Crystal structure

Review: Molecules I

Every property of a molecule can be calculated using quantum mechanics.

$$H_{\mathrm{mp}} = -\sum_i \frac{\hbar^2}{2m_e}\nabla_i^2 - \sum_a \frac{\hbar^2}{2m_a}\nabla_a^2 - \sum_{a,i} \frac{Z_a e^2}{4\pi\epsilon_0|\vec{r}_i - \vec{r}_a|} + \sum_{i<j} \frac{e^2}{4\pi\epsilon_0|\vec{r}_i - \vec{r}_j|} + \sum_{a<b} \frac{Z_a Z_b e^2}{4\pi\epsilon_0|\vec{r}_a - \vec{r}_b|}$$

Make some approximations.

$$H_{\mathrm{red}} = -\sum_i \frac{\hbar^2}{2m_e}\nabla_i^2 - \cancel{\sum_a \frac{\hbar^2}{2m_a}\nabla_a^2} - \sum_{a,i} \frac{Z_a e^2}{4\pi\epsilon_0|\vec{r}_i - \vec{r}_a|} + \cancel{\sum_{i<j} \frac{e^2}{4\pi\epsilon_0|\vec{r}_i - \vec{r}_j|}} + \sum_{a<b} \frac{Z_a Z_b e^2}{4\pi\epsilon_0|\vec{r}_a - \vec{r}_b|}.$$

$$H_{\mathrm{red}}(\vec{r}_1, \vec{r}_1, \cdots, \vec{r}_N) = H_{\mathrm{mo}}(\vec{r}_1) + H_{\mathrm{mo}}(\vec{r}_2) + \cdots + H_{\mathrm{mo}}(\vec{r}_N).$$

$$\Psi_{\mathrm{red}}(\vec{r}_1, \vec{r}_1, \cdots, \vec{r}_N) = |\psi_{\mathrm{mo}}(\vec{r}_1)\psi_{\mathrm{mo}}(\vec{r}_2)\cdots\psi_{\mathrm{mo}}(\vec{r}_N)\rangle.$$

Molecular orbital Hamiltonian: $$H_{\mathrm{mo}} = -\frac{\hbar^2}{2m_e}\nabla^2 - \sum_a \frac{Z_a e^2}{4\pi\epsilon_0|\vec{r} - \vec{r}_a|}.$$

The exact solution to H_{red} can be constructed from the solutions to H_{mo}.

Review: Molecules II

$$H_{\mathrm{mo}} = -\frac{\hbar^2}{2m_e}\nabla^2 - \sum_a \frac{Z_a e^2}{4\pi\epsilon_0|\vec{r}-\vec{r}_a|}\,.$$

The molecular orbitals are constructed using LCAO.

$$\psi_{\mathrm{mo}}(\vec{r}) = \sum_a \sum_{ao} c_{ao,a}\phi_{ao}^{Z_a}(\vec{r}-\vec{r}_a).$$

Substitute into $H_{\mathrm{mo}}\psi_{\mathrm{mo}} = E\psi_{\mathrm{mo}}$, construct the Roothaan equations.

The many electron wavefunction is constructed as a Slater determinant.

$$\Psi(\vec{r}_1,\vec{r}_2,\cdots,\vec{r}_N) \approx |\psi_{\mathrm{mo1}}\uparrow(\vec{r}_1),\psi_{\mathrm{mo2}}\uparrow(\vec{r}_2),\cdots,\psi_{\mathrm{moN}}\uparrow(\vec{r}_N)\rangle.$$

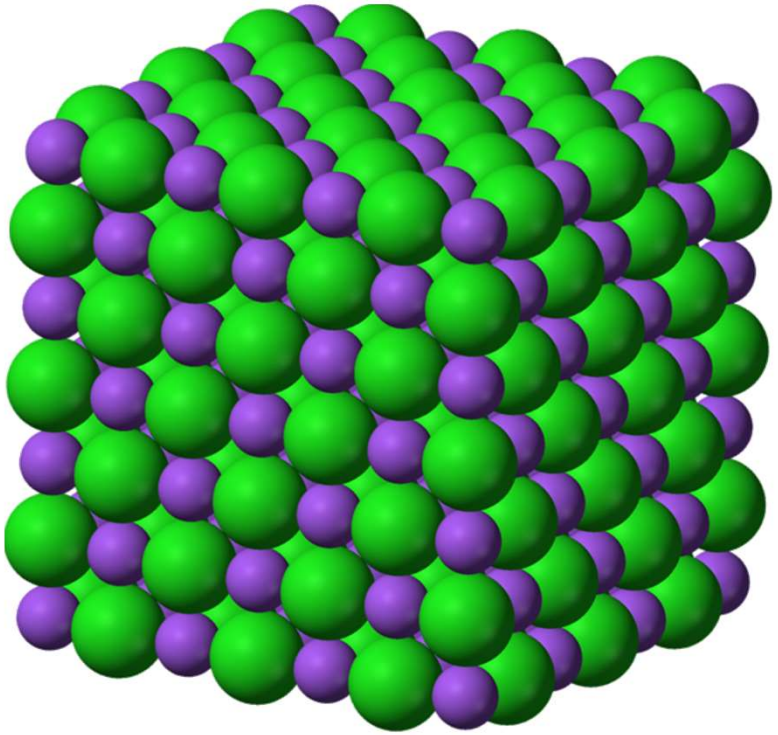
This is an exact solution to H_{red} and an approximate solution to H_{mp}.

The energy is calculated including the electron-electron interactions.

$$E = \frac{\langle\Psi|H_{mp}|\Psi\rangle}{\langle\Psi|\Psi\rangle}$$

Crystal structure

A crystal is a three dimensional periodic arrangement of atoms.



