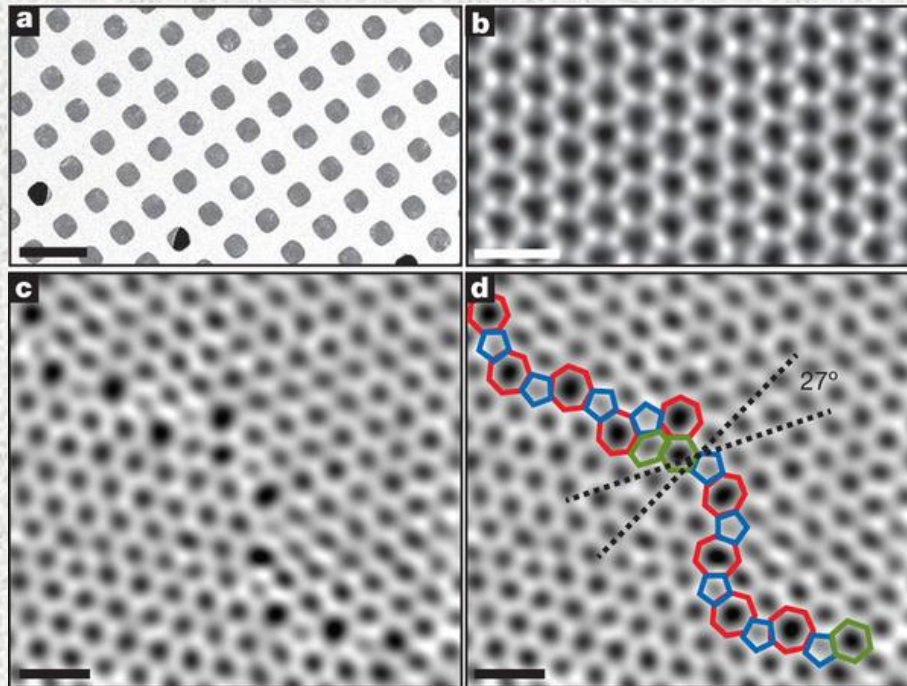


# Defect in crystals



Primer in Materials Science  
Spring 2021

# Introduction

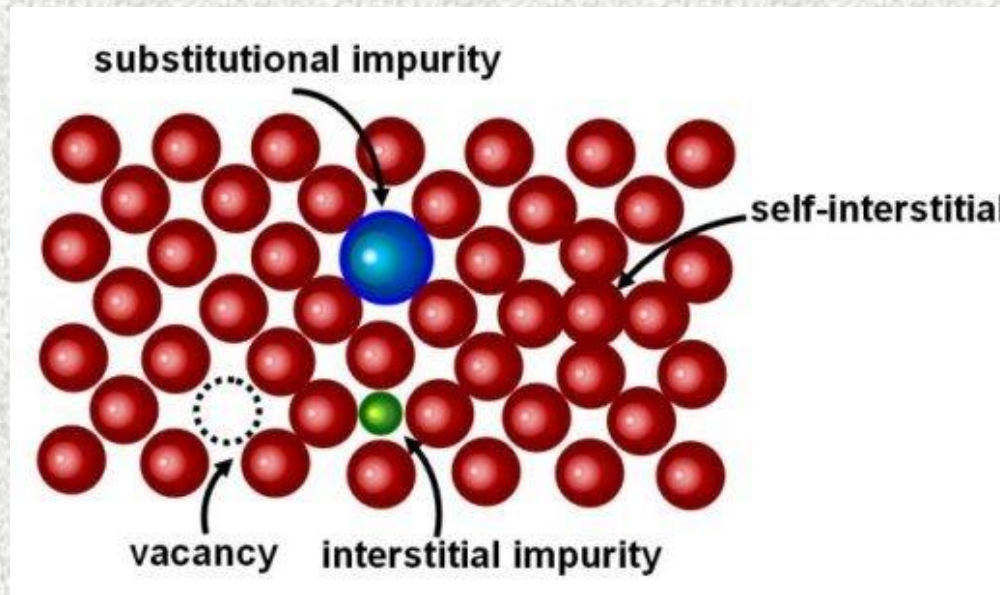
- **The arrangement of the atoms in all materials contains imperfections which have profound effect on the behavior of the materials**
- **Lattice defects can be sorted into three**
  1. **Point defects (vacancies, interstitial defects, substitution defects)**
  2. **Line defect (screw dislocation, edge dislocation)**
  3. **surface defects (material surface, grain boundaries)**

