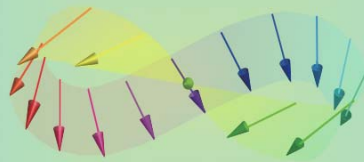


Introductory Nanotechnology

~ Basic Condensed Matter Physics ~



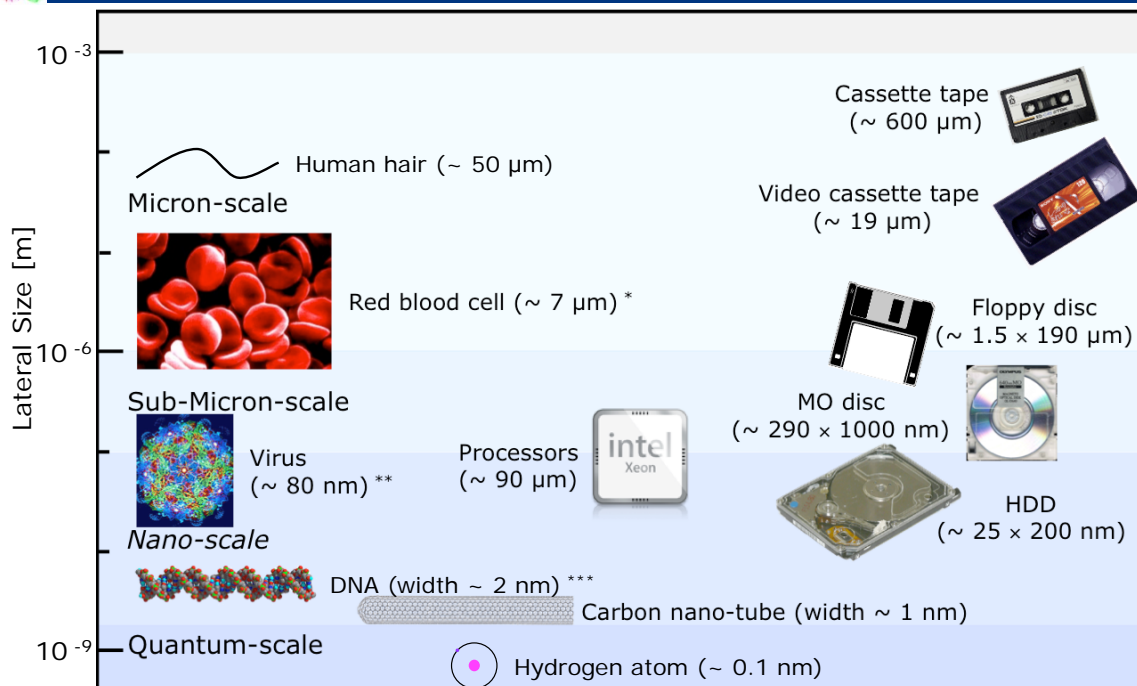
Atsufumi Hirohata

Department of Electronics

THE UNIVERSITY of York



Go into Nano-Scale



* http://www.esa.int/esaKIDSen/SEMOC68LURE_LifeInSpace_1.html

** <http://www.guardian.co.uk/pictures/image/0,8543,-11404142447,00.html>

*** <http://www.wired.com/medtech/health/news/2003/02/57674>



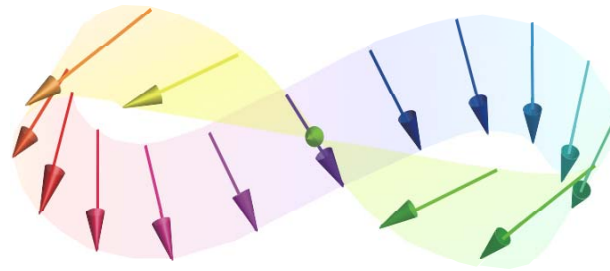
Nanotechnology

Materials Science

- States of matters
- Crystalline structures

Electronics

- Electron transport
- Thermal conductivity
- Semiconductor
- Ferromagnet



Physics

- Theory (quantum mechanics, thermodynamics, electromagnetism)



Contents of Introductory Nanotechnology

First half of the course : Atsufumi Hirohata (ah566@ohm.york.ac.uk, P/Z 023)

Basic condensed matter physics (Weeks 2-5, Tues. & Weds. 12:15-13:15)

1. Why *solids* are *solid* ?
2. What is the *most common atom* on the earth ?
3. How does an electron travel in a material ?
4. How does lattices vibrate thermally ?
5. What is a *semi-conductor* ?
6. How does an electron tunnel through a barrier ?
7. Why does a magnet attract / retract ?
8. What happens at interfaces ?