7 Crystal Systems

triclinic: a ≠ b ≠ c and $\alpha \neq \beta \neq \gamma \neq 90°$

monoclinic: a ≠ b ≠ c and $\alpha \neq 90° \ \beta = \gamma = 90°$

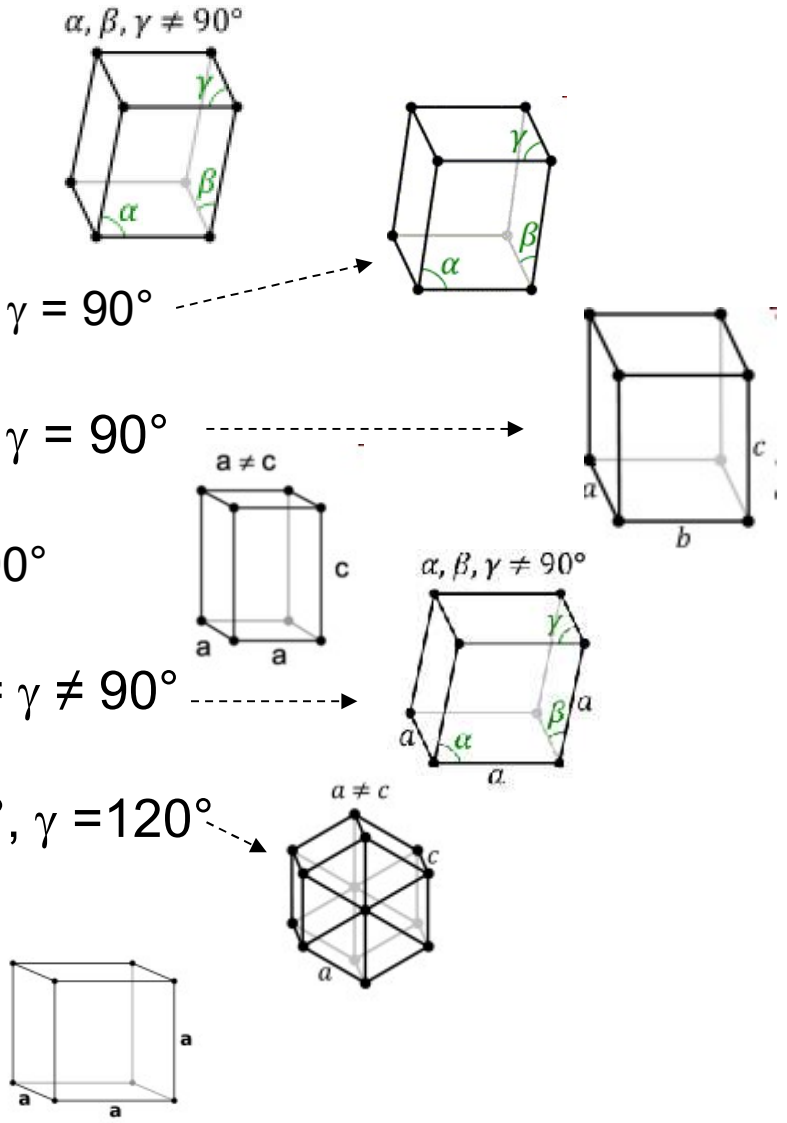
orthorhombic: a ≠ b ≠ c and $\alpha = \beta = \gamma = 90°$

tetragonal: a = b ≠ c and $\alpha = \beta = \gamma = 90°$

rhombohedral: a = b = c and $\alpha \neq \beta \neq \gamma \neq 90°$

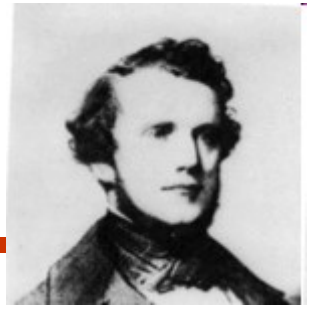
hexagonal: a = b ≠ c and $\alpha = \beta = 90°, \gamma = 120°$