# Why defect are important?

There are a lot of properties that are controlled or affected by defects, for example:

- ❖ **Electric and thermal conductivity in metals** (strongly reduced by point defects).
- ❖ **Electronic conductivity in semi-conductors** (controlled by substitution defects).
- ❖ **Diffusion** (controlled by vacancies).
- ❖ **Ionic conductivity** (controlled by vacancies).
- ❖ **Plastic deformation in crystalline materials** (controlled by dislocation).
- ❖ **Colors** (affected by defects).
- ❖ **Mechanical strength** (strongly depended on defects).

# Points defects



**Self-interstitial** – A self-interstitial is an atom from the crystal that is crowded into an interstitial site, a small void space that under ordinary circumstances is not occupied.

the formation of this defect is not highly probable, and it exists in very small concentrations



# Vacancies

- A **vacancy** is produced when an atom is missing from a normal site.
- The equilibrium number of vacancies  $N_v$  has Temp depends:
  - ❖  $N$  – Total number of atoms
  - ❖  $Q_v$  – energy require for vacancy formation

$$N_v = N \exp\left(-\frac{Q_v}{kT}\right)$$

## Example 3.1

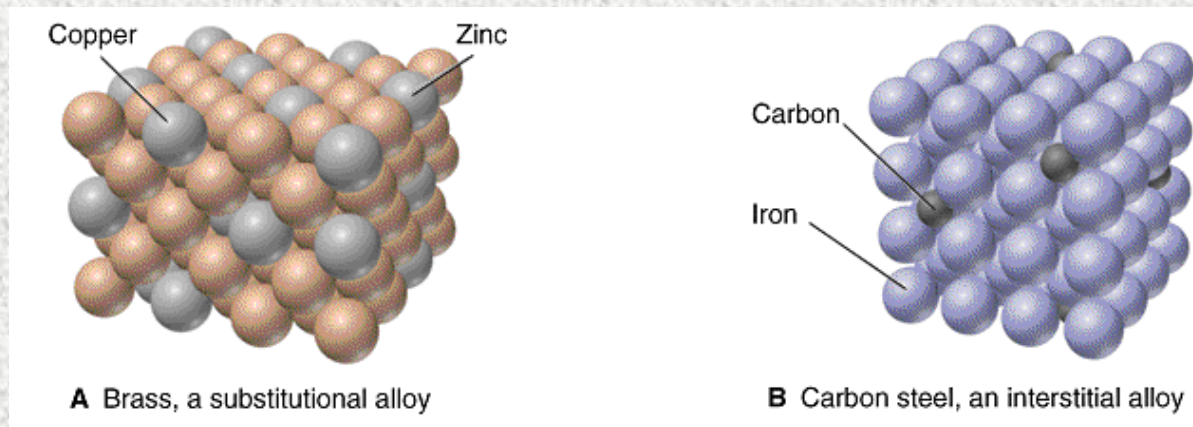
Calculate the equilibrium value of vacancies concentration for copper at 1000K. the energy for vacancy formation is 0.9 eV/atom;

$$\begin{aligned}
 Q_v &:= 0.9 \text{ eV} & k_B &:= 1.38 \cdot 10^{-23} \frac{\text{J}}{\text{K}} & T &:= 1000 \text{ K} \\
 & & & & & 1 \text{ eV} = 1.602 \times 10^{-19} \text{ J} \\
 \frac{-Q_v}{k_B \cdot T} &= 2.939 \times 10^{-5}
 \end{aligned}$$

