2019 Fall

# Introduction to Materials Science and Engineering

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*Contents for previous class*

## *Atomic Bonding in Solids* : an attempt to fill electron shells

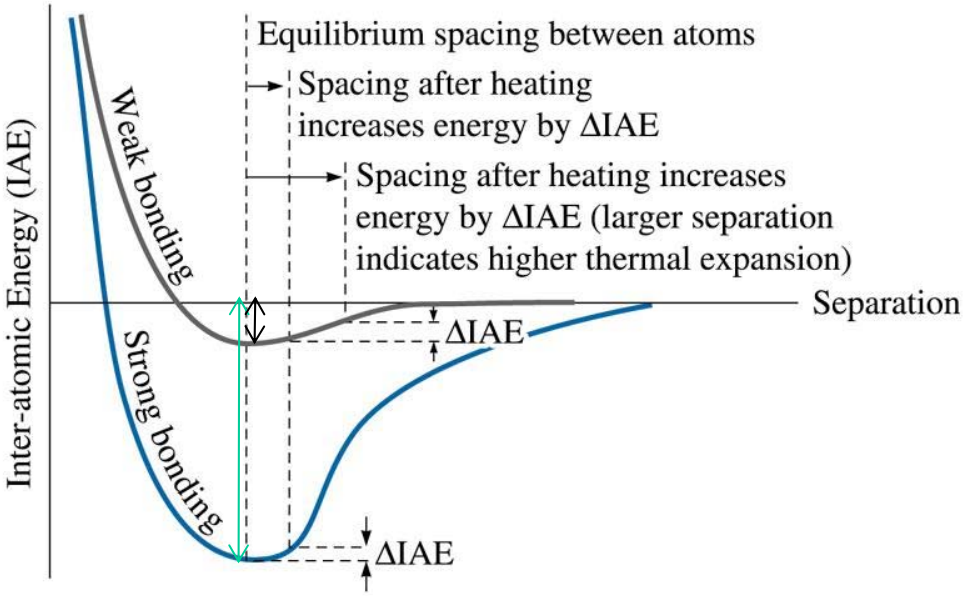
### a. Primary bonding

(1) Ionic bonds
(2) Covalent bonds
(3) Metallic bonds

### b. Secondary bonding

(1) Van der Waals
(2) Hydrogen bonding

### c. Properties From Bonding




If $E_o$ is larger,

$T_m$ (melting temp.→ Broken Bonds ), 

E (elastic modulus), ((possibly))

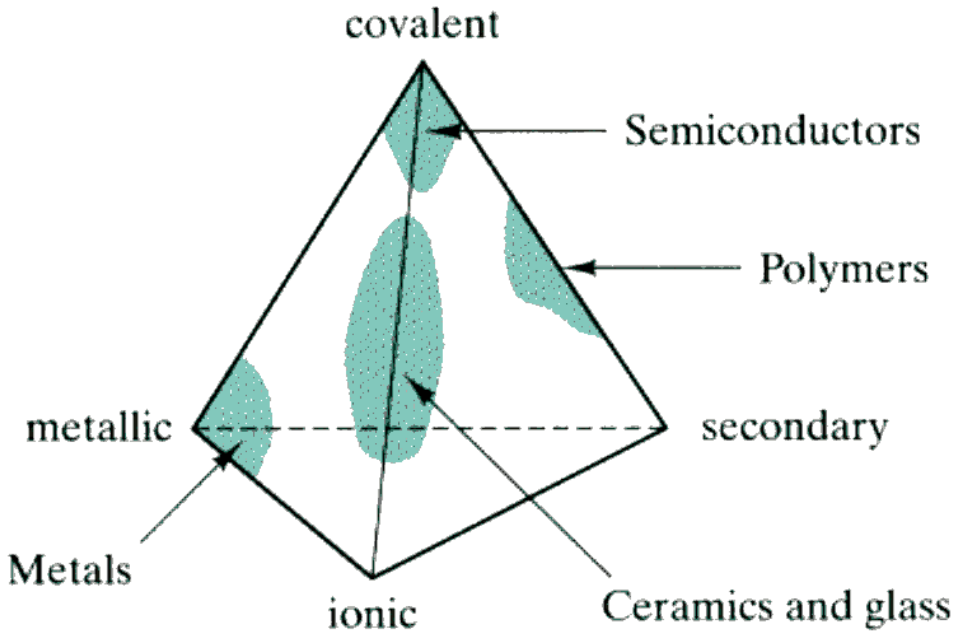
Yield strength is larger,

but $\alpha$ is smaller.
(thermal expansion coefficient)

*Contents for previous class*

# Materials-Bonding Classification

| Material type | Bonding character | Example |
|---|---|---|
| Metal | Metallic | Iron (Fe) and the ferrous alloys |
| Ceramics and glasses | Ionic/covalent | Silica ($SiO_2$): crystalline and noncrystalline |
| Polymers | Covalent and secondary | Polyethylene $+C_2H_4+_n$ |
| Semiconductors | Covalent or covalent/ionic | Silicon (Si) or cadmium sulfide (CdS) |




< 실제 많은 재료는 2개 혹은 그 이상의 결합에 혼합 >

*Contents for previous class*

# Summary: Properties from Bonds

## Ceramics

(Ionic & covalent bonding):

Large bond energy
- large $T_m$
- large $E$
- small $\alpha$

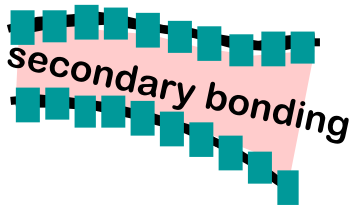
## Metals

(Metallic bonding):

Variable bond energy
- moderate $T_m$
- moderate $E$
- moderate $\alpha$

## Polymers

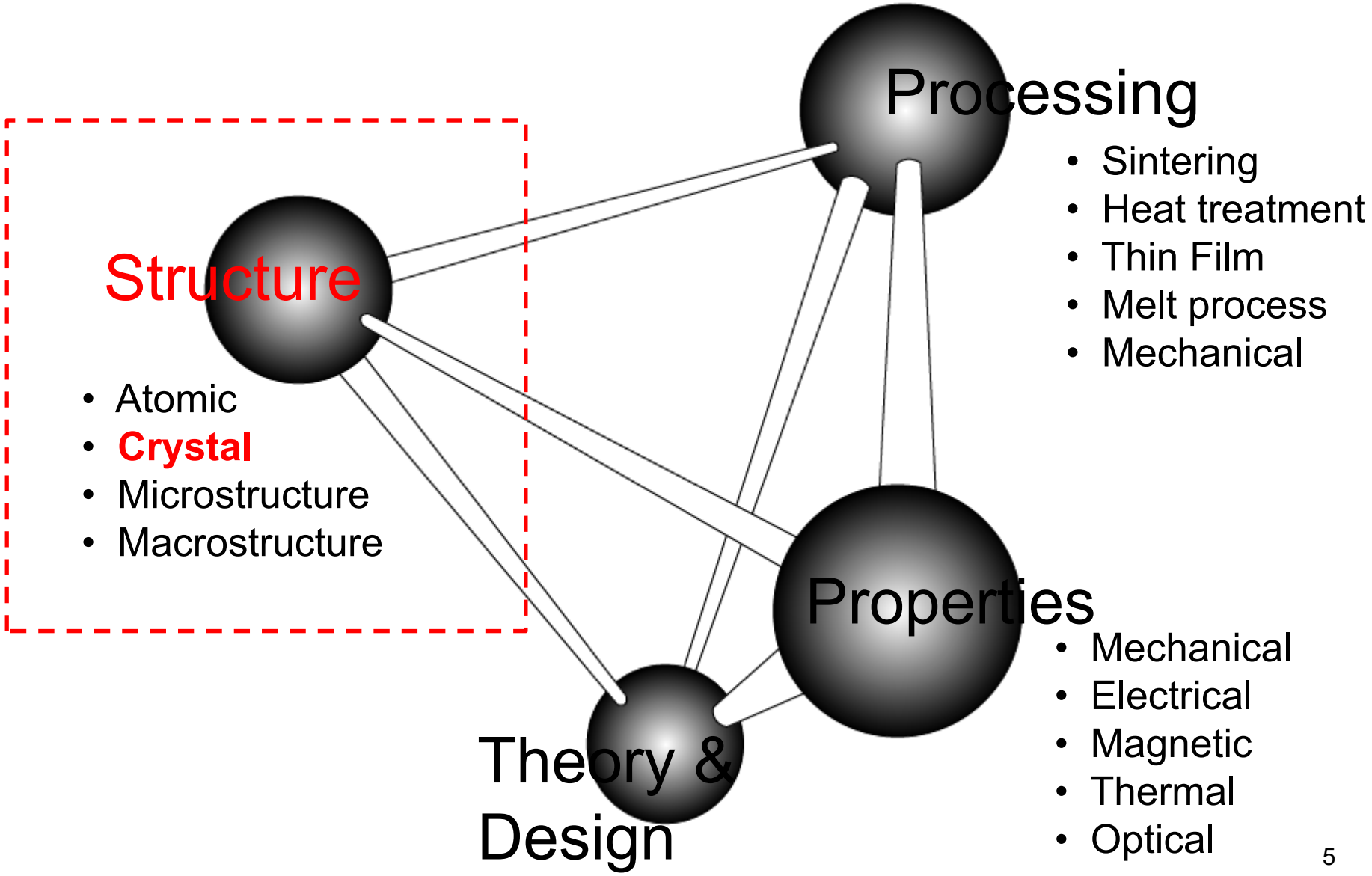
(Covalent & Secondary):




Directional Properties

Secondary bonding dominates
- small $T_m$
- small $E$
- large $\alpha$

# Materials Science and Engineering



*Contents for today's class*

# CHAPTER 3:
# Fundamentals of Crystallography

***I. Crystal Structures***

- Lattice, Unit Cells, Crystal system

***II. Crystallographic Points, Directions, and Planes***

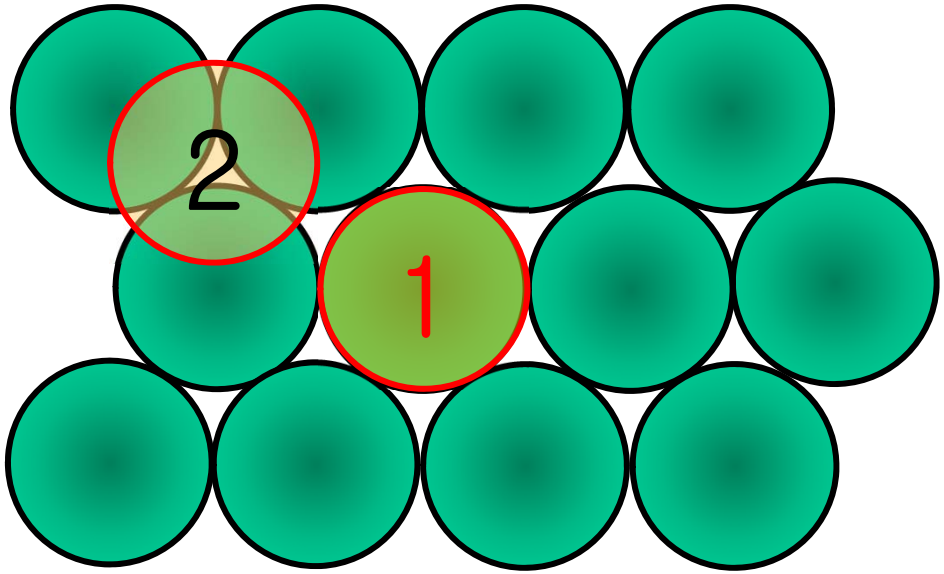
- Point coordinates, Crystallographic directions, Crystallographic planes

***III. Crystalline and Noncrystalline Materials***

- Single crystals, Polycrystalline materials, Anisotropy, Noncrystalline solids

# Stacking of atoms in solid

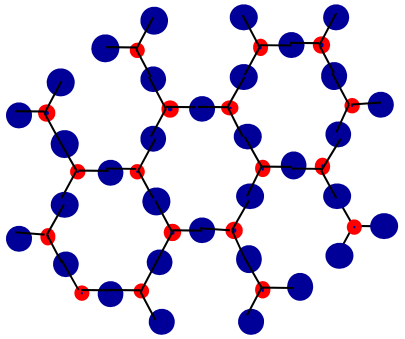
## Finding stable position




- Minimize energy configuration
  - Related to the bonding nature

# Materials and Packing

Crystalline materials...
- atoms pack in periodic, 3D arrays
- typical of: -metals
  -many ceramics
  -some polymers



crystalline $SiO_2$

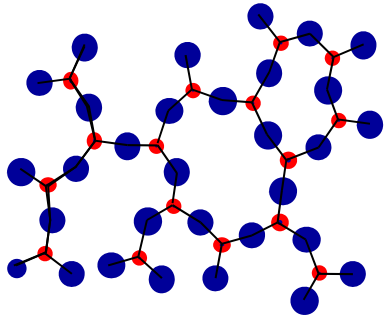
Adapted from Fig. 3.22(a), *Callister 7e.*

Quasicrystalline materials...

Noncrystalline materials...
- atoms have no periodic packing
- occurs for: -complex structures
  -rapid cooling

"Amorphous" = Noncrystalline

• Si ● Oxygen



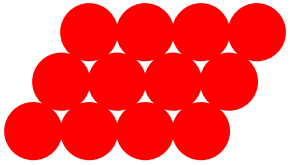
noncrystalline $SiO_2$

# atomic arrangement in the solid state

- Solid materials are classified according to the **regularity** with which atoms and ions are arranged with respect to one another.

- So, how are they arranged ?

  (a) **periodically** – having long range order in 3-D

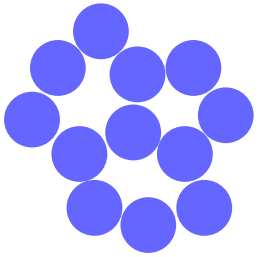


Crystal

  (b) **quasi-periodically**

Quasicrystal

  (c) **randomly** – having short range order with the characteristics of bonding type but losing the long range order



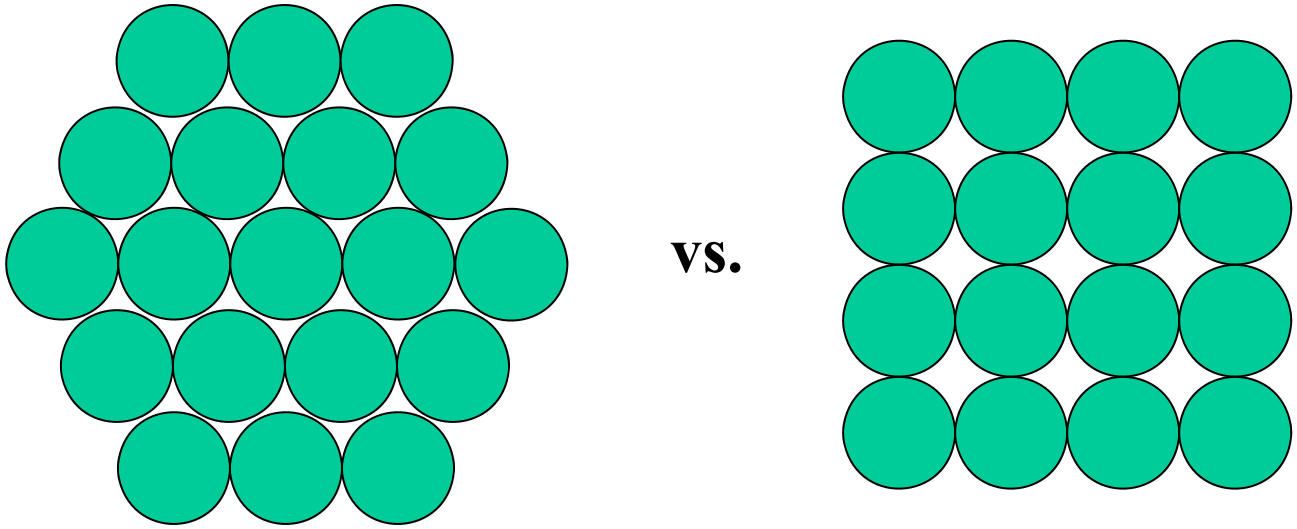
Amorphous

- **Crystal: Perfection → Imperfection**

# I. Crystal structures

- **How can we stack metal atoms to minimize empty space?**

**2-dimensions**




Now stack these 2-D layers to make 3-D structures

Crystalline materials - three-dimensional periodic arrangement of atoms, ions, or molecules- translational periodicity

**Crystal – related topics**

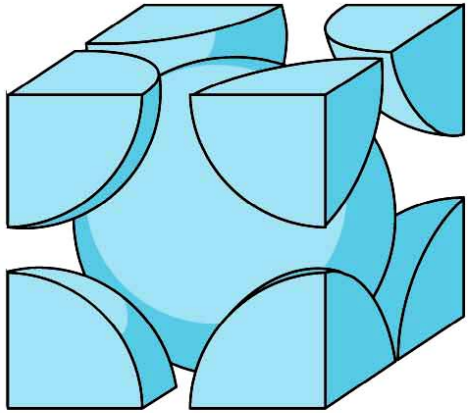
- Periodicity (주기성)
- Symmetry (대칭성)
- Anisotropy (비등방성)
- Directions and Planes (방향과 면)
- Interplanar spacing & angles (면간거리와 각도)
- Diffraction (회절)

# I. Crystal structure

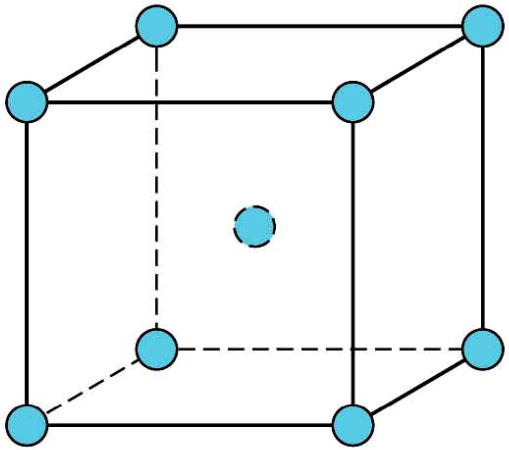
## (1) Lattice : 결정 공간상에서 점들의 규칙적인 기하학적 배열

- 3D point array in space, such that each point has identical surroundings. These points may or may not coincide with atom positions.
- Simplest case : each atom → its center of gravity → point or space lattice → pure mathematical concept

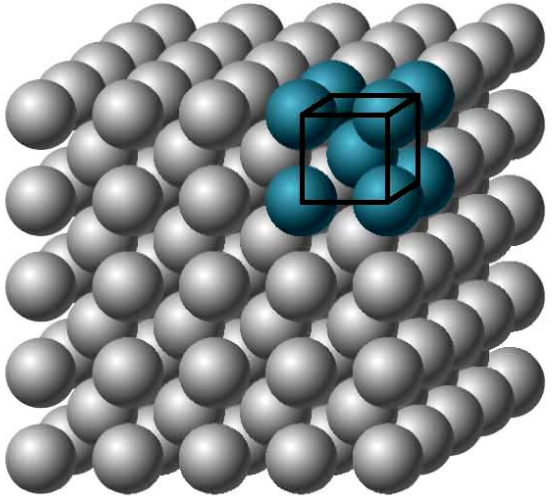
example: sodium (Na) ; body centered cubic