cubic a = b = c and $\alpha = \beta = \gamma = 90°$

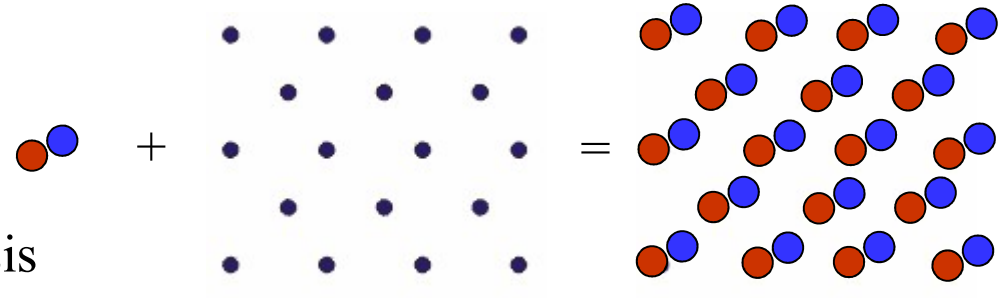


α is the angle between b and c

Bravais lattice



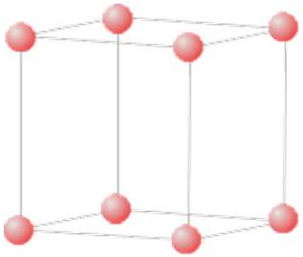
Auguste Bravais



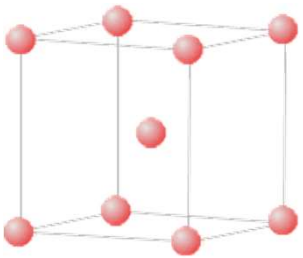
basis

Bravais lattice

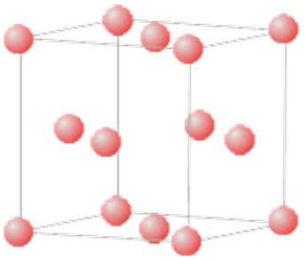
Crystal



simple cubic

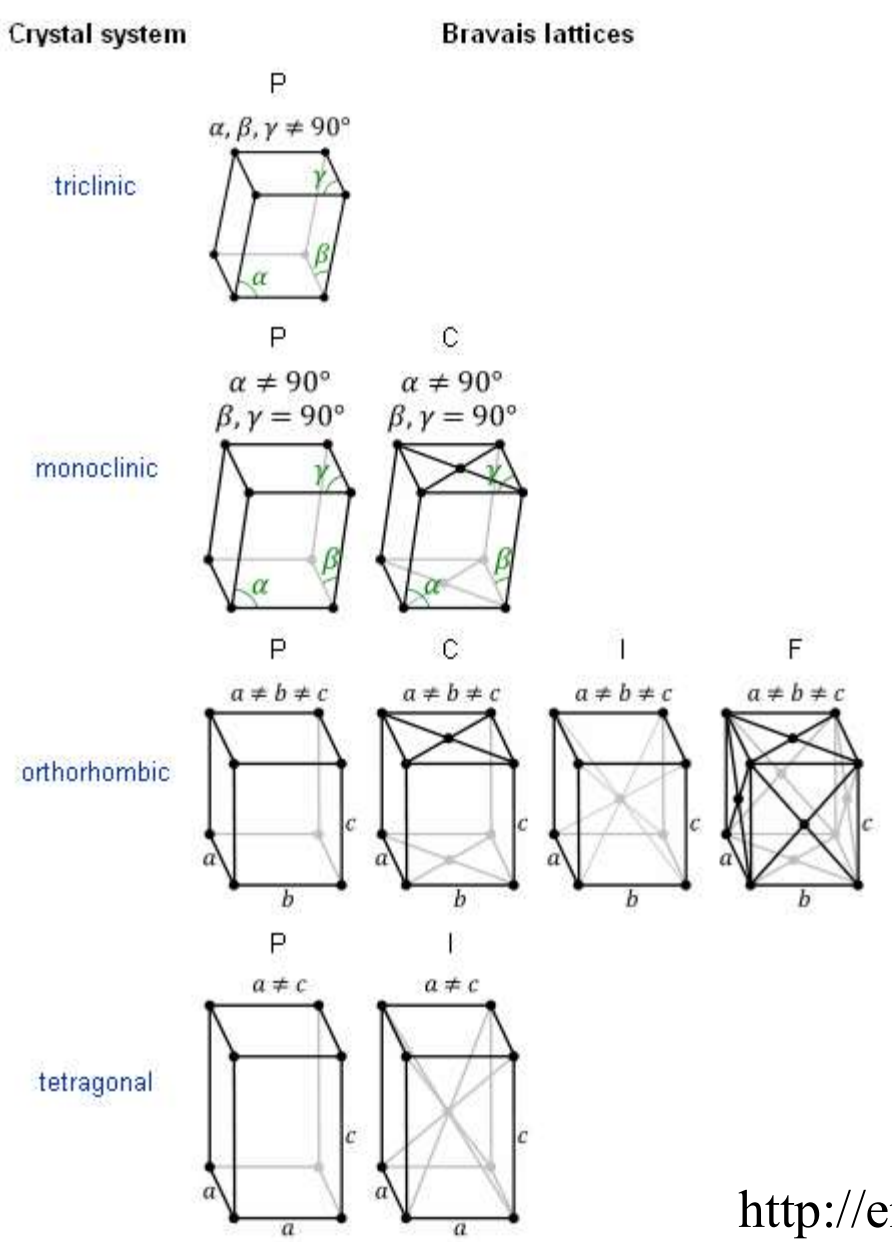


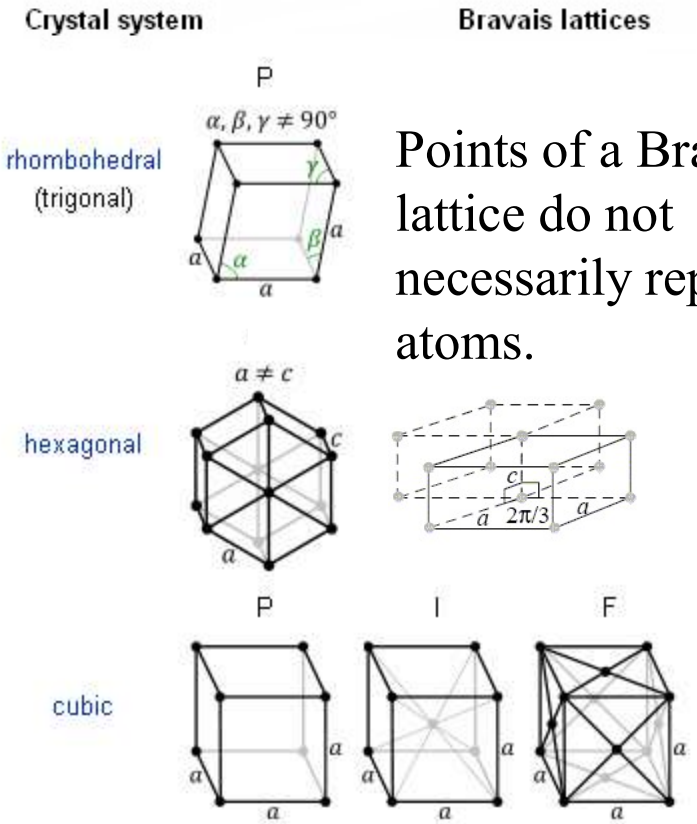
body centered cubic, bcc



face centered cubic, fcc

14 Bravais lattices





Points of a Bravais lattice do not necessarily represent atoms.