One vacancy per  $\frac{1}{(2.939 \times 10^{-5})} = 3.403 \times 10^4$  copper atoms

# Impurities in solids

- A pure metal consisting of only one type of atom just isn't possible.
- impurity or foreign atoms will always be present, and some will exist as crystalline point defects.
- The addition of impurity atoms to a metal will result in the formation of a solid solution



- Impurity point defects are found in solid solutions, of which there are two types:
  1. **Substitutional** – one atom is replaced by as different type of atom
  2. **Interstitial** – extra atom is inserted into the lattice structure at a normally unoccupied position

# Hume-Rothery rules

For the substitutional type there are several features of the solute and solvent atoms that determine the degree to which the former dissolves in the latter, as follows:

1. **Atomic size factor** – The atomic radii of the solute and solvent atoms must differ by no more than 15%
2. **Crystal structure** - The crystal structures of solute and solvent must match.
3. **Electronegativity** - The solute and solvent should have similar electronegativity. If the electronegativity difference is too great, the metals will tend to form intermetallic compounds instead of solid solutions.
4. **Valences** - Complete solubility occurs when the solvent and solute have the same valency. A metal will have more of a tendency to dissolve another metal of higher valence than one of a lower valence

# Example 3.2

Using Hume-Rothery rule please predict whether these metals will or will not be soluble in each other

- a) Fe and Cu.  $r_{\text{Cu}}=0.128\text{nm}$ ,  $r_{\text{Fe}}=0.126\text{ nm}$ ; Fe=BCC, Cu=FCC;  $\text{Cu}^+/\text{Cu}^{+2}$ ,  $\text{Fe}^{3+}/\text{Fe}^{+2}$   
- No soluble at room temperature, slightly soluble at high temperature
- b) Ni and Cu.  $r_{\text{Cu}}=0.128\text{nm}$ ,  $r_{\text{Ni}}=0.125\text{ nm}$ ; Ni=FCC, Cu=FCC;  $\text{Ni}^{+2}$ ,  $\text{Cu}^+/\text{Cu}^{+2}$   
- fully soluble
- c) Al and Ag.  $r_{\text{Al}}=0.143\text{nm}$ ,  $r_{\text{Ag}}=0.144\text{ nm}$ , Al=FCC, Cu=FCC;  $\text{Al}^{+3}$ ,  $\text{Ag}^{+1}$   
- Al is soluble in Ag, Ag is slightly soluble in Al.



# The Ratio Between The Interstitial Atom Radius (**r**) and The Lattice Atom (**R**)

**SC**: cubic-  $r \leq 0.732R$

**FCC**: octahedron-  $r \leq 0.414R$

tetrahedron-  $r \leq 0.224R$

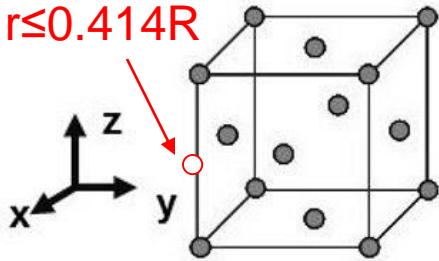
**BCC**: octahedron-  $r \leq 0.154R$

# Example 3.3

Explain why FCC steel does not transform to BCC steel when rapidly cooled from 750°C to room temperature

