# 재료의 기계적 거동
# (Mechanical Behavior of Materials)

## Defects, Dislocations

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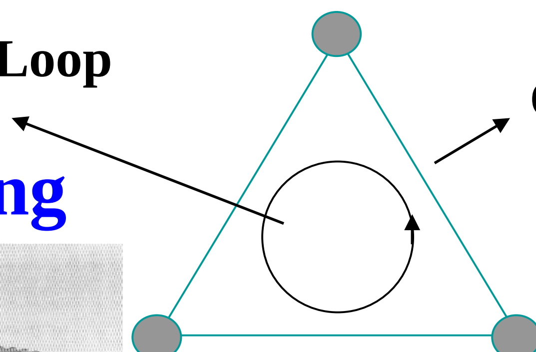
# Why study defects in materials?

- Defects are present in all materials.
- It is defects that make materials much more interesting !
- Defects affect microstructures and properties of materials.
- Processing controls the presence and concentration of defects.

**Microstructure**

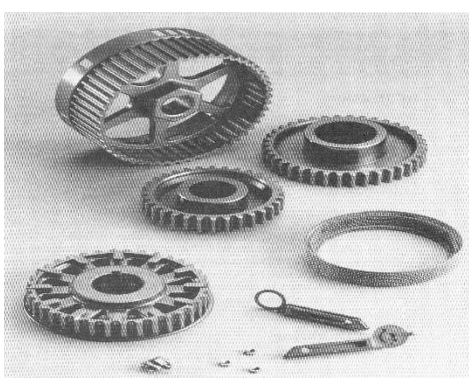
**Materials Optimization Loop**

**Observation**



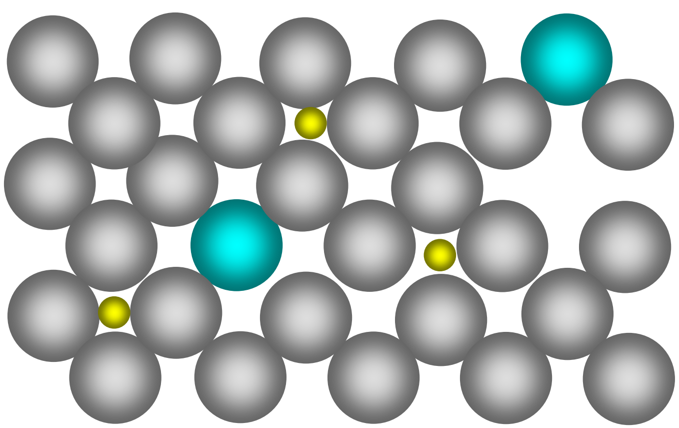
**Processing**

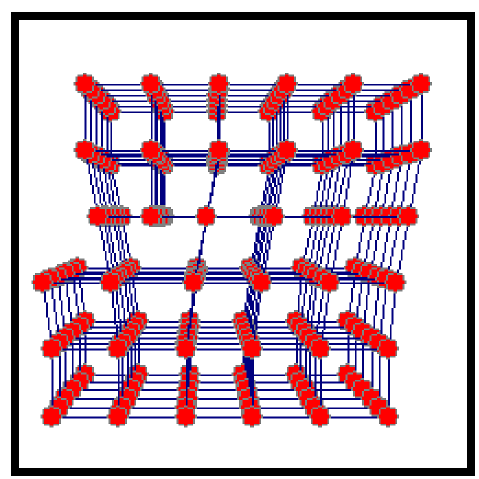
**Properties**

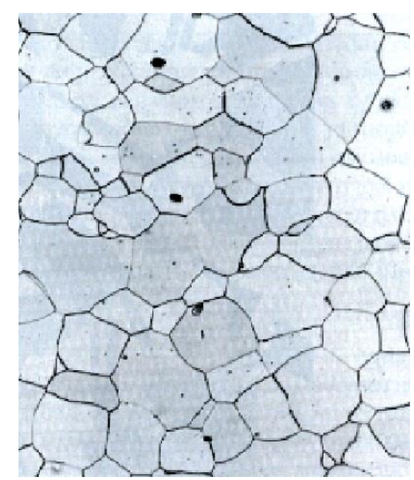


# Types of Defect

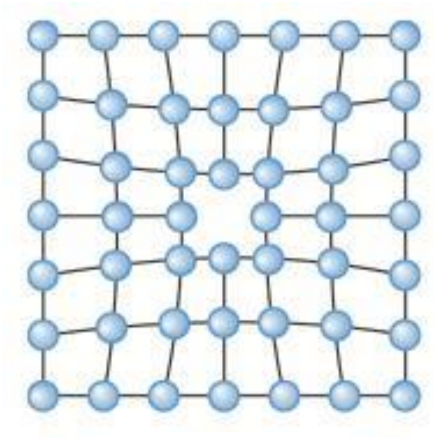
| | | |
|---|---|---|
| 0-dimensional | Point defects | Vacancy atoms<br>Interstitial atoms<br>Substitutional atoms |
| 1-dimensional | Line defects | Dislocations |
| 2-dimensional | Planar (Area) defects | Surface<br>Grain boundary<br>Stacking fault |