P … primitive
I … body centered
F … face centered
C … centered

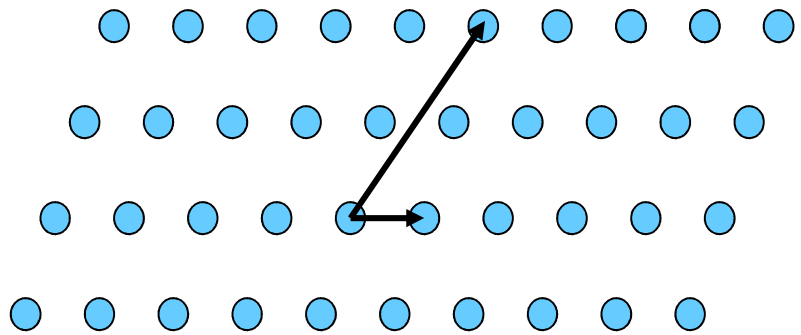
http://en.wikipedia.org/wiki/Bravais_lattice

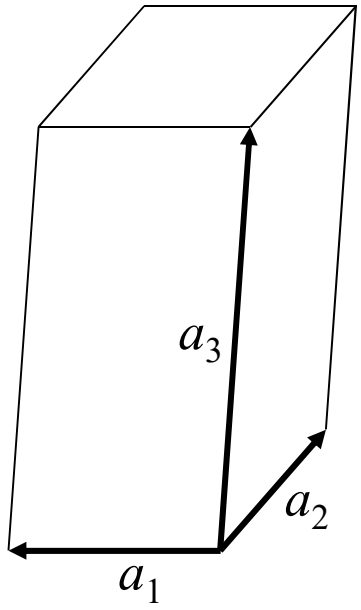
Primitive lattice vectors

Every point of a Bravais lattice can be reached from another point on the lattice by a translation vector

Translation vector

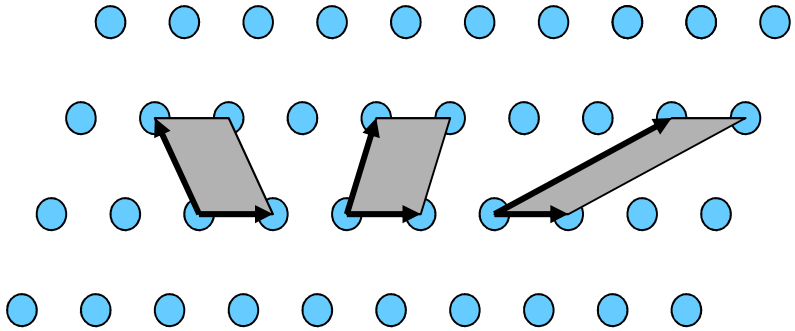
$$\vec{T} = n_1\vec{a}_1 + n_2\vec{a}_2 + n_3\vec{a}_3 \qquad n_1, n_2, n_3 = \cdots -2, -1, 0, 1, 2, \cdots$$



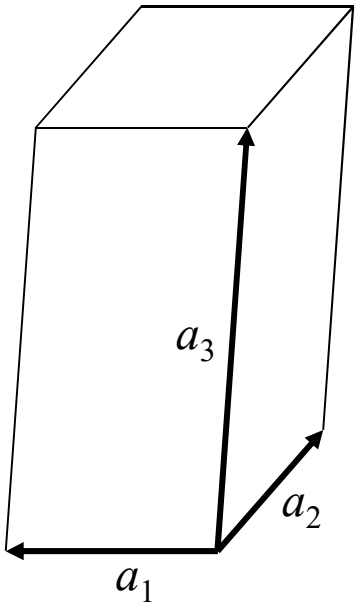


Primitive lattice vectors

Primitive Unit Cell



There is more than one choice for a primitive unit cell



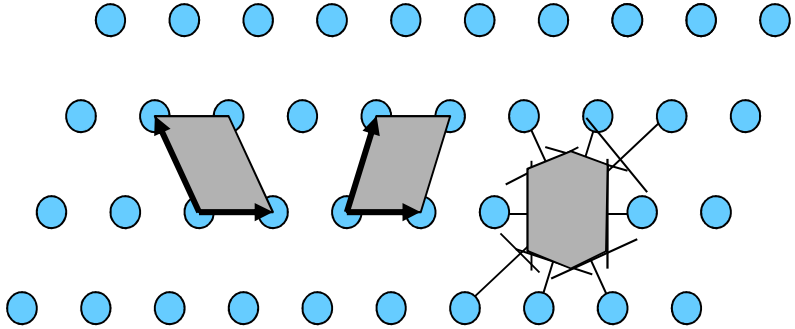
volume of a unit cell =

$$|\vec{a}_1 \cdot (\vec{a}_2 \times \vec{a}_3)|$$

$$\vec{T} = n_1\vec{a}_1 + n_2\vec{a}_2 + n_3\vec{a}_3 \qquad n_1, n_2, n_3 = \cdots -2, -1, 0, 1, 2, \cdots$$

Unit Cells

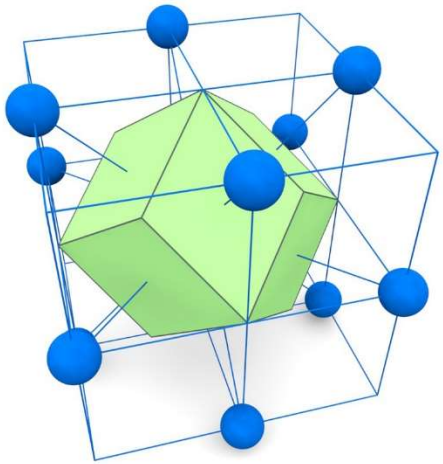
There is more than one choice for a primitive unit cell



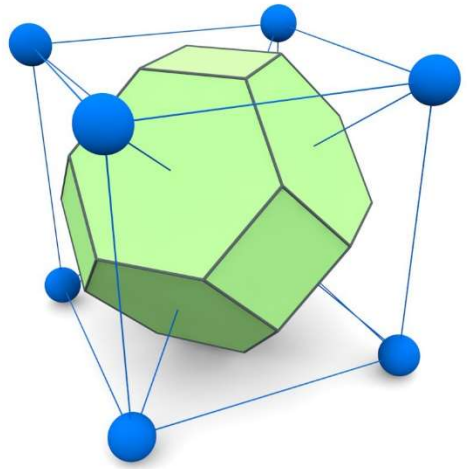
Eugene Wigner

Frederick Seitz

Wigner-Seitz primitive unit cell



fcc



bcc

Wigner-Seitz cells

The set of planes perpendicular to a vector $A_x\hat{x} + A_y\hat{y} + A_z\hat{z}$ is,

$$A_x x + A_y y + A_z z = C,$$

where C is any constant. If a point (x_0, y_0, z_0) on the plane is known, C can be calculated,

$$C = A_x x_0 + A_y y_0 + A_z z_0.$$

The app below will solve 3 linear equations for three unknowns. (It determines the point where three planes intersect.)

