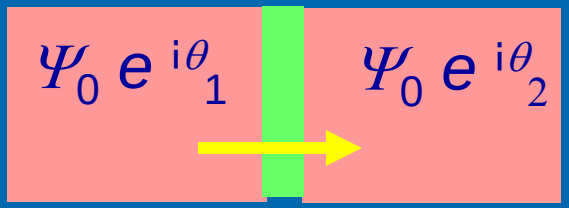
Shield current will flow
until critical current is reached
=>This decides the gradient of
the magnetic flux density

The shape of a sand hill
(Critical state of self-organization)

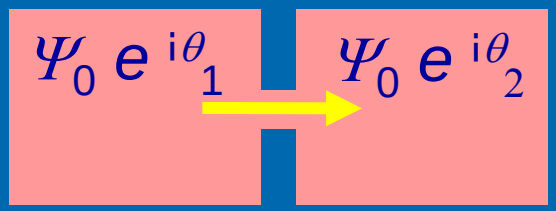
Magnetization Curve



Josephson Junction



Tunnel Junction

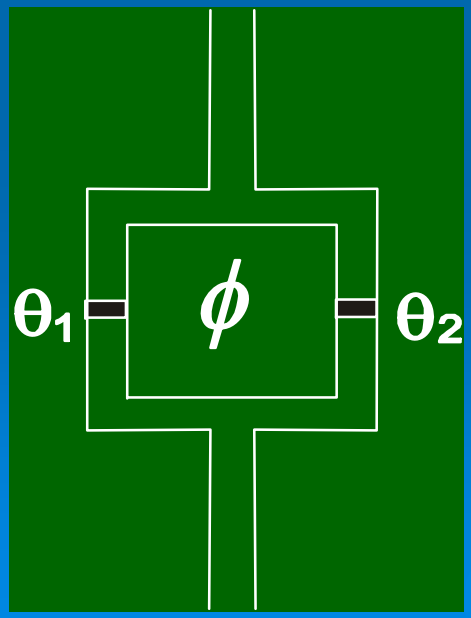


Weak Junction

Josephson Current
Depends on phase contrast of the junction

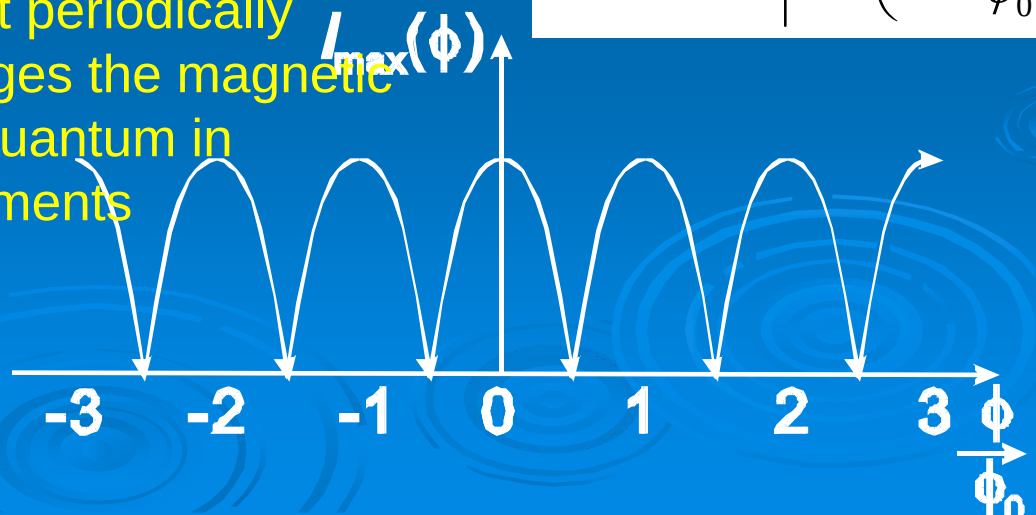
$$J = J_c \sin(\theta_1 - \theta_2)$$

Superconducting Quantum Interference Device (SQUID)