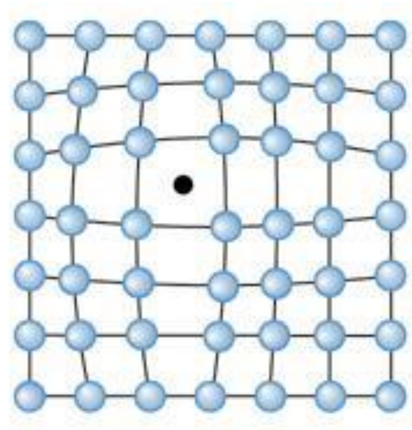




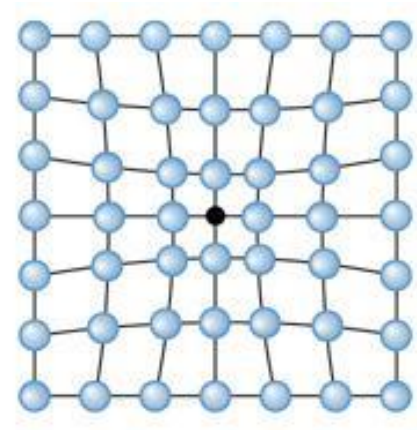
# Point Defects



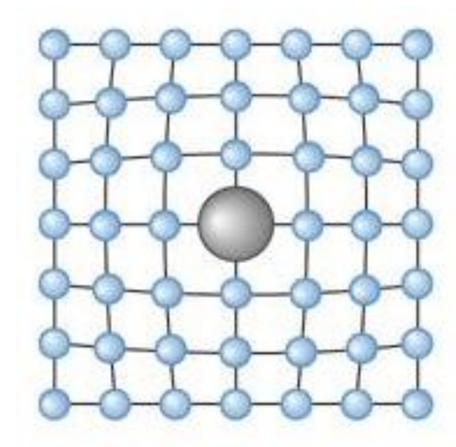
vacancy



interstitial atom



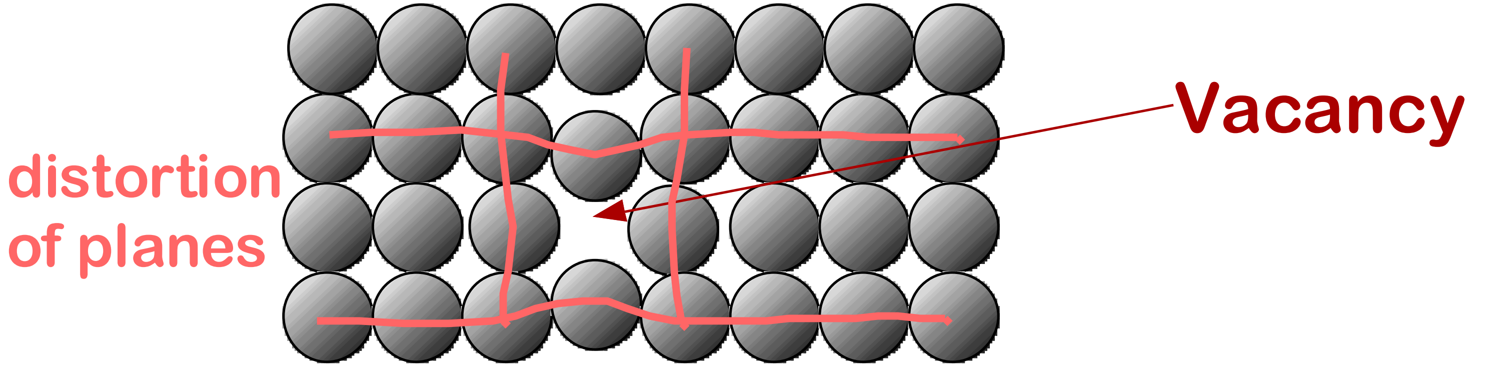
small substitutional atom



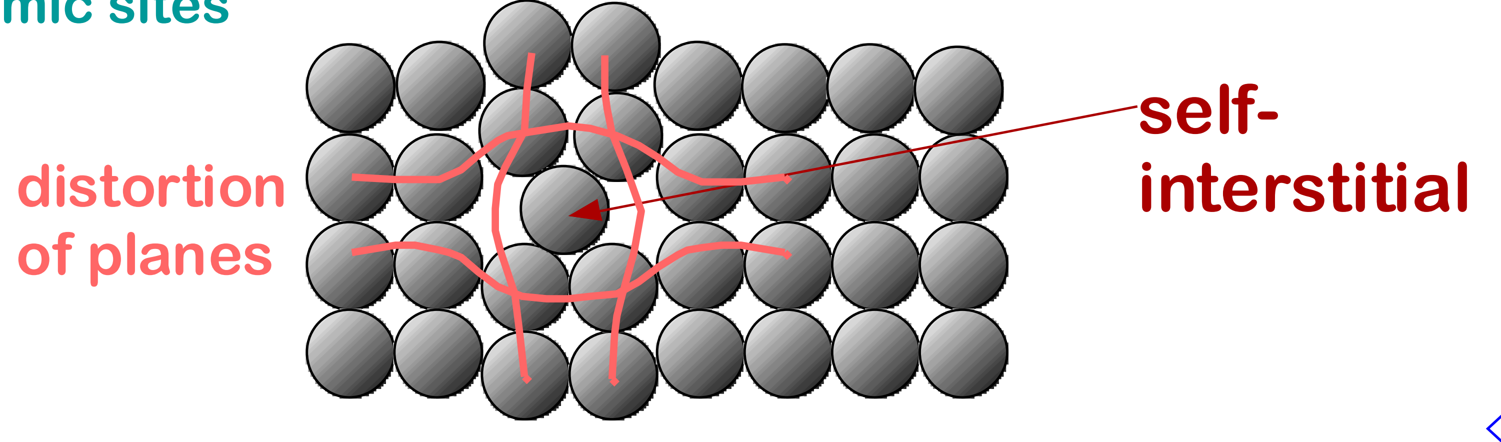
large substitutional atom

# Point Defects

- **Vacancies :** vacant atomic sites in a structure

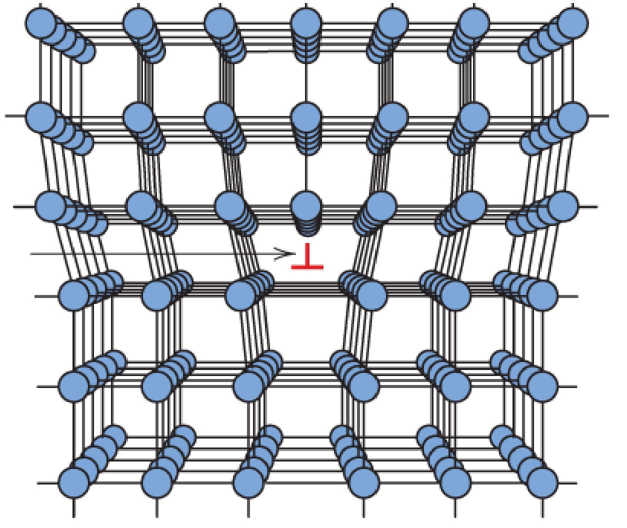


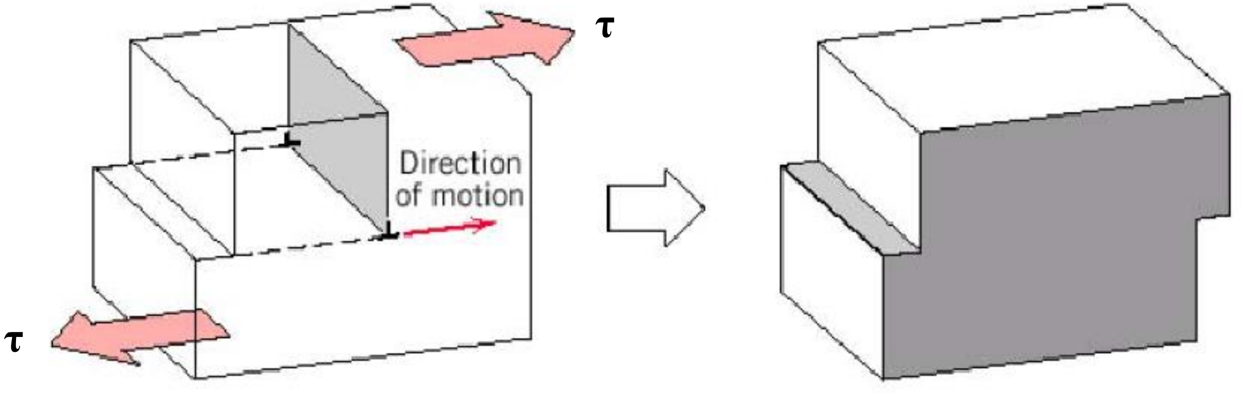

- **Self-Interstitials :** "extra" atoms positioned between atomic sites



# Line defects (one dimension)

❖ **Edge Dislocation**

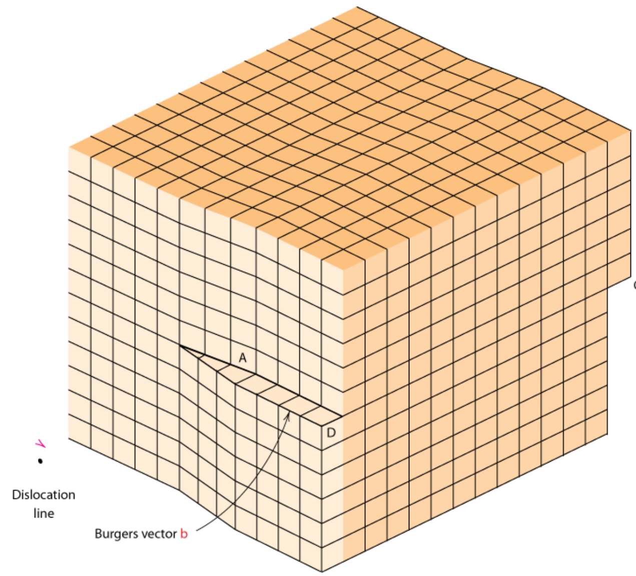


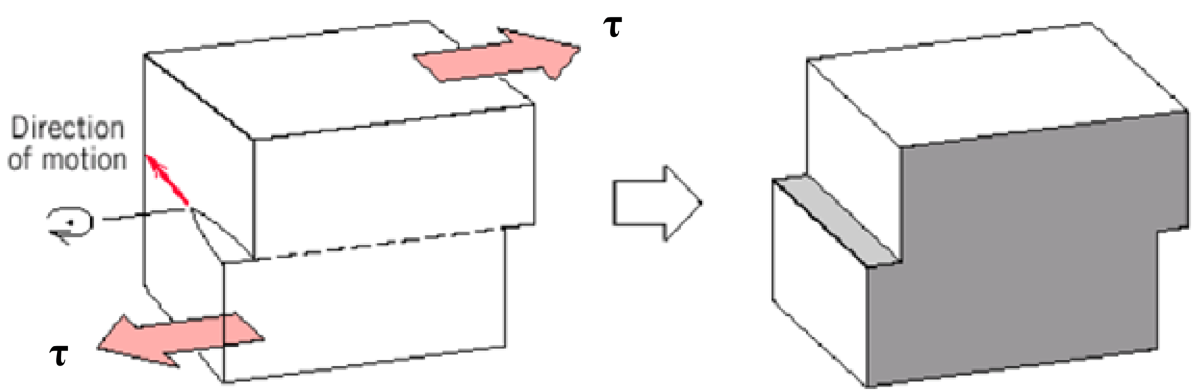



Edge dislocation line moves parallel to applied stress

# Line defects (one dimension)

## ❖ Screw Dislocation




**Screw dislocation line moves perpendicular to applied stress**

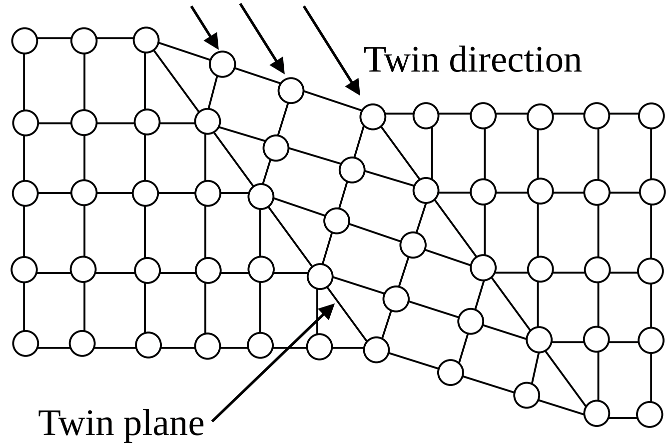
# Dislocation

## Dislocations are visible in electron micrographs

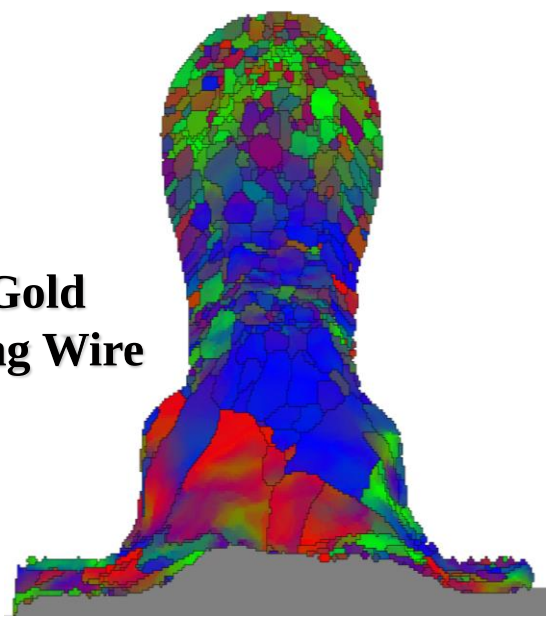
Adapted from Fig. 4.6, *Callister 7e.*

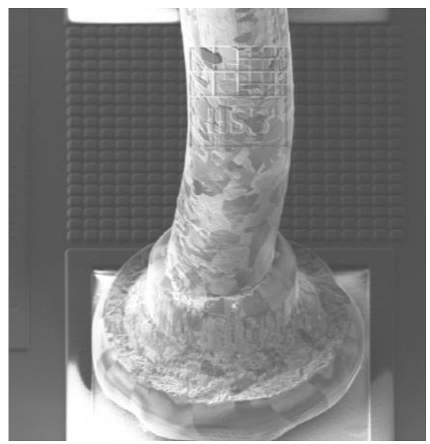
# Planar defects (two dimension)

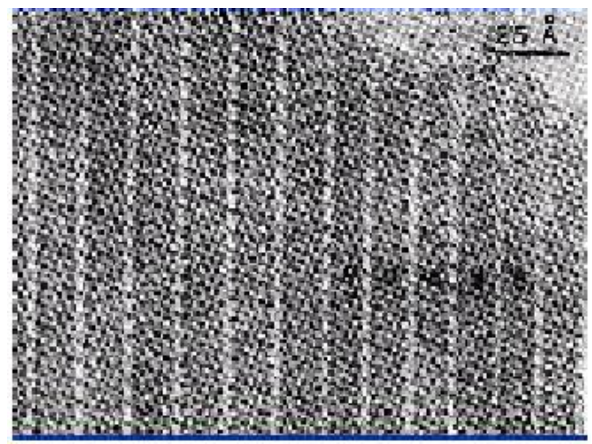
- Grain boundaries
- Twin boundaries
- Stacking faults
- Phase boundaries