Hard-sphere unit cell



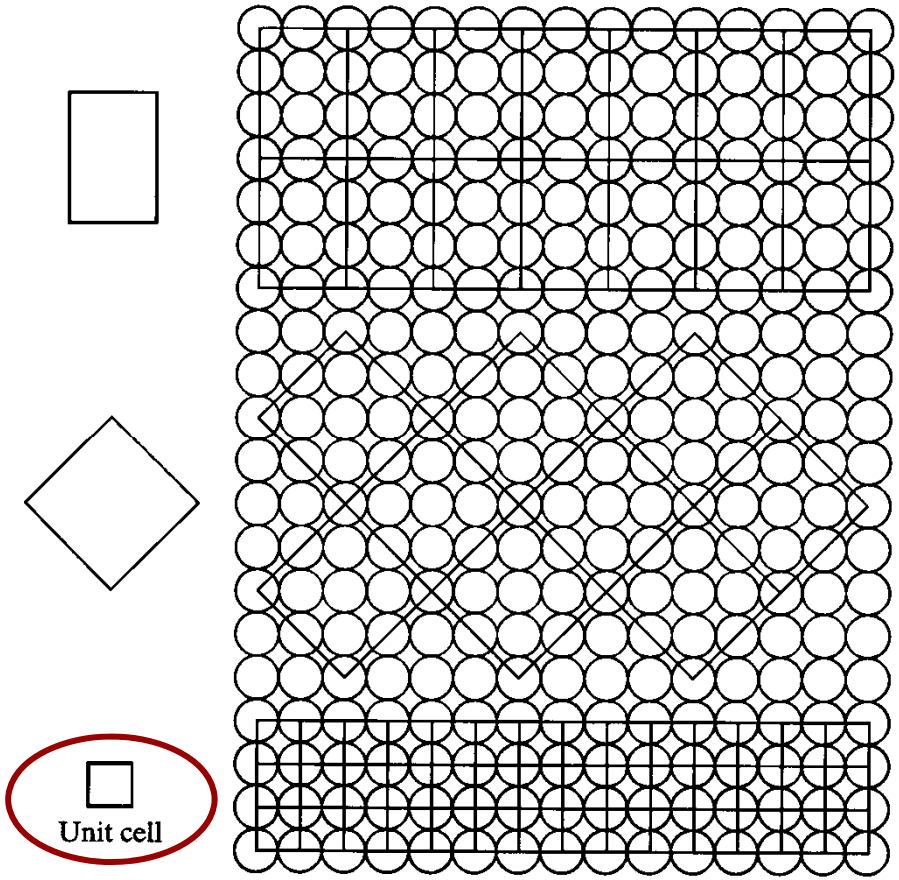
Reduced sphere unit cell



Aggregate of many atoms

# (2) Unit cell

: smallest repetitive volume which contains the complete lattice pattern of a crystal



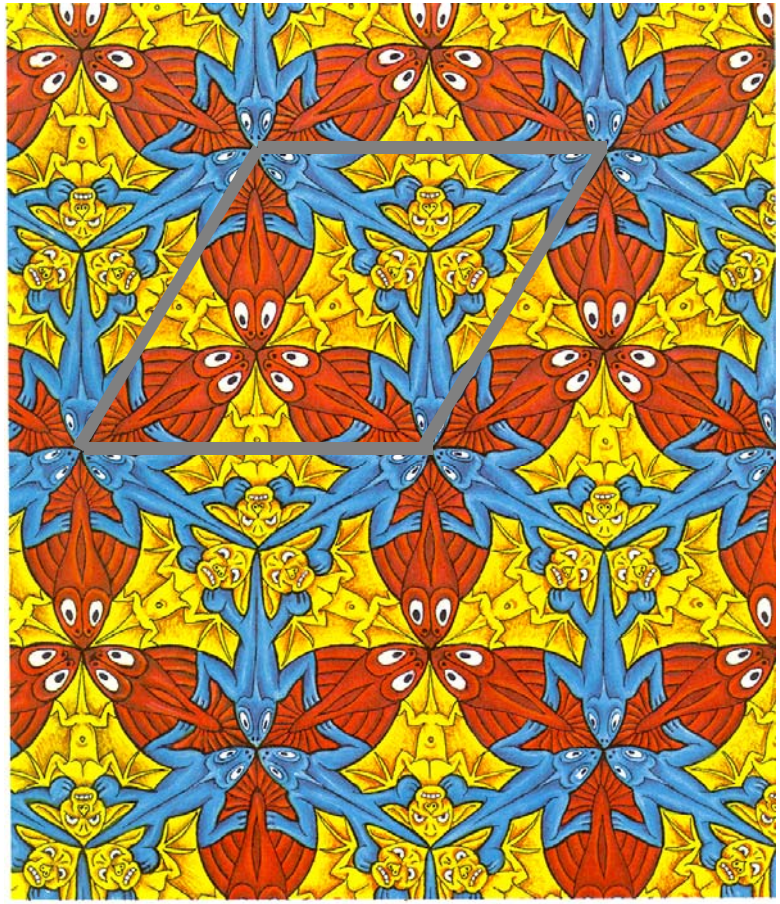
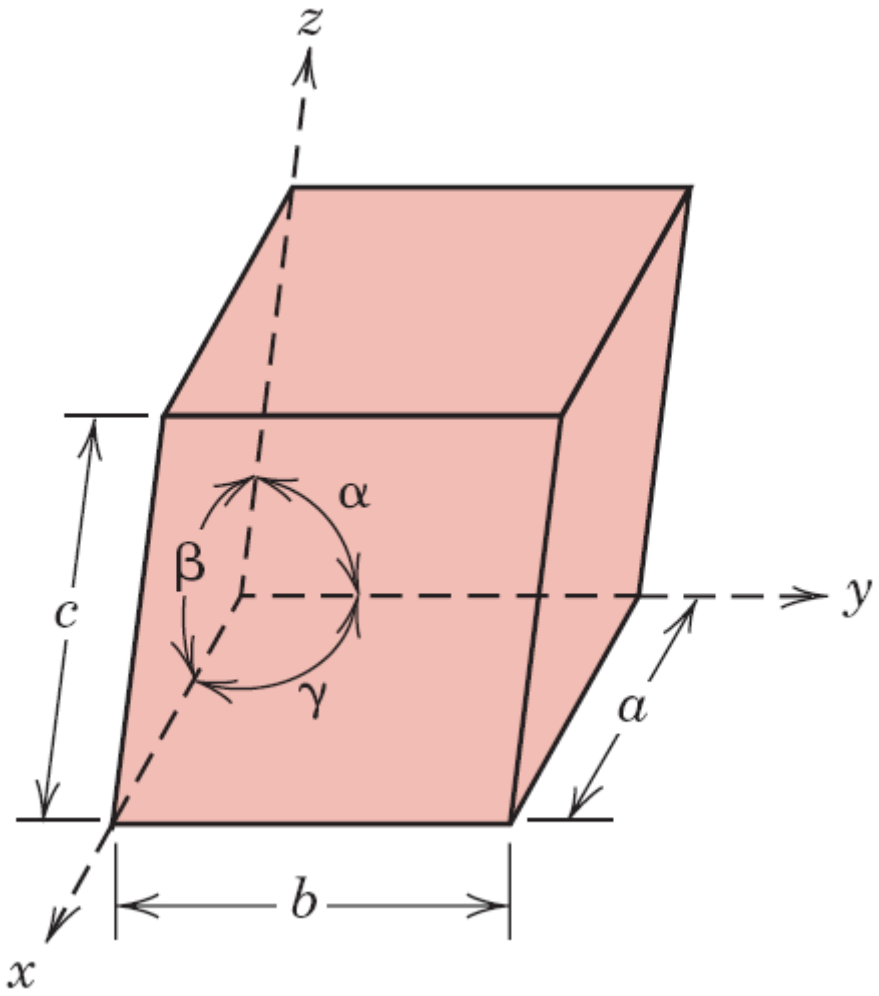



PLATE 9

**Unit cell**

# (3) Lattice parameter

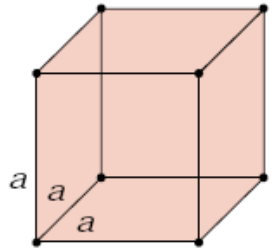
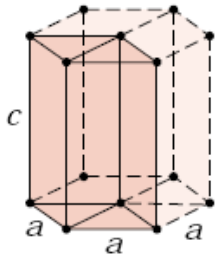
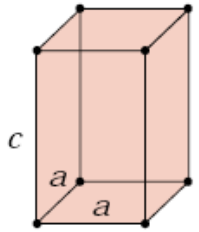



length: a, b, c

angle: α, β, γ

# (4) 7 crystal systems

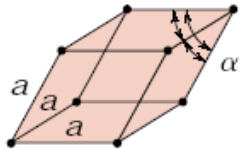
**Unit cell**

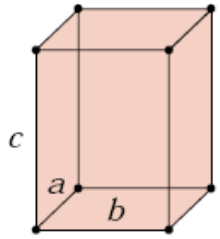
| *Crystal System* | *Axial Relationships* | *Interaxial Angles* | *Unit Cell Geometry* |
|---|---|---|---|
| Cubic | $a = b = c$ | $\alpha = \beta = \gamma = 90°$ |   |
| Hexagonal | $a = b \neq c$ | $\alpha = \beta = 90°, \gamma = 120°$ |   |
| Tetragonal | $a = b \neq c$ | $\alpha = \beta = \gamma = 90°$ |   |

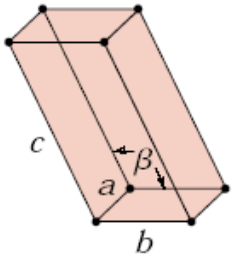
# (4) 7 crystal systems (continued)

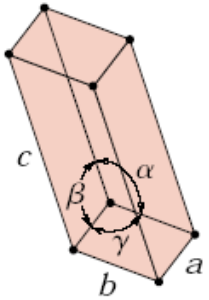
**Unit cell**

| | | |
|---|---|---|
| Rhombohedral | $a = b = c$ | $\alpha = \beta = \gamma \neq 90°$ |
| Orthorhombic | $a \neq b \neq c$ | $\alpha = \beta = \gamma = 90°$ |
| Monoclinic | $a \neq b \neq c$ | $\alpha = \gamma = 90° \neq \beta$ |
| Triclinic | $a \neq b \neq c$ | $\alpha \neq \beta \neq \gamma \neq 90°$ |



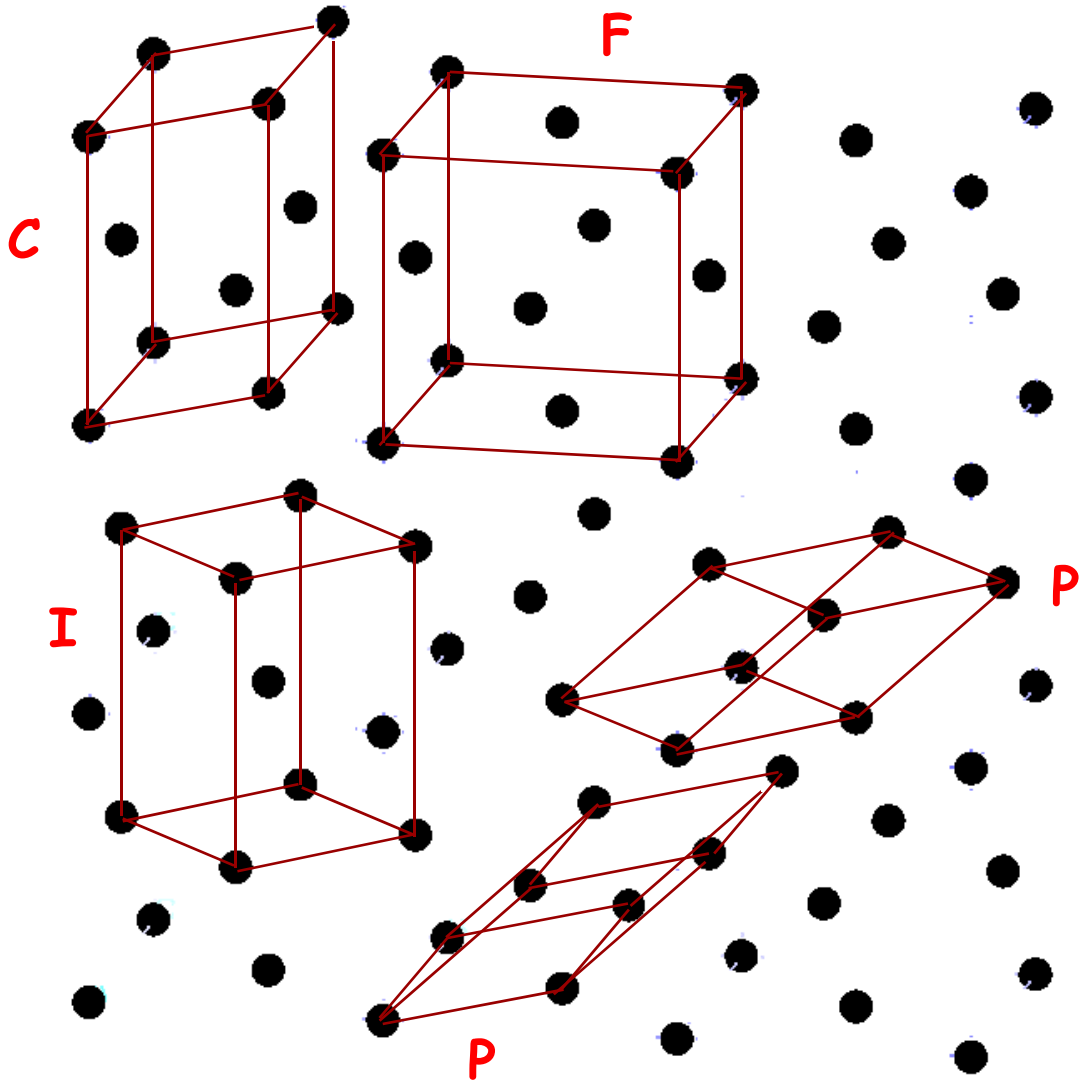



# Unit cell

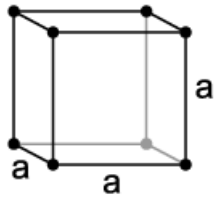
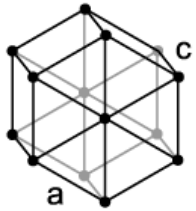
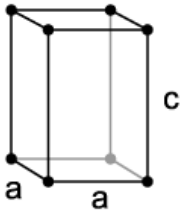
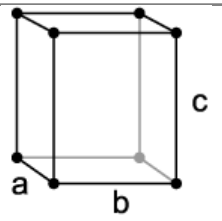
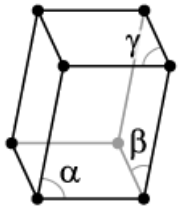
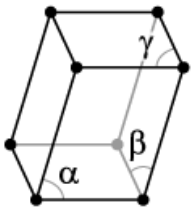
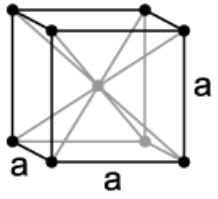
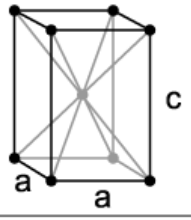
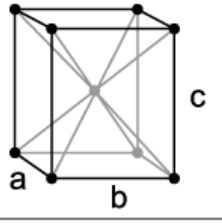
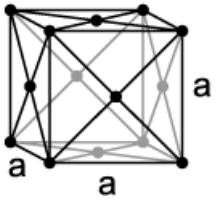
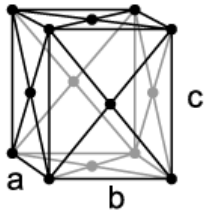
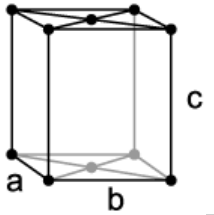
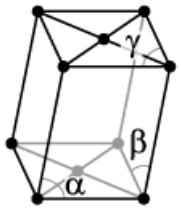
- P, I, F, C

- ❑ *P* : Primitive
- ❑ *I* : Body centered
- ❑ *F* : Face centered
- ❑ *C* : Base centered



# Unit cell

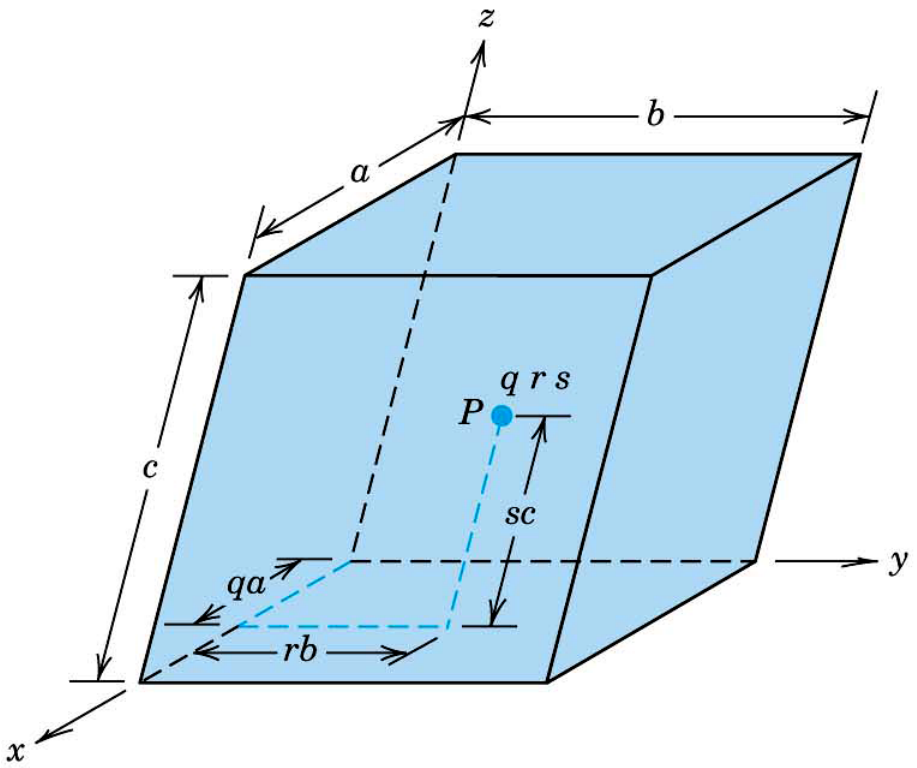
## (5) 14 Bravais Lattice - Only 14 different types of unit cells are required to describe all lattices using symmetry

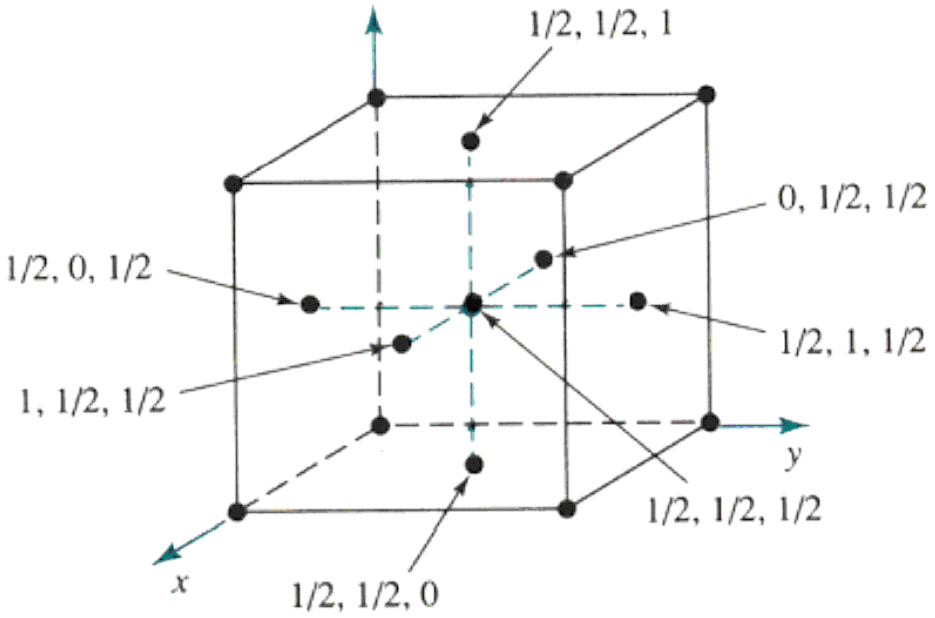
| | cubic | hexagonal | rhombohedral (trigonal) | tetragonal | orthorhombic | monoclinic | triclinic |
|---|---|---|---|---|---|---|---|
| P |  |  |  |  |  |  |  |
| I |  | | |  |  | | |
| F |  | | | |  | | |
| C | | | | |  |  | |