Second half of the course : Yongbing Xu (yx2@ohm.york.ac.uk, D 016)

Nano-fabrication and device applications (Weeks 6-10)

Workshops : Ian Will (iwg@ohm.york.ac.uk, D 018)

Nanotechnology Teaching Laboratory (P/Z 011)

(Weeks 4, 6, 9 and 10, Thus. 9:15-10:15)



References

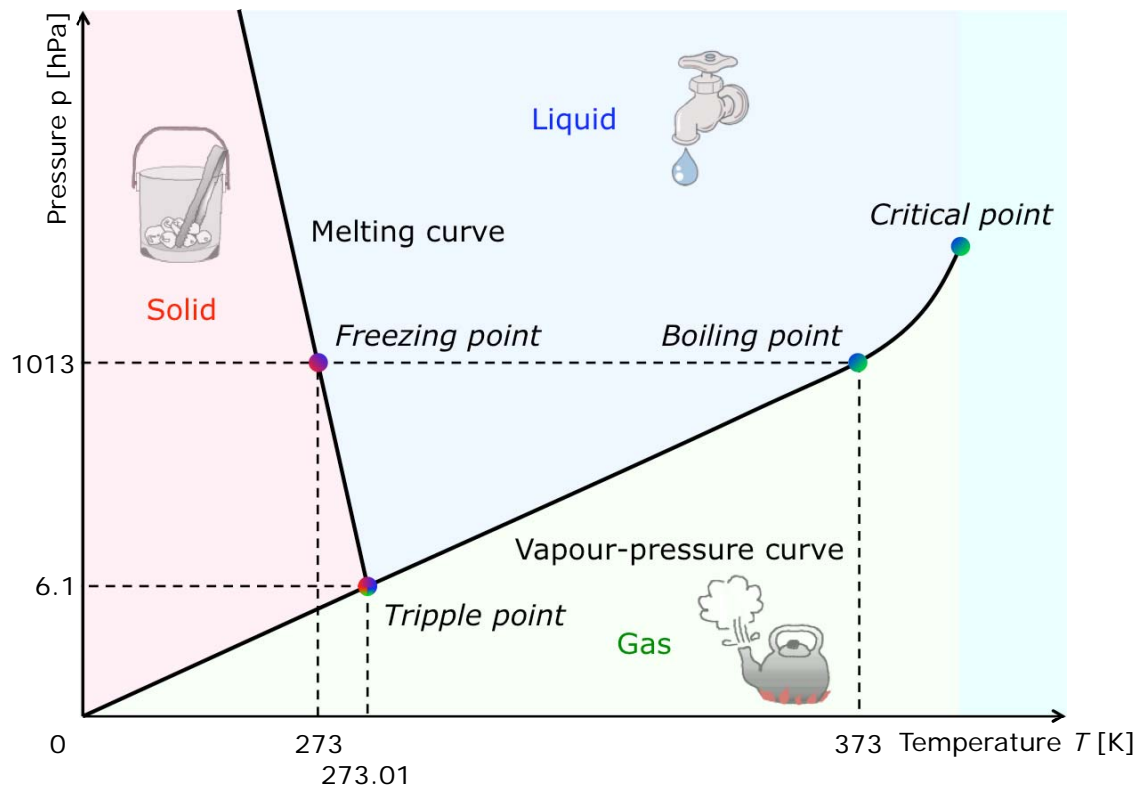
General textbooks in condensed matter physics :

- C. Kittel, *Introduction to Solid State Physics* (John Wiley, New York, 1986).
covers all the topics in the field but very general.
- N. W. Ashcroft and N. D. Mermin, *Solid State Physics* (Thomson, London, 1976).
explains details in theoretical models with many questions.
- M. P. Marder, *Condensed Matter Physics* (John-Wiley, New York, 2000).
covers all the topics in the field in general.
- H. Ibach and H. Lüth, *Solid-State Physics* (Springer, Berlin, 2003).
describes basic properties of materials.
- B. G. Streetman and S. Banerjee, *Solid State Electronics Devices* (Prentice Hall, New Jersey, 2005).
specialises in semiconductor devices.