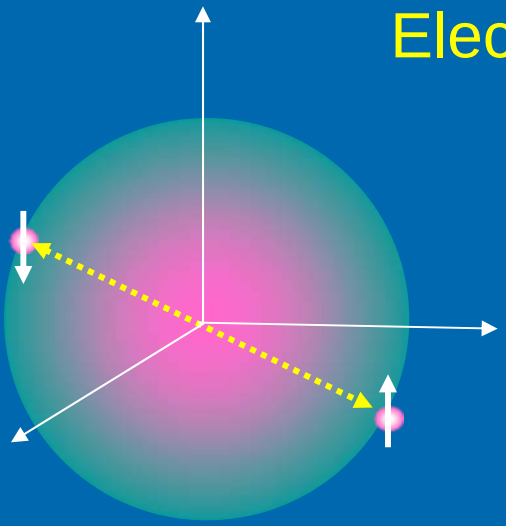
A superconducting current that flows in a circuit periodically changes the magnetic flux quantum in increments

$$I_{max} = 2I_c \left| \cos\left(2\pi \frac{\phi}{\phi_0} \right) \right|$$



Mechanisms of Super-conduction

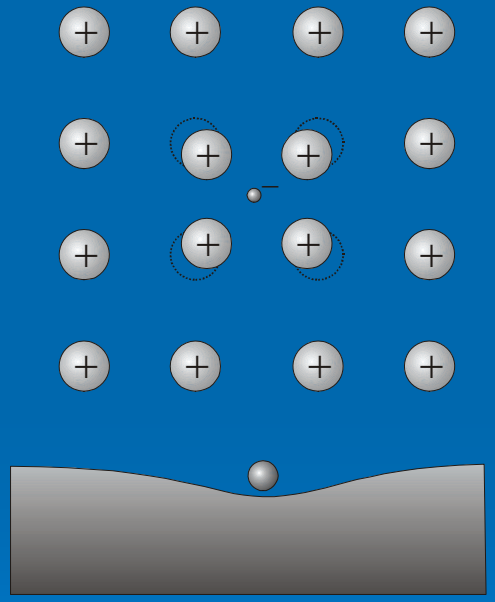
Cooper Pair Configuration

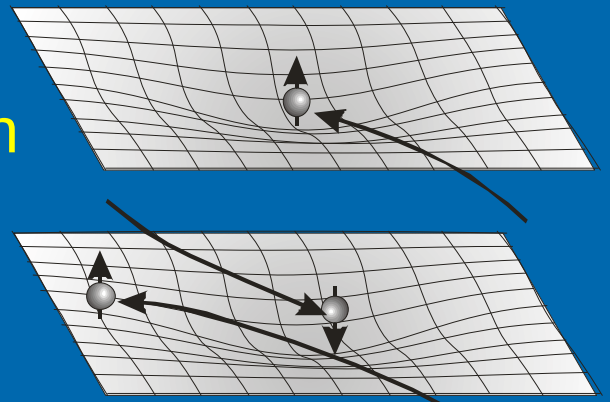


When attractive force acts on two electrons on the Fermi plane, a bound state (Cooper Pair) takes shape.

Origin of Attraction?

Electron lattice Interaction





When the inter-electron attractive force that mediates electron particle interaction over-powers the inter-electron Coulomb repulsive force, pure attraction is able to function.

Super-conduction Transition Temp.

$$T_c = 1.14\Theta_D \exp\left(-\frac{1}{N(0)V}\right)$$

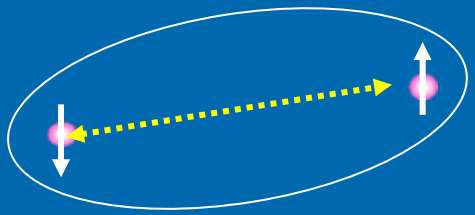
Bardeen, Cooper, and Schrieffer (BCS) Mechanism

Inter-electron attractive forces overcome the inter-electron Coulomb repulsive forces