# II. Crystallographic points, directions and planes

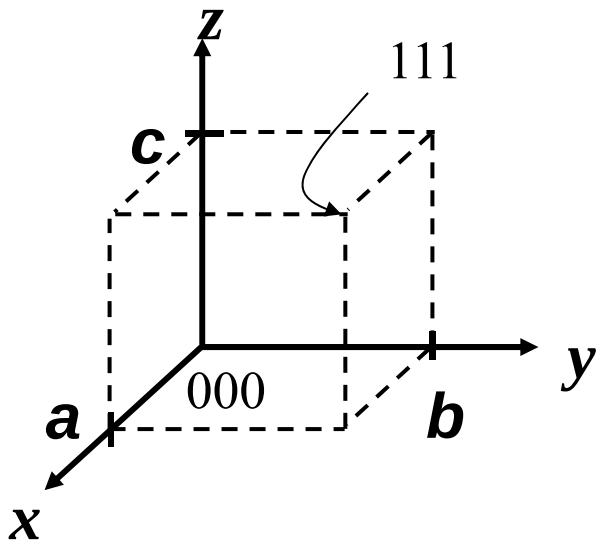
***Chapter 3.5 Point coordinates***

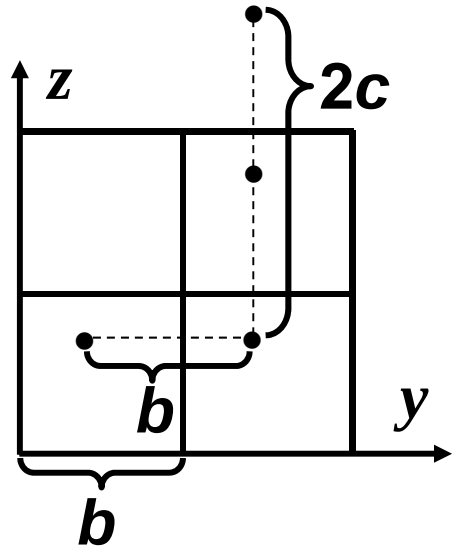
- **position: fractional multiples of the unit cell edge lengths**
  - **ex) P: q,r,s**




cubic unit cell



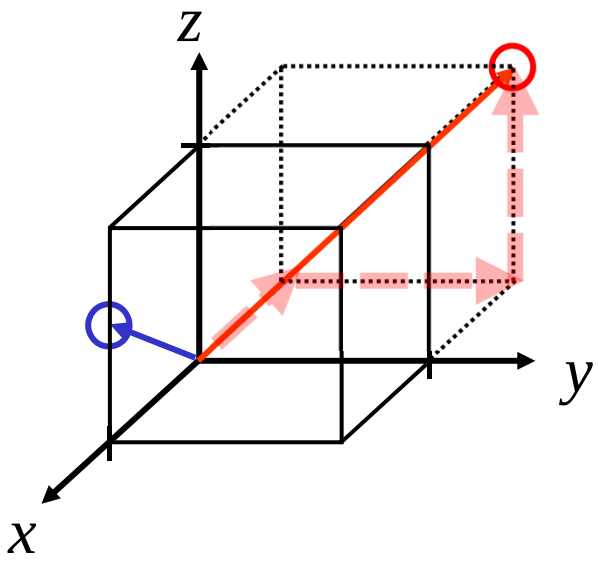

**Point coordinates for unit cell center are**

***a*/2, *b*/2, *c*/2** ½ ½ ½

**Point coordinates for unit cell corner are 111**

**Translation: integer multiple of lattice constants → identical position in another unit cell**

# Crystallographic Directions




## Algorithm

1. Vector repositioned (if necessary) to pass through origin.
2. Read off projections in terms of unit cell dimensions *a*, *b*, and *c*
3. Adjust to smallest integer values
4. Enclose in square brackets, no commas

[*uvw*]

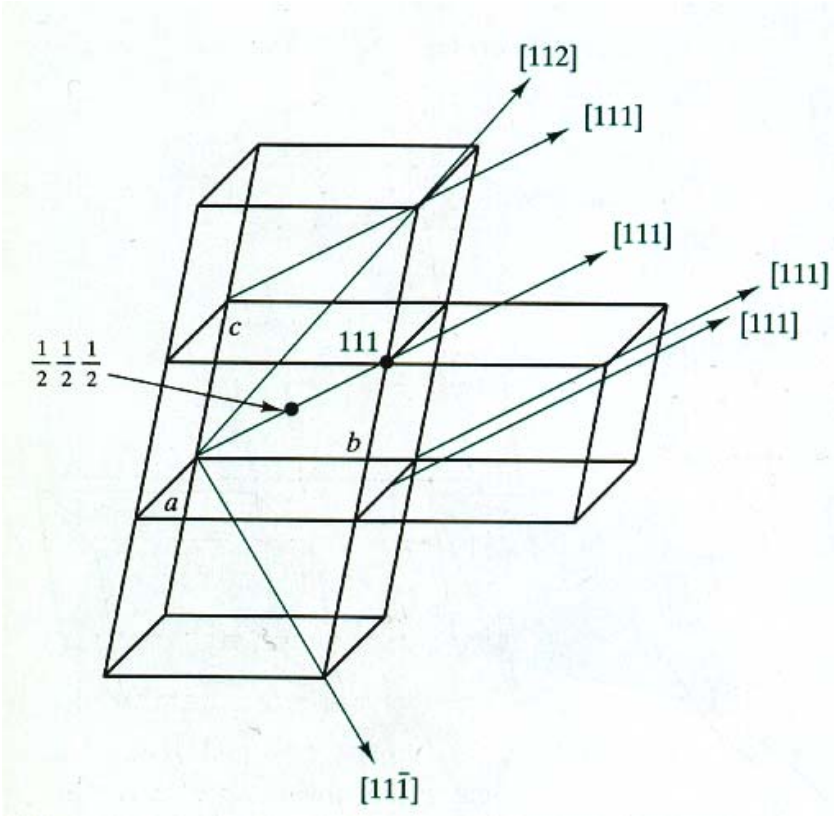
ex: 1, 0, ½ => 2, 0, 1 => [201]

-1, 1, 1 => $[\bar{1}11]$ where overbar represents a negative index

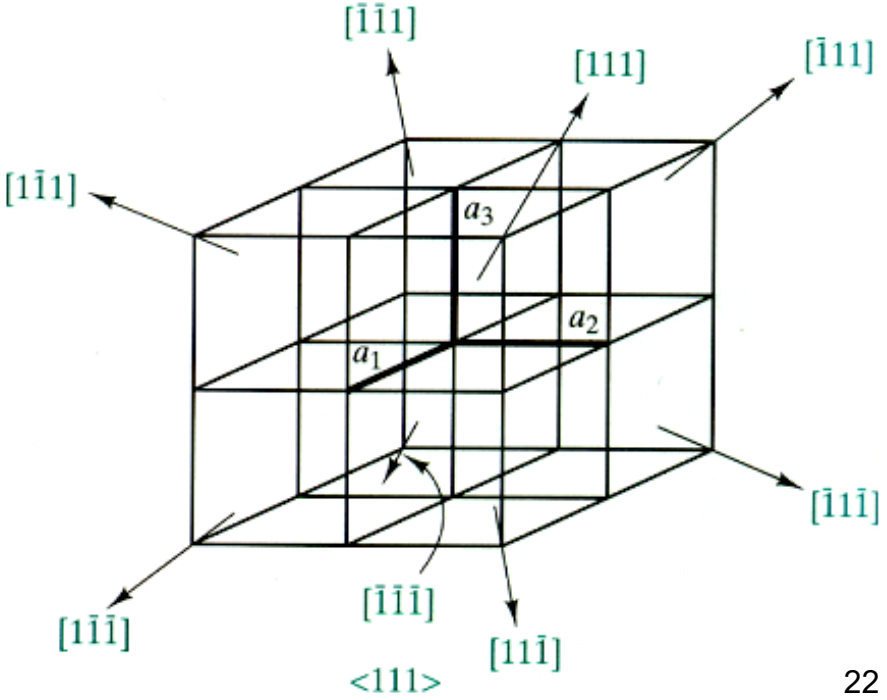
families of directions <*uvw*>

# Crystallographic Directions

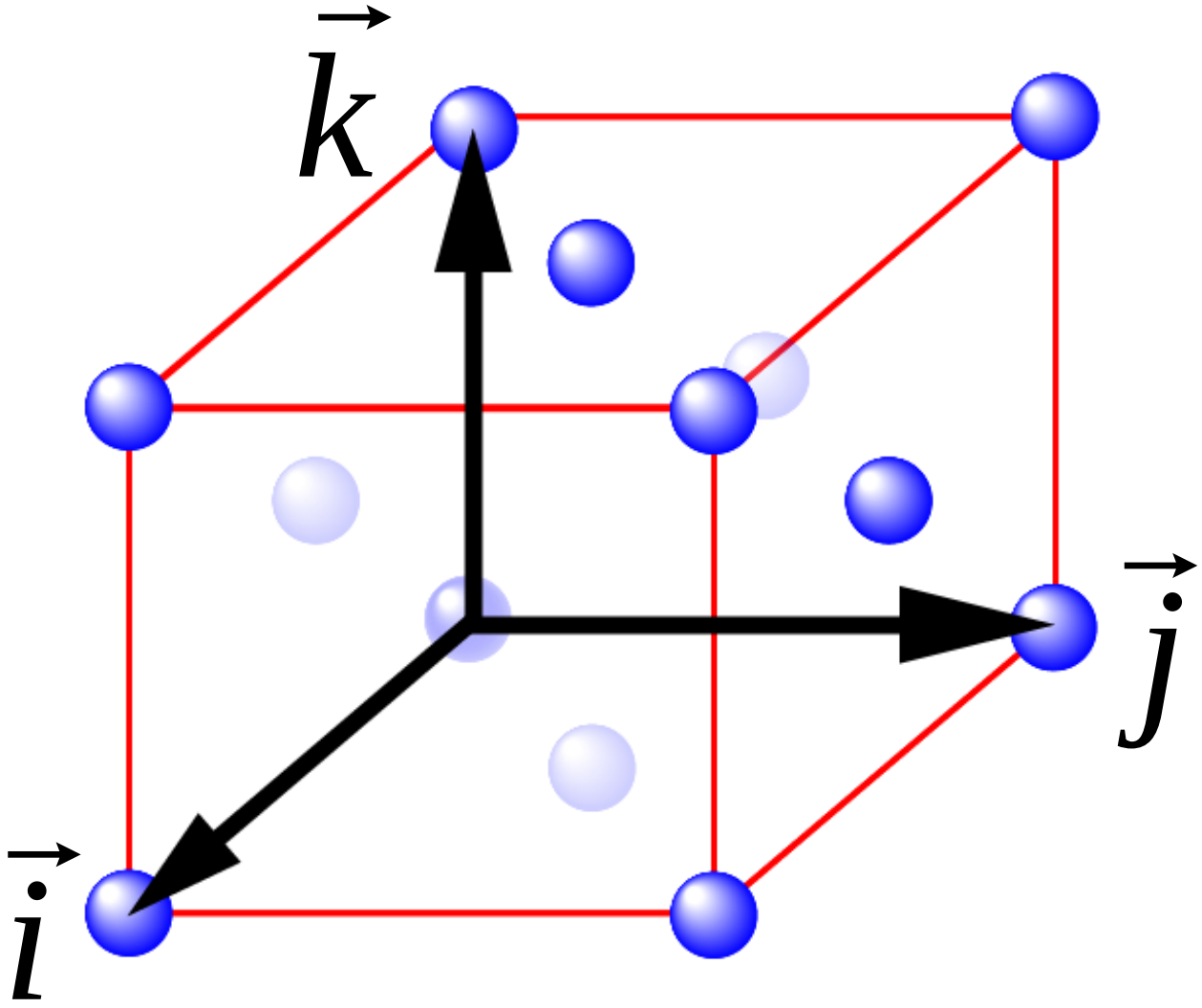
- a line between two points or a vector
- [uvw] square bracket, <u>smallest integer</u>
- families of directions: <uvw> angle bracket




cubic



# Impose index coordination



# Directional indices

<100> ⇒ [100], [010], [001]
[$\bar{1}$00], [0$\bar{1}$0], [00$\bar{1}$]

<110> ⇒ [110], [101], [011],
[$\bar{1}\bar{1}$0], [$\bar{1}$0$\bar{1}$], [0$\bar{1}\bar{1}$],
[1$\bar{1}$0], [10$\bar{1}$], [01$\bar{1}$],
[$\bar{1}$10], [$\bar{1}$01], [0$\bar{1}$1]

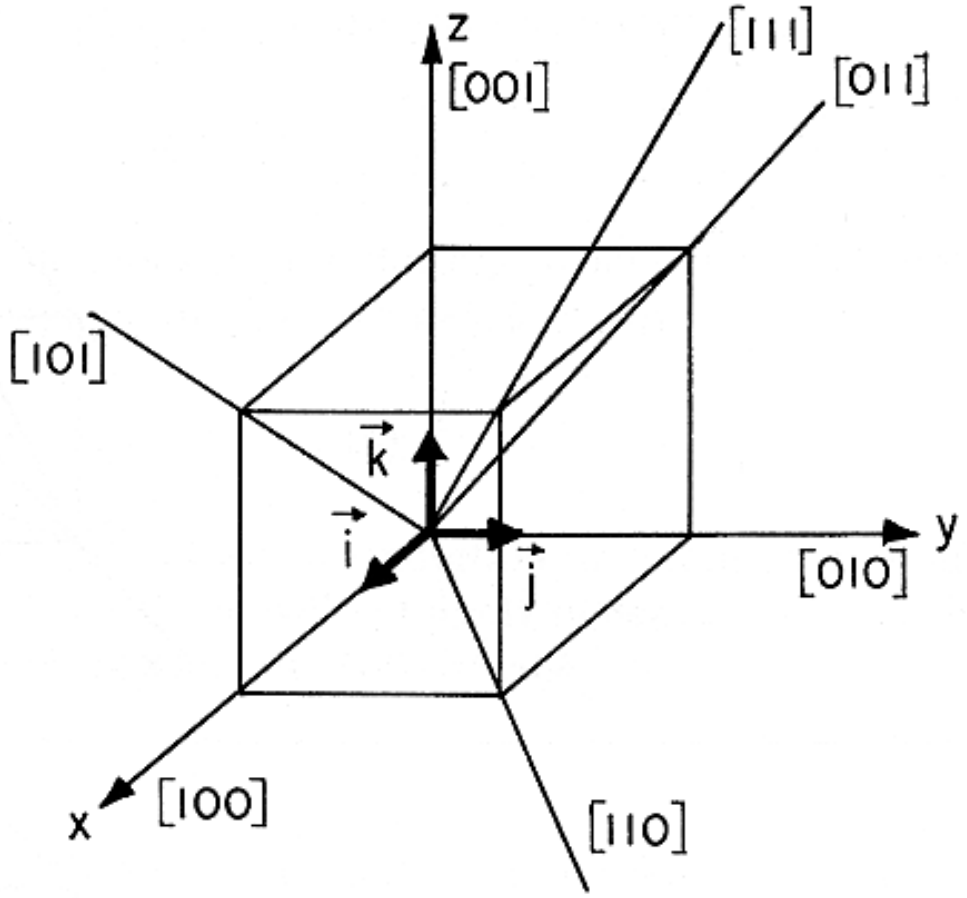
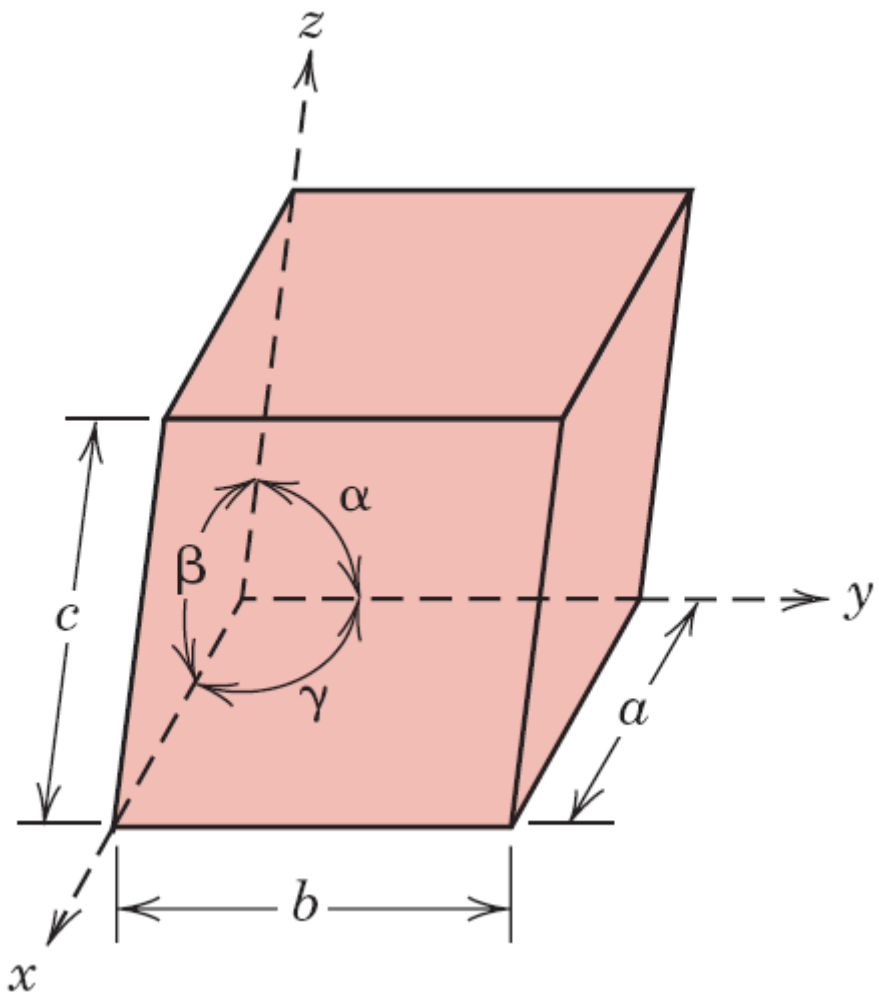



**Figure 1.8** Directions in a cubic unit cell.

$< i\ j\ k >$ : permutation of $[\ i\ j\ k]$

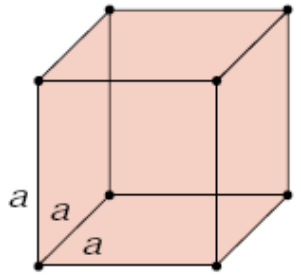
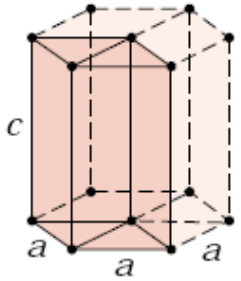
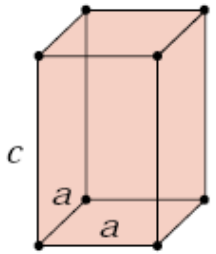
# Lattice Parameter



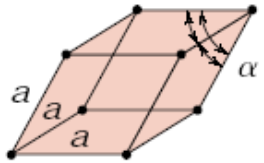

length: a, b, c

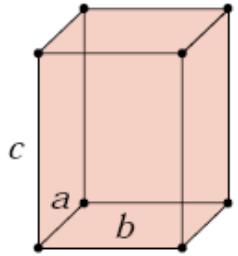
angle: α, β, γ

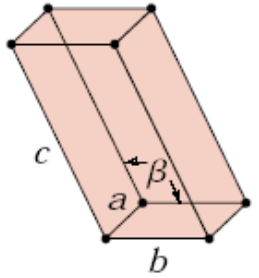
**Table 3.6 Lattice Parameter Relationships and Figures Showing Unit Cell Geometries for the Seven Crystal Systems**

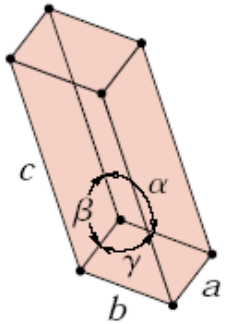
| *Crystal System* | *Axial Relationships* | *Interaxial Angles* | *Unit Cell Geometry* |
|---|---|---|---|
| Cubic | $a = b = c$ | $\alpha = \beta = \gamma = 90°$ |   |
| Hexagonal | $a = b \neq c$ | $\alpha = \beta = 90°, \gamma = 120°$ |   |
| Tetragonal | $a = b \neq c$ | $\alpha = \beta = \gamma = 90°$ |   |

| | | |
|---|---|---|
| Rhombohedral | $a = b = c$ | $\alpha = \beta = \gamma \neq 90°$ |
| Orthorhombic | $a \neq b \neq c$ | $\alpha = \beta = \gamma = 90°$ |
| Monoclinic | $a \neq b \neq c$ | $\alpha = \gamma = 90° \neq \beta$ |
| Triclinic | $a \neq b \neq c$ | $\alpha \neq \beta \neq \gamma \neq 90°$ |