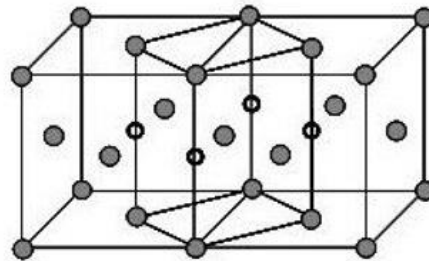
Interstitial site

$$r \leq 0.414R$$



$\gamma$ -FCC

● Fe    ○ C



Bain model

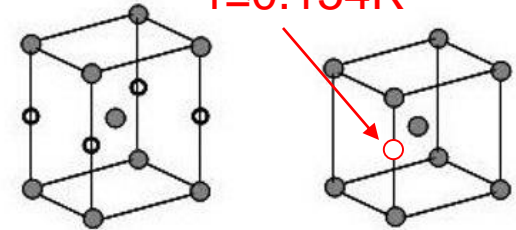
$$R_{\text{Fe}} = 156 \text{ pm}$$

$$r_{\text{C}} = 67 \text{ pm}$$

$$r_{\text{C}}/R_{\text{Fe}} = 0.43$$

Interstitial site

$$r \leq 0.154R$$

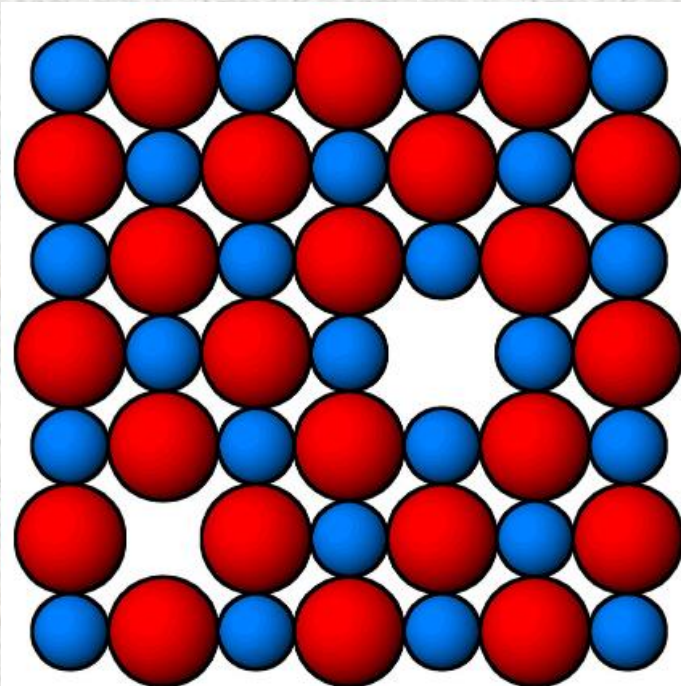


$\alpha'$ -BCT  
martensite

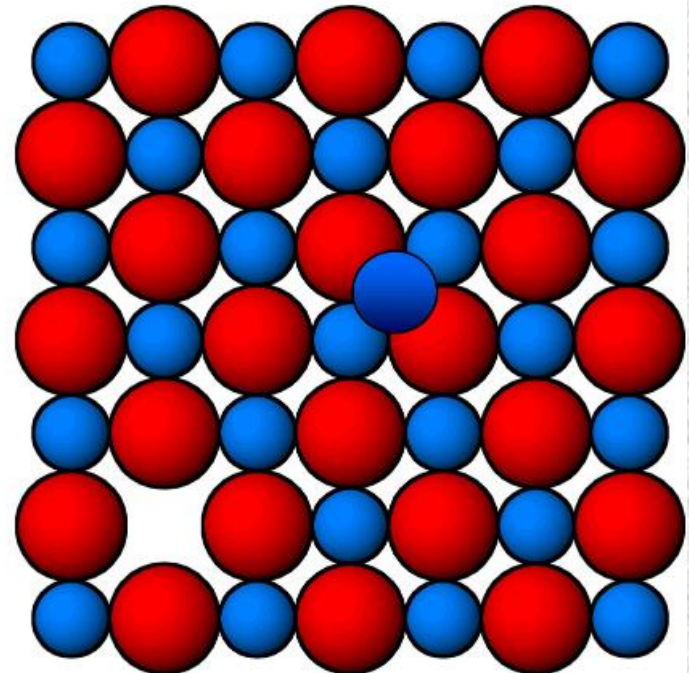
$\alpha$ -BCC

# Other points defects

- **Frenkel defect** – ion jumps from a normal lattice point to an interstitial site, leaving behind a vacancy (vacancy-interstitial)
- **Schottky** – pair of vacancies in ionically bonded material. Both anion and cation must be missing from the lattice to maintain the crystal neutral.