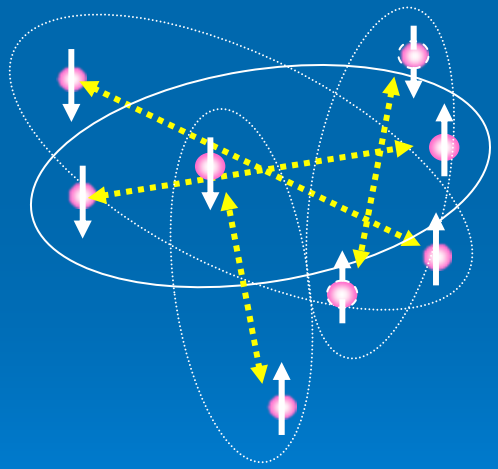
Formation of Cooper Pair

Bose-Einstein Condensation of Cooper Pair
=> Super-Conductive State

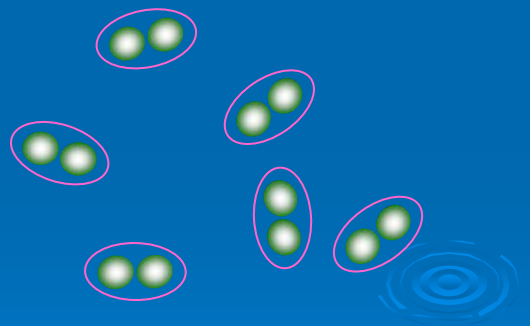
Size of Cooper Pair



Coherence length



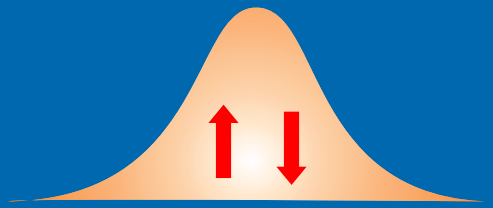
Cooper Pairs overlap each other



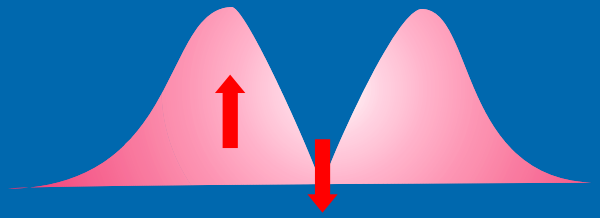
In the case of normal molecules, the size of the molecule is smaller than the distance between the particles.