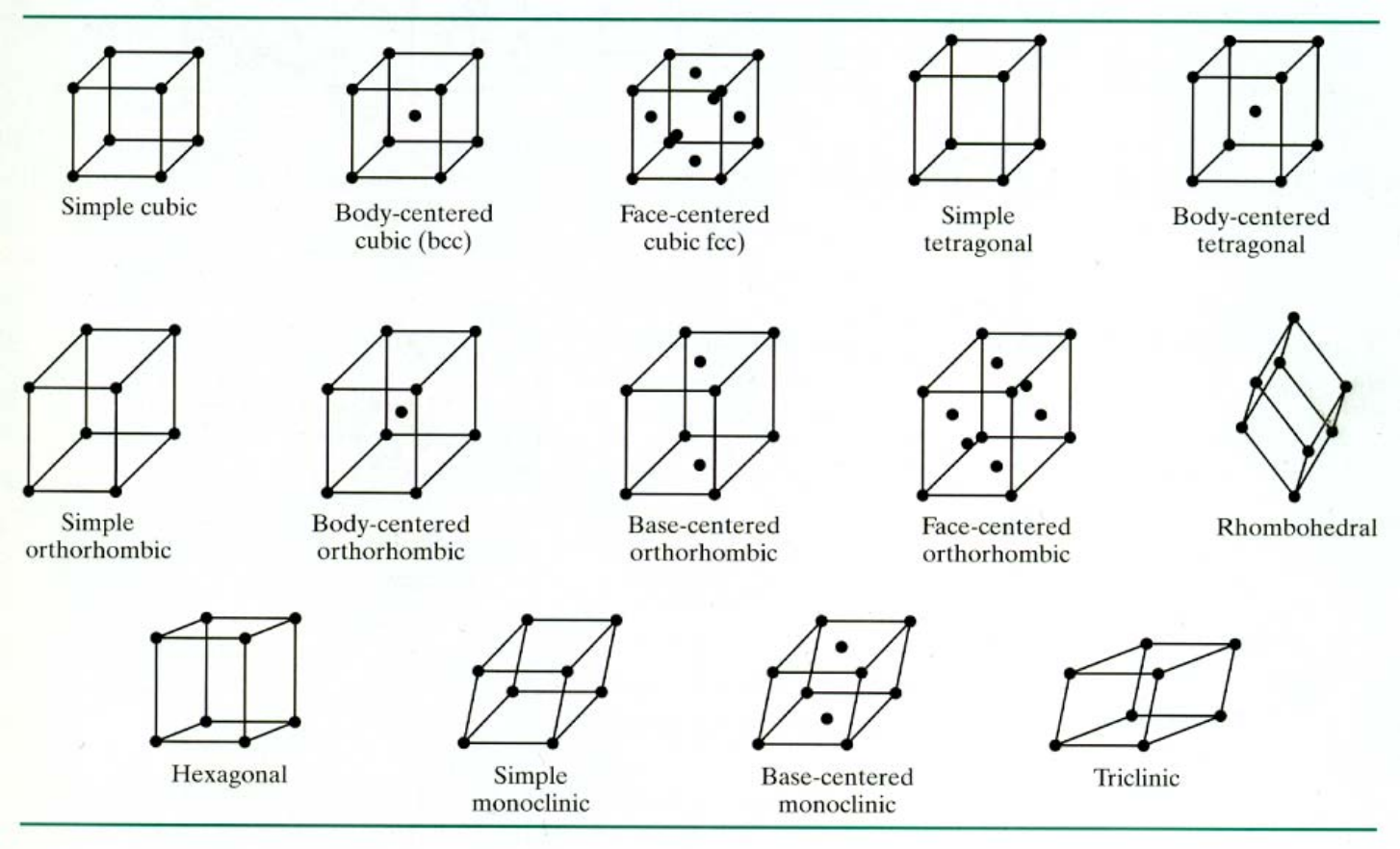


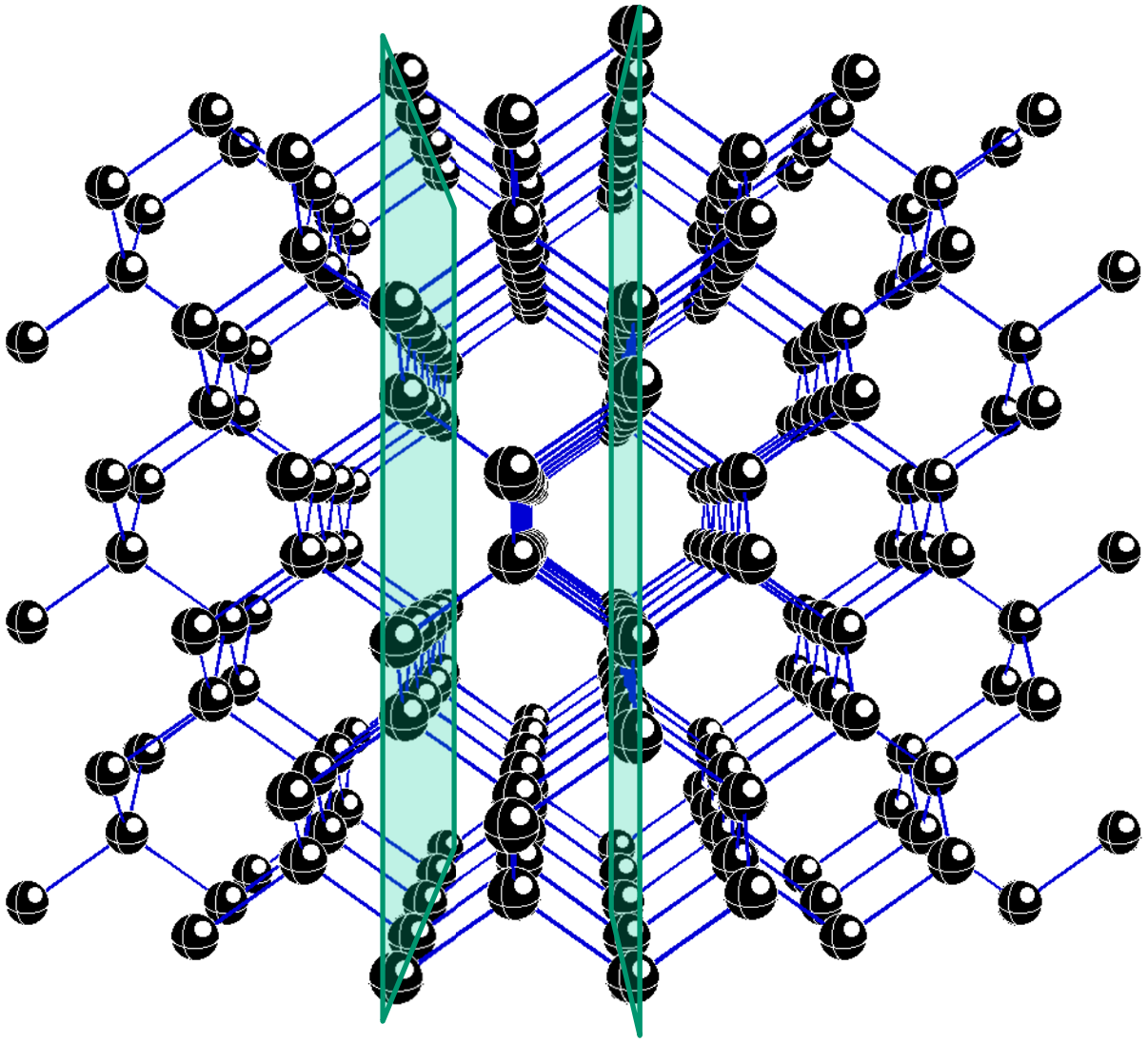



# 14 Bravais Lattice

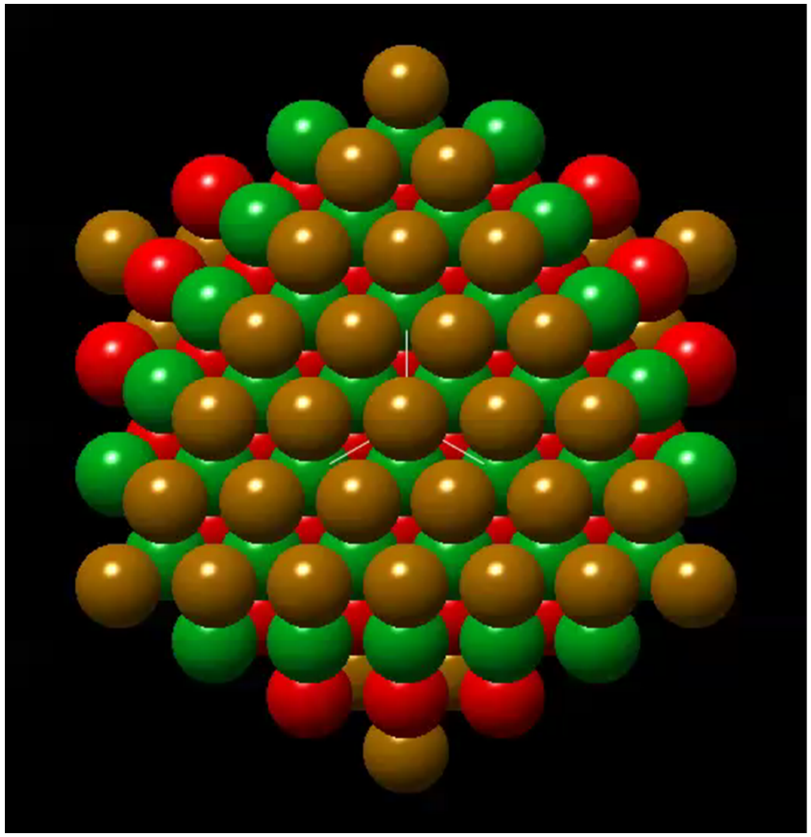



- **Only 14 different types of unit cells are required to describe all lattices using symmetry**
- **simple (1), body-centered (2), base-centered (2) face-centered (4 atoms/unit cell)**

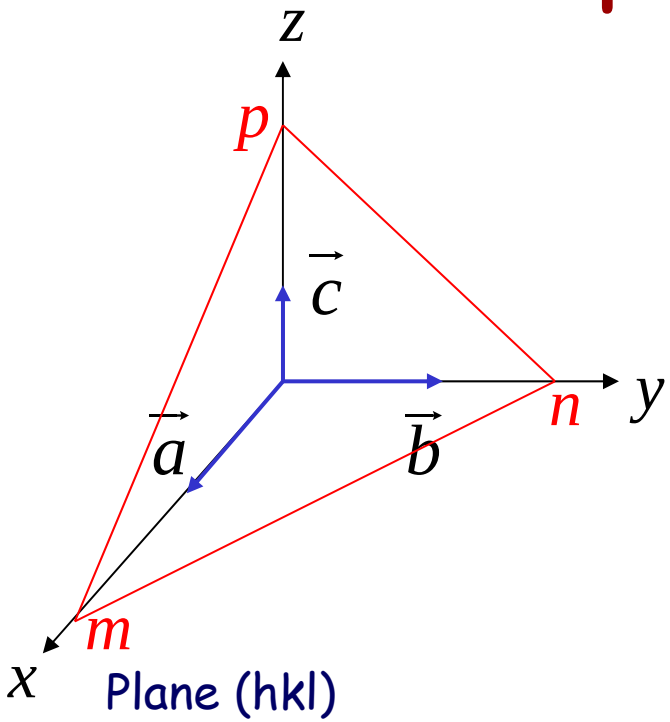
# Crystal view -Silicon



# Crystallographic planes



# Lattice plane (Miller indices)



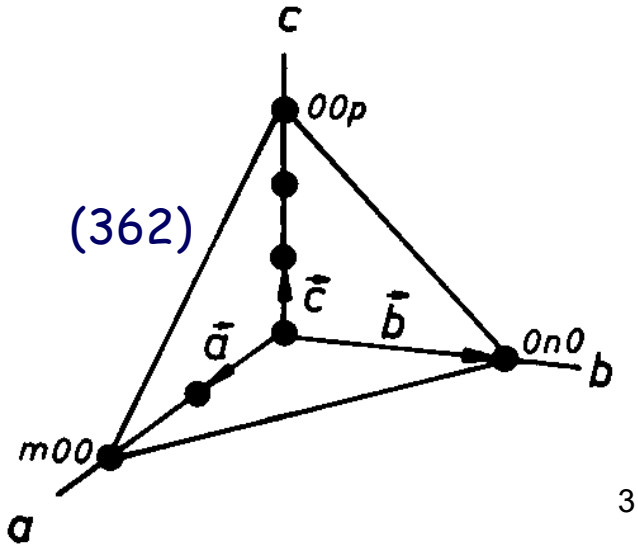

Plane (hkl)
Family of planes {hkl}

m00, 0n0, 00p: define lattice plane

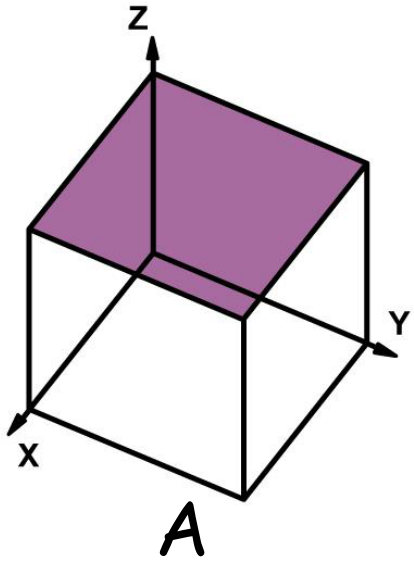
m, n, ∞ : no intercepts with axes

| Intercepts @ (mnp) | 2 | 1 | 3 |
|---|---|---|---|
| Reciprocals | ½ | 1 | 1/3 |
| Miller indicies | 3 | 6 | 2 |
| (362) plane | | | |

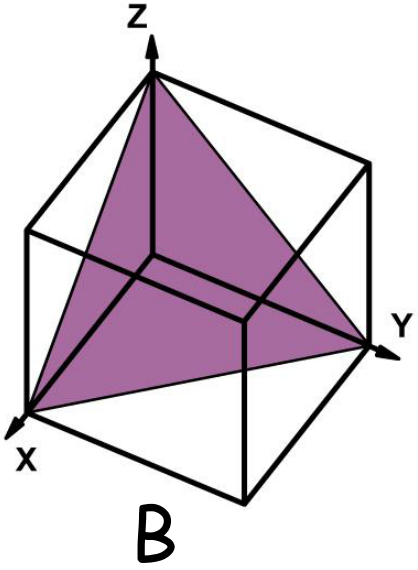
Miller indicies ; defined as the smallest integral multiples of the reciprocals of the plane intercepts on the axes



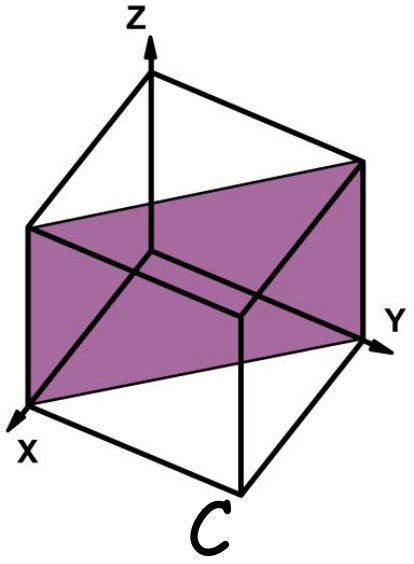
# Crystallographic Planes



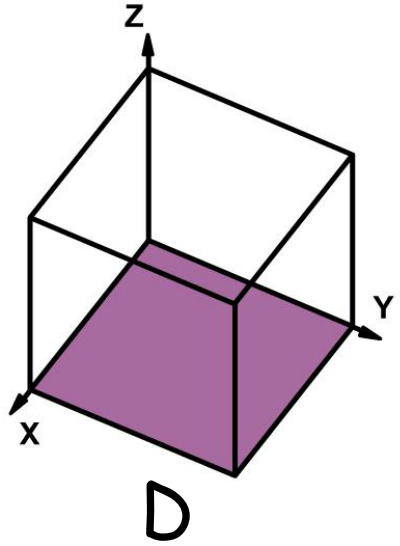
A



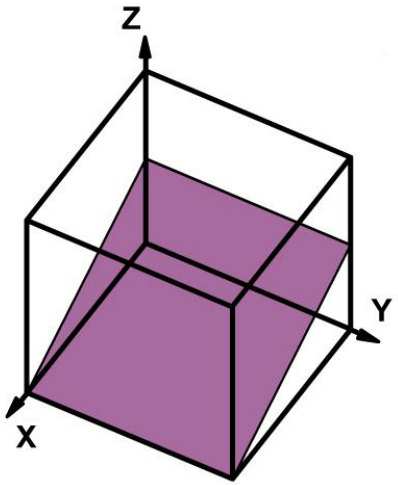
B



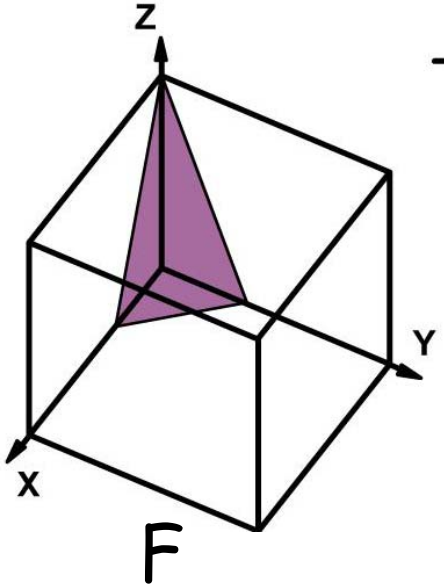
C



D



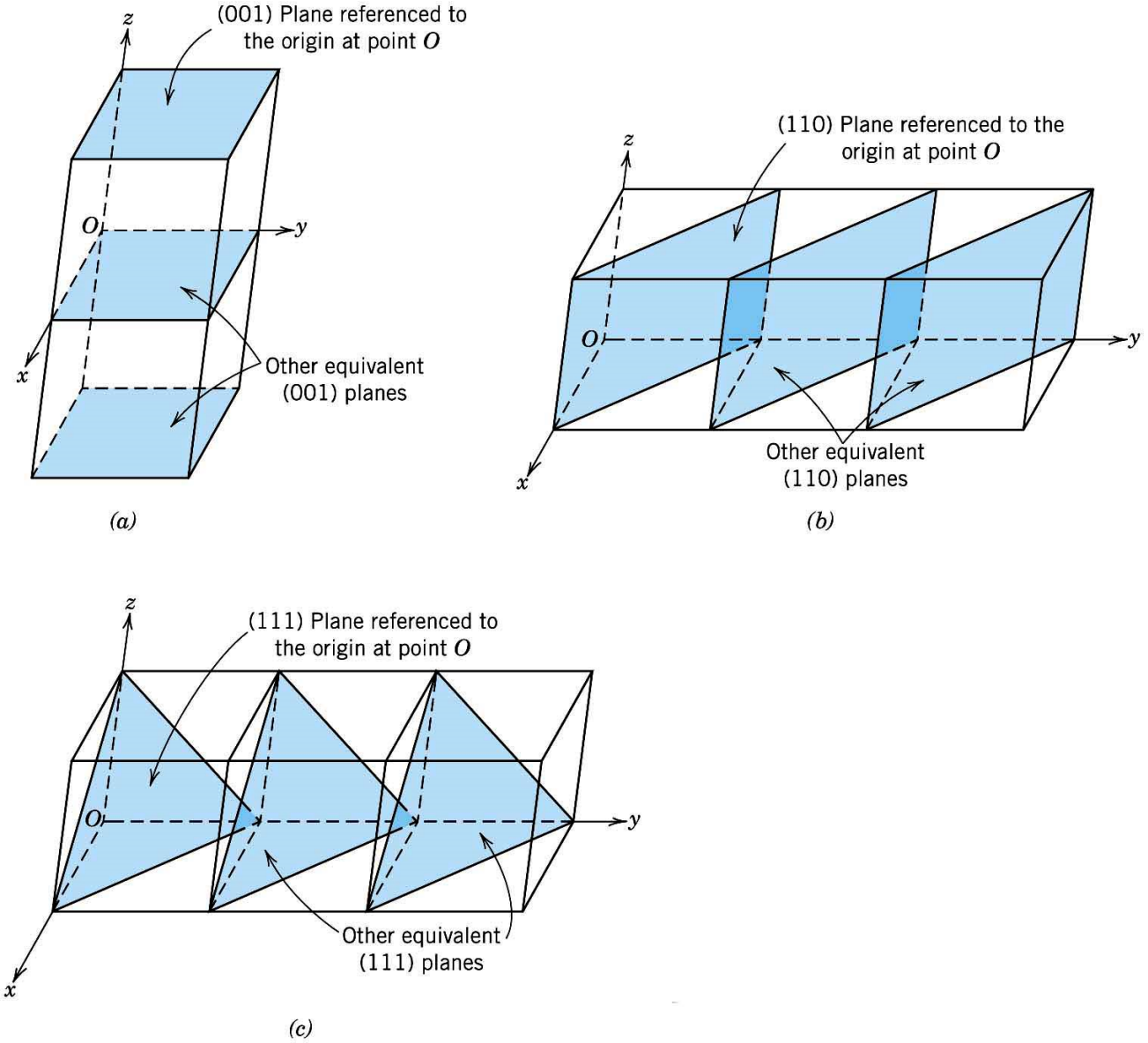
E



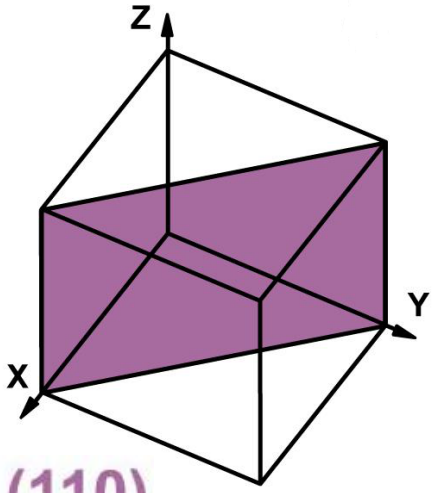
F

| Plane | Intercepts | Indices |
|---|---|---|
| A | ∞, ∞, 1 | (001) |
| B | 1, 1, 1 | (111) |
| C | 1, 1, ∞ | (110) |
| D | ∞, ∞, -1 | $(00\bar{1})$ |
| E | 1, ∞, 1/2 | ( ) |
| F | 1/3, 1/3, 1 | ( ) |