7	$x+$	3	$y+$	2	$z =$	6
5	$x+$	9	$y+$	4	$z =$	6
2	$x+$	1	$y+$	8	$z =$	2

solve

https://lampx.tugraz.at/~hadley/ss1/bzones/drawing_WS.php

Drawing Wigner-Seitz Cells

The form below takes the primitive lattice vectors in real space as input and calculates the Bravais lattice vectors $\vec{R}_{hkl}$, the planes (hkl) that form the Wigner-Seitz cell boundaries, and the corners of the Wigner-Seitz cell.

Primitive lattice vectors:

$\vec{a}_1 =$ 3 $\hat{x}+$ 0 $\hat{y}+$ 0 $\hat{z}$ [Å]
$\vec{a}_2 =$ 0 $\hat{x}+$ 3 $\hat{y}+$ 0 $\hat{z}$ [Å]
$\vec{a}_3 =$ 0 $\hat{x}+$ 0 $\hat{y}+$ 3 $\hat{z}$ [Å]

submit
sc fcc bcc hex

A boundary of the Wigner-Seitz cell is a plane normal to $\vec{R}_{hkl}$, that passes through the point $\frac{\vec{R}_{hkl}}{2}$. For the planes that make up the Wigner-Seitz cell boundary, the distance from $\frac{\vec{R}_{hkl}}{2}$ to the origin is smaller than the distance from $\frac{\vec{R}_{hkl}}{2}$ to any of the other Bravais lattice vectors. By computing these distances, the planes that make up the Wigner-Seitz cell can be determined.

The Wigner-Seitz cell consists of 6 planes.

(0 0 1)
(0 0 -1)
(0 1 0)
(0 -1 0)
(1 0 0)
(-1 0 0)

The Miller indices are given in terms of the primitive lattice vectors.

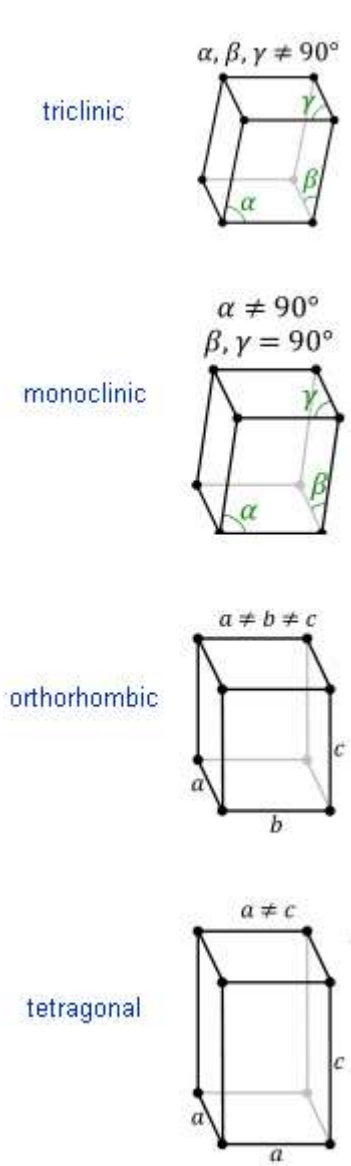
Once the planes are known, the points at the corners of the Wigner-Seitz cell can be determined by considering the intersections of the planes. The formula for the (hkl) plane is,

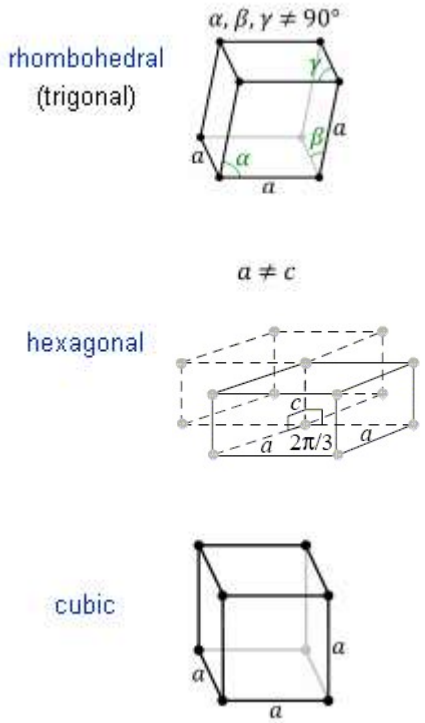
$$R_{hkl,x}k_x + R_{hkl,y}k_y + R_{hkl,z}k_z = \frac{R_{hkl,x}^2}{2} + \frac{R_{hkl,y}^2}{2} + \frac{R_{hkl,z}^2}{2}.$$

By solving the sets of linear equations, the corners can be determined.