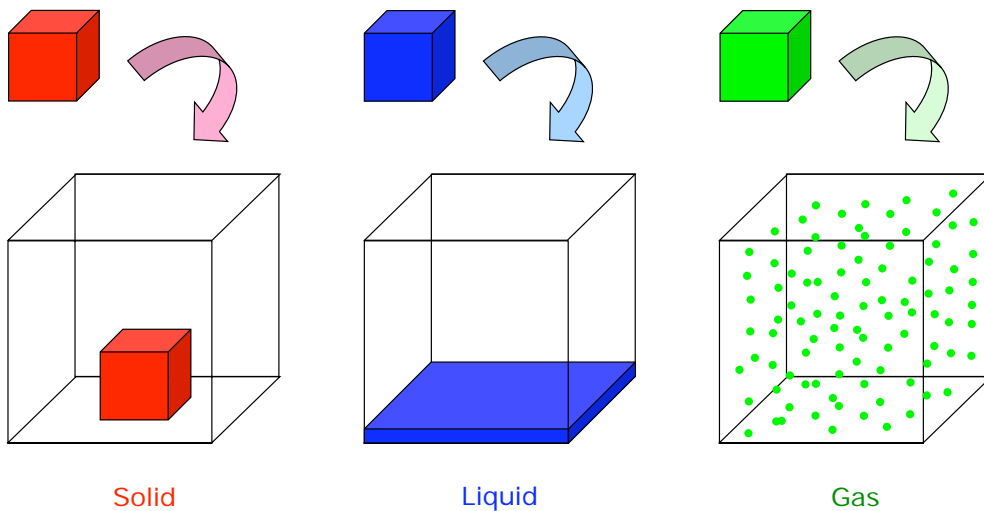
Why *Solids* Are *Solid* ?

- Solid / liquid / gas
- Crystal / amorphous
- Density / time-scale
- *Condensed* matter
 - Atomic force
 - Bonding types
- Crystalline structures

Phase Diagram of Water



States of Matter



- Constant shape
- Constant volume

- Shape of container
- Constant volume

- Shape of container
- Volume of container

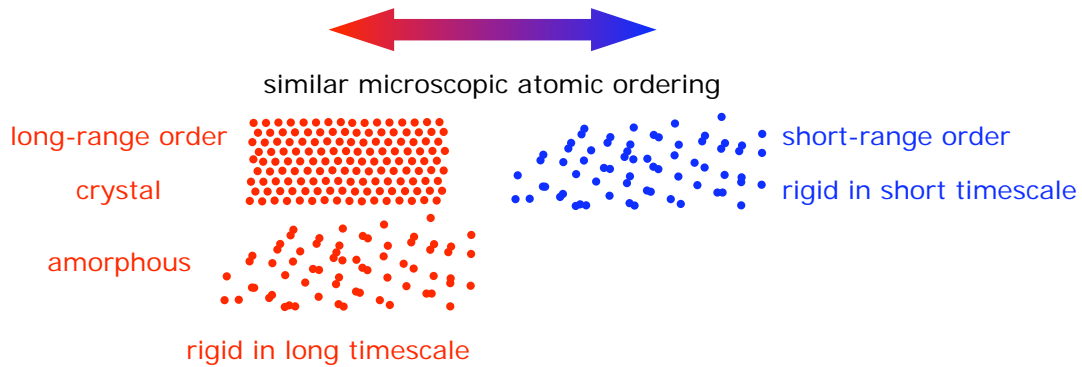


Densities of Three States

Densities of both solids, liquids and gases :