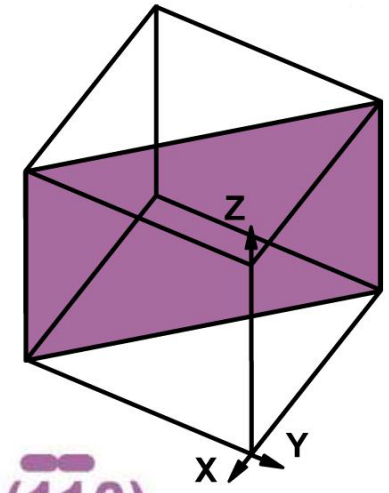
# Crystallographic Planes



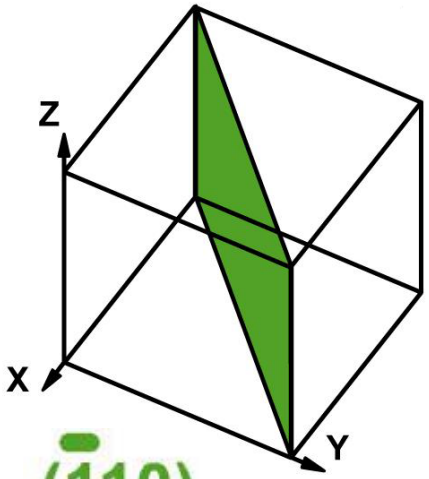
# {110} Family



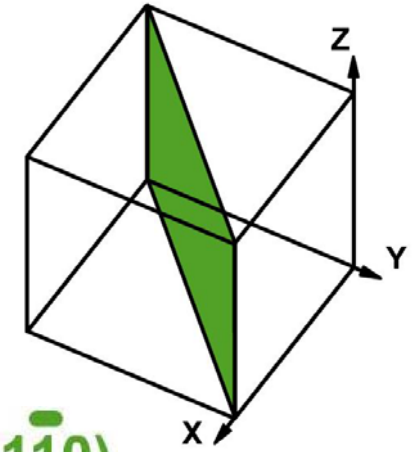

(110)



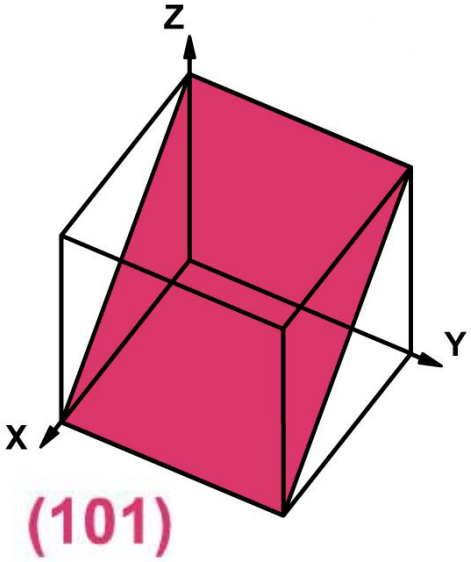

$(\bar{1}\bar{1}0)$



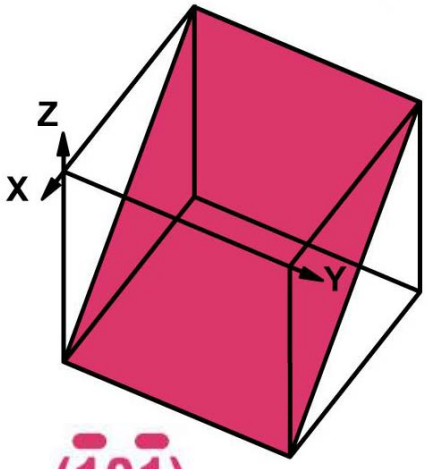

$(\bar{1}10)$




$(1\bar{1}0)$

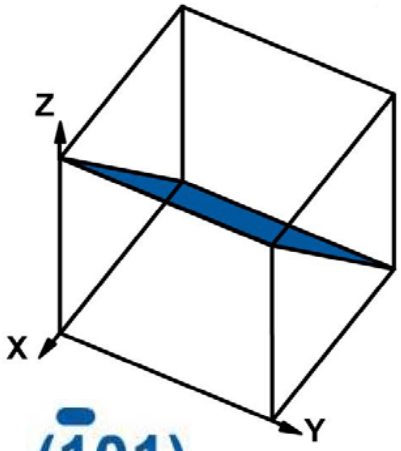



(101)

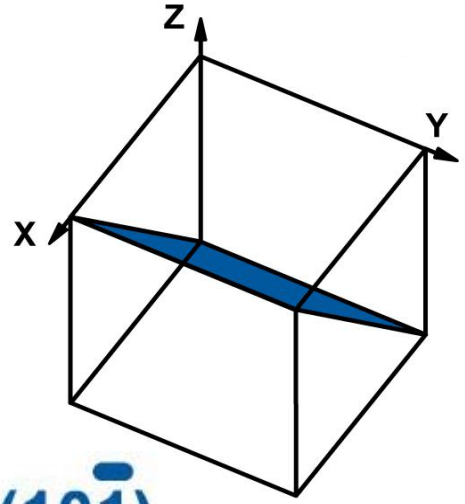



$(\bar{1}0\bar{1})$

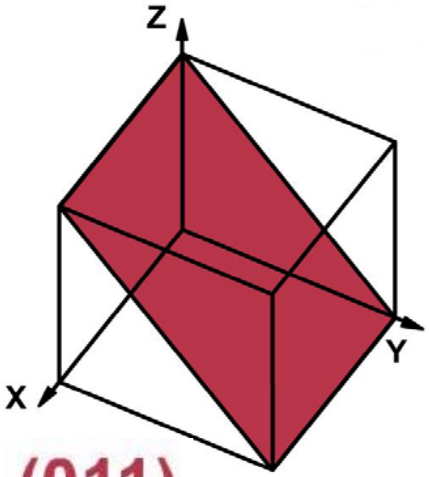
# {110} Family



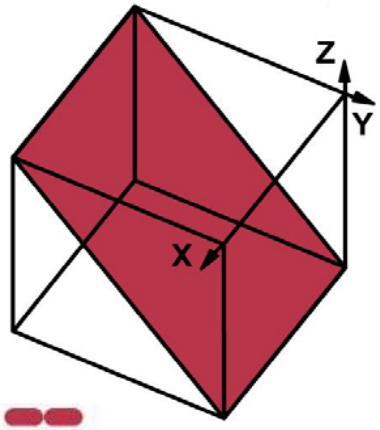

$(\bar{1}01)$



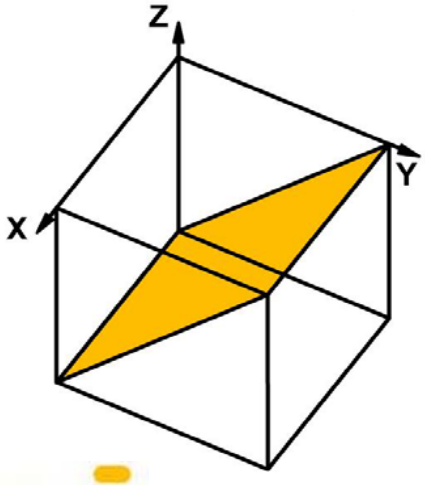

$(10\bar{1})$



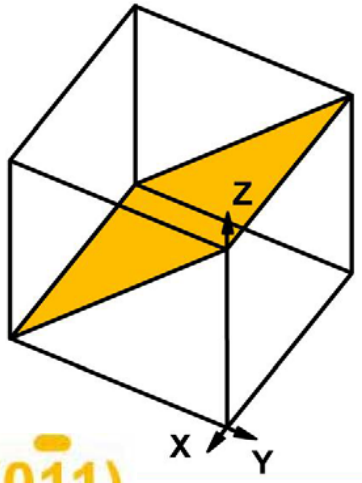

(011)




$(0\bar{1}\bar{1})$




$(01\bar{1})$




$(0\bar{1}1)$

# Directions, Planes, and Family

- line, direction
  - [111] square bracket
  - <111> angular bracket - family

- Plane
  - (111) round bracket (Parentheses)
  - {111} braces - family

# HCP Crystallographic Directions

- **Hexagonal Crystals**
  - 4 parameter Miller-Bravais lattice coordinates are related to the direction indices (i.e., *u′ v′ w′*) as follows.

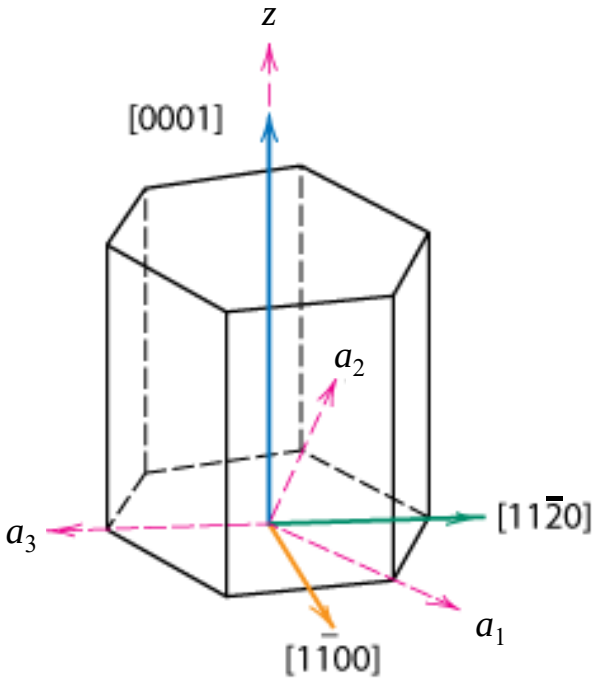



Fig. 3.8(a), *Callister 7e.*

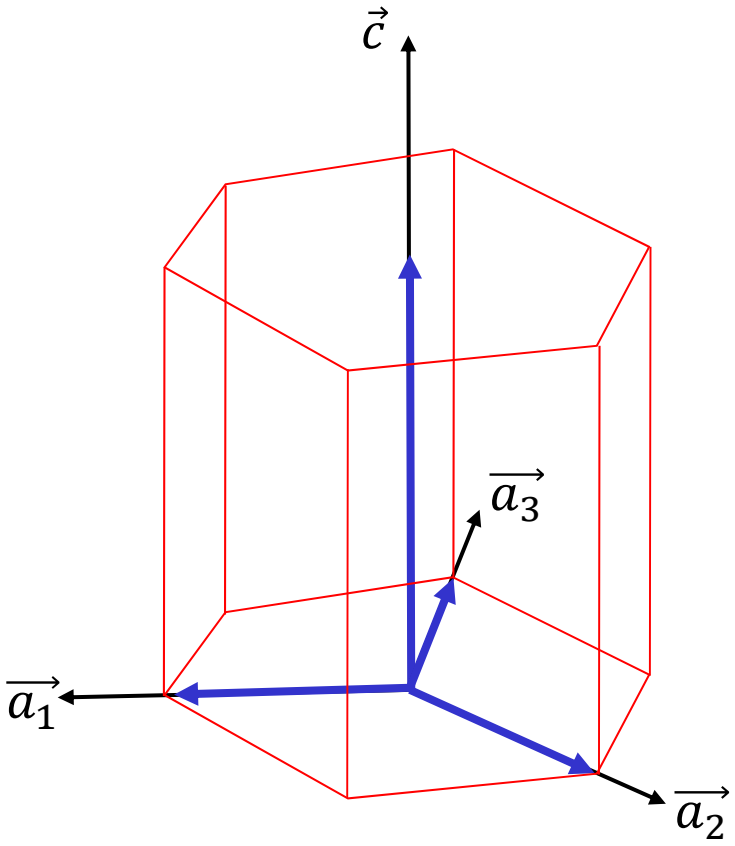
$$[u'v'w'] \rightarrow [uvtw]$$

$$u = \frac{1}{3}(2u' - v')$$

$$v = \frac{1}{3}(2v' - u')$$

$$t = -(u + v)$$

$$w = w'$$


$\vec{c}$
$\overrightarrow{a_3}$
$\overrightarrow{a_1}$
$\overrightarrow{a_2}$

Miller index $[100]$

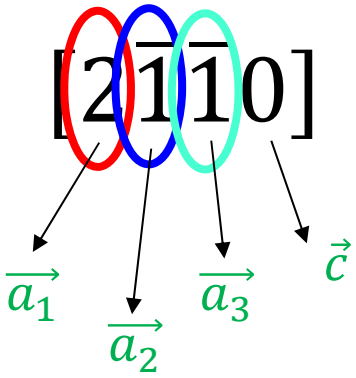
$$\left.\begin{aligned} u &= \frac{1}{3}(2u'-v') \\ v &= \frac{1}{3}(2v'-u') \\ w &= w' \end{aligned}\right\} \quad \left.\begin{aligned} u &= \frac{2}{3} \\ v &= \frac{-1}{3} \\ w &= 0 \end{aligned}\right\}$$

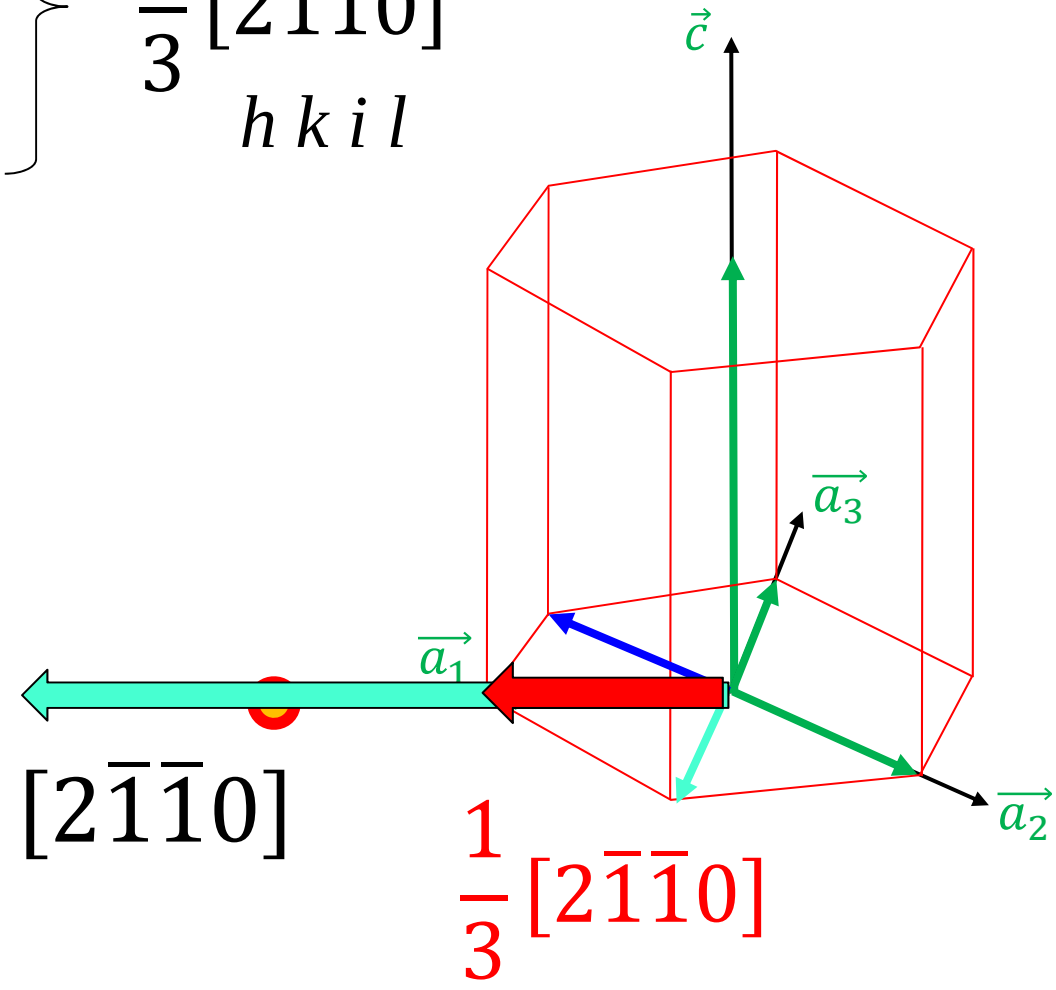
Miller-Bravais index

$i=-(h+k)$

$$\frac{1}{3}[2\bar{1}\bar{1}0]$$

$h\ k\ i\ l$



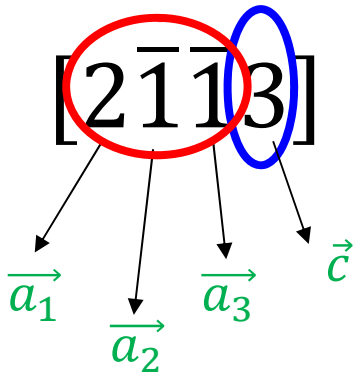



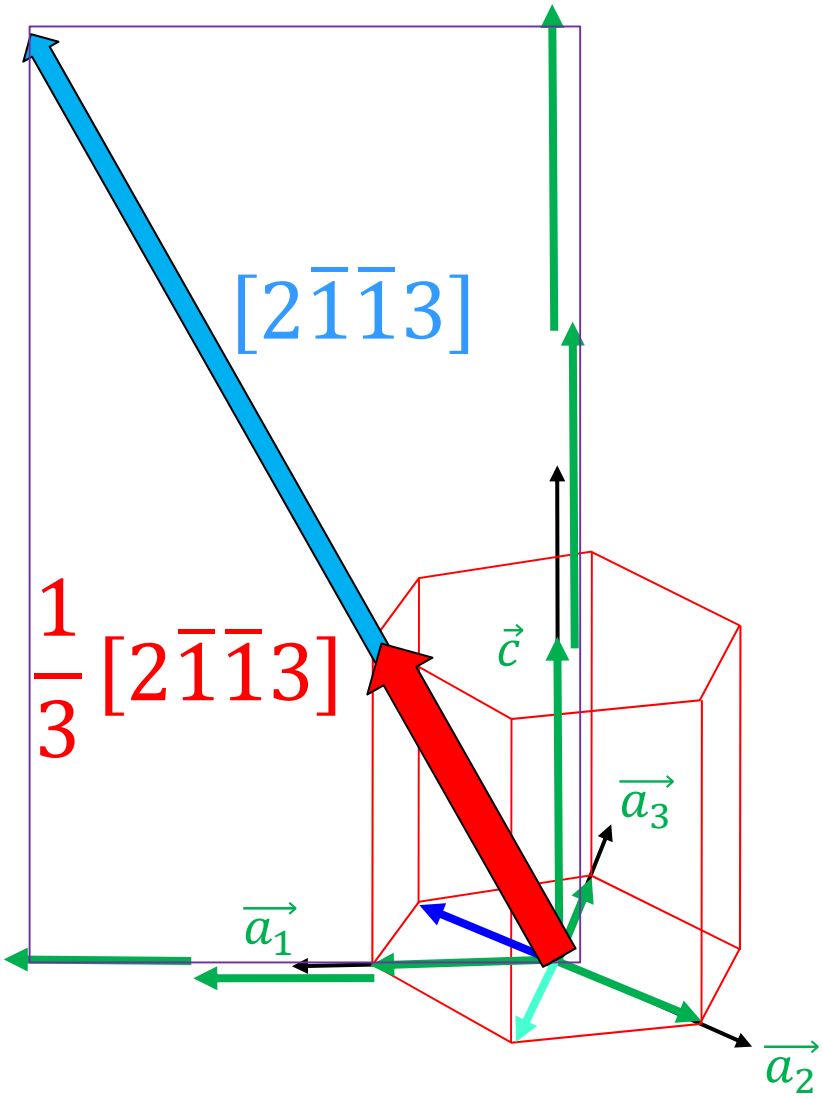
Miller index $[101]$

$$\left.\begin{aligned} u &= \frac{1}{3}(2u'-v') \\ v &= \frac{1}{3}(2v'-u') \\ w &= w' \end{aligned}\right\} \quad \left.\begin{aligned} u &= \frac{2}{3} \\ v &= \frac{-1}{3} \\ w &= 1 \end{aligned}\right\}$$