There are 8 corners:

Conventional (crystallographic) unit cell





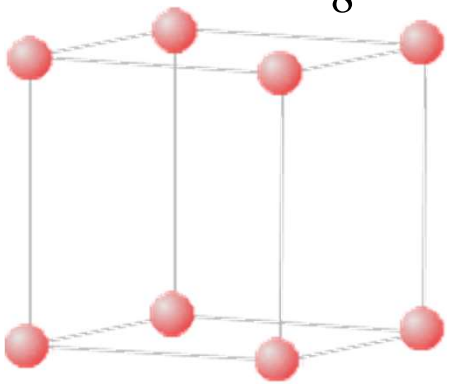
α is the angle between *b* and *c*
β is the angle between *a* and *c*
γ is the angle between *a* and *b*

6 faces, 8 corners

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

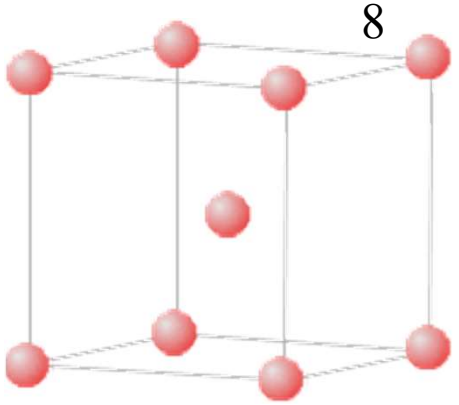
Conventional (crystalographic) unit cell