Atoms	Solid		Liquid		Gas	
	T [K]	d [g/cm ³]	T [K]	d [g/cm ³]	T [K]	d [g/cm ³]
Ar	0	1.809	90	1.38	273	0.001784
Kr	0	3.28	127	2.155	273	0.003739
O	0	1.568	90.5	1.118	273	0.001429
H	13.1	0.0763	20.5	0.0710	273	0.0000898

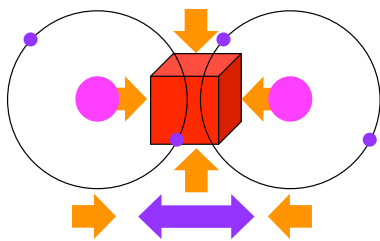
difference of 3 orders of magnitude



Condensed Matter - Solid and Liquid

For both **solid** and **liquid**,

volume change by compression is *very small* as compared with **gas**.



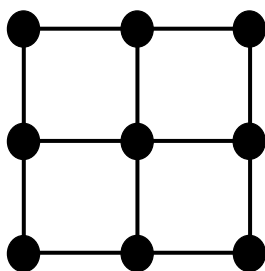
2 Electrons cannot occupy the same states.

← Pauli's exclusion principle

→ Repulsive force

→ Condensed matter

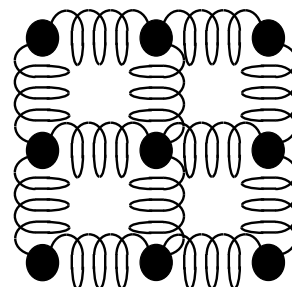
Rigid model :



rigid body :

- ideal solid body
- no deformation

In reality :

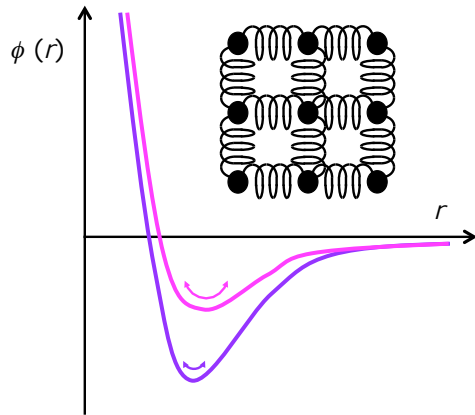


atomic force



Solidness and Thermal Fluctuation

Curvature at equilibrium points in atomic force :



Soft solid :

- Curvature of $\phi(r)$ is small.
- Spring constant between atoms is small.
- Frequency $\omega = (\alpha / m)^{1/2}$ is small.

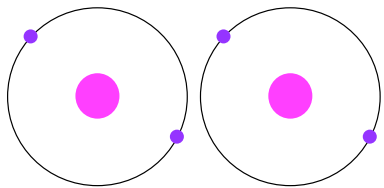
Hard solid :

- Curvature of $\phi(r)$ is large.
- Spring constant between atoms is large.
- Frequency $\omega = (\alpha / m)^{1/2}$ is large.

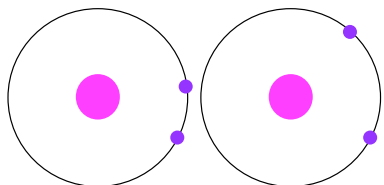


Major Crystals 1 - van der Waals Crystal

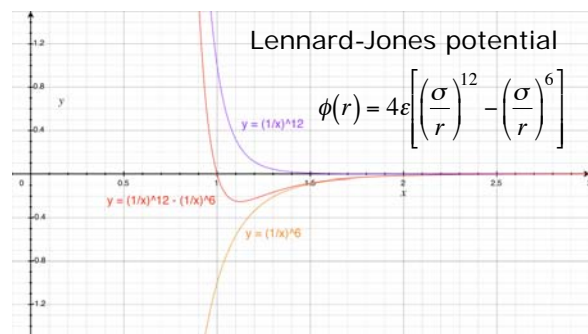
Stable closed-shell atoms :