Miller-Bravais index

$$\frac{1}{3}[2\bar{1}\bar{1}3]$$



Miller index

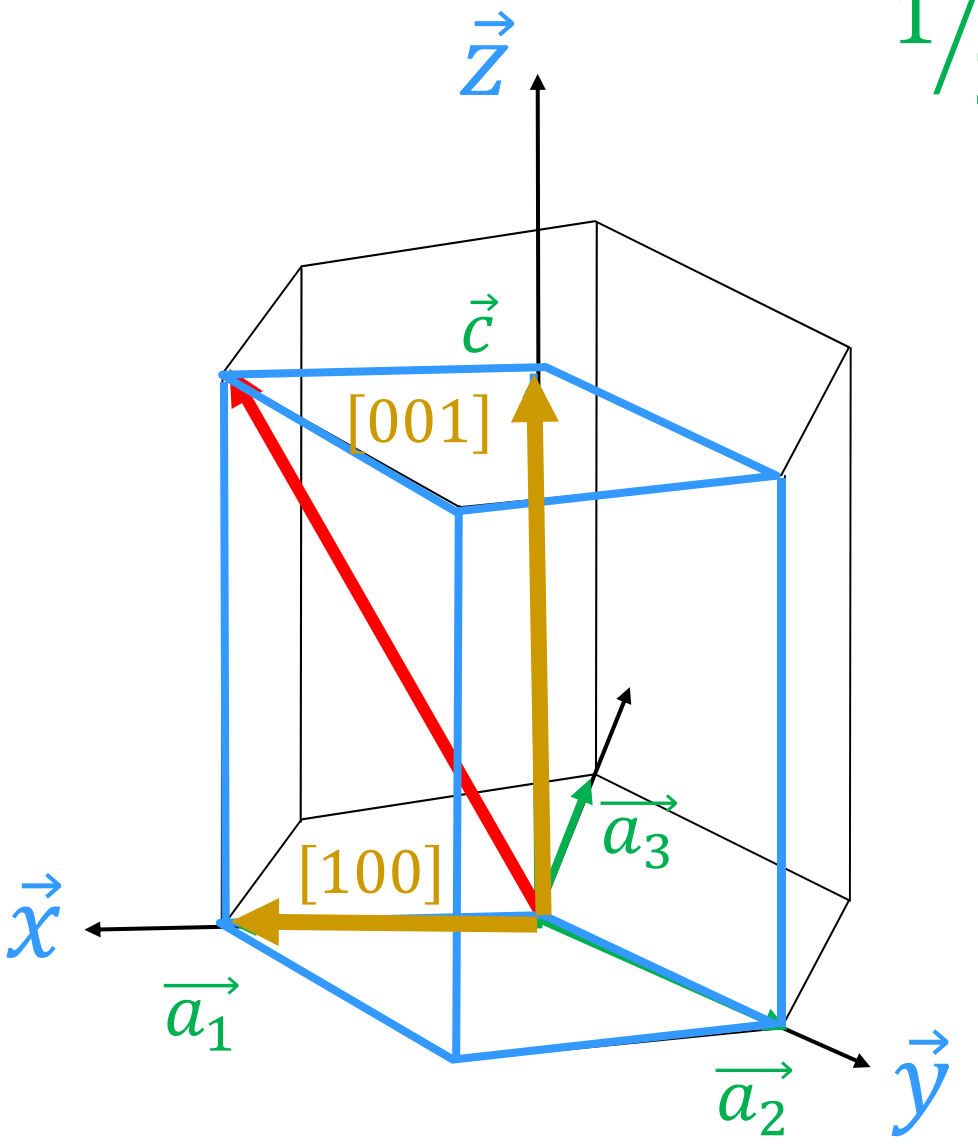
$[101]$

$x$ $y$ $z$

Miller-Bravais index

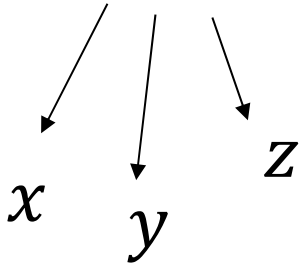
$^{1}/_{3}[2\bar{1}\bar{1}3]$

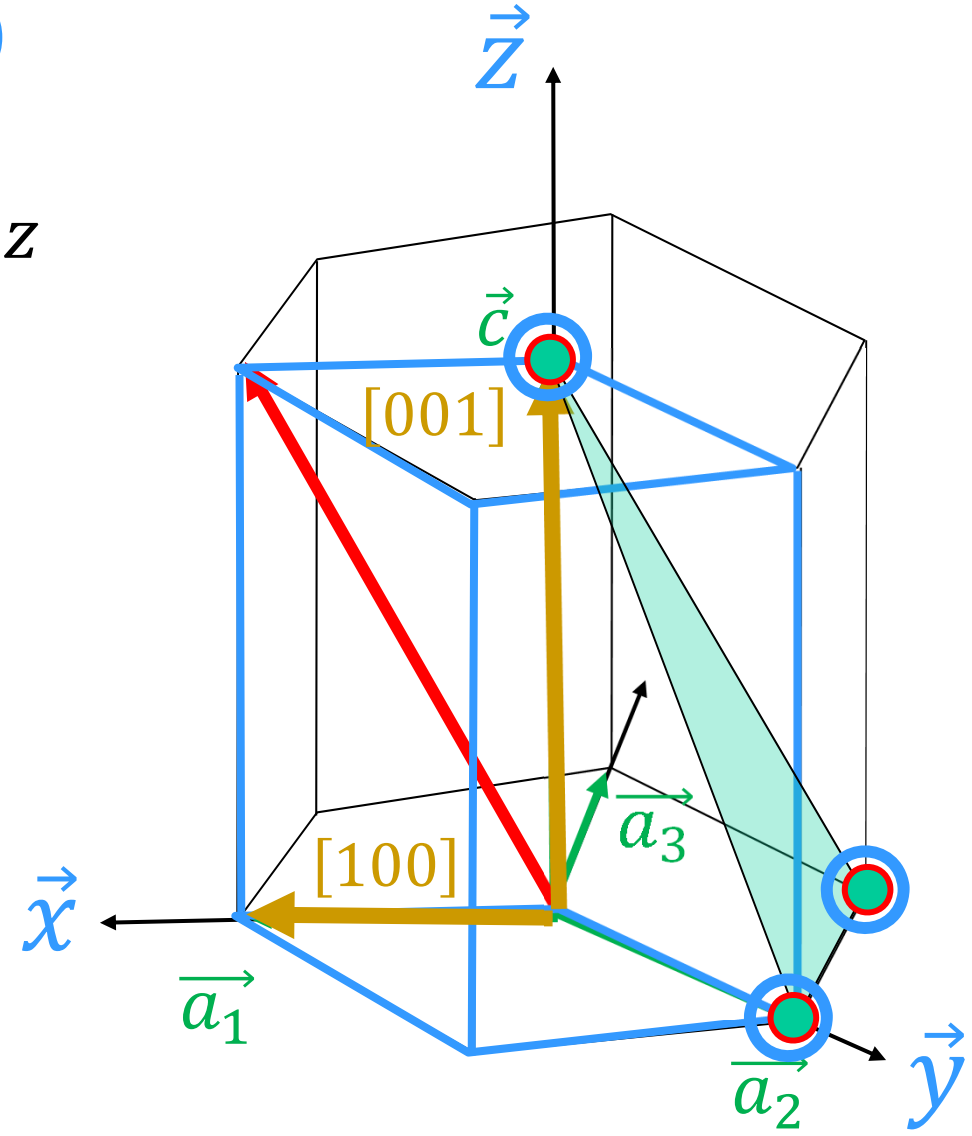
$\overrightarrow{a_1}$ $\overrightarrow{a_2}$ $\overrightarrow{a_3}$ $\vec{c}$



Miller index

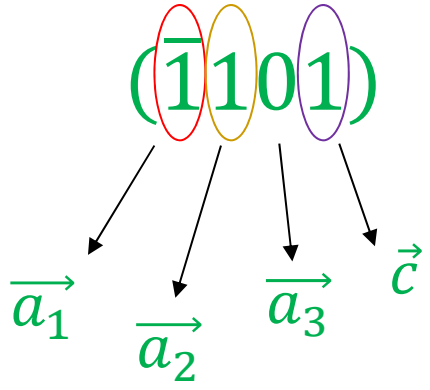
$(\bar{1}11)$




Miller-Bravais index

$(\bar{1}101)$




$$u' = u - t = 2u + v$$

$$v' = v - t = 2v + u$$

$$w' = w$$

Miller index

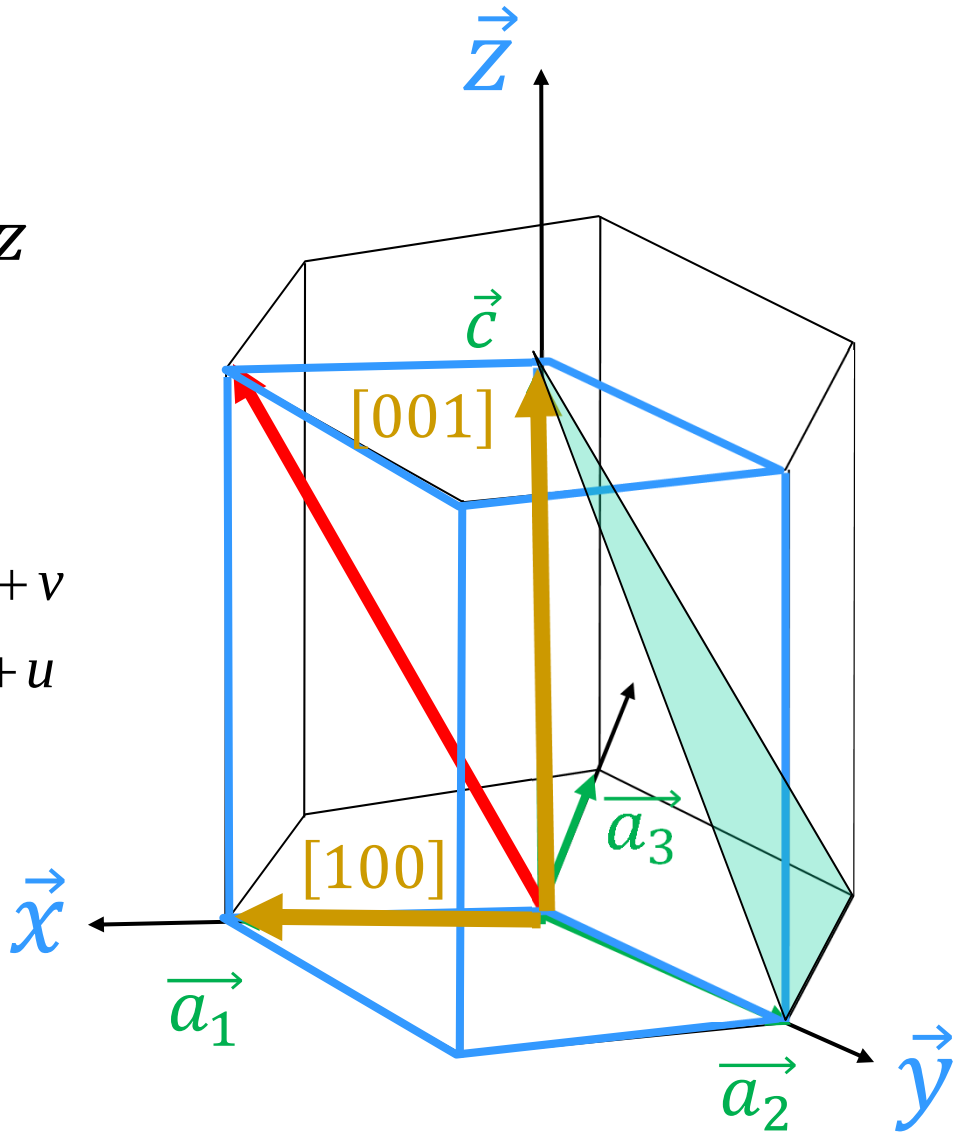
$(\bar{1}11)$

## Miller index

$(\bar{1}11)$

$x$ $y$ $z$

$$u' = u - t = 2u + v$$
$$v' = v - t = 2v + u$$
$$w' = w$$




## Miller-Bravais index

$(\bar{1}101)$

$\vec{a_1}$ $\vec{a_2}$ $\vec{a_3}$ $\vec{c}$

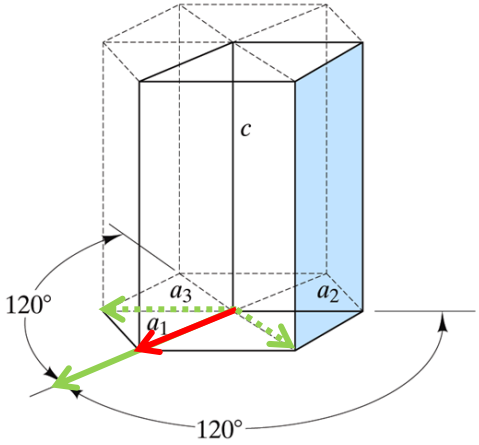
$(10\bar{1}0)$

$$u = \frac{1}{3}(2u' - v')$$
$$v = \frac{1}{3}(2v' - u')$$
$$w = w'$$

# Miller-Bravais vs. Miller index system in Hexagonal system

## Directions

| Miller | Miller–Bravais | Miller | Miller–Bravais |
|---|---|---|---|
| [100] | $[2\bar{1}\bar{1}0]$ | [010] | $[\bar{1}2\bar{1}0]$ |
| [110] | [1120] | $[\bar{1}10]$ | |
| [001] | [0001] | | |
| [011] | $[\bar{1}2\bar{1}3]$ | [111] | $[11\bar{2}3]$ |
| [210] | $[10\bar{1}0]$ | [120] | $[01\bar{1}0]$ |
| [211] | $[10\bar{1}1]$ | [112] | $[11\bar{2}6]$ |




## Conversion of 4 index system (Miller-Bravais) to 3 index (Miller)

$$\vec{t} = u'\vec{a}_1 + v'\vec{a}_2 + w'\vec{c} = u\vec{a}_1 + v\vec{a}_2 + t\vec{a}_3 + w\vec{c}$$

*Miller-Bravais to Miller*
*4 to 3 axis*

$$u' = u - t = 2u + v$$
$$v' = v - t = 2v + u$$
$$w' = w$$

*Miller to Miller-Bravais*
*3axis to 4 axis system*

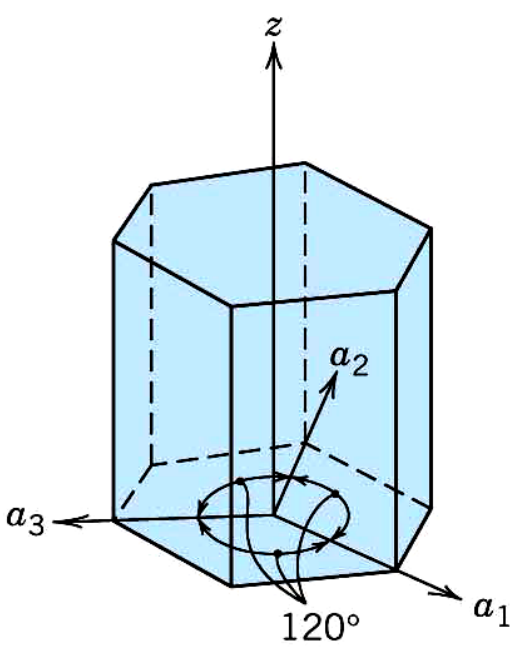
$$u = \frac{1}{3}(2u' - v')$$
$$v = \frac{1}{3}(2v' - u')$$
$$w = w'$$

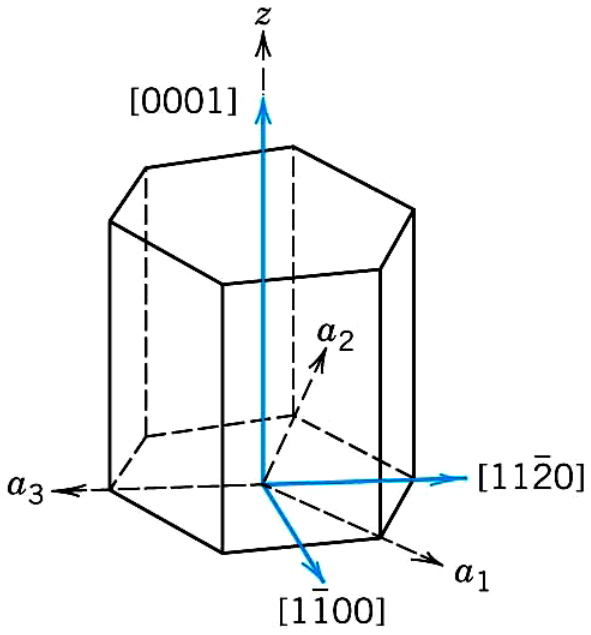
Ex. M [100]
*u=(1/3)(2*1-0)=2/3*
*v=(1/3)(2*0-1)=-1/3*
*w=0*
*=> 1/3[2 -1 -1 0]*

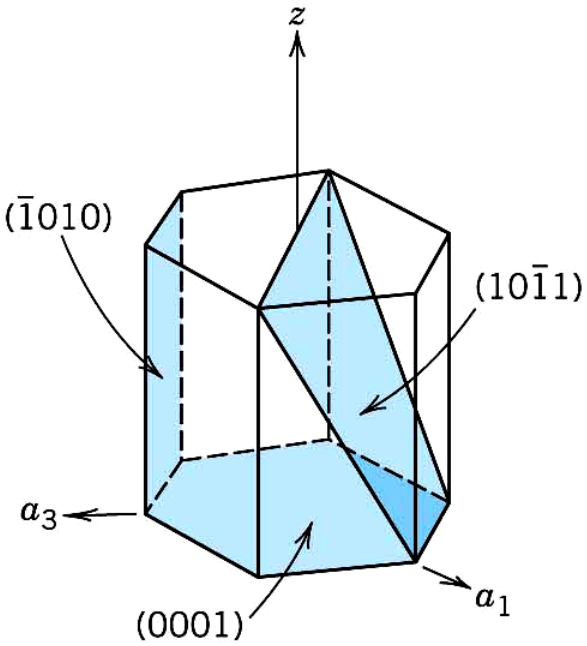
Ex. M-B [1 0 -1 0]
*u'=2*1+0=2*
*v'=2*0+1=1*
*w'=0*
*=> [2 1 0]*

# Hexagonal Crystal

- **Miller-Bravais scheme**



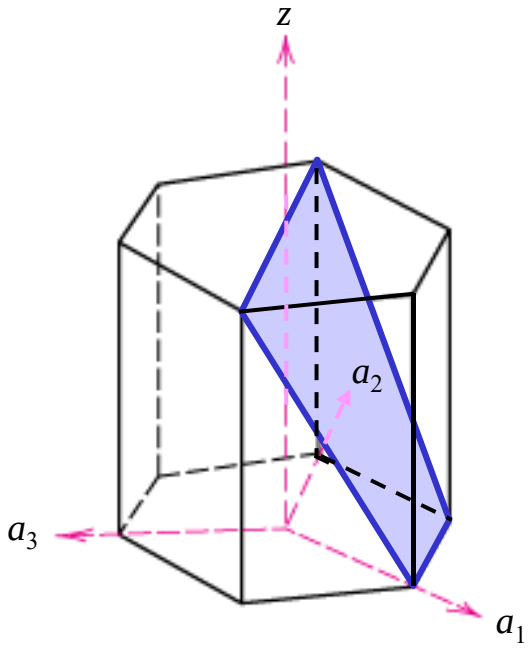

$[uvtw]$ $\qquad$ $(hkil)$

$t = -(u+v)$ $\qquad$ $i = -(h+k)$

# Crystallographic Planes (HCP)

- **In hexagonal unit cells the same idea is used**

| example | $a_1$ | $a_2$ | $a_3$ | $c$ |
|---|---|---|---|---|
| 1. Intercepts | 1 | $\infty$ | -1 | 1 |
| 2. Reciprocals | 1 | $1/\infty$ | -1 | 1 |
| | 1 | 0 | -1 | 1 |
| 3. Reduction | 1 | 0 | -1 | 1 |
| 4. Miller-Bravais Indices | $(10\bar{1}1)$ | | | |