MKE Gold
Bonding Wire

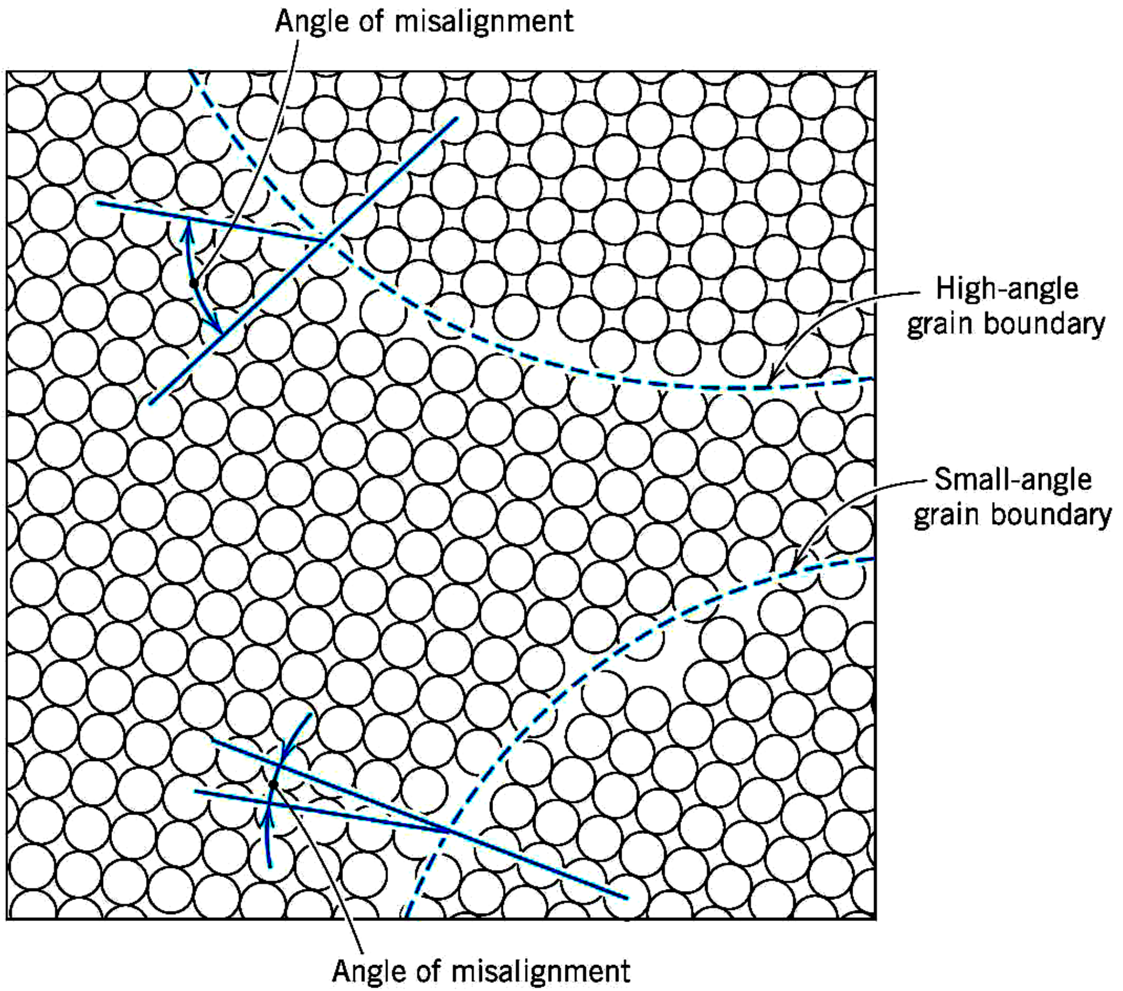


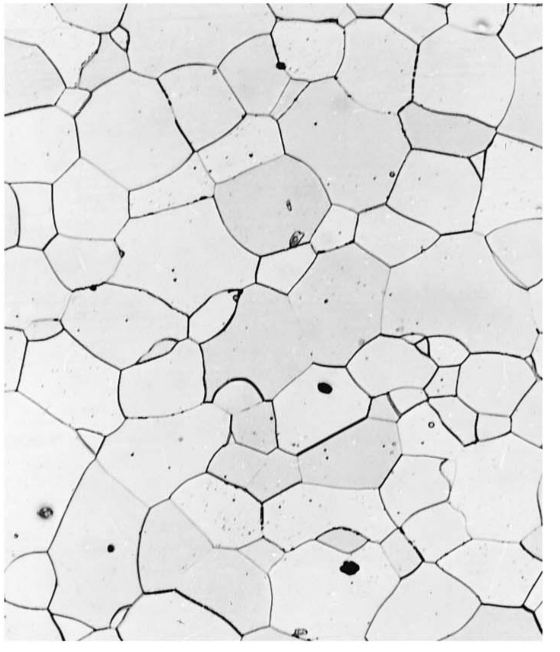




Stacking Fault

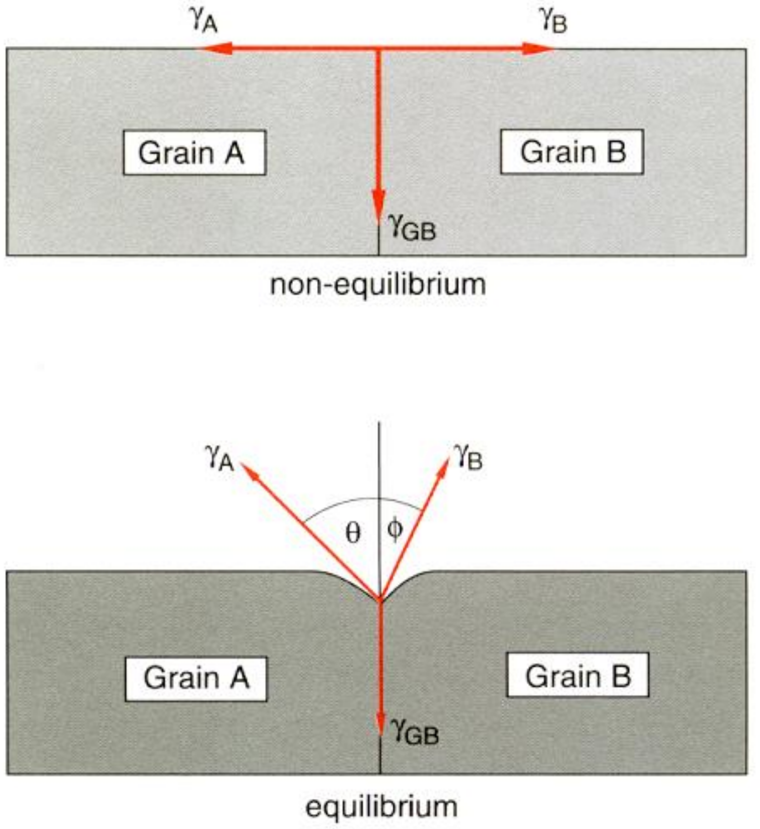
# Grain Boundary

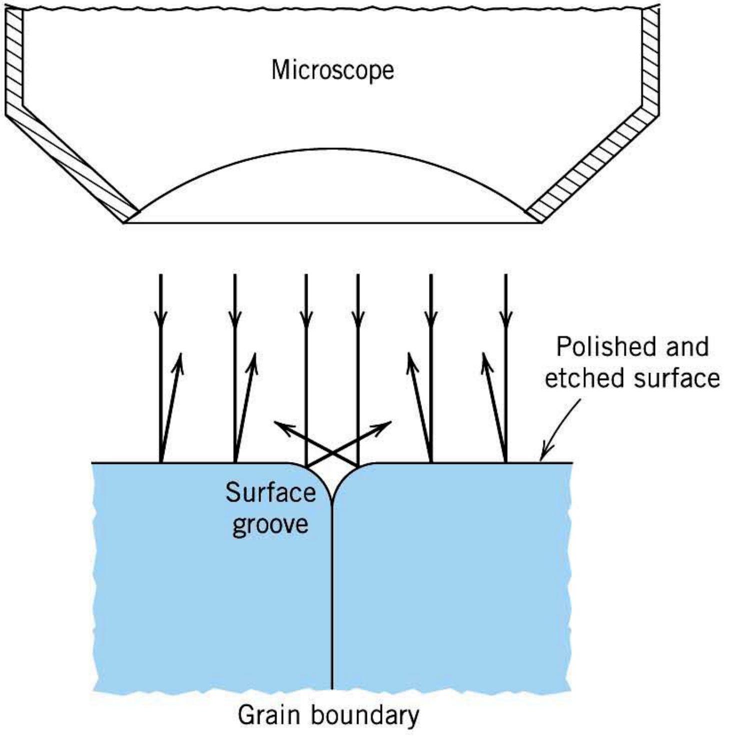


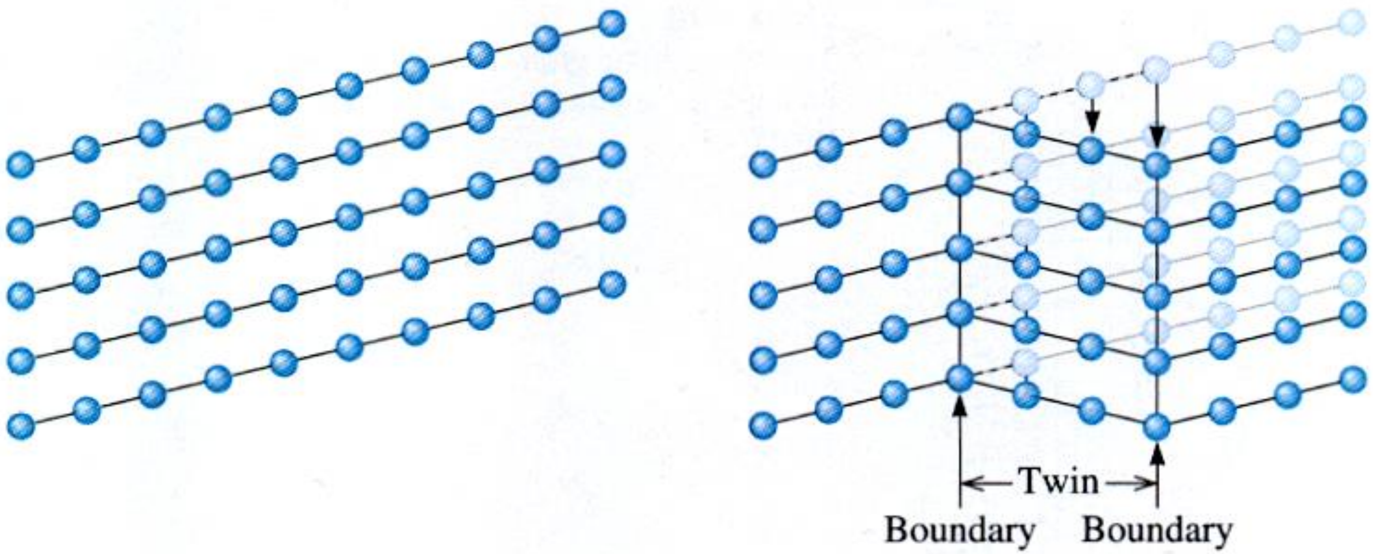
# Observation of Grain Boundary

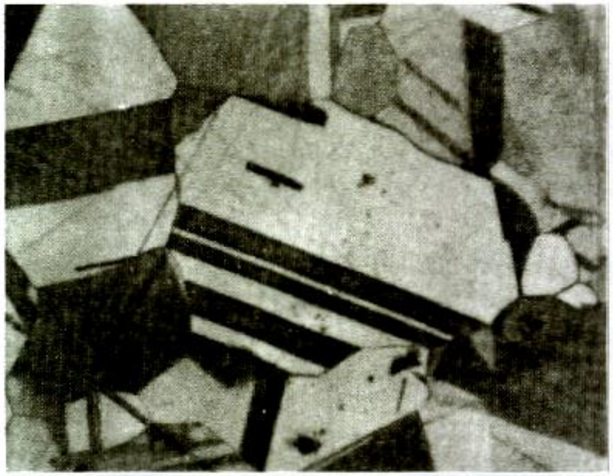
- **Chemical etching**
- **Thermal etching → groove**



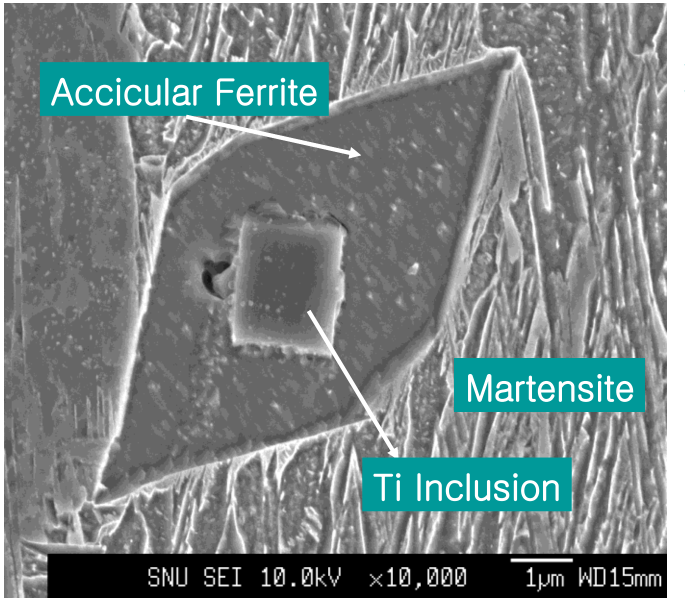
# Twin Boundary

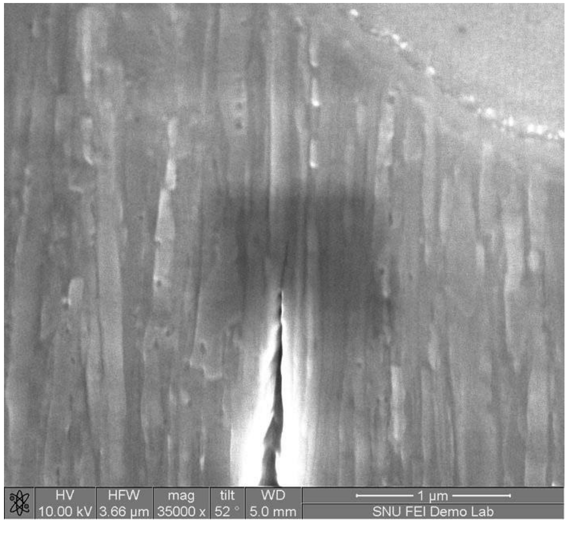


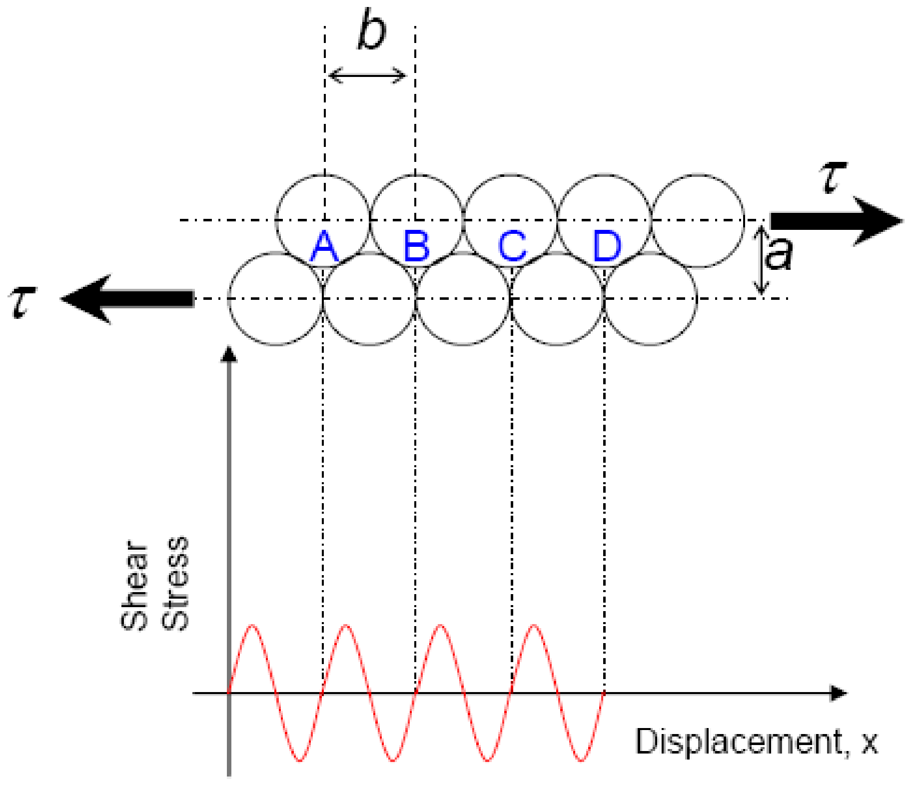
# Bulk defects (three dimension)

- Voids
- Cracks
- Inclusions



# Theoretical strength of a perfect crystal




$$\tau_{max} = \frac{Gb}{2\pi a} \cong \frac{G}{2\pi}$$

$$\tau_{max} \cong \frac{G}{30}$$

$$\tau = \tau_{max} \sin\left(\frac{2\pi x}{b}\right), \gamma = \frac{x}{a}$$

# Theoretical Strength & Experimental Strength

| Material | $\tau_{th}$ (= $G/30$) ($10^9$ N/m$^2$) | $\tau_{exp}$ ($10^6$ N/m$^2$) | $\tau_{exp}/\tau_{th}$ | $\tau_f$ ($10^6$ N/m$^2$)* |
|---|---|---|---|---|
| Ag | 1.0 | 0.37 | 0.00037 | 20 |
| Al | 0.9 | 0.78 | 0.00087 | 30 |
| Cu | 1.4 | 0.49 | 0.00035 | 51 |
| Ni | 2.6 | 3.2 | 0.0070 | 121 |
| α-Fe | 2.6 | 27.5 | 0.011 | 150 |

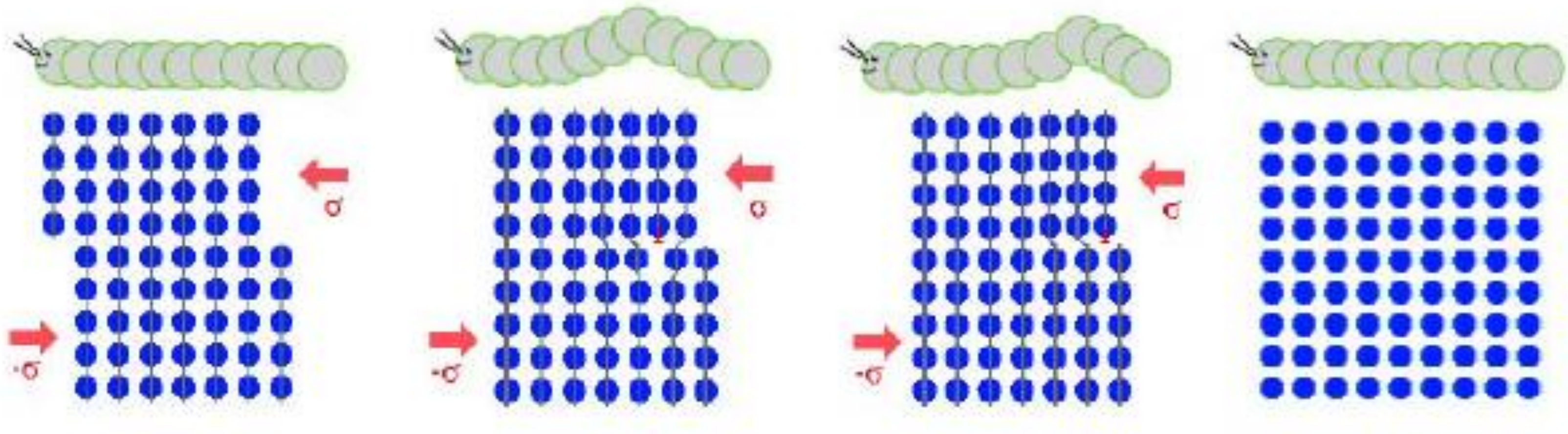
There is much difference between theoretical and experimental strength.