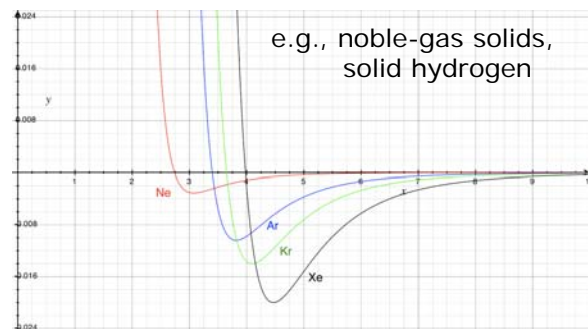
- Symmetric electron distributions
- Electrically neutral
 - No static electrical interactions



- Fluctuation induces asymmetry.
- Electric dipoles / electric fields
 - **Attractive force**



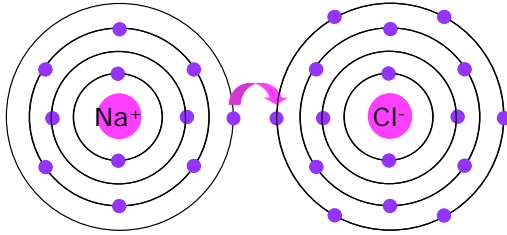
ϵ and σ : element specific parameters



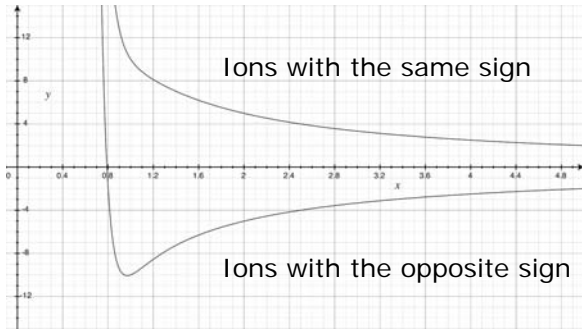


Major Crystals 2 - Ionic Crystal

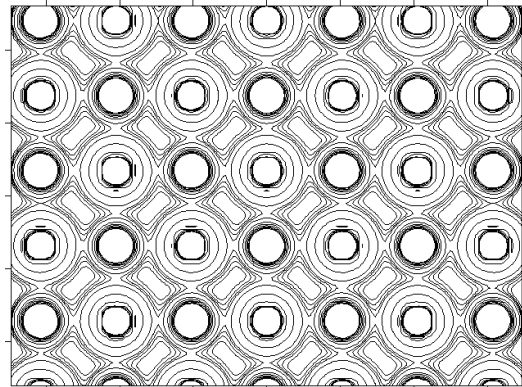
In addition to the van der Waals force, *Coulomb interaction* is taken into account :



Each atom becomes closed shell.
→ Electron distribution becomes spherical symmetric.



Electron density map :



$$\phi(r) = \frac{q_1 q_2}{4\pi\epsilon_0 r} + 4\epsilon \left[\left(\frac{\sigma}{r}\right)^{12} - \left(\frac{\sigma}{r}\right)^6 \right]$$

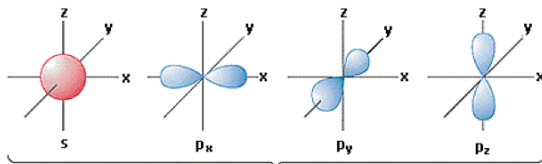
$q_{1,2}$: electron charge and ϵ_0 : permittivity

* www.geo.arizona.edu/xtal/geos306/fall05-3.htm

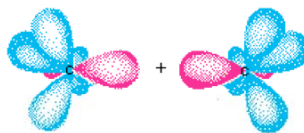


Major Crystals 3 - Covalent Crystal

Covalent bond formation in C (2s)² (2p)² atom :



sp³ hybridisation



Covalent bond

Opposite spin-polarised electrons

The strongest bonding in crystals.

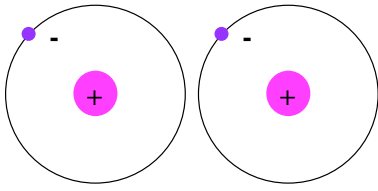
Ideal case : diamond !

