Plastic Deformation

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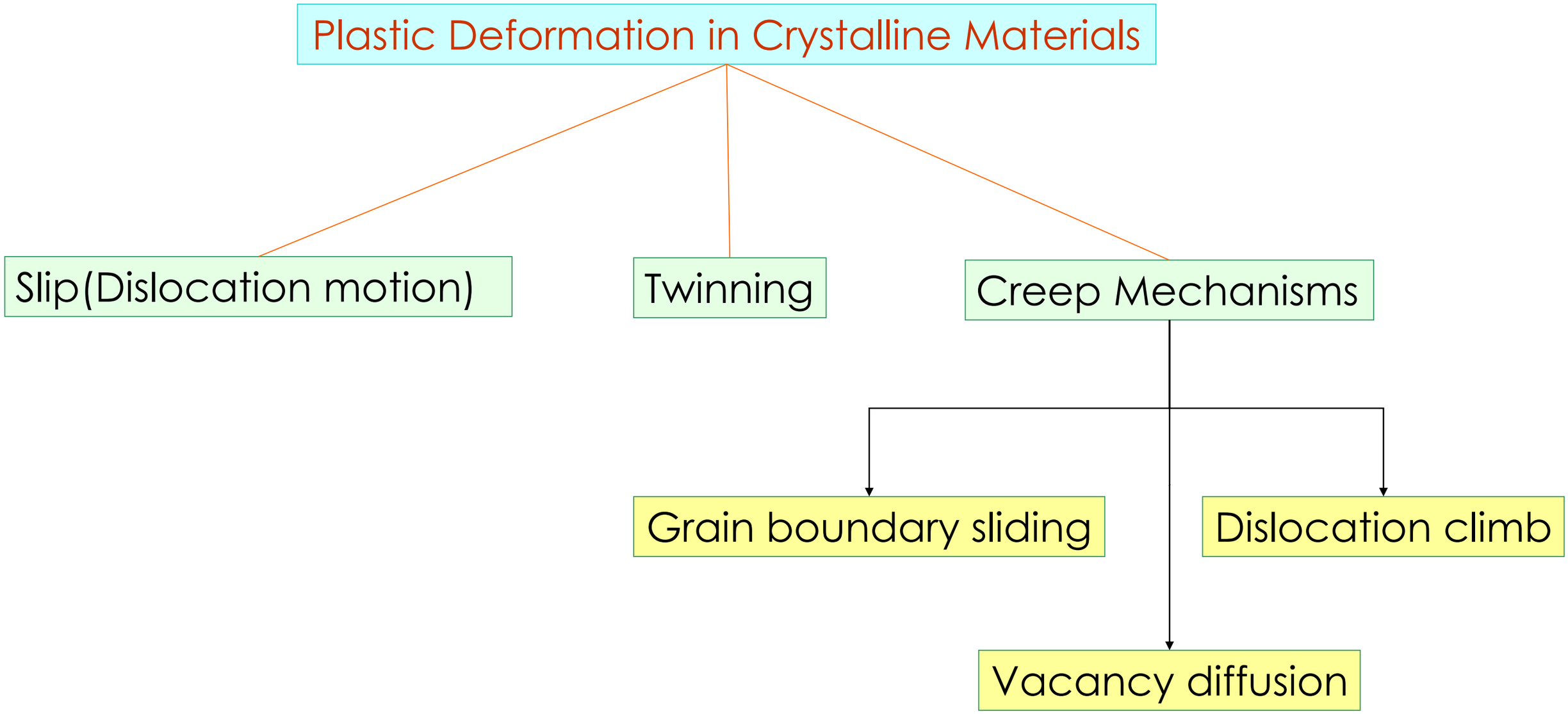