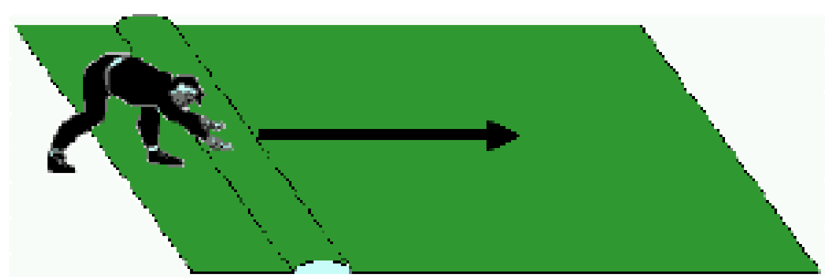
The reasons are:

1. Defects are present in all perfect crystals.
2. One type of defects, called dislocation, moves during plastic deformation and makes plastic deformation easier than predicted by the Frenkel calculation.

* Whisker is close to the theoretical strength.

# Analogy between caterpillar and dislocation motion



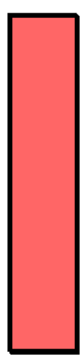
# Dislocation

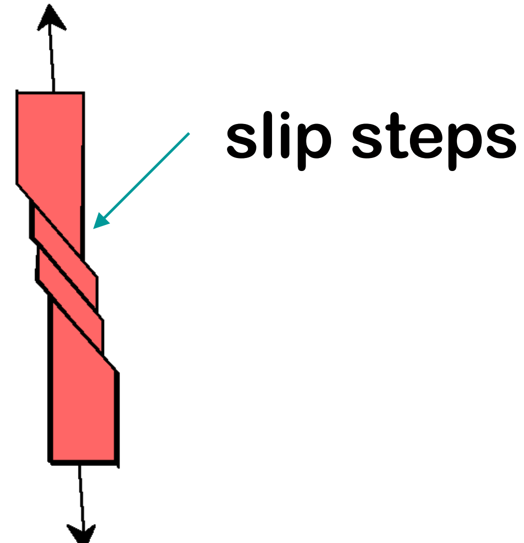
Dislocations:

- are line defects,
- cause slip between crystal plane when they move,
- produce permanent (plastic) deformation.

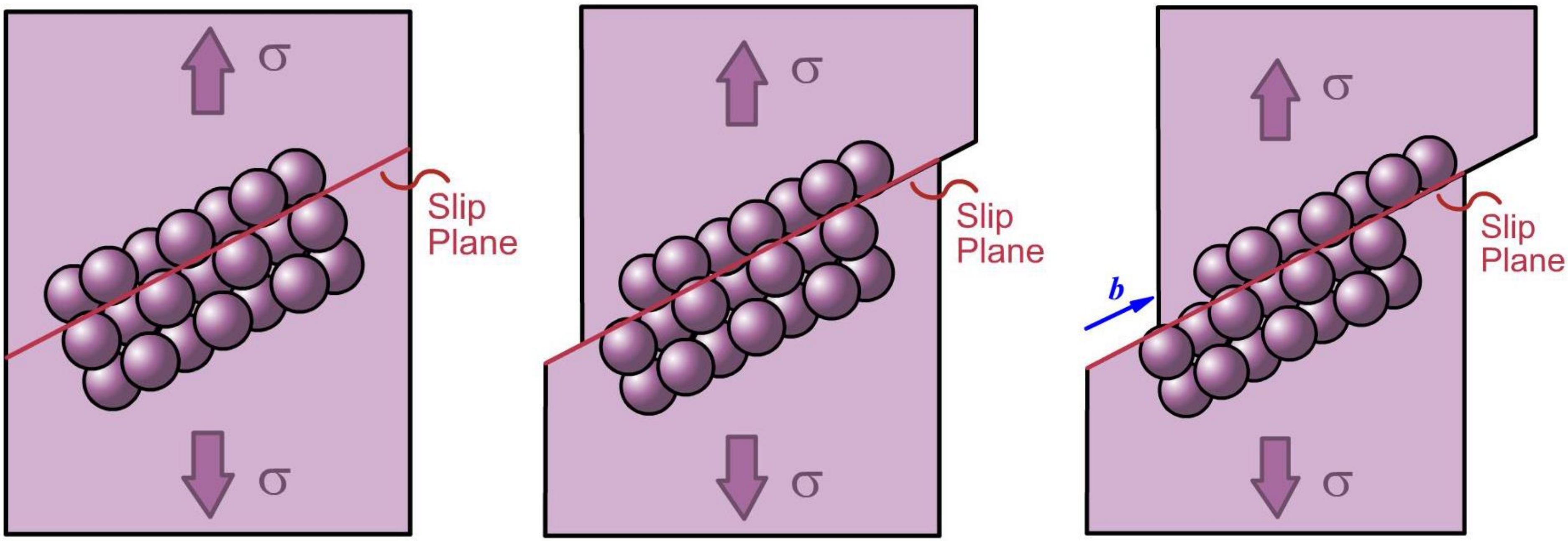
Schematic of a Zinc (HCP):

- before deformation
- after tensile elongation



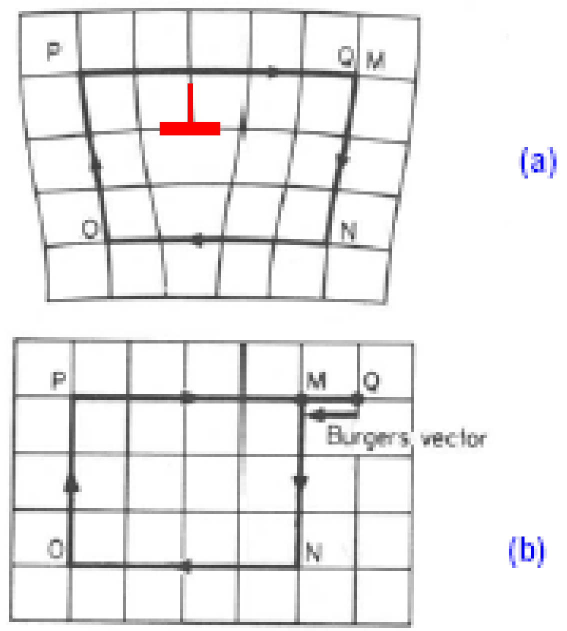


# Slip



# Burgers circuit & Burgers vector

- Burgers circuit: any close loop contains dislocations by an atom to atom path
- Burgers vectors: the vector required to complete the circuit in a perfect crystal; the direction of atom displacement

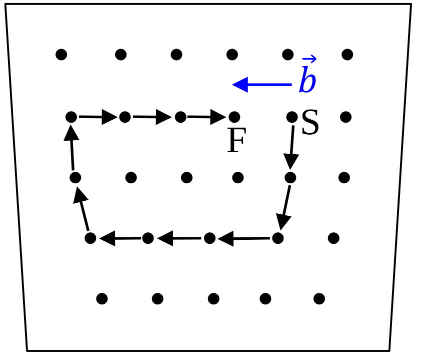



(a) Burgers circuit round an edge dislocation
(b) the same circuit in a perfect crystal

**Edge Dislocation**

*The Burgers vectors for given dislocations never change!*

# Burgers circuit & Burgers vector




**Burgers vector :** closure failure of Burgers circuit.

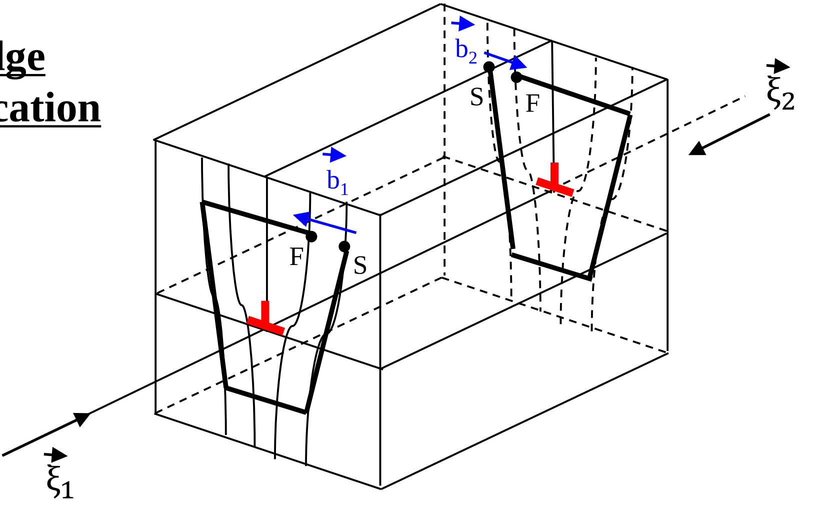
drawn from Start(S) to Finish(F)

RH / SF convention.

(circuit must be drawn around dislocation line.)

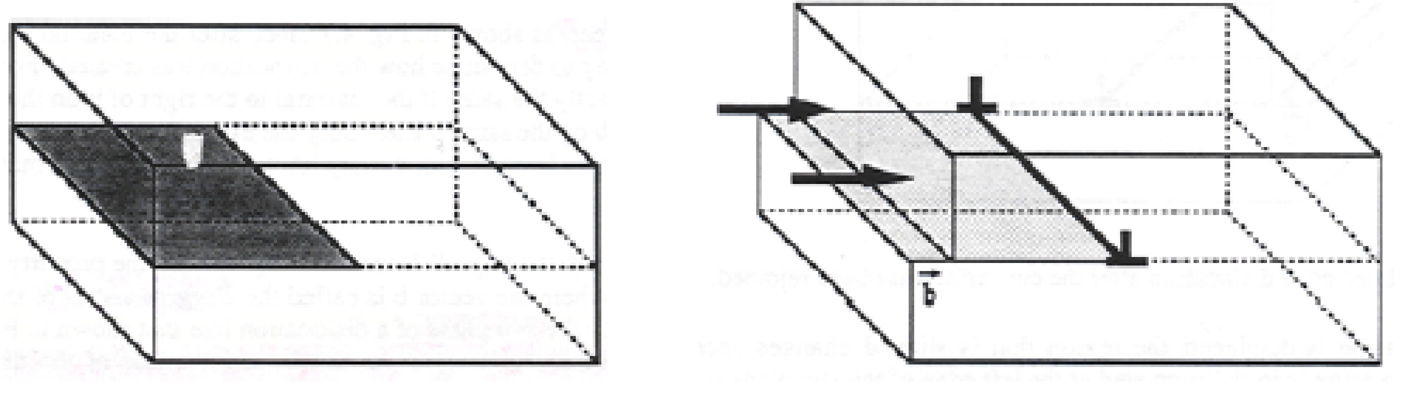
Character of Dislocation based on vector Description

**Edge Dislocation**

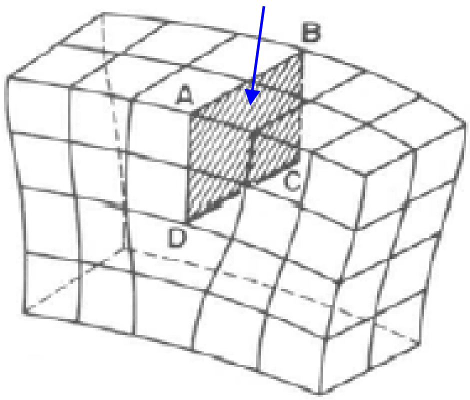


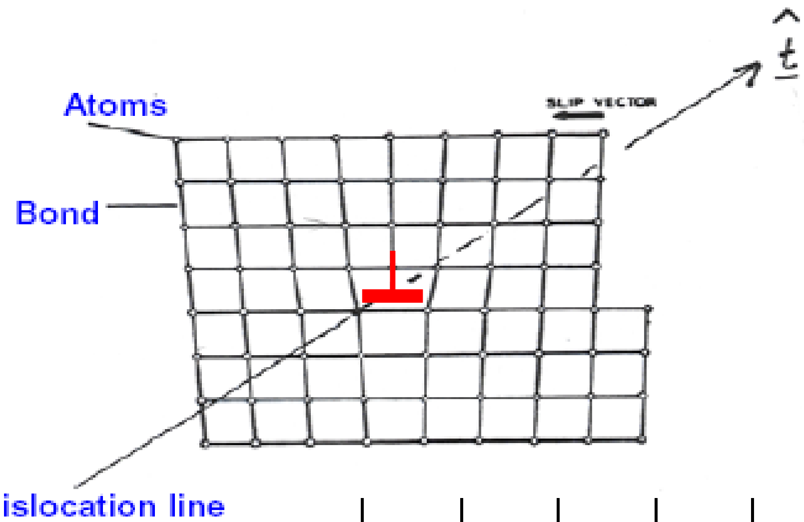
# Geometry of dislocation: edge dislocation