* <http://www.goiit.com/posts/list/community-shell-resonance-atomic-orbitals-only-for-iiit-6685.htm>



Major Crystals 4 - Metallic Crystal

Conduction (Free) electrons in a metal :



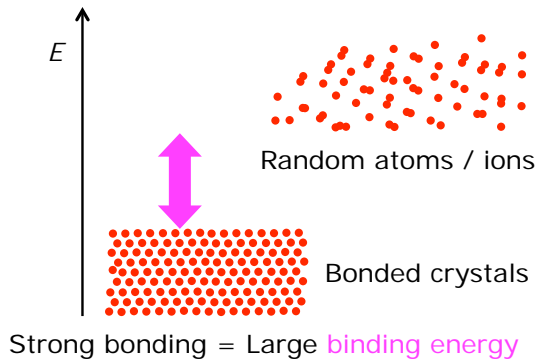
Outer-shell electrons can move freely in the crystal.

- Coulomb interaction bonds the atoms.
- Electron conductivity
- Thermal conductivity



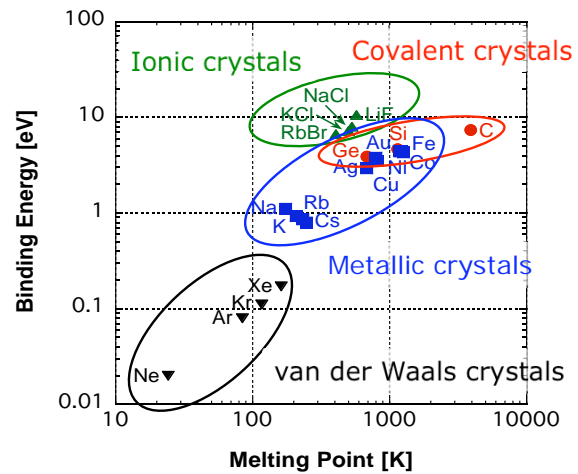
Why Do Matters Condense ?

Binding energy :



- van der Waals force : very weak
→ very small binding energy

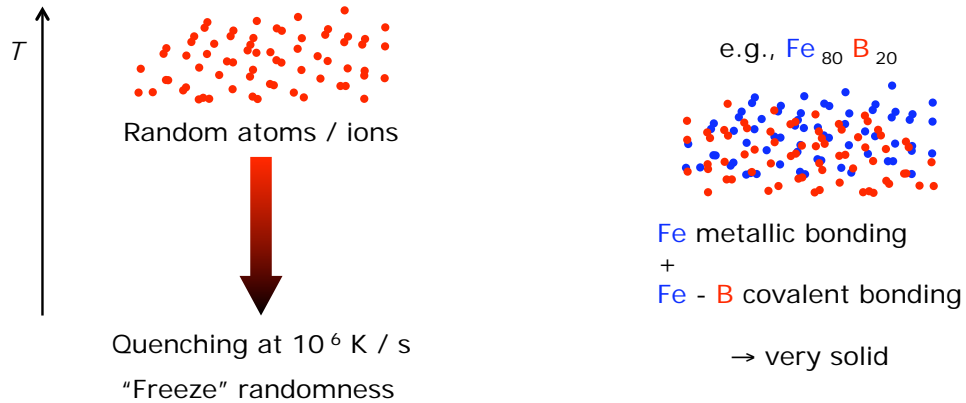
- Bonding for ionic / covalent crystals : strong
→ very large binding energy (~10 eV)





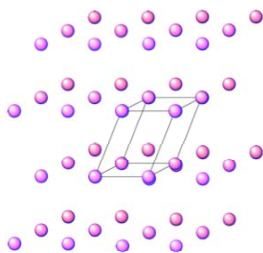
Other Solid Material - Amorphous / Ceramics

Amorphous state can be achieved by quenching :

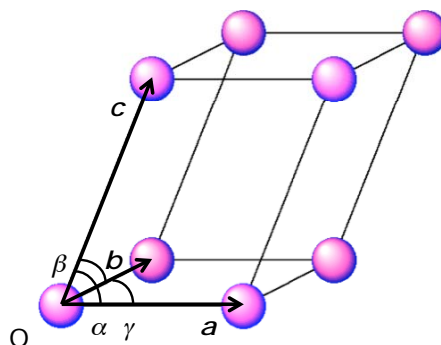


Crystalline Structures

Unit cell in a crystal :