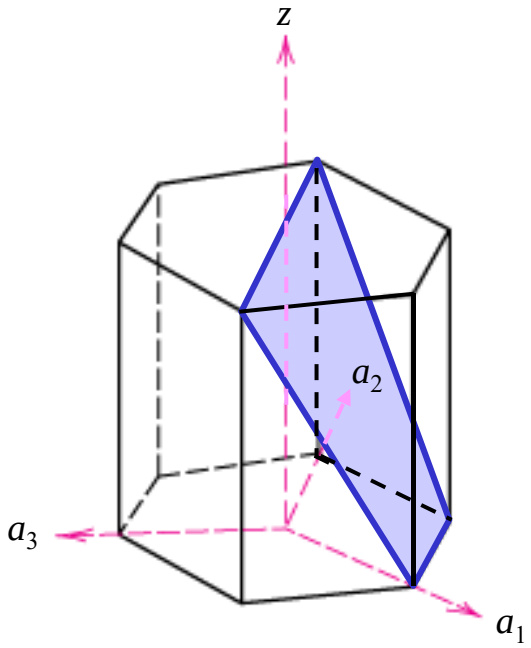



Adapted from Fig. 3.8(a), *Callister 7e.*

# Crystallographic Planes (HCP)

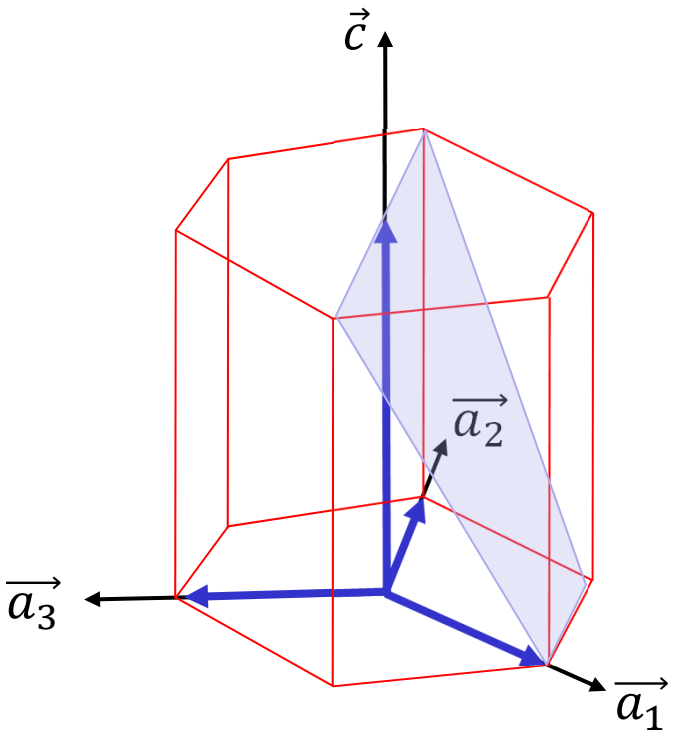
- **In hexagonal unit cells the same idea is used**

| example | | $a_1$ | $a_2$ | $a_3$ | $c$ |
|---|---|---|---|---|---|
| 1. | Intercepts | 1 | ∞ | -1 | 1 |
| 2. | Reciprocals | 1 | 1/∞ | -1 | 1 |
| | | 1 | 0 | -1 | 1 |
| 3. | Reduction | 1 | 0 | -1 | 1 |
| 4. | Miller-Bravais Indices | $(10\bar{1}1)$ | | | |



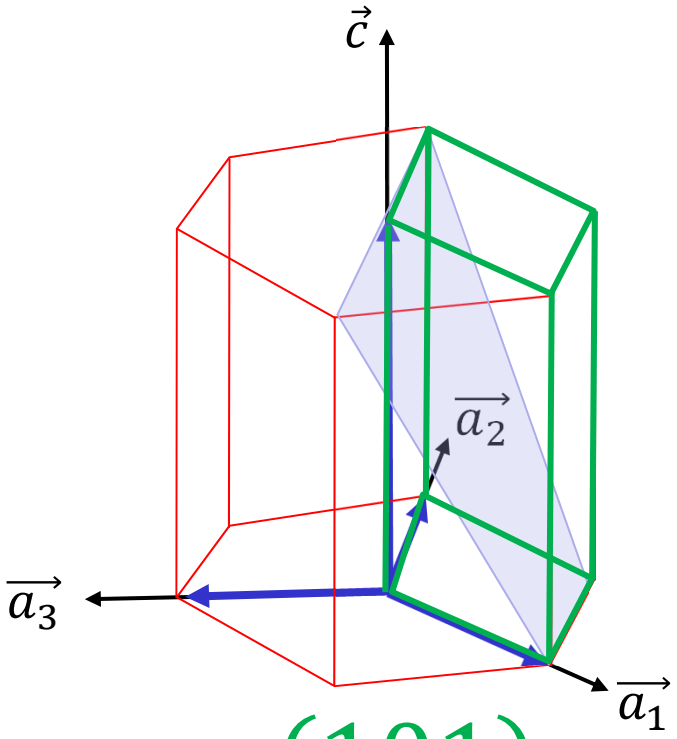

Adapted from Fig. 3.8(a), *Callister 7e.*

## Miller-Bravais index




$(10\bar{1}1)$

## Miller index




$(101)$

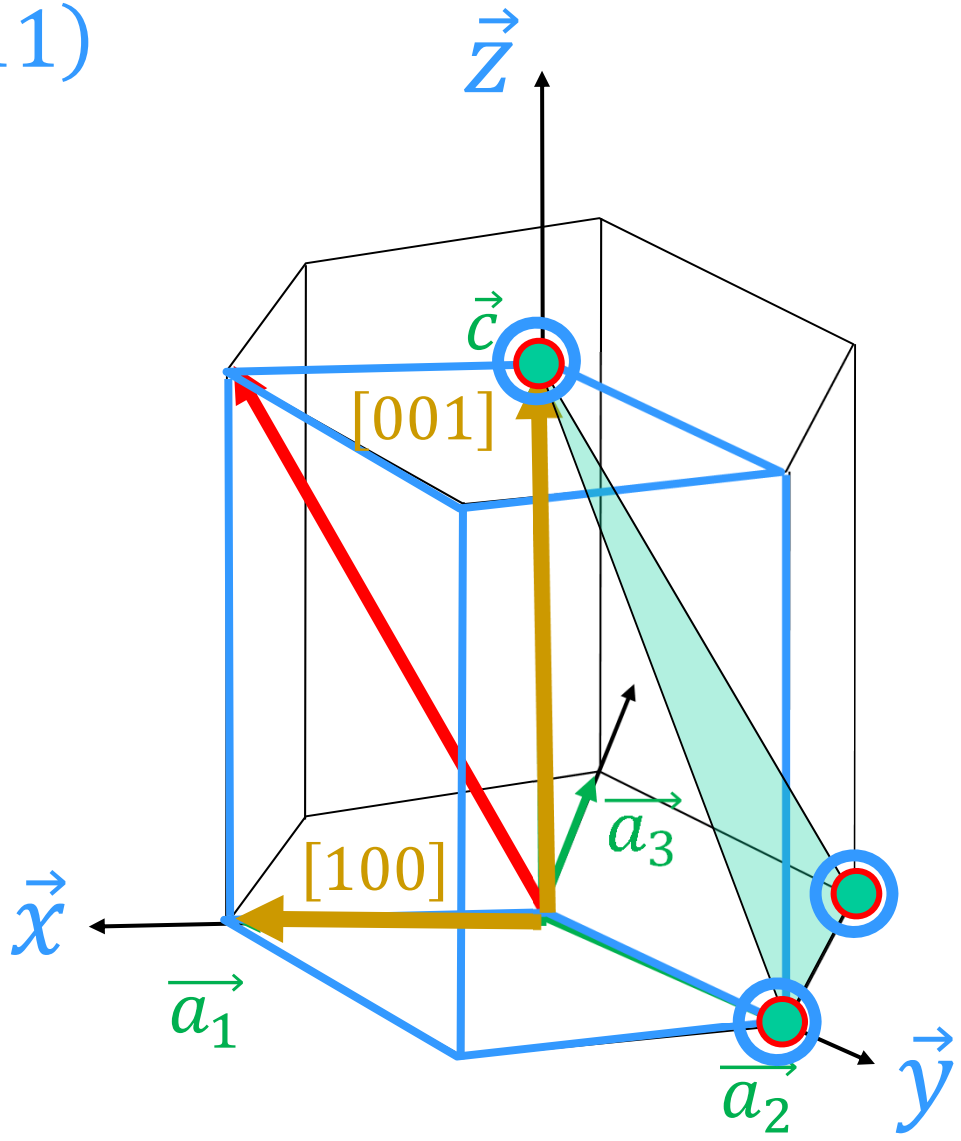
Inverse of 1 =1
Position at $\overrightarrow{a_1}$=1