Schottky Defect (missing pair of ions)

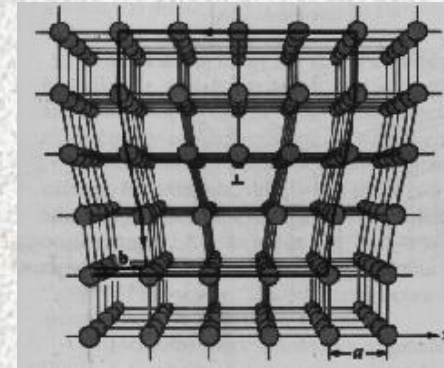
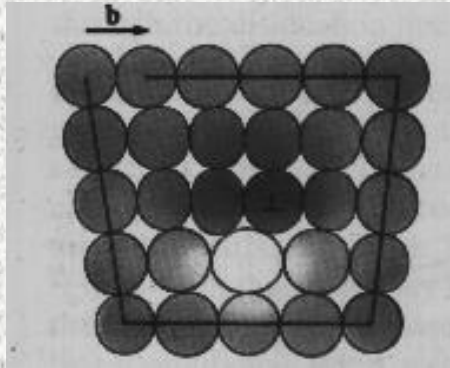


Frenkel Defect (cation in interstitial hole)

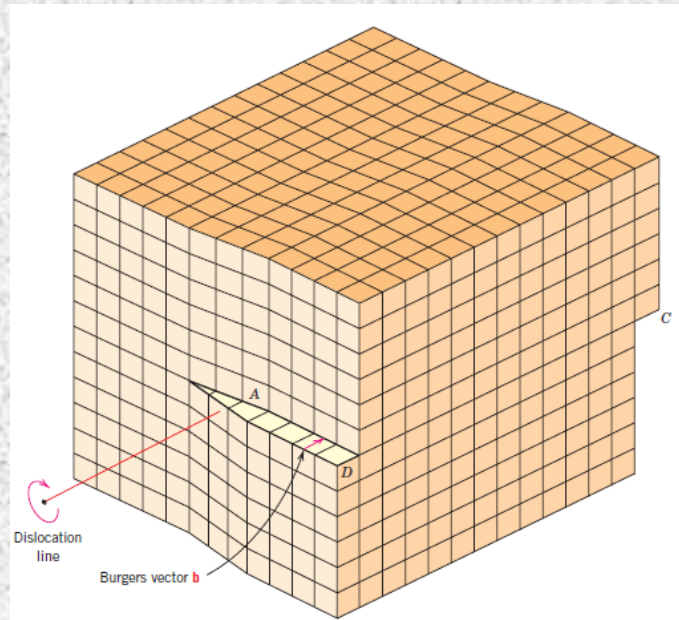


# Line defects - Dislocations

## Edge Dislocation



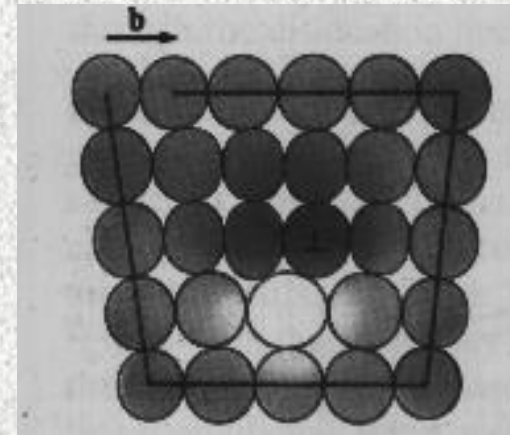
## Screw Dislocation





# Burgers vector

- **Burgers vector** represents the magnitude and direction of the lattice distortion resulting from a dislocation in a crystal lattice. In **edge dislocation**, Burgers vector is **perpendicular** to the dislocation line and in **screw dislocation**, Burgers vector is **parallel** to the dislocation line.
- For mobile dislocation, the direction of the vector is **usually** on one of the most packed crystallographic planes (**slip planes**) and **always** in the most packed crystallographic directions (**slip directions**). The slip plane is the **plane that contains both** the Burgers vector and the dislocation line.
- The slip planes + the slip directions call the **slip systems** and represent the planes and the directions in which **plastic deformation** can occur.