Smallest possible volume for spatial arrangement of atoms



a , b and c : crystal axes

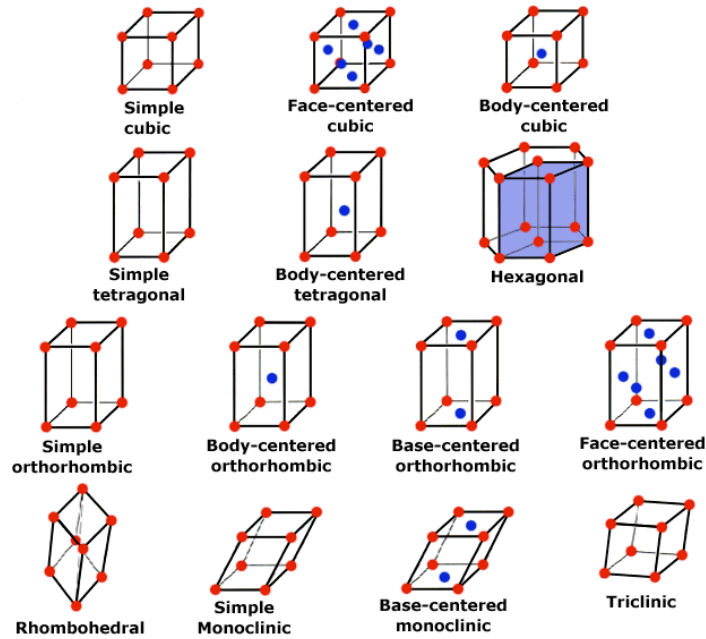
$|a|$, $|b|$, $|c|$, α , β and γ : lattice constants

Positions of atoms : lattice points



14 Basic Crystalline Structures

Bravais lattices :

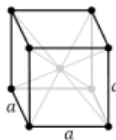


<http://www.seas.upenn.edu/~chem101/sschem/solidstatechem.html>



Major Crystalline Structures

Body-centred cubic (bcc) :

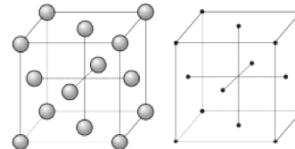


Nearest neighbour atoms :

Atoms in a unit cell :

Filling rate :

Face-centred cubic (fcc) :

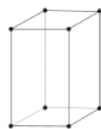
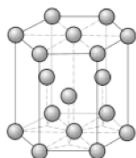


Nearest neighbour atoms :

Atoms in a unit cell :

Filling rate :

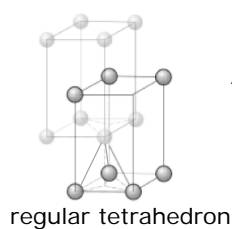
Hexagonal close-packed (hcp) structure :



Nearest neighbour atoms :

Atoms in a unit cell :

Filling rate :





Miller Indices

A direction in a unit cell :

a , b and c : axes of coordinate

a , b and c : lattice constants

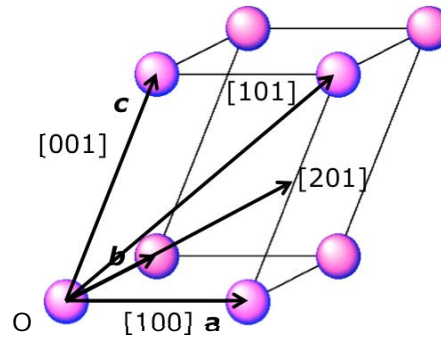
u , v and w : coordinates (\bar{u} : negative)

a/u b/v c/w : ratios \rightarrow smallest integers

$[x\ y\ z]$: lattice directions

$\langle x\ y\ z \rangle$: directions of a form

$\langle 100 \rangle = [100], [010], [001], \dots$

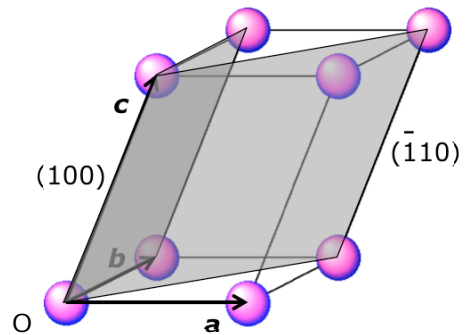


A plane in a unit cell (lattice plane) :