- Slip plane: where slip occurs.
- Dislocation line: boundary between the slipped and unslipped part of a crystal
- Slip plane contains both Burgers vectors and dislocation line
- Edge dislocation: dislocation line is perpendicular to Burgers vector



# Model of an edge dislocation

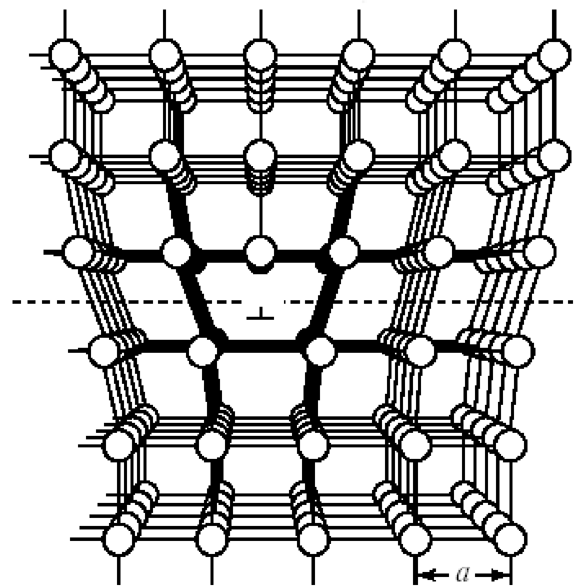



**Symbols:**

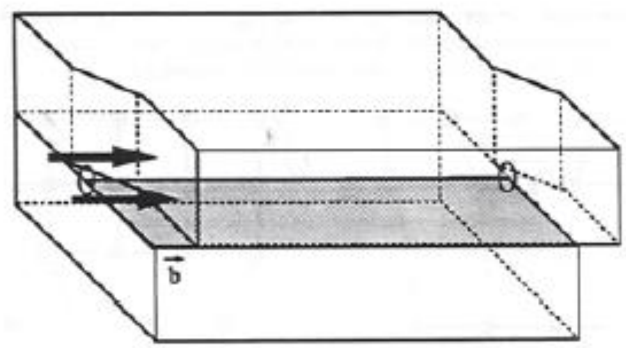
⊥: Positive edge dislocation

T : Negative edge dislocation

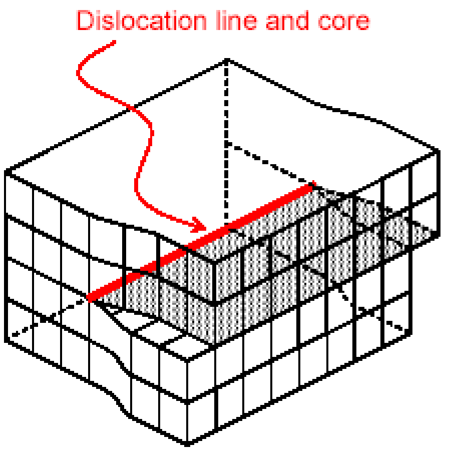


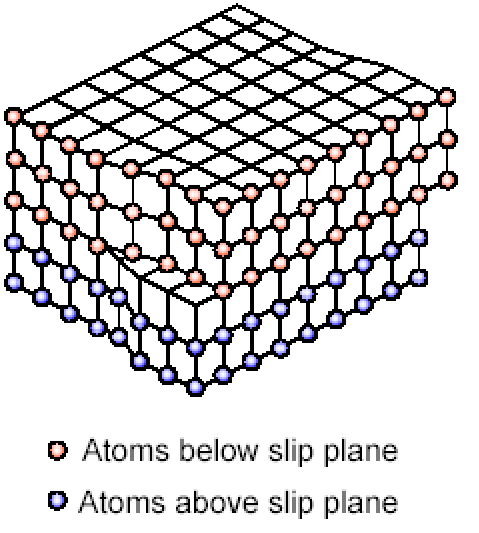
# Geometry of dislocation: screw dislocation

- Screw dislocation: the dislocation line is parallel to Burgers vector



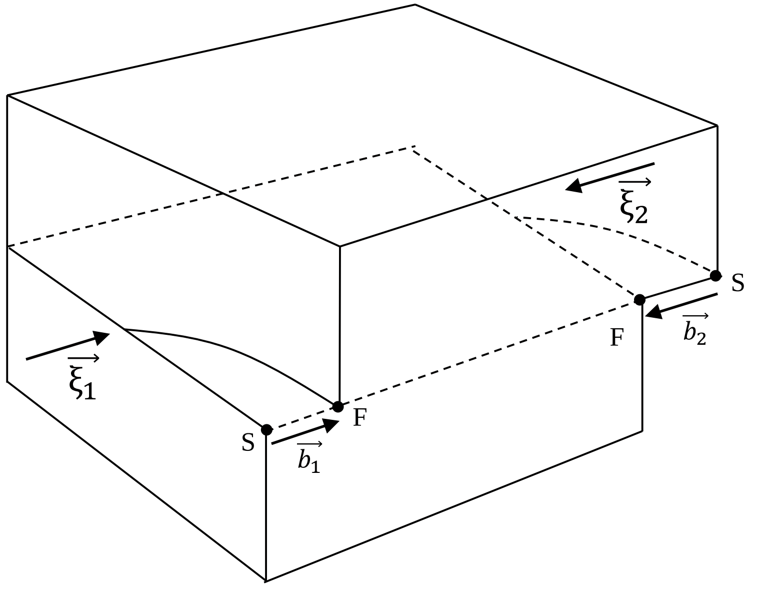

Screw dislocation



# Burgers circuit & Burgers vector

## Screw Dislocation



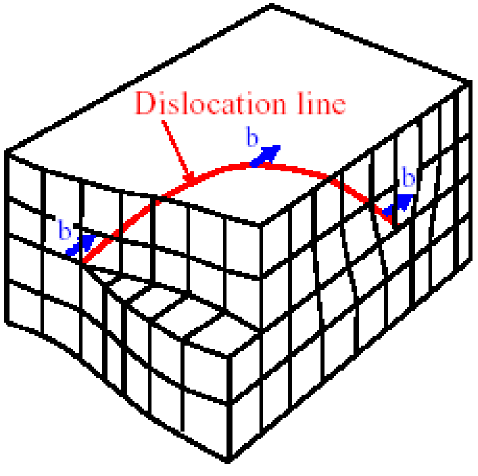

$\vec{\xi} \cdot \vec{b}$ = positive for RHS.

Neither $\vec{\xi}$ nor $\vec{b}$ unique.

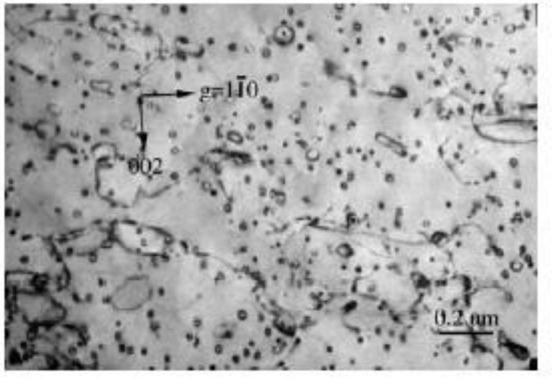
$\vec{\xi} \cdot \vec{b}$ = negative for LHS.

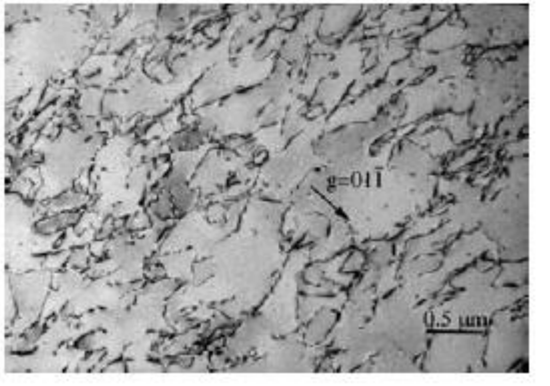
# Characteristics of dislocations

| Dislocation Characteristic | Type of Dislocation | | |
|---|---|---|---|
| | Edge | Screw | **Mixed** |
| Slip direction | // to *b* | // to *b* | Not // to *b* |
| Relation between dislocation line and *b* | ⊥ | // | Not // or ⊥ |
| Direction of line movement relative to *b* | // | ⊥ | // and ⊥ |