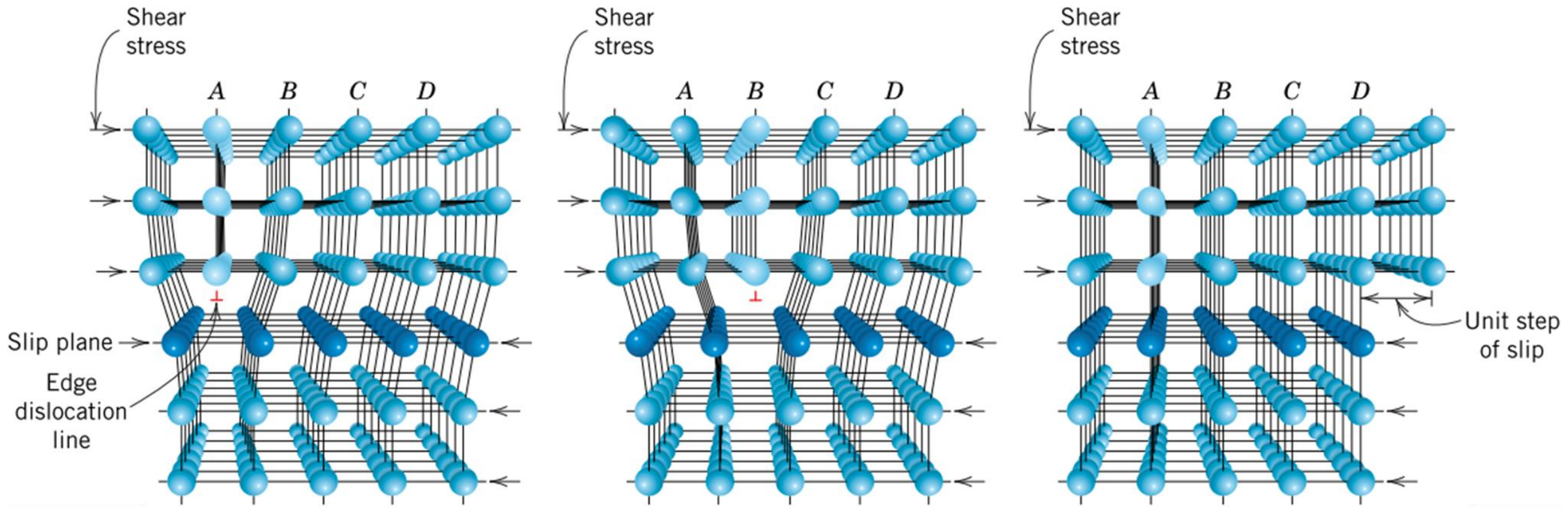
Plastic deformation

How the plastic deformation takes place at the microscopic level?

What happens to crystal structure after plastic deformation?

Plastic deformation by slip

1. Slip is a shear deformation that moves atoms by many interatomic distances relative to their initial positions.
2. Steps are created at the surface of the crystal during slip, but orientation of crystal remains same.
3. Edge dislocation slides over adjacent plane/half planes of atoms.

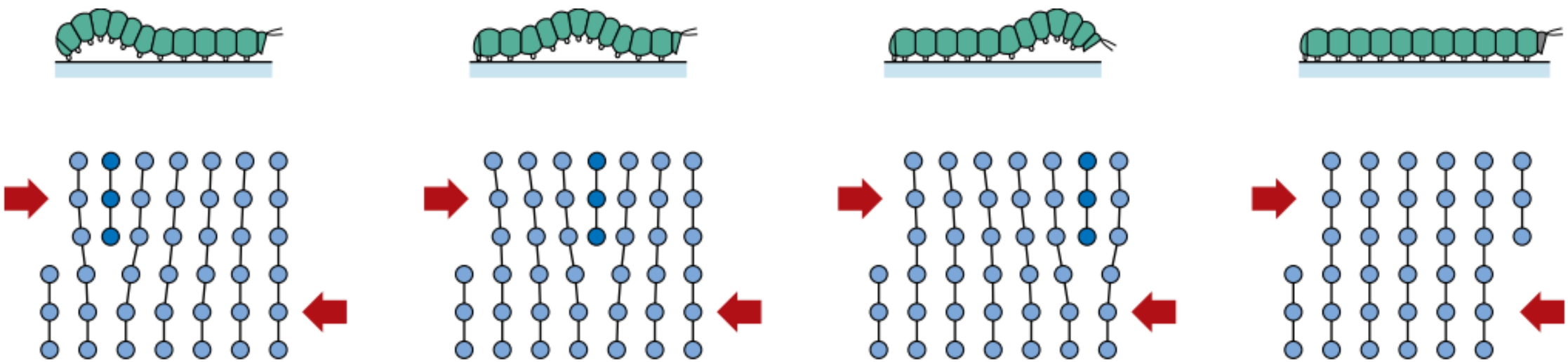


Adapted from Fig. 8.1, *Callister & Rethwisch 3e.*

- If dislocations can't move, plastic deformation doesn't occur!

Dislocation motion

Analogy between caterpillar and dislocation motion.