$(h\ k\ l)$: Miller indices

$\{h\ k\ l\}$: planes of a form

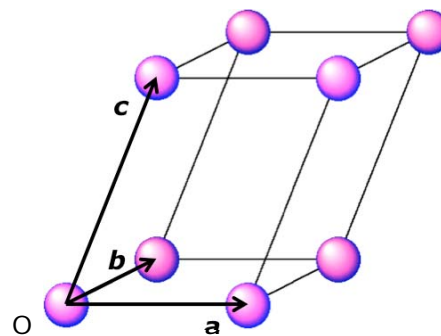
$\{100\} = (100), (010), (001), \dots$



Questions - Miller Indices

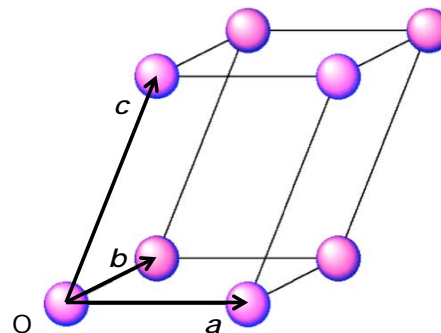
1. Indicate the following lattice orientations :

$[102]$, $[210]$ and $[311]$



2. Indicate the following lattice planes :

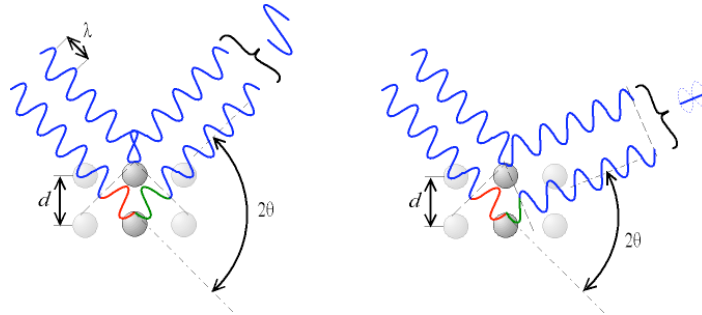
(102) , (110) and (111)



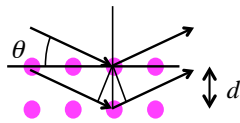


Structural Analysis

When X-ray is introduced onto a crystal :



Bragg's law :



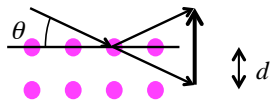
Path difference should satisfy $n\lambda$ for constructive interference :

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



Reciprocal Lattice

Reciprocal lattice vector :



- Orientation : perpendicular to the lattice plane
- Magnitude : $2\pi / a \times n$

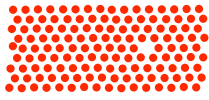
Reciprocal lattice :

- Interplane distance : $1 / a$
- Real space \rightarrow Fourier transformation \rightarrow reciprocal space
- Position \rightarrow Fourier transformation \rightarrow wave vector

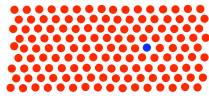


Lattice Defects

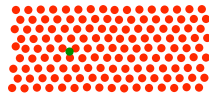
Point defects :



atomic vacancy



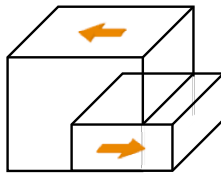
substitution



insertion

1 ~ a few atoms

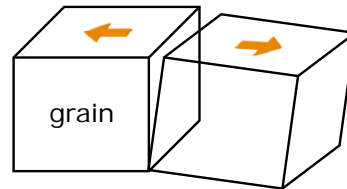
Line defect :



dislocation

slip plane

Plane defect :



grain

grain boundary