Anisotropic Super Conduction

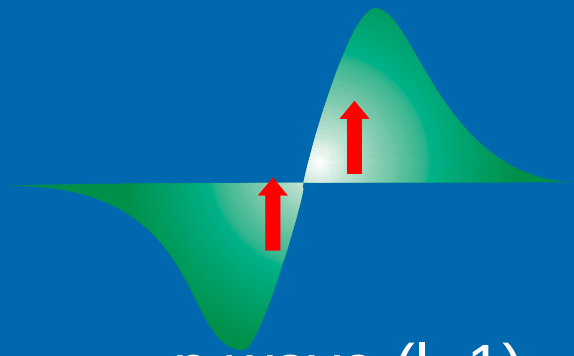
Symmetry of Cooper Pairs



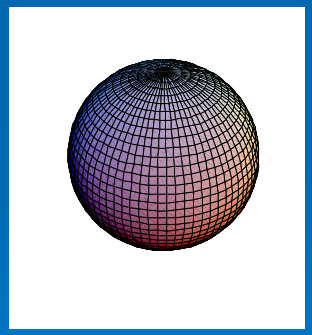
s wave (l=0)
Spin Singlet



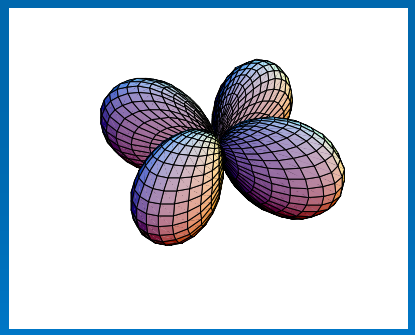
d wave (l=2)
Spin Singlet



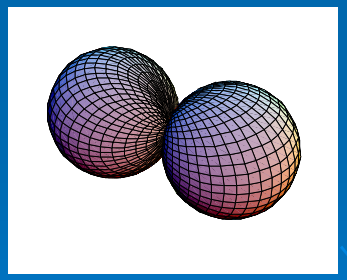
p wave (l=1)
Spin Triplet



Super-Conduction of
Most substances



Copper-oxide High-temp
Super-Conducting
substance etc

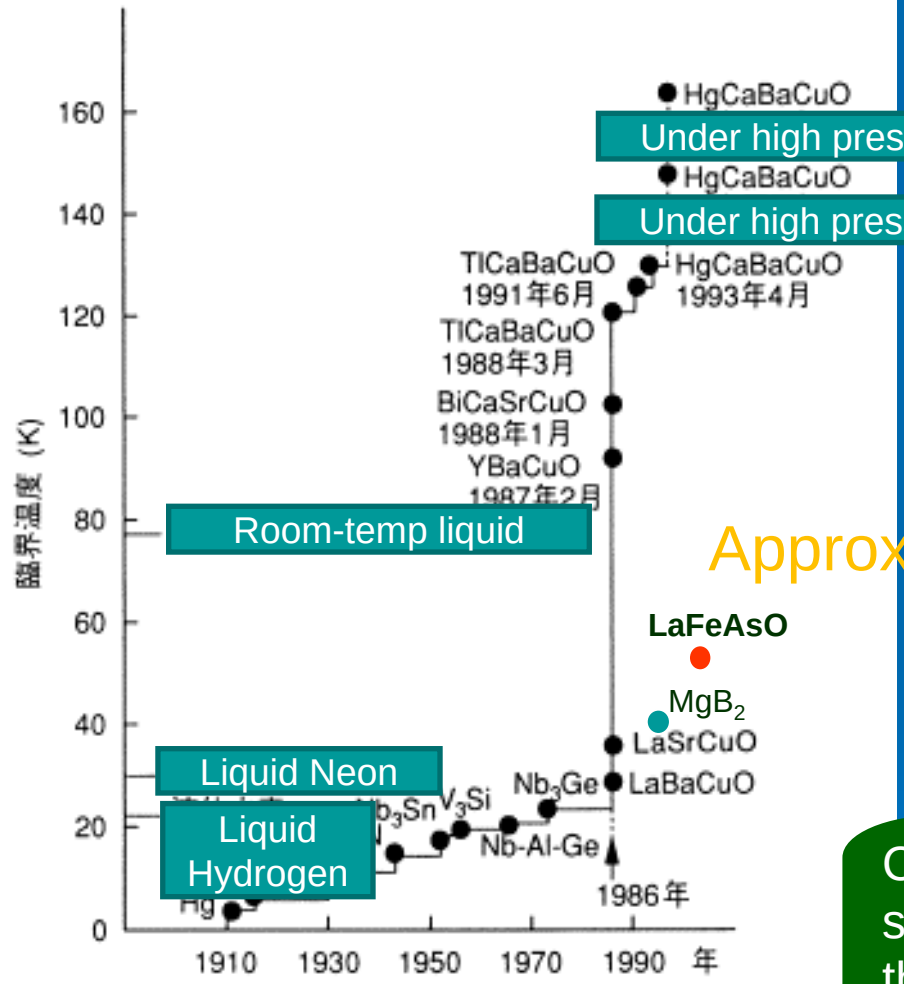


Ruthenium-oxide UPt_3
Super-conductivity of
^3He

Exotic super-conduction

- Copper Oxide superconductors（$YBa_2Cu_3O_7$, $Bi_2Sr_2CaCu_2O_8$）
- Sr_2RuO_4
- Heavy Fermion（UPt_3 , $CeCu_2Si_2$ ）
- Organic Superconductors(($(TMTSF)_2PF_6$, （$(BEDT\text{-}TTF)_2Cu(NCS)_4$）
- MgB_2
- Alkali-Doped Fullerene K_3C_{60}
- Boron-Doped Diamond
- LaOFeAs

What is Room Temp. Super-conduction?



Super-conduction transition temp.

$$T_c = 1.14\Theta_D \exp\left(-\frac{1}{N(0)V}\right)$$

Characteristic energy scale of lattice vibration

Strength of electron lattice interaction

Approx ~30K is the limit?

$$T_c \approx T^* \exp\left(-\frac{1}{\lambda}\right)$$

Characteristic energy scale of prime excitation that intermediates inter-electron attraction

Strength of interaction

Room Temp. Super-conduction : there's no reason it isn't possible

Summary

- Cohesive forces and crystal structure of atoms
- Electron state within solids (Band Structure)
  - Ban
- Electrical Conduction
  - Metal, Insulator, Semi-conductor
  - Metal/Insulator Conversion, Mott Insulator, Strongly Correlated Electron System
- Magnetism
  - Magnetic Moment of Atoms => Exchange Interaction => Magnetic Domain
  - Spintronics
- Super-conduction
  - Fundamental nature of super-conduction (Zero Resistance, Meissner Effect)
  - BCS Mechanism
  - The search for superconducting substances => Room Temp. Super-conduction?