Mixed dislocation

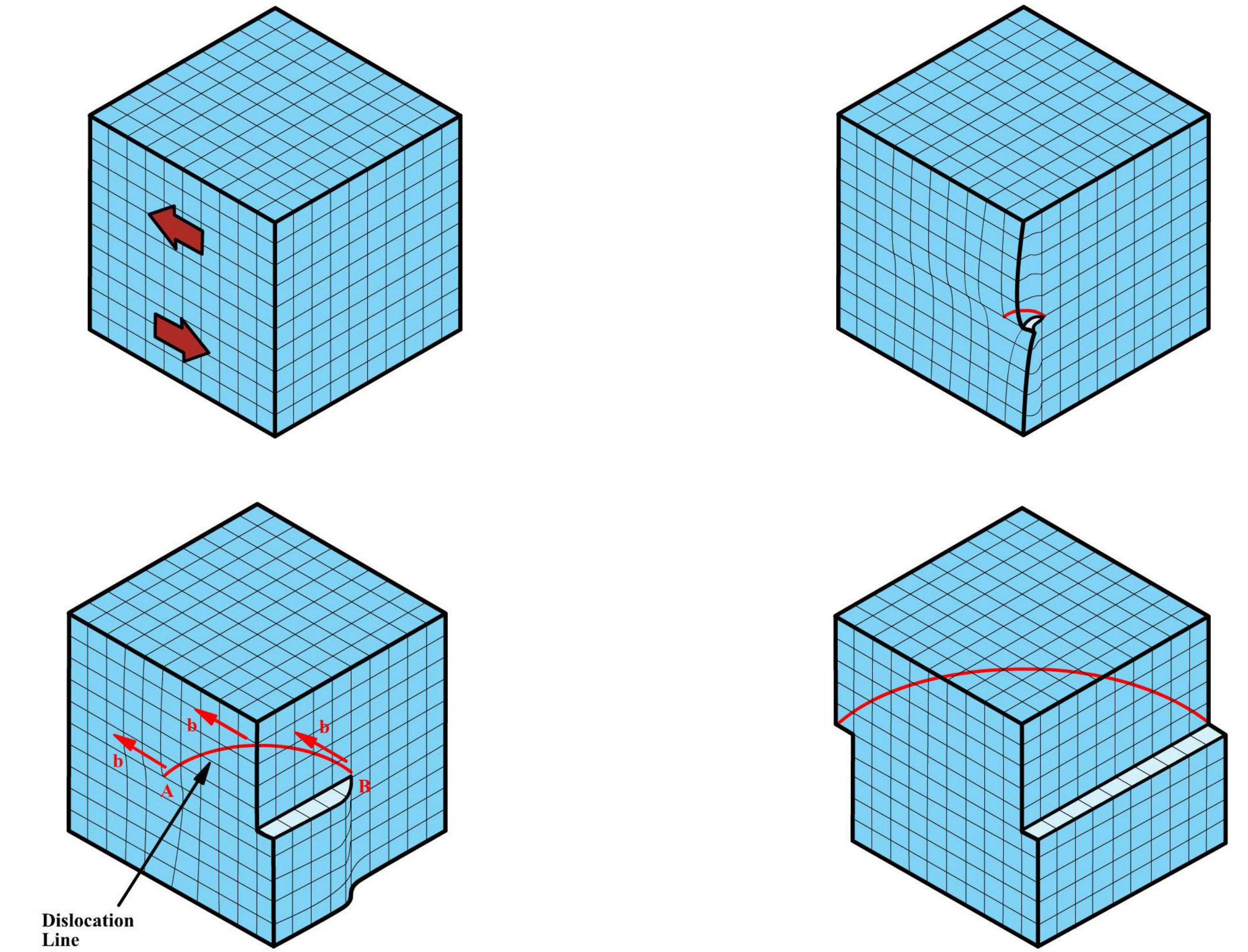


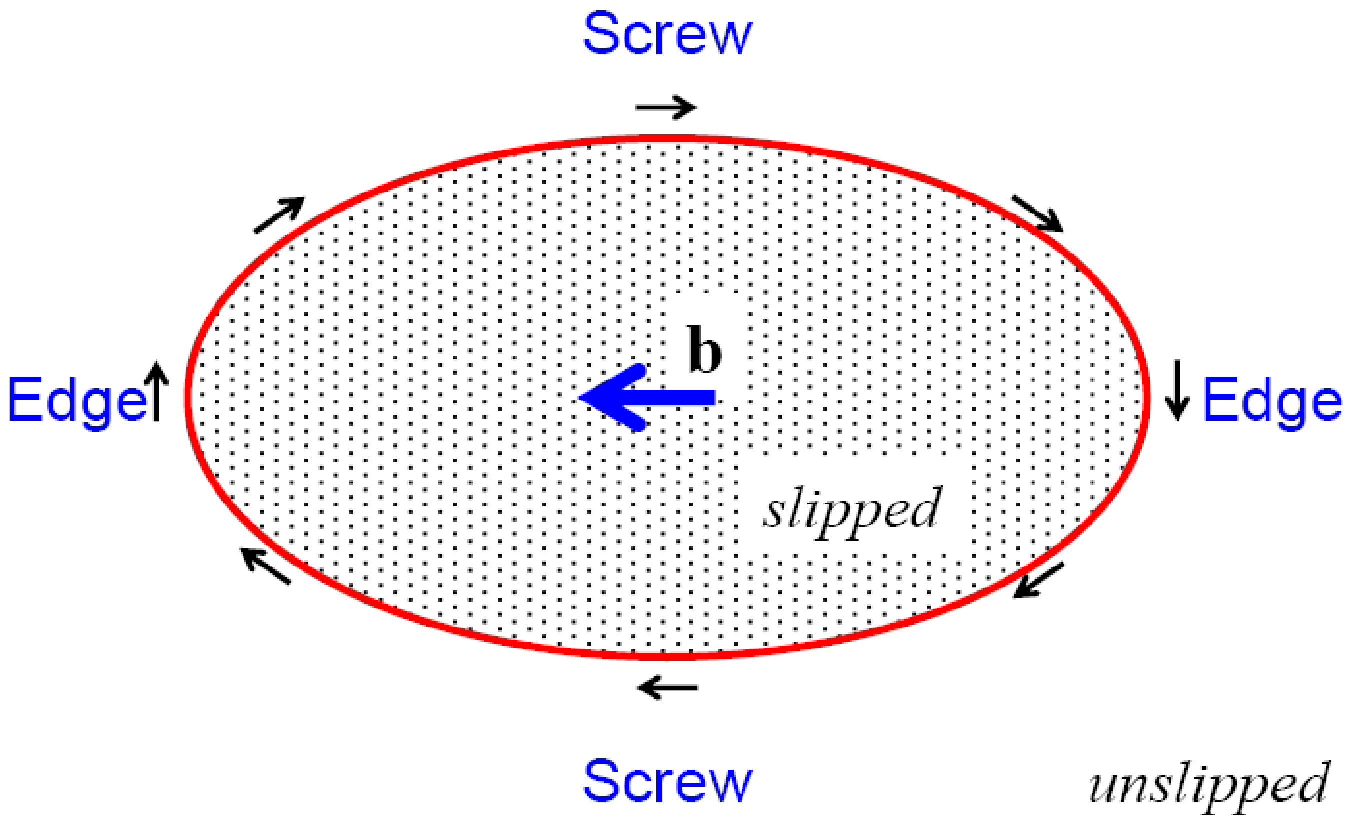

Dislocations imaged in NiAl-0.5Zr single crystals deformed at elevated temperatures.

Most dislocations are curved.

# Motion of Mixed Dislocations



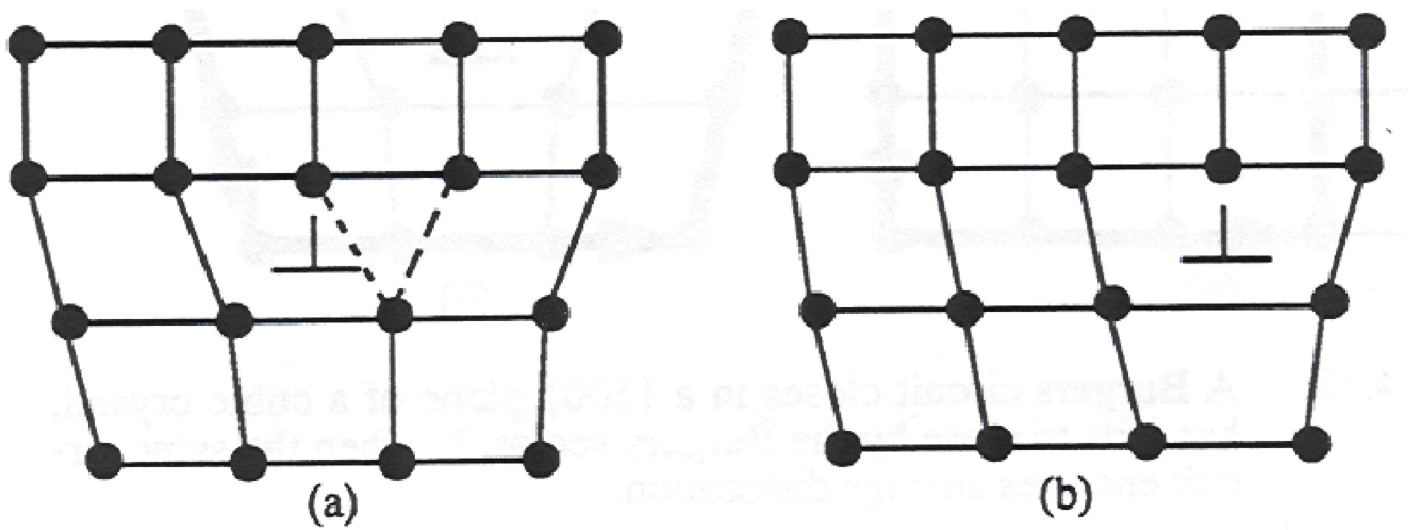
# Dislocations move via slip



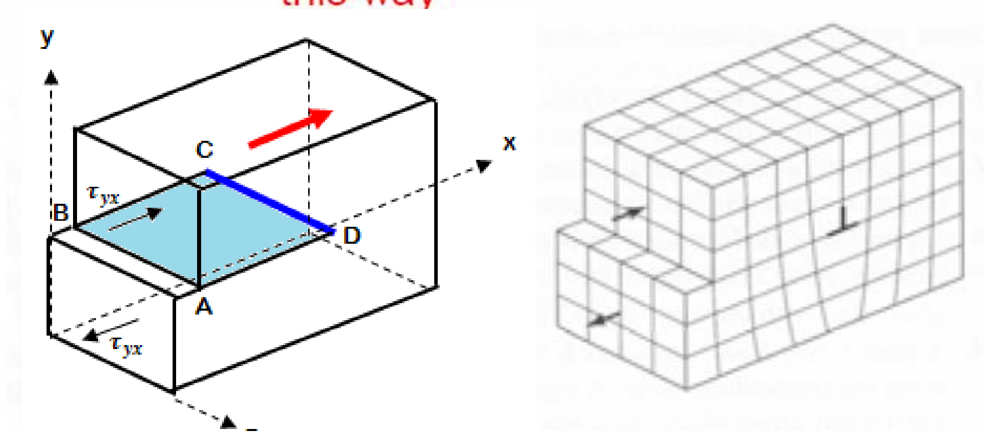

Schematic representation of a *dislocation loop*

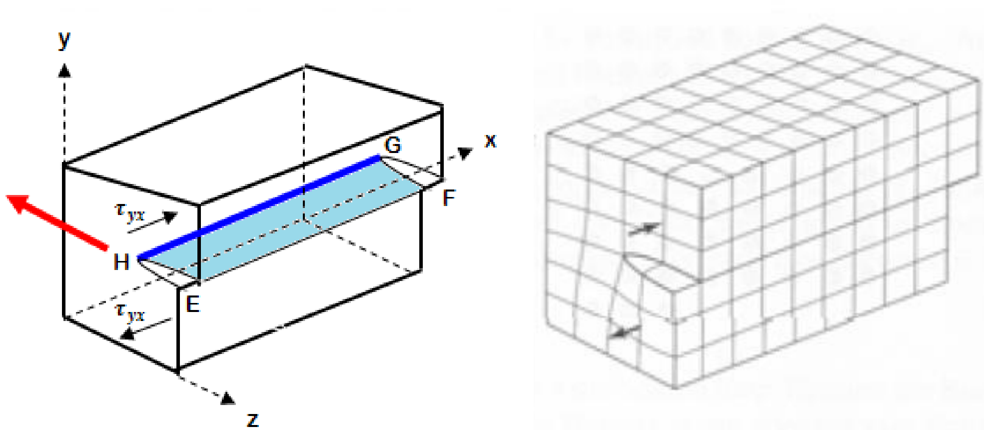
# Movement of Dislocations

- Glide--conservative motion: dislocation moves in the surface which contains both its line and Burgers vector

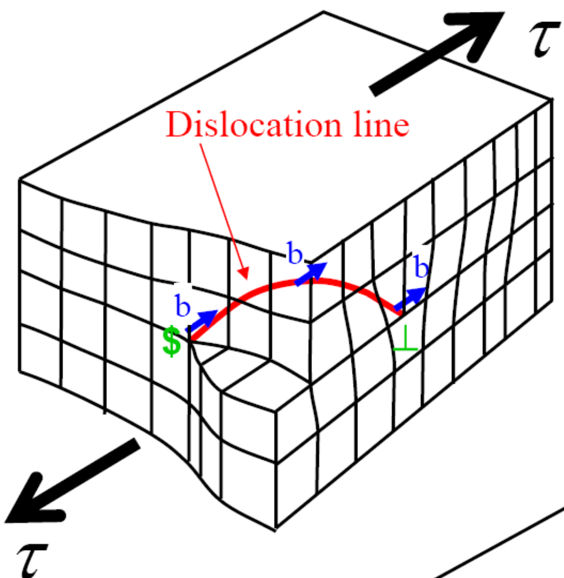


# Movement of Dislocations (glide)

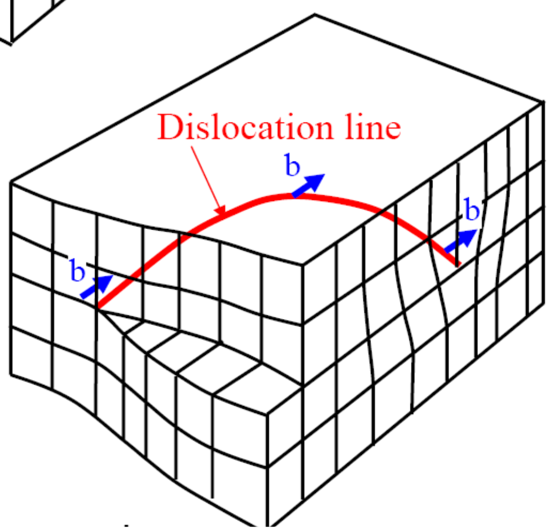


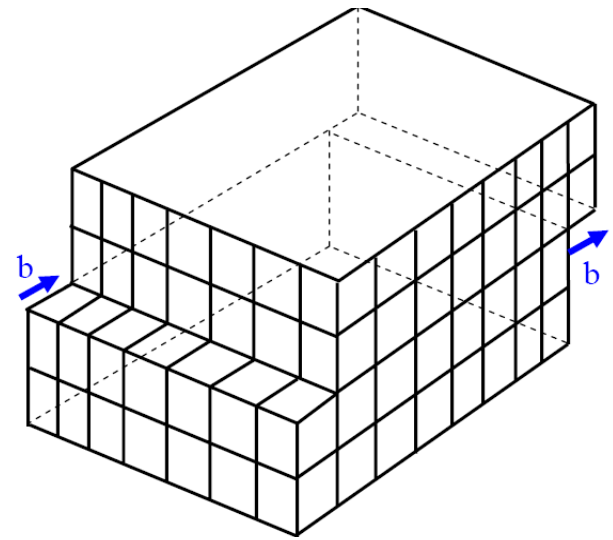



# Movement of Dislocations (glide)




**Process of slip by expansion of a dislocation loop in a slip plane.**



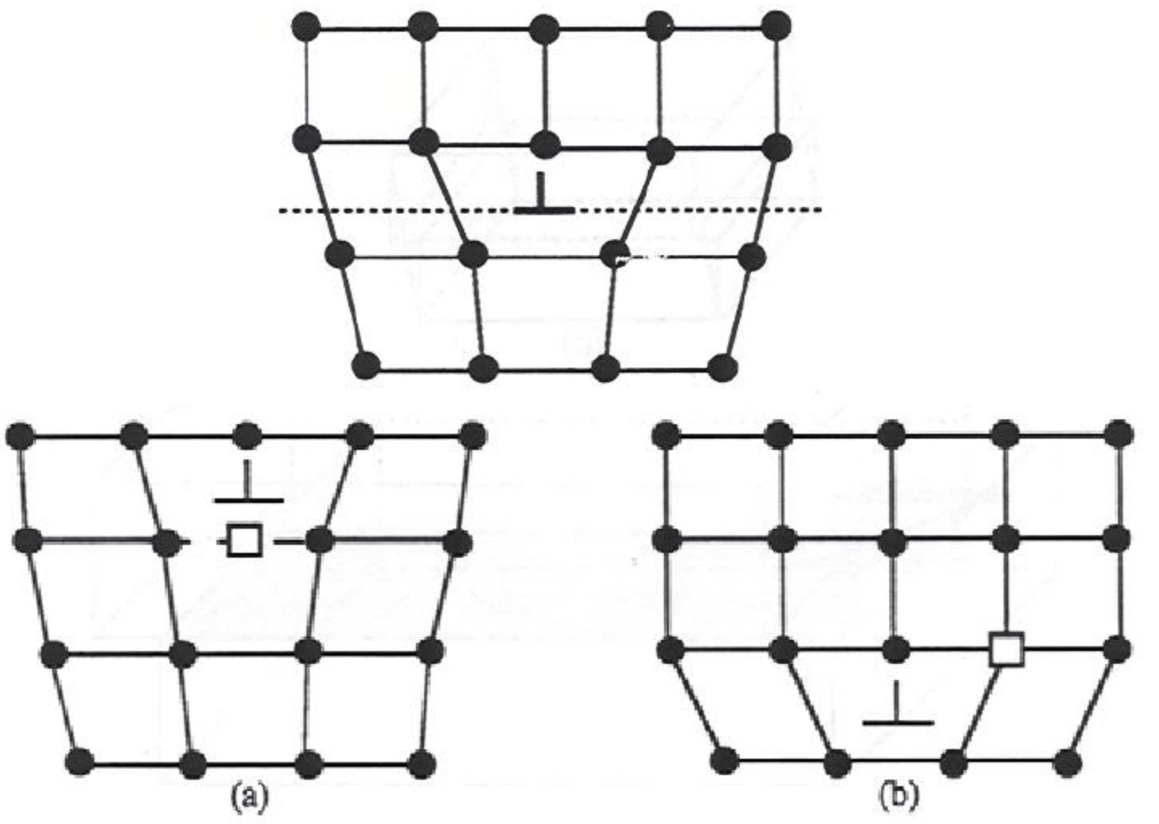




- Edge, screw, and mixed segments move.