$$8 \times \frac{1}{8} = 1$$



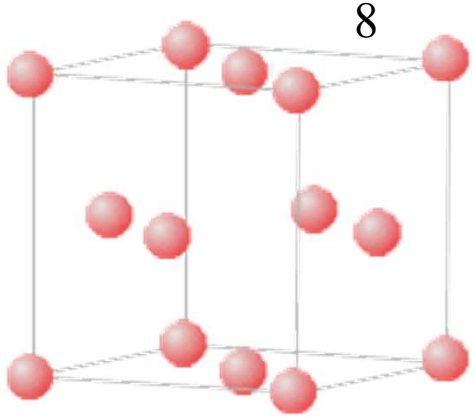
simple cubic

$$8 \times \frac{1}{8} + 1 = 2$$

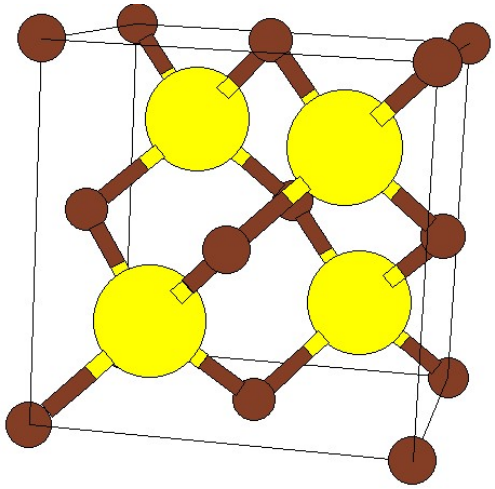


bcc

$$8 \times \frac{1}{8} + 6 \times \frac{1}{2} = 4$$

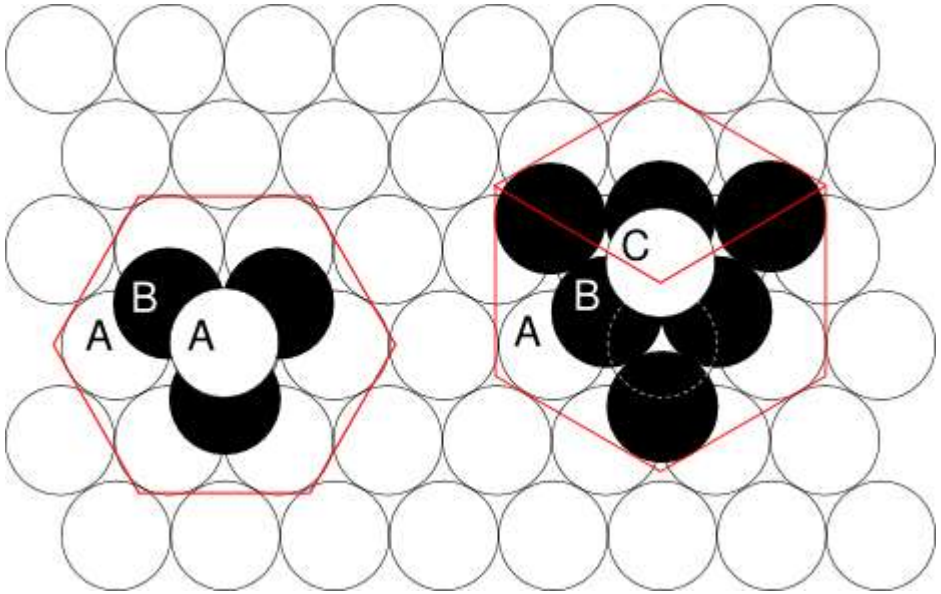


fcc

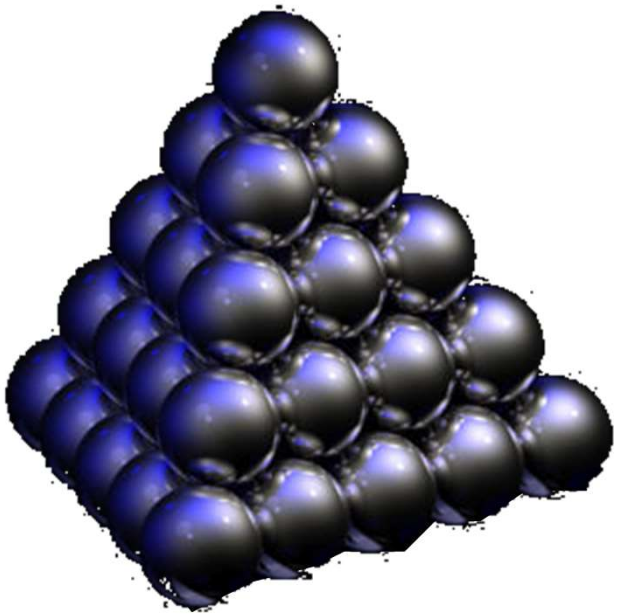


zincblende

Close packing

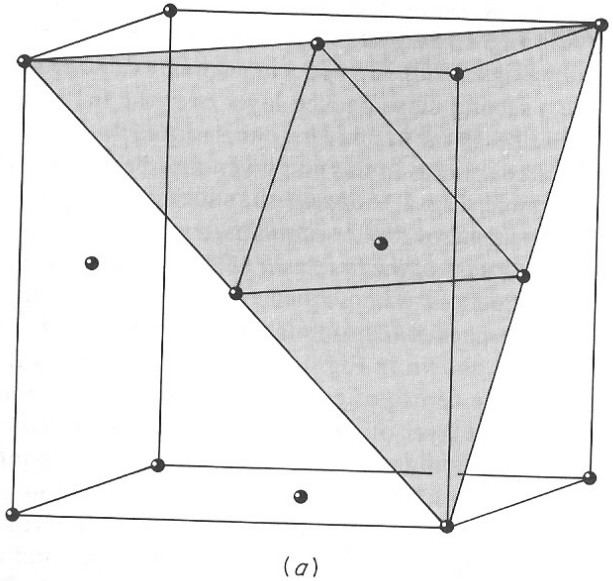


HCP FCC

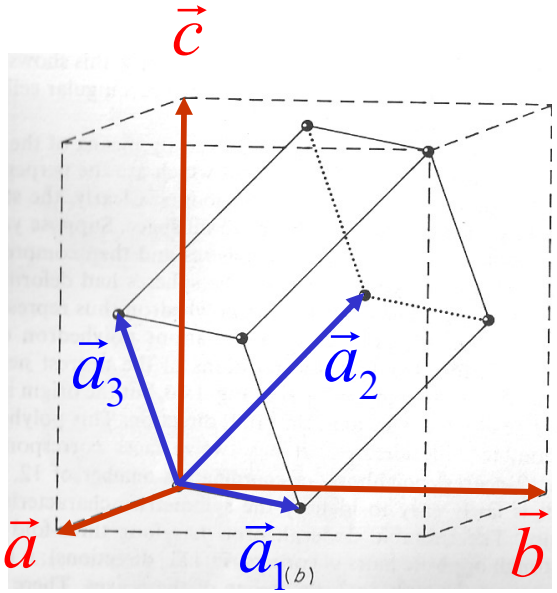


HCP = Hexagonal close pack
Hexagonal Bravais lattice with two atoms in the basis.

Fcc

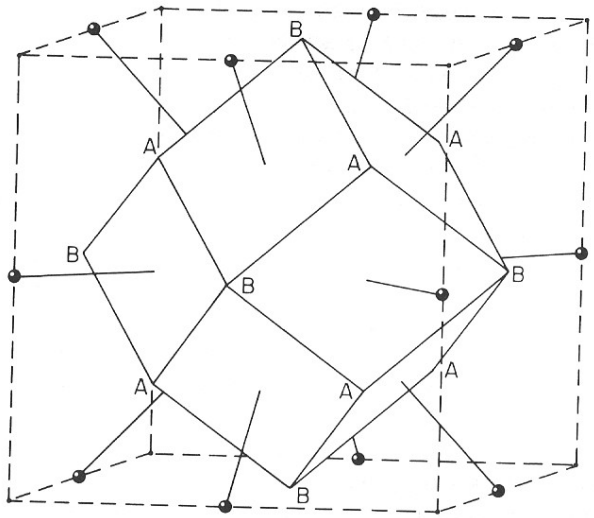


Crystalographic unit cell showing close packed plane



Crystalographic lattice vectors

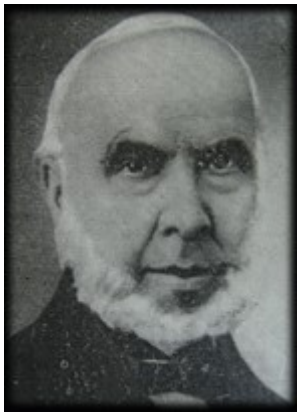
Primitive lattice vectors



Wigner-Seitz cell

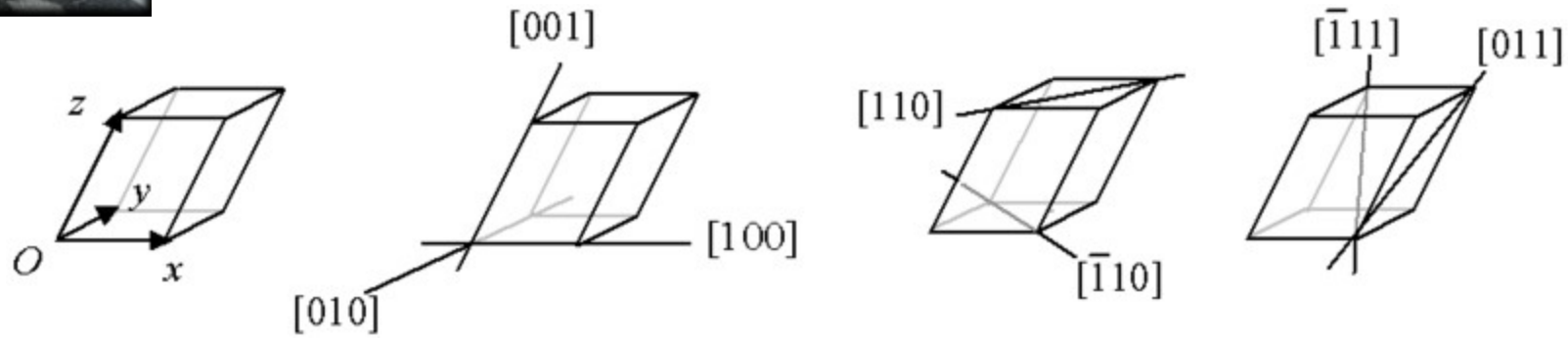
From: Hall, Solid State Physics

Miller indices: Crystal direction [*uvw*]