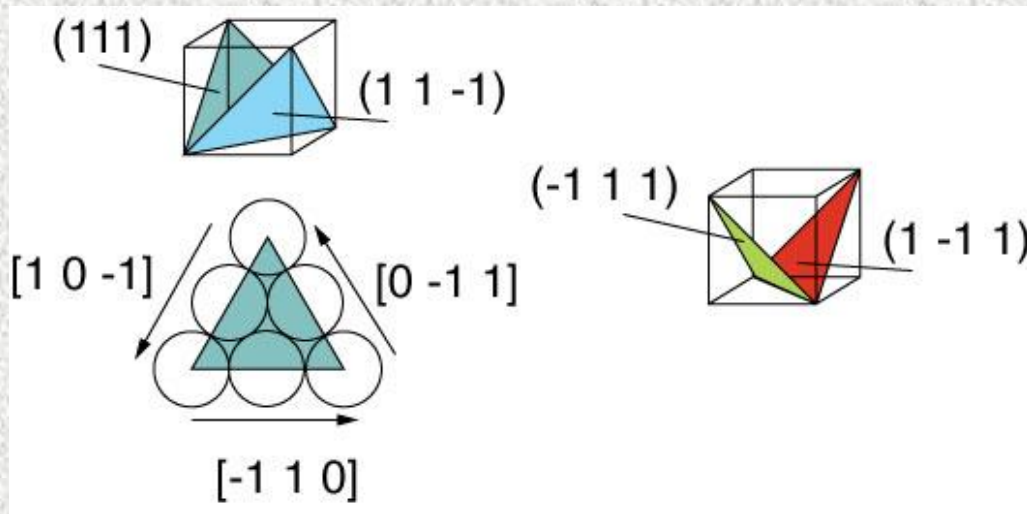
# Example 3.4

Calculate the magnitude of Burgers vector and number of slip system for FCC.

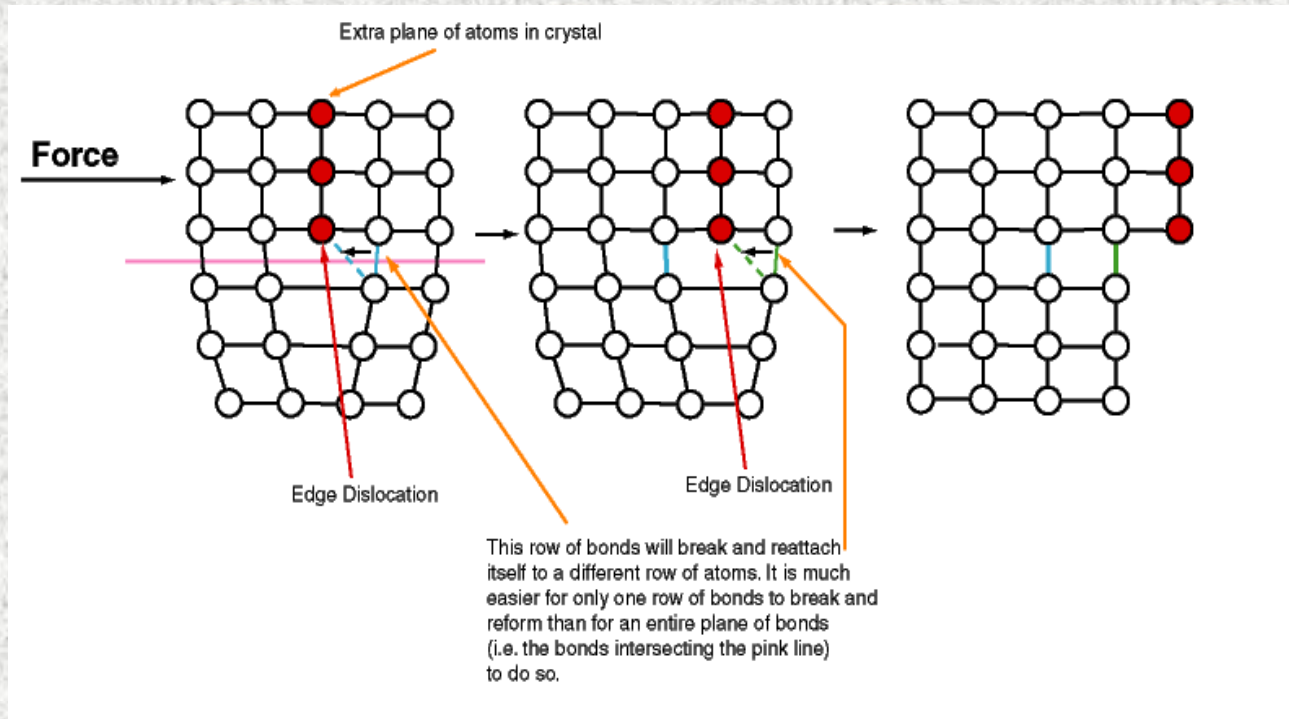
The most dense directions in FCC are  $\langle 110 \rangle$ . These directions are in  $\{111\}$  planes.