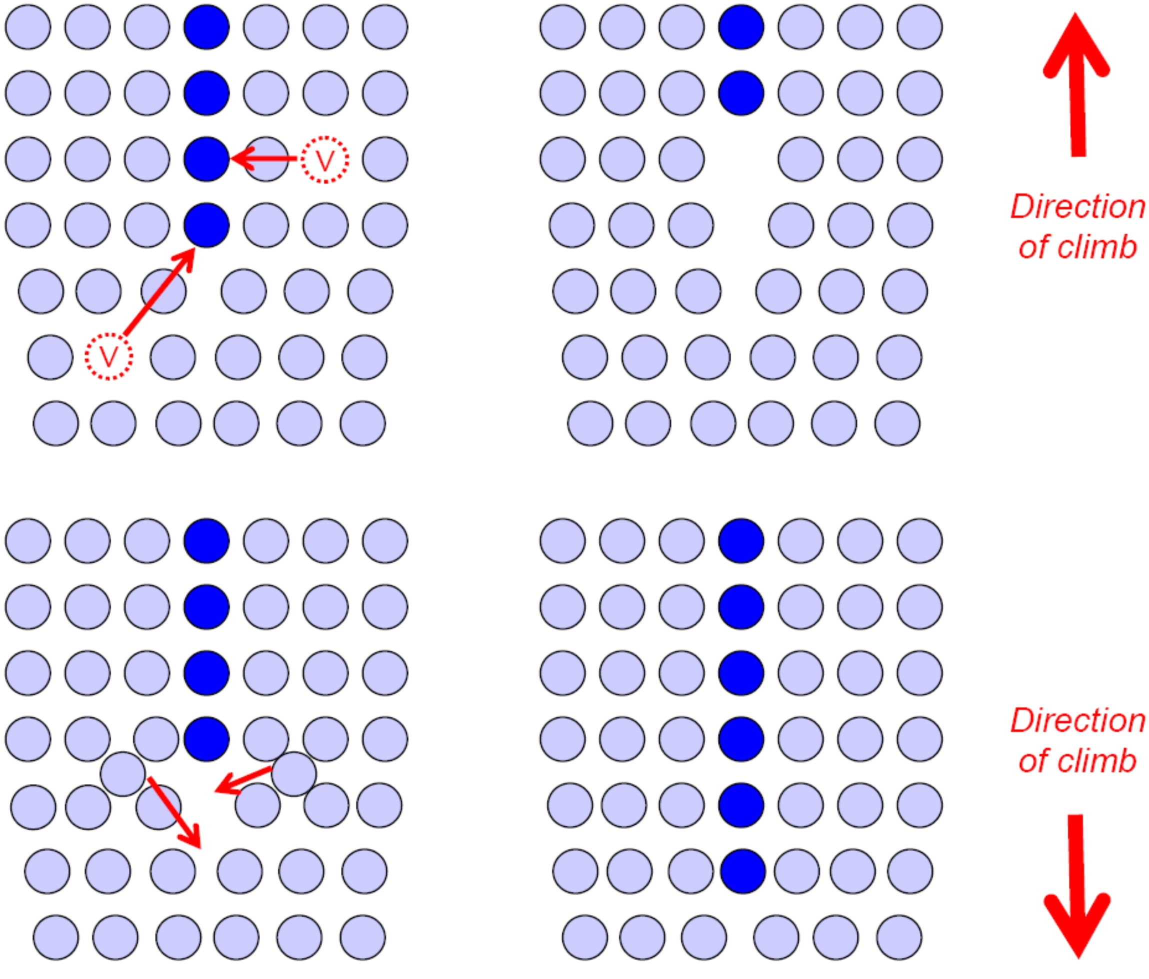
- Final shear of crystal is produced by edge and screw dislocations.

# Movement of Dislocations

- Climb-- non-conservative motion: dislocation moves out of the glide surface normal to the Burgers vector



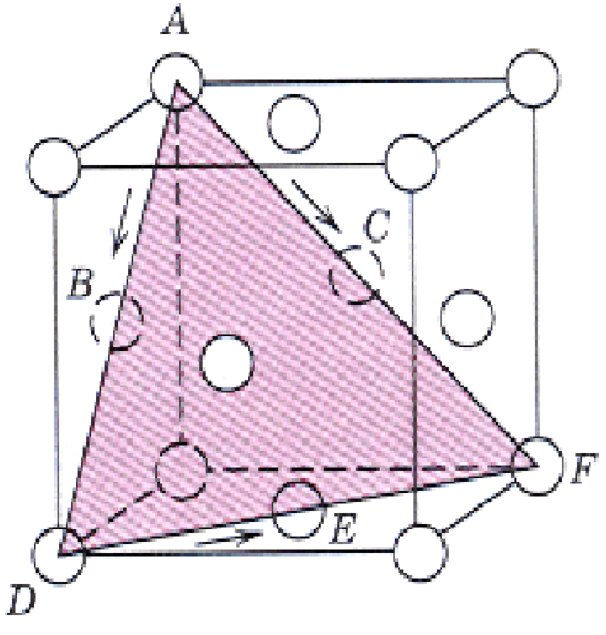
# Movement of Dislocations (climb)



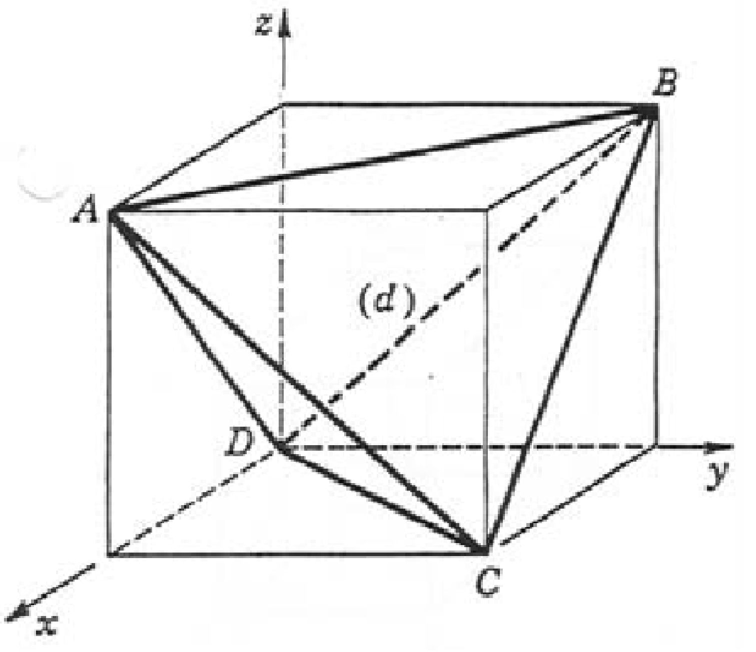

**Vacancies or Atoms diffuse to bottom of dislocation line.**

# Acting slip system in FCC

- A {111}<110> slip system in Fcc unit cell

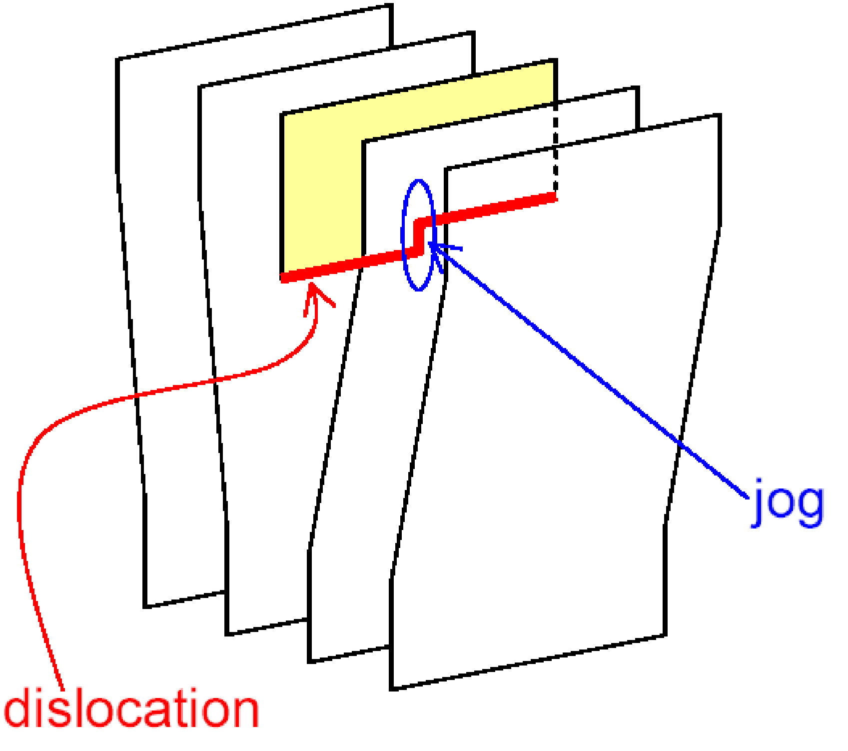



(a)