Inverse of 1 =1
Position at $\vec{c}$ =1

Does not
Meet with $\overrightarrow{a_2}$

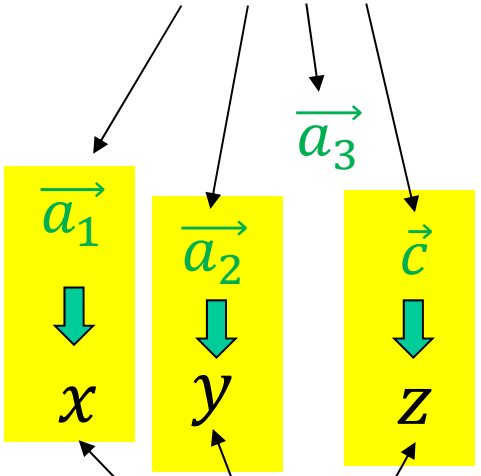
Miller index

$(\bar{1}11)$



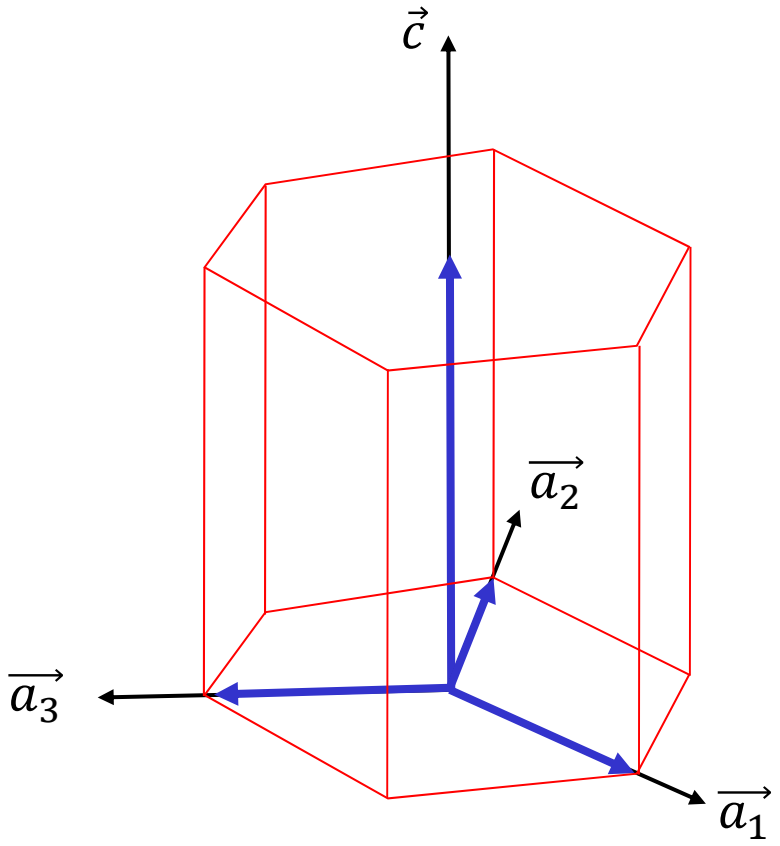

Miller-Bravais index

$(\bar{1}101)$

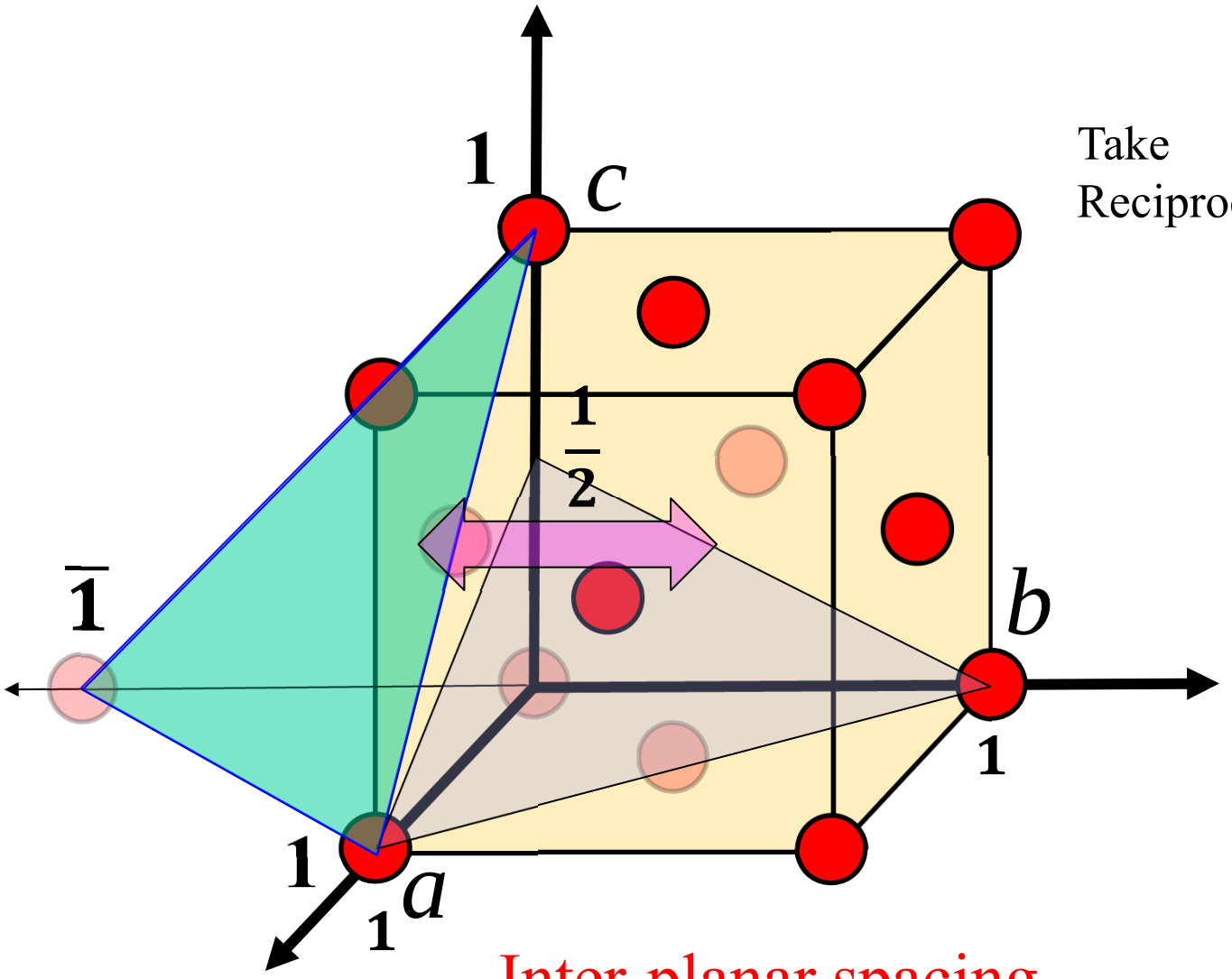



$(\bar{1}11)$

Miller index


$\vec{c}$
$\overrightarrow{a_2}$
$\overrightarrow{a_3}$
$\overrightarrow{a_1}$

# Schematic view of planes



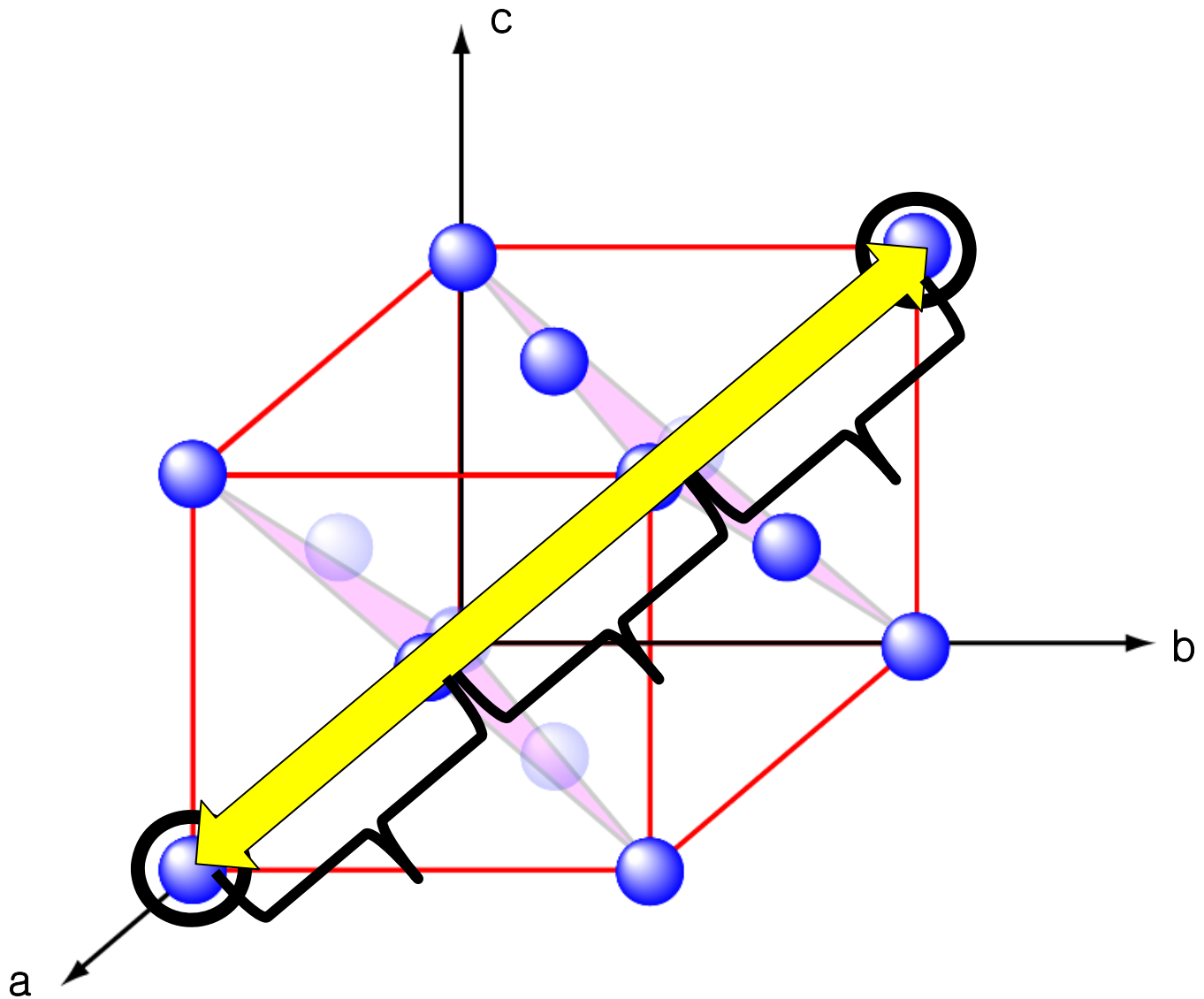

$(112)$

Take Reciprocal $\Rightarrow 1\ 1\ \frac{1}{2}$

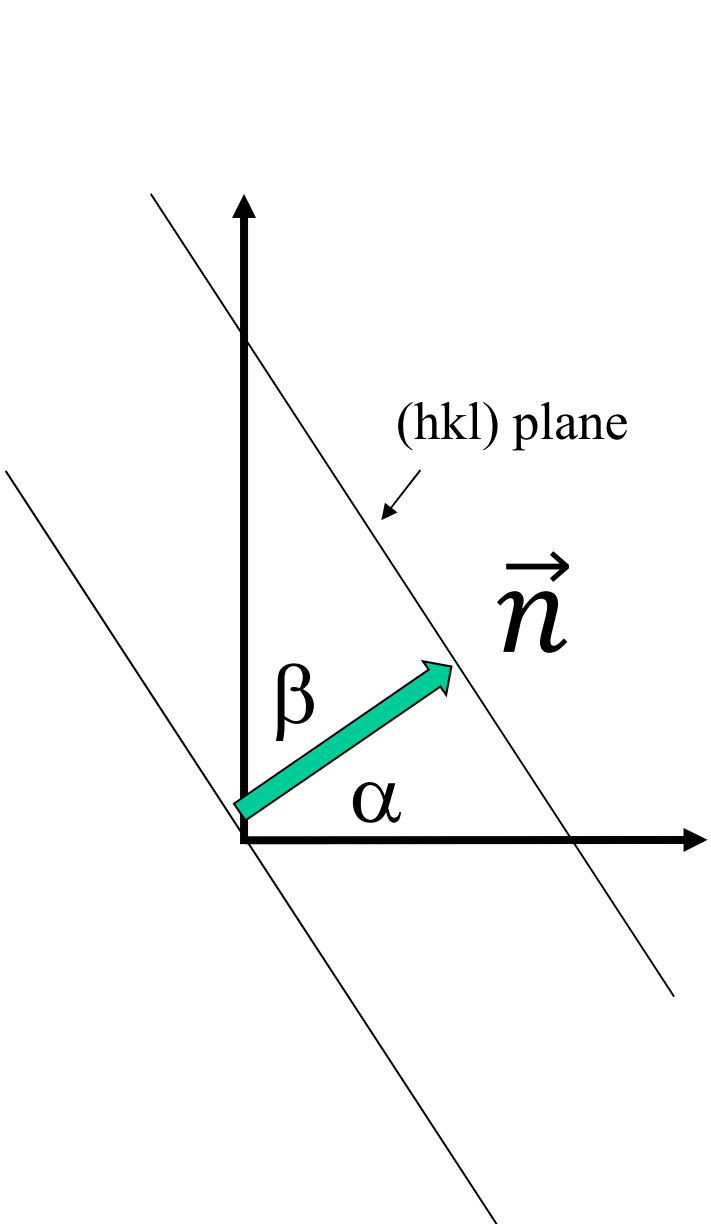
$(1\bar{1}1)$

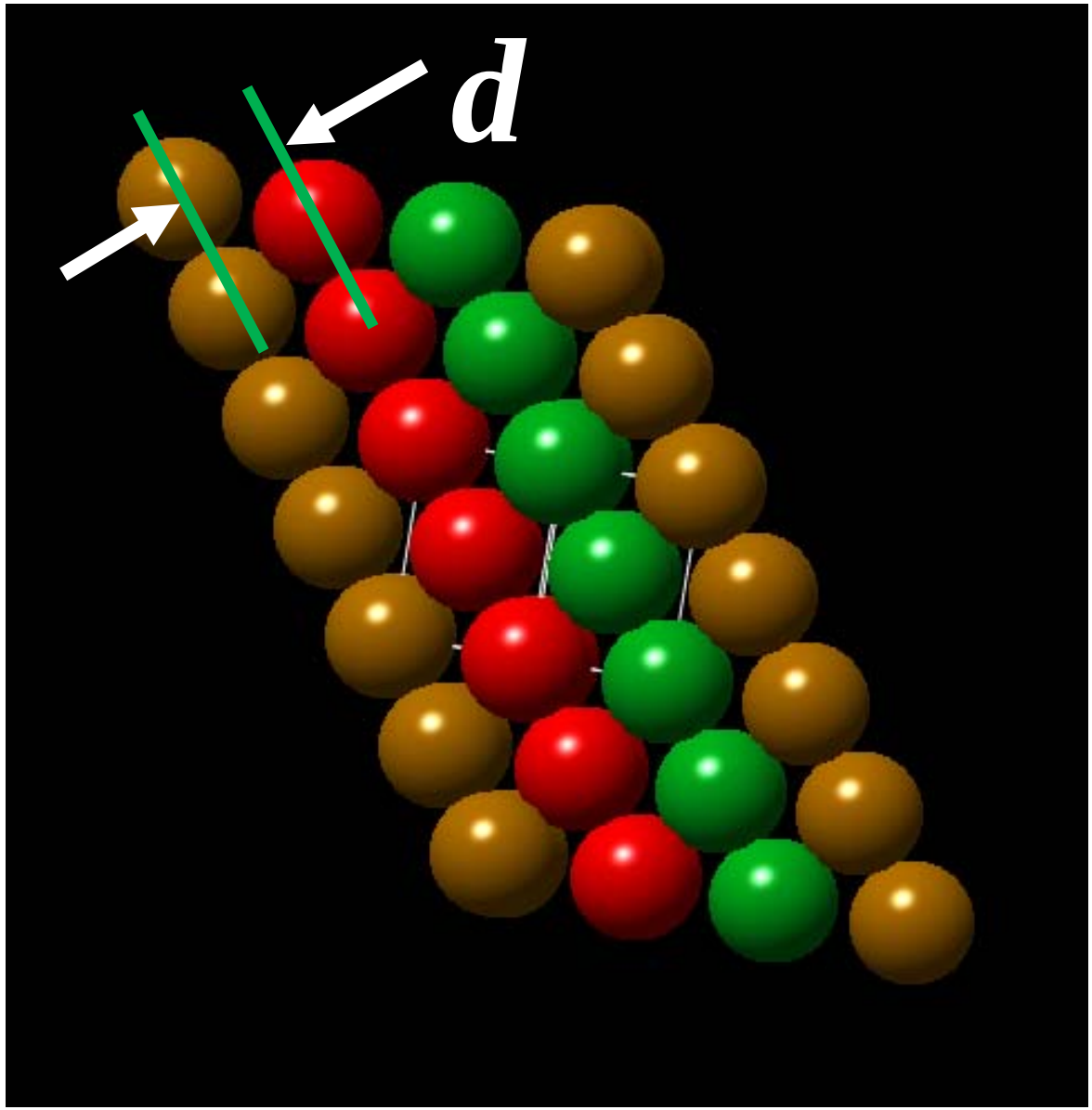
Inter-planar spacing

# Schematic view of $(\bar{1}11)$ plane



# Inter-planar distance (면간거리)



# Interplanar spacing of the (*hkl*) plane

The value of *d* which characterizes the distance between adjacent planes in the set of planes with Miller indices (hkl) is given by the following relations. The cell edges and the angles are *a*, *b*, *c* and α, β ,γ.

*Cubic* :
$$\frac{1}{d^2} = \frac{h^2 + k^2 + l^2}{a^2}$$

*Tetragonal* :
$$\frac{1}{d^2} = \frac{h^2 + k^2}{a^2} + \frac{l^2}{c^2}$$

*Orthorhombic* :
$$\frac{1}{d^2} = \frac{h^2}{a^2} + \frac{k^2}{b^2} + \frac{l^2}{c^2}$$

*Hexagonal* :
$$\frac{1}{d^2} = \frac{4}{3}\left(\frac{h^2 + hk + k^2}{a^2}\right) + \frac{l^2}{c^2}$$

*Rhombohedral* :
$$\frac{1}{d^2} = \frac{1}{\sin^2\beta}\left(\frac{h^2}{a^2} + \frac{k^2\sin^2\beta}{b^2} + \frac{l^2}{c^2} - \frac{2hl\cos\beta}{ac}\right)$$

*Monoclinic* :
$$\frac{1}{d^2} = \frac{(h^2 + k^2 + l^2)\sin^2\alpha + 2(hk + kl + hl)(\cos^2\alpha - \cos\alpha)}{a^2(1 - 3\cos^2\alpha + 2\cos^3\alpha)}$$

*Triclinic* :
$$\frac{1}{d^2} = \frac{1}{V^2}(S_{11}h^2 + S_{22}k^2 + S_{33}l^2 + 2S_{12}hk + 2S_{23}kl + 2S_{31}hl)$$

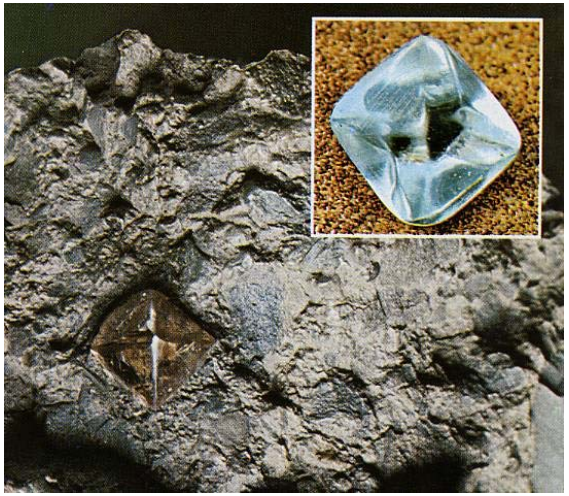
*Where* :
$$V^2 = a^2b^2c^3(1 - \cos^2\alpha - \cos^2\beta - \cos^2\gamma + 2\cos\alpha\cos\beta\cos\gamma)$$

$$S_{11} = b^2c^2\sin^2\alpha$$
$$S_{22} = a^2c^2\sin^2\beta$$
$$S_{33} = a^2b^2\sin^2\gamma$$
$$S_{12} = abc^2(\cos\alpha\cos\beta - \cos\gamma)$$
$$S_{23} = a^2bc(\cos\beta\cos\gamma - \cos\alpha)$$
$$S_{31} = ab^2c(\cos\gamma\cos\alpha - \cos\beta)$$

# CRYSTALS AS BUILDING BLOCKS

- ***Some*** **engineering applications require single crystals:**

**--diamond single crystals**
**Natural and artificial**



**(Courtesy Martin Deakins, GE Superabrasives, Worthington, OH. Used with permission.)**

**--turbine blades**

**Fig. 8.30(c), *Callister 6e.* (Fig. 8.30(c) courtesy of Pratt and Whitney).**

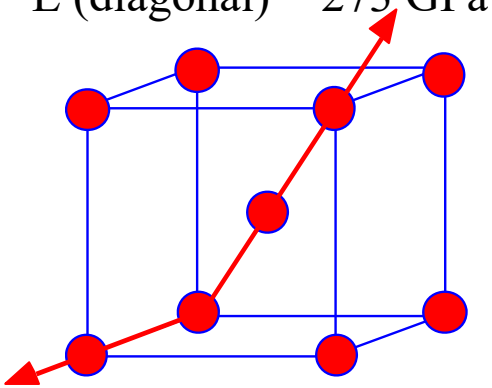
- **Crystal properties reveal features of atomic structure.**

**--Ex: Certain crystal planes in quartz fracture more easily than others.**

**(Courtesy P.M. Anderson)**

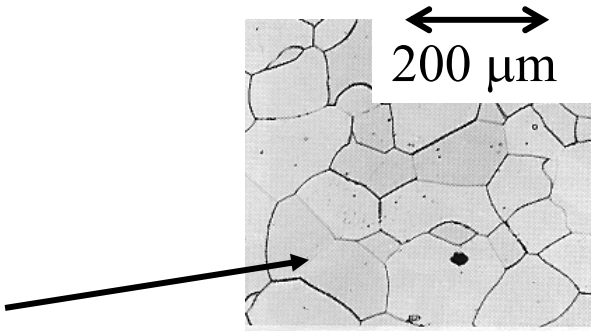
# Single vs Polycrystals

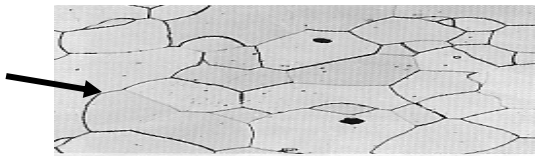
- Single Crystals
  - -Properties vary with direction: anisotropic.
  - -Example: the modulus of elasticity (E) in BCC iron:




Data from Table 3.3, *Callister 7e*. (Source of data is R.W. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, 3rd ed., John Wiley and Sons, 1989.)

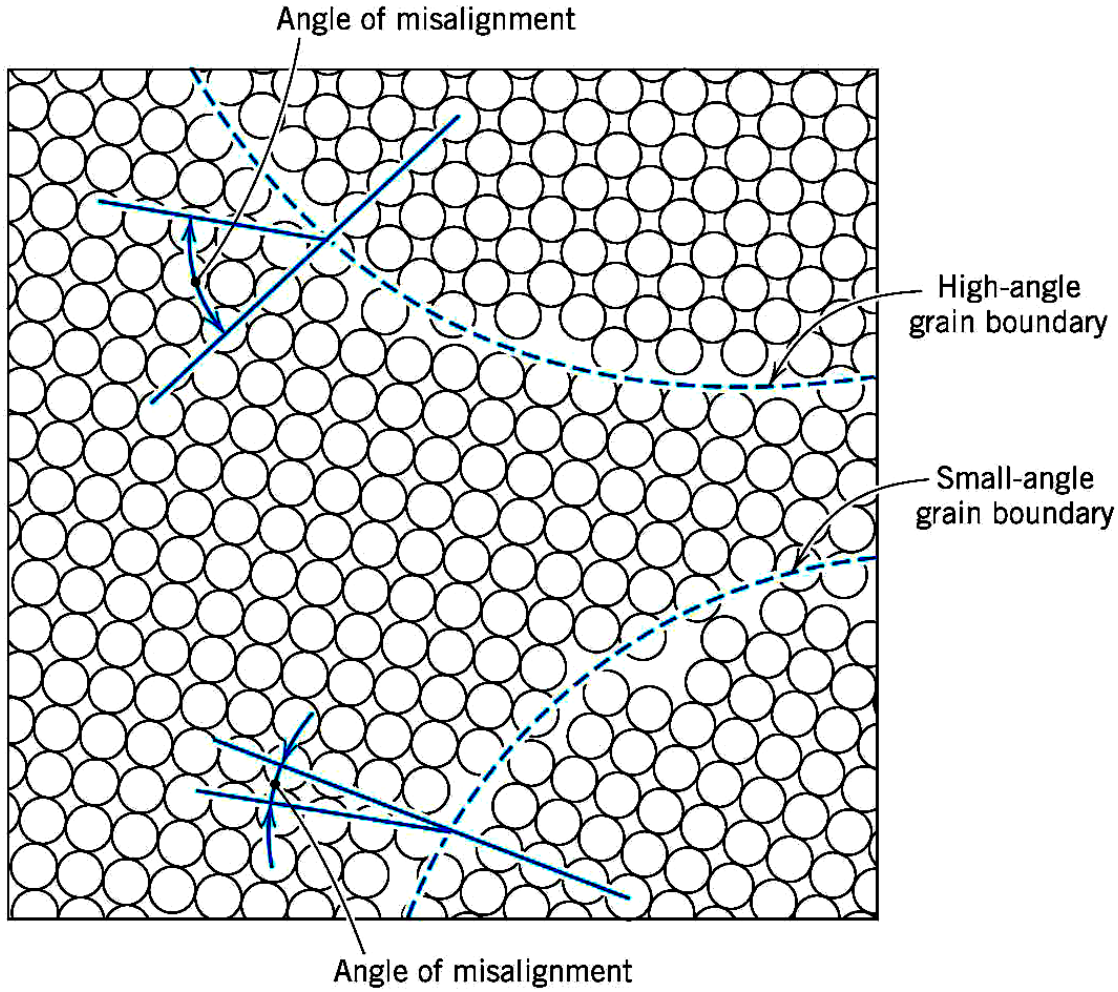
- Polycrystals
  - -Properties may/may not vary with direction.
  - -If grains are randomly oriented: isotropic. ($E_{poly\ iron}$ = 210 GPa)
  - -If grains are textured, anisotropic.

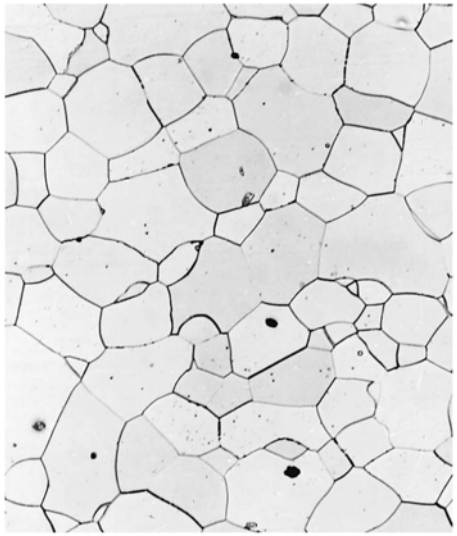


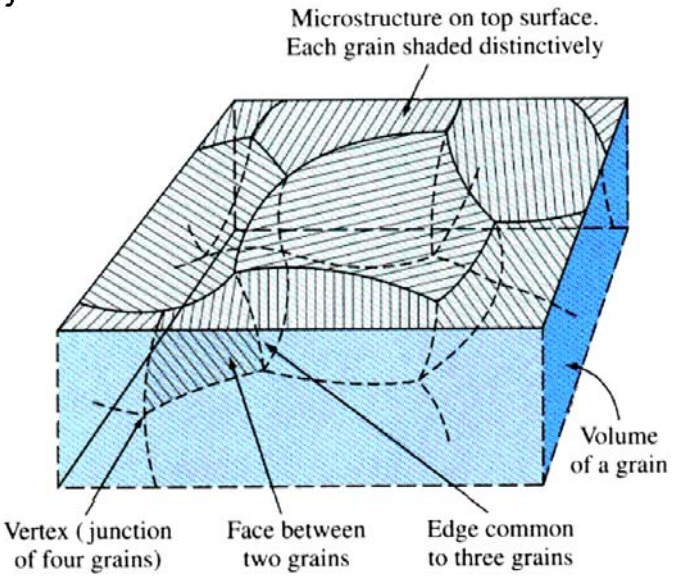



Adapted from Fig. 4.14(b), *Callister 7e*. (Fig. 4.14(b) is courtesy of L.C. Smith and C. Brady, the National Bureau of Standards, Washington, DC [now the National Institute of Standards and Technology, Gaithersburg, MD].)

# Grain Boundaries





# Polycrystals

- *Most* engineering materials are polycrystals.


Adapted from Fig. K, color inset pages of *Callister 5e*. (Fig. K is courtesy of Paul E. Danielson, Teledyne Wah Chang Albany)

- Nb-Hf-W plate with an electron beam weld.
- Each "grain" is a single crystal.
- If grains are randomly oriented,
  overall component properties are not directional.
- Grain sizes typ. range from 1 nm to 2 cm
  (i.e., from a few to millions of atomic layers).

# Polymorphism

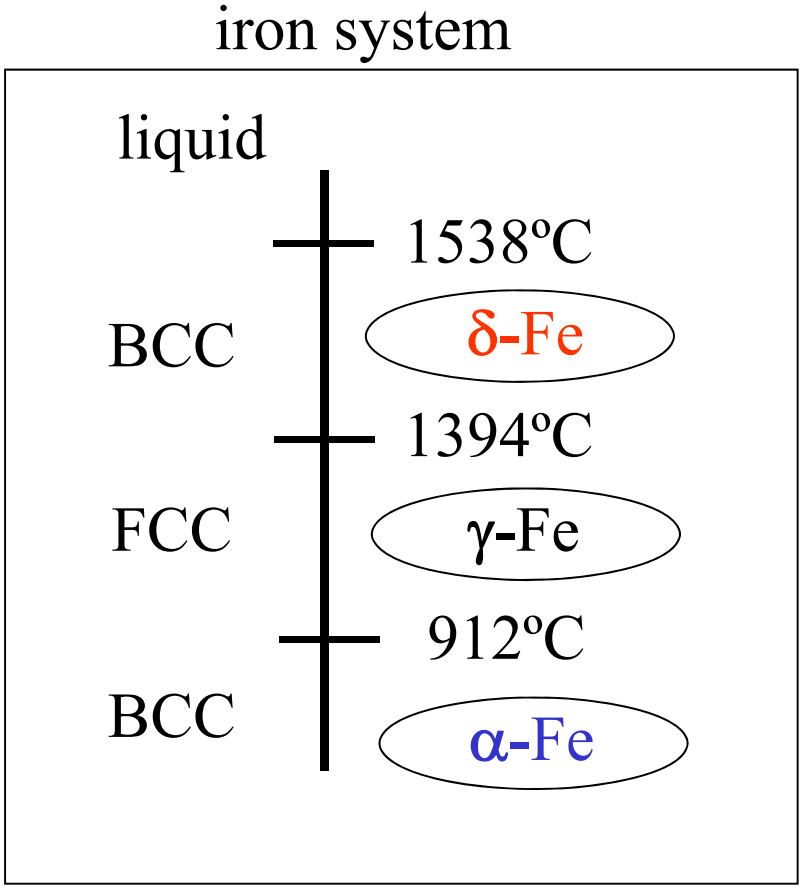
- **Two or more distinct crystal structures for the same material (allotropy/polymorphism)**

**titanium**

$\alpha$, $\beta$-**Ti**

**carbon**

**diamond, graphite**



# DEMO: HEATING AND COOLING OF AN IRON WIRE

- Demonstrates "polymorphism" ← The same atoms can have more than one crystal structure.