[*uvw*] = vector in direction $u\,\mathbf{a} + v\,\mathbf{b} + w\,\mathbf{c}$

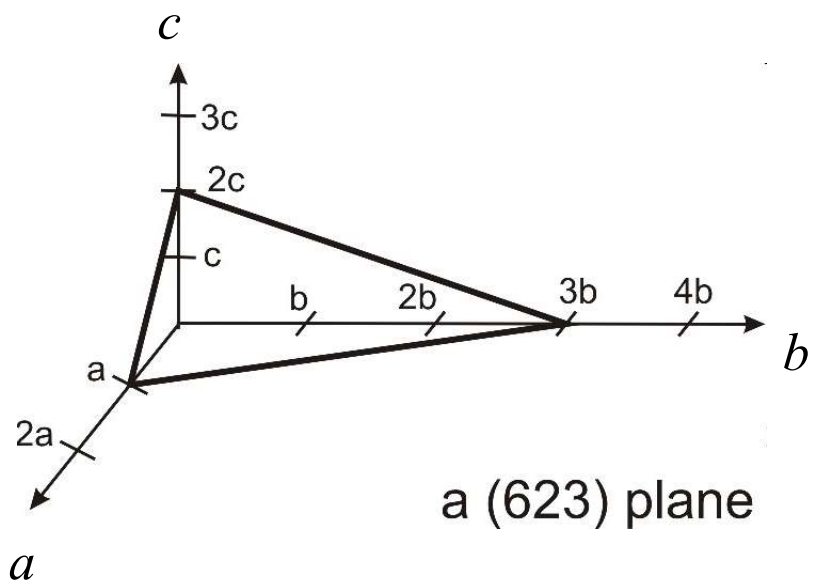
lattice vectors of the crystallographic unit cell



notation: -1 = $\bar{1}$

[ ] specific direction
< > family of equivalent directions

Miller indices: Crystal planes



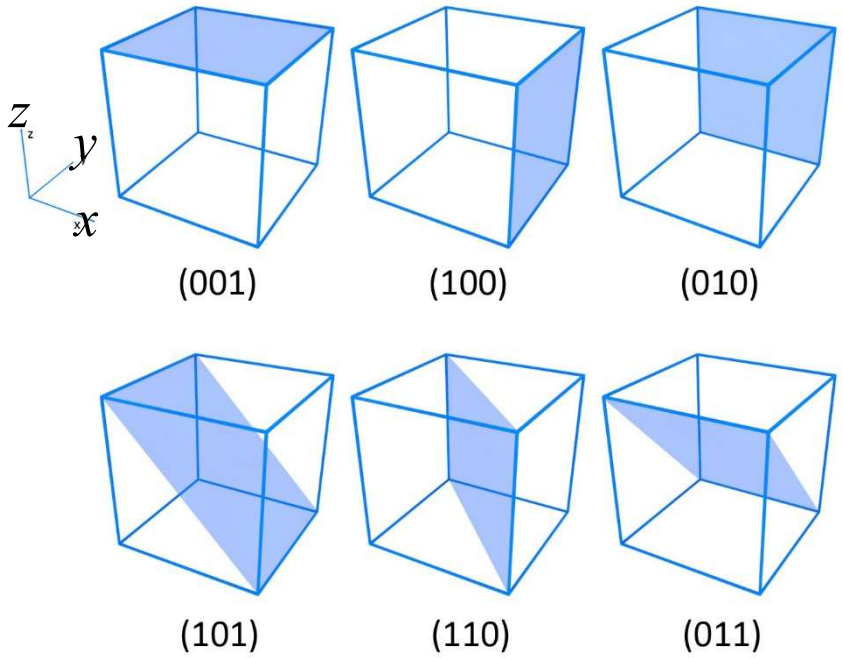
A plane with the intercepts $1/h, 1/k, 1/l$ is the (h,k,l) plane.

always use integers for h,k,l

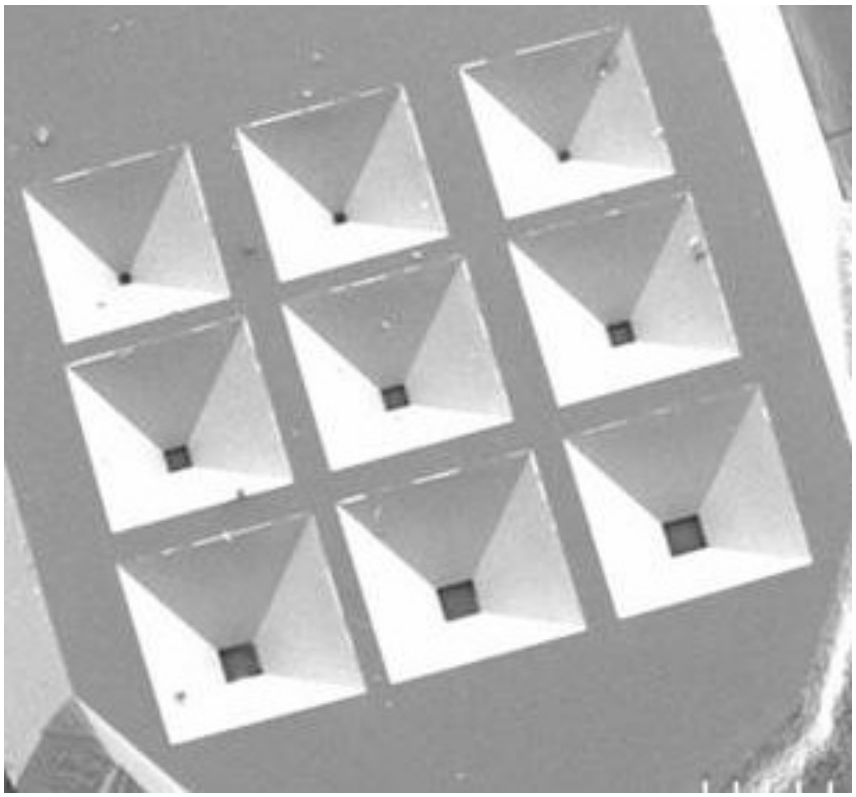
( ) specific plane

{ } family of equivalent planes

MOSFETs are made on {100} wafers



KOH etching of silicon



KOH etches Si {110} > {100} > {111}, producing a characteristic anisotropic V-etch, with sidewalls that form a 54.7° angle with the surface (35.3° from the normal).

http://www.ece.uncc.edu/research/clean_room/fabprocesses/KOH-EtchingAndDecon.pdf