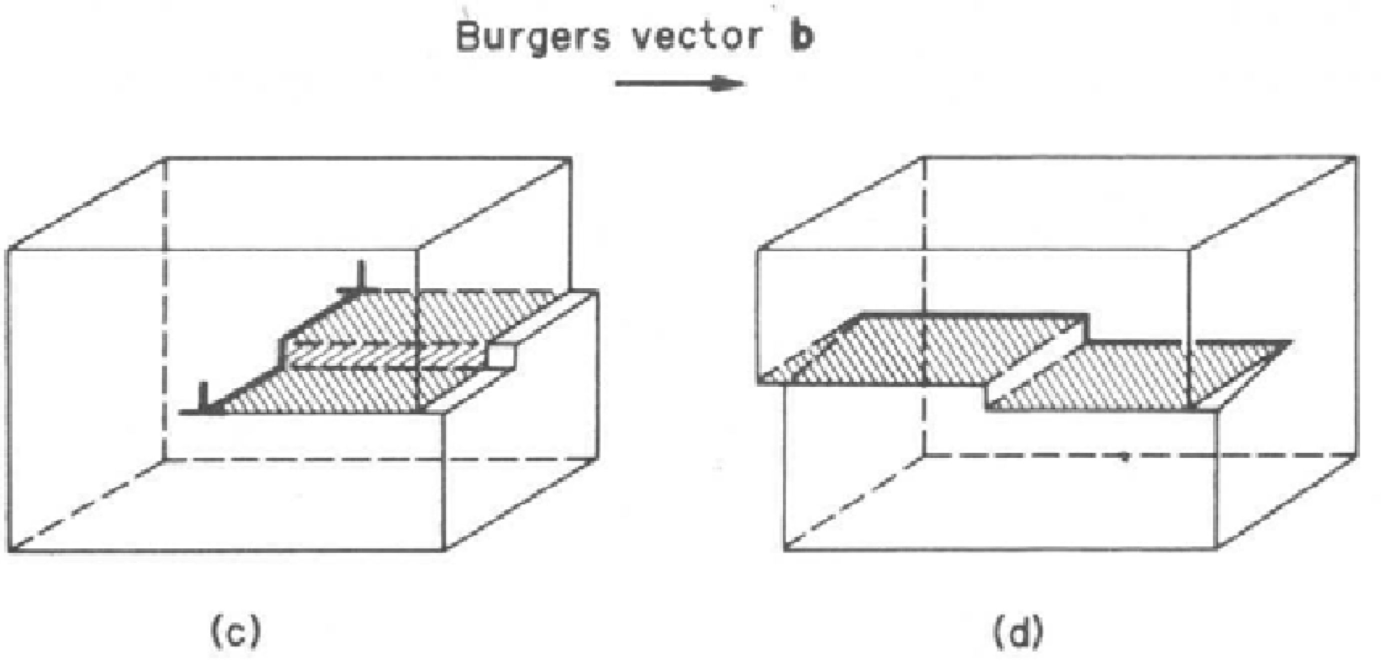
# Jogs

**Jogs: steps on the dislocation which move it from one atomic slip plane to another**



# Jogs

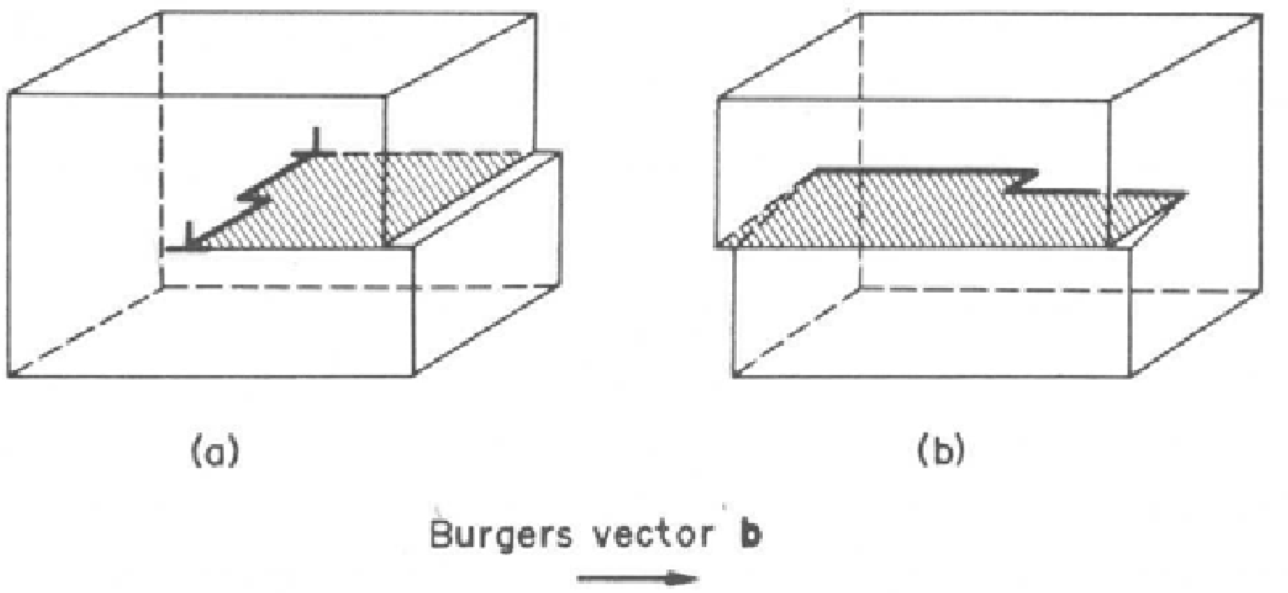
- Jogs on edge dislocations do not impede glide
- Jogs on screw dislocations have edge character and impede glide




The jogs in (c) edge and (d) screw dislocations

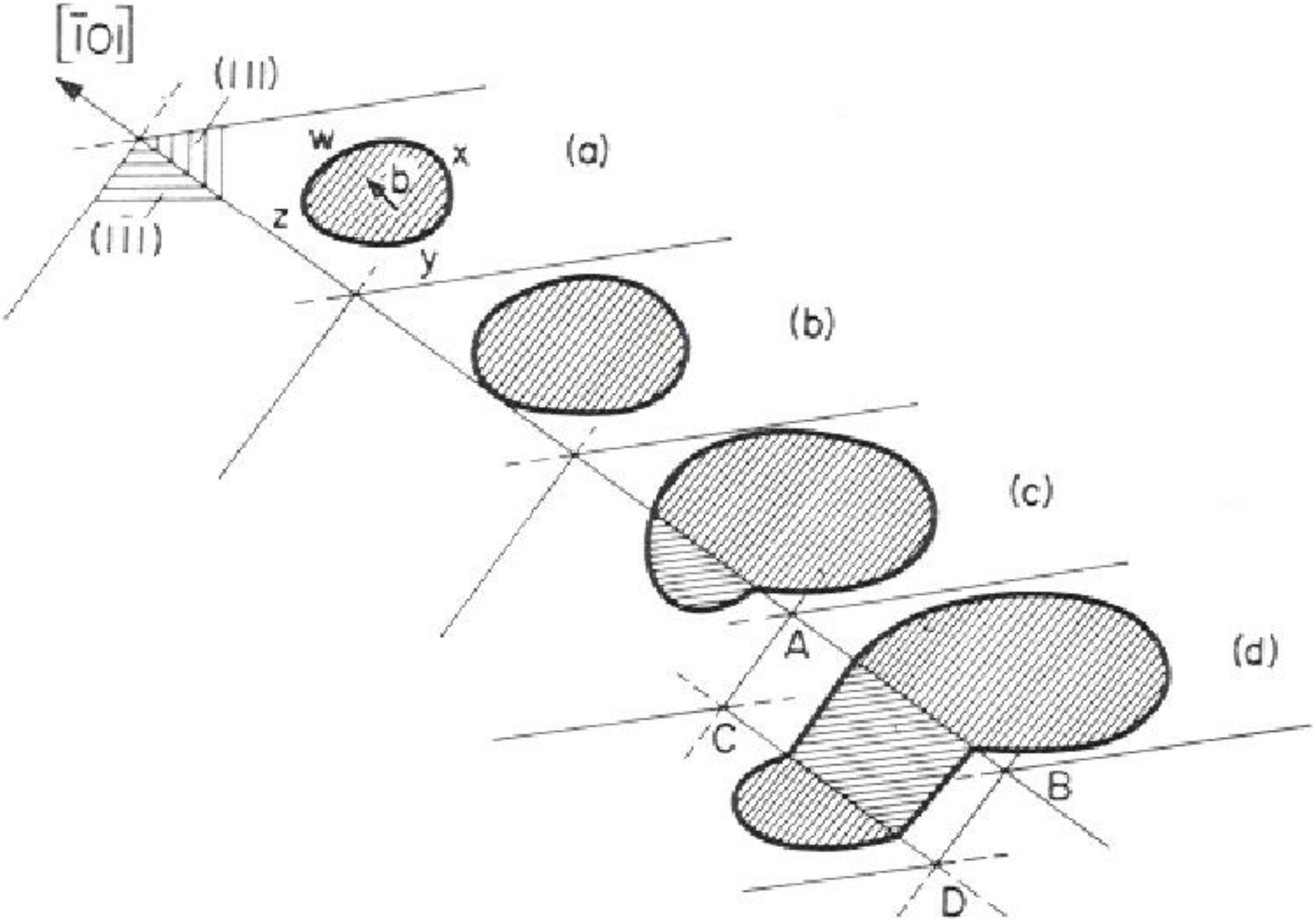
# Kink

- Kinks: steps on the dislocation which displace it on the same slip plane
- Kinks in edge and screw dislocations do not impede glide of the dislocation

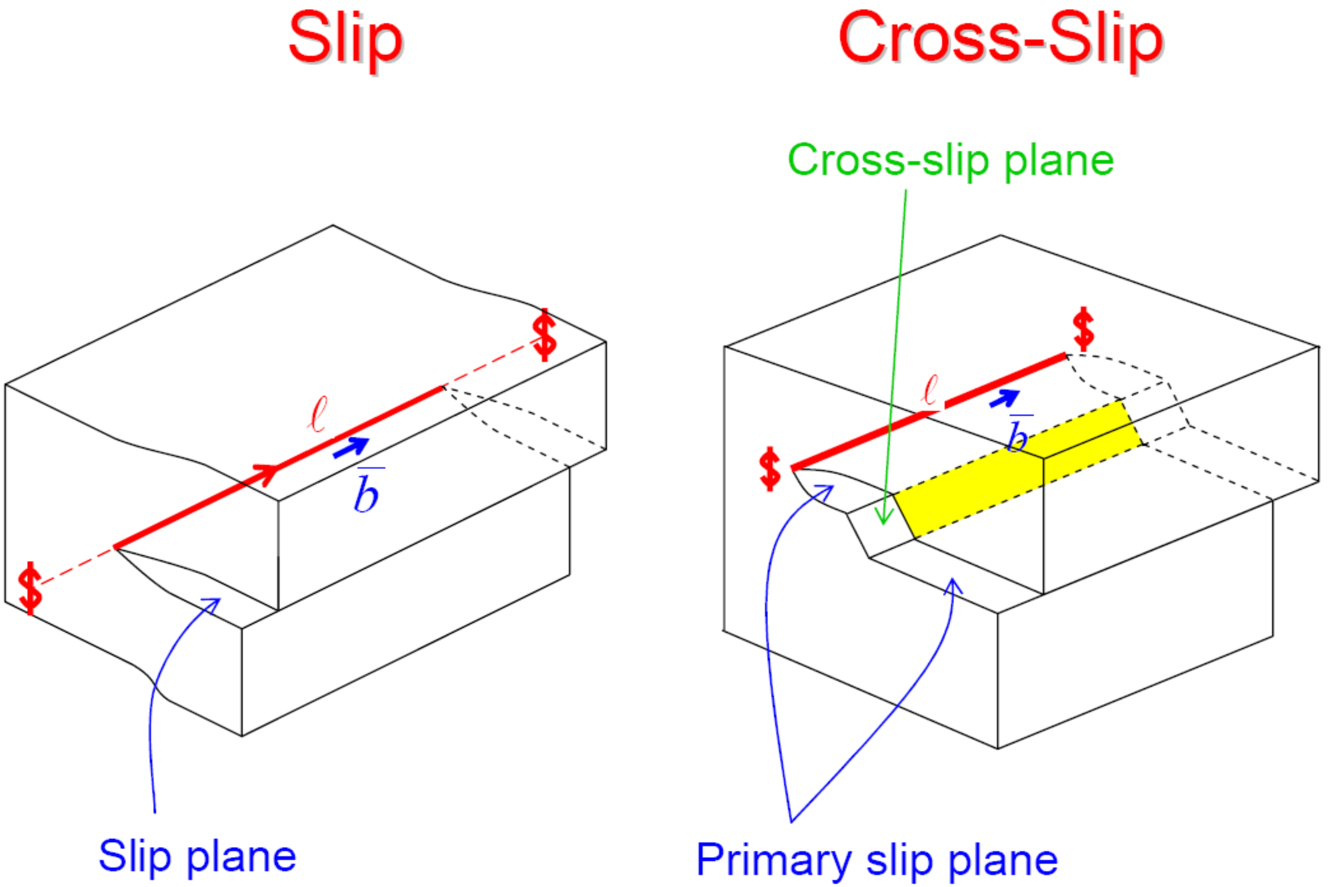



**The kinks in edge (a) and screw (b) dislocations**

# Cross slip

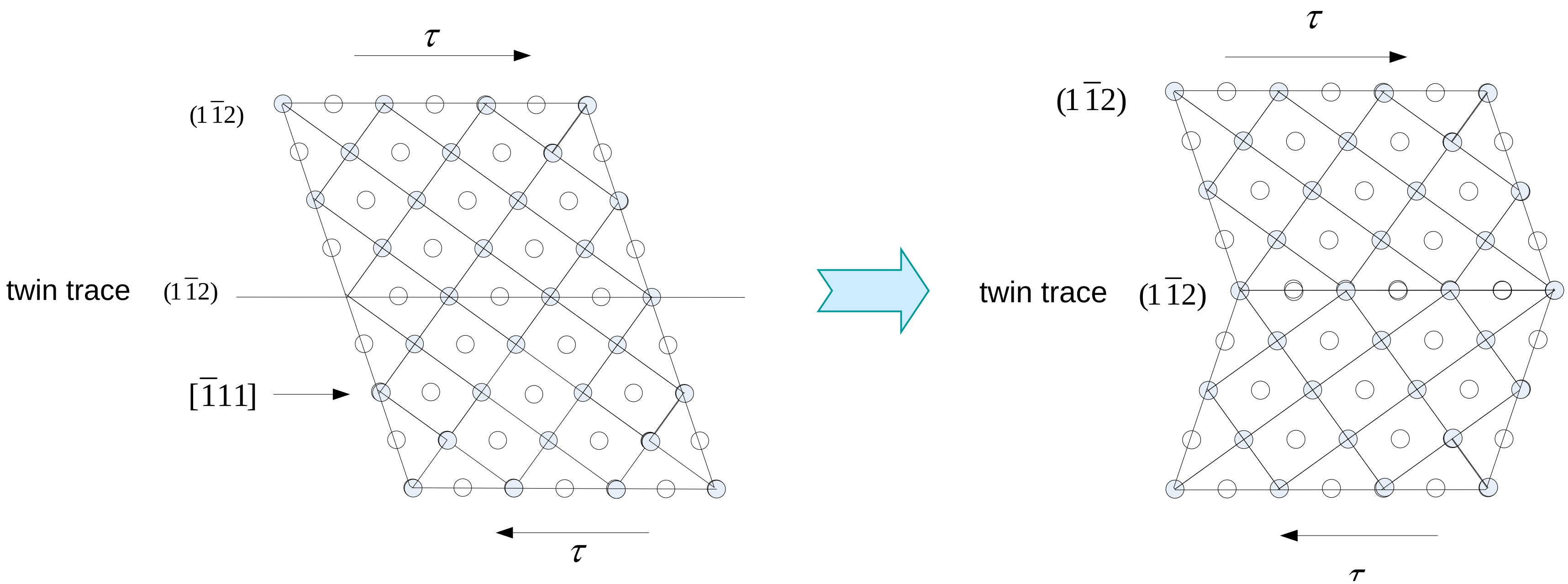


# Cross slip




Screw dislocations can cross-slip
Edge dislocations cannot

# Twinning




- Twinning unassisted by dislocation motion requires cooperative and simultaneous motion of a number of atoms

: theoretical twinning stress is high

: believed associated with dislocation motion

: requires cooperative dislocation displacements