$$|\vec{b}| = a/2 \langle 110 \rangle = a(\sqrt{2}/2)$$

3 directions X 4 planes = 12 slip systems



# Dislocation movement



Theoretical Shear strength  $\sim G/10$

Real Shear strength  $\sim G/1000$

# Hardness

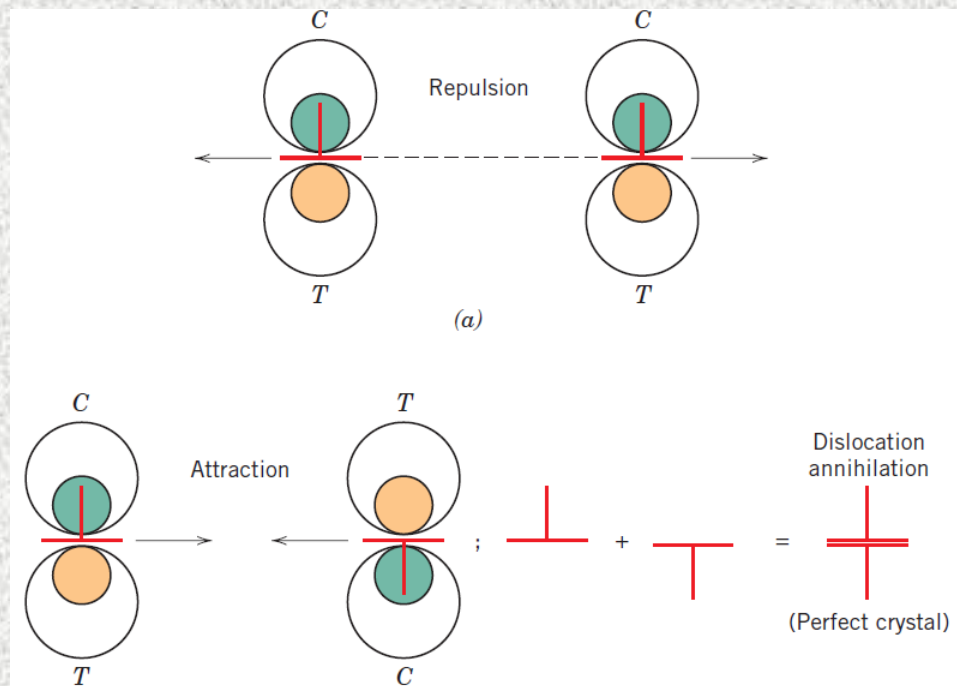
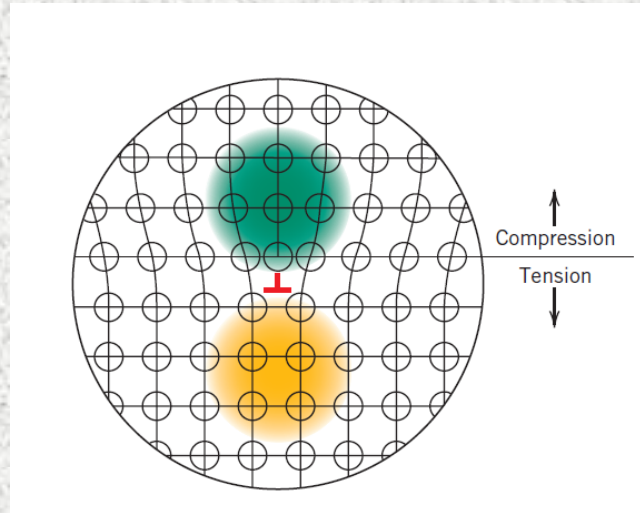
**Hardness**- the ability to resist plastic deformation