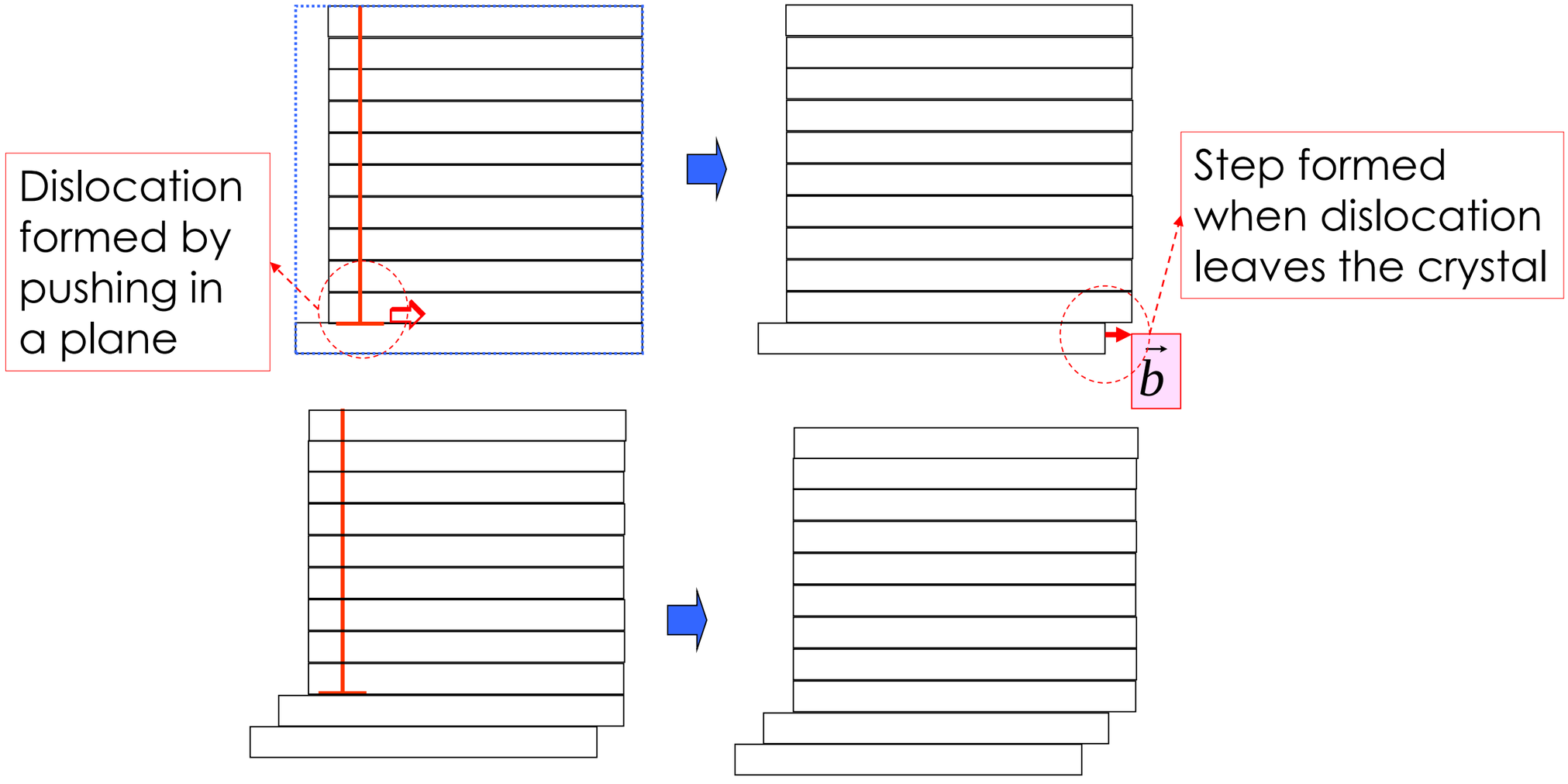


Plastic deformation ➔ Slip

Slip ➔ dislocations

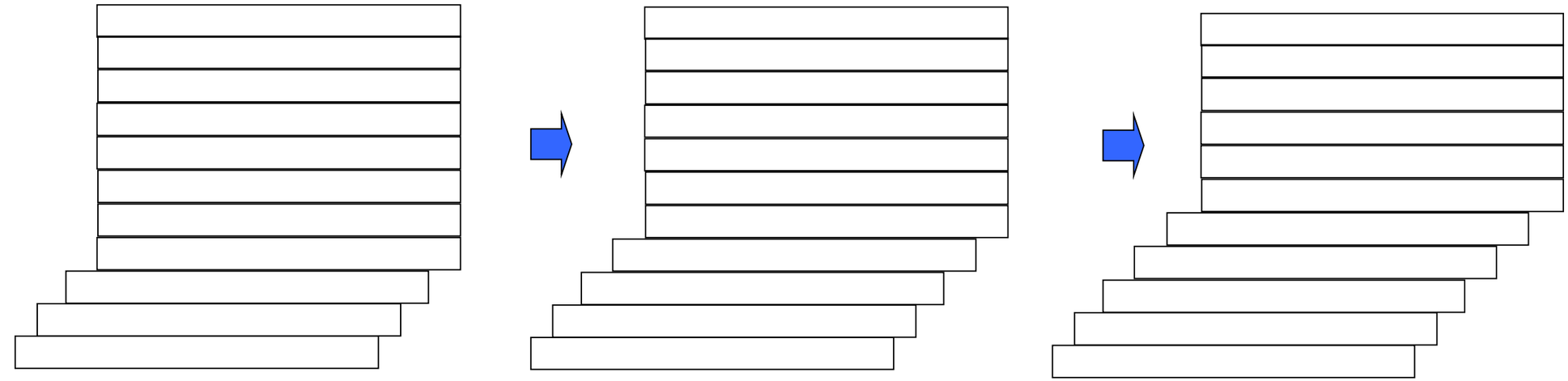
Plastic deformation requires movement of dislocations on the slip plane.

Slip movement