We can increase the hardness by:

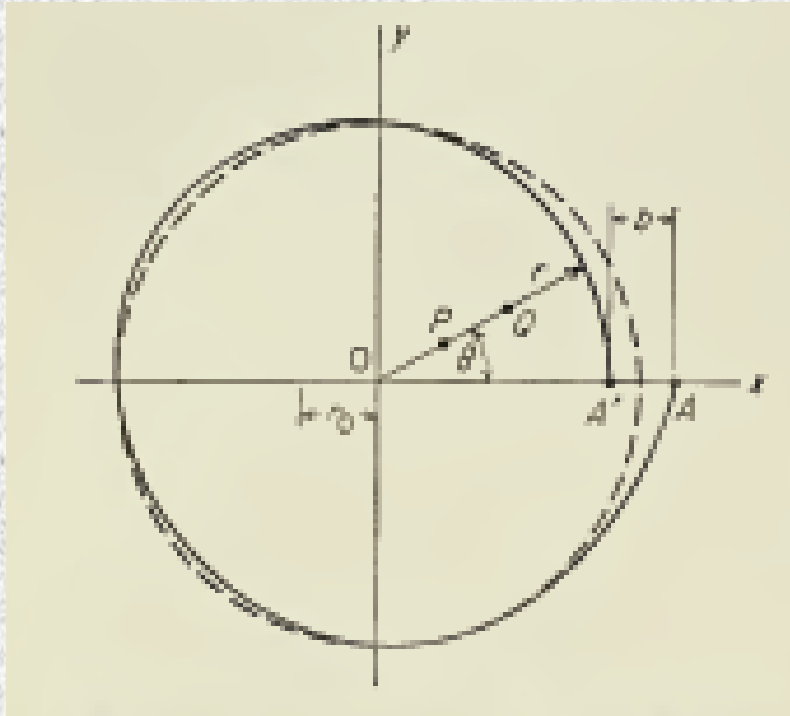
- Impurities
- Internal Stress
- Increasing the dislocation concentration



# Dislocation interactions



# Strain Energy and Force Between Dislocations



$U$  – energy per unit length  
 $r_0$  – core radius  
 $r$  – dislocation radius  
 $G$  – shear modulus  
 $R$  – distance between dislocations

$$U_{Ed} = \frac{Gb^2}{4\pi(1-\nu)} \ln \frac{r}{r_0}$$

$$U_{Sc} = \frac{Gb^2}{4\pi} \ln \frac{r}{r_0}$$

$$U_{core} = \frac{Gb^2}{2\pi}$$

$$r_0 \approx b \sim 2\text{\AA}; r \sim 1000\text{\AA}$$

$$F_{Sc} = \frac{Gb^2}{2\pi R}$$

# Example 3.5

What will happen to two dislocations,  $(a/2)[-1-11]$  and  $(a/2)[111]$ , in  $(10-1)$  plane BCC ?

$$(a/2)[111] + (a/2)[-1-11] \longrightarrow a[001]$$

$$U \propto b^2 \longrightarrow 3/4a^2 + 3/4a^2 > a^2$$

Since  $a[001]$  is not in the most dense direction, this dislocation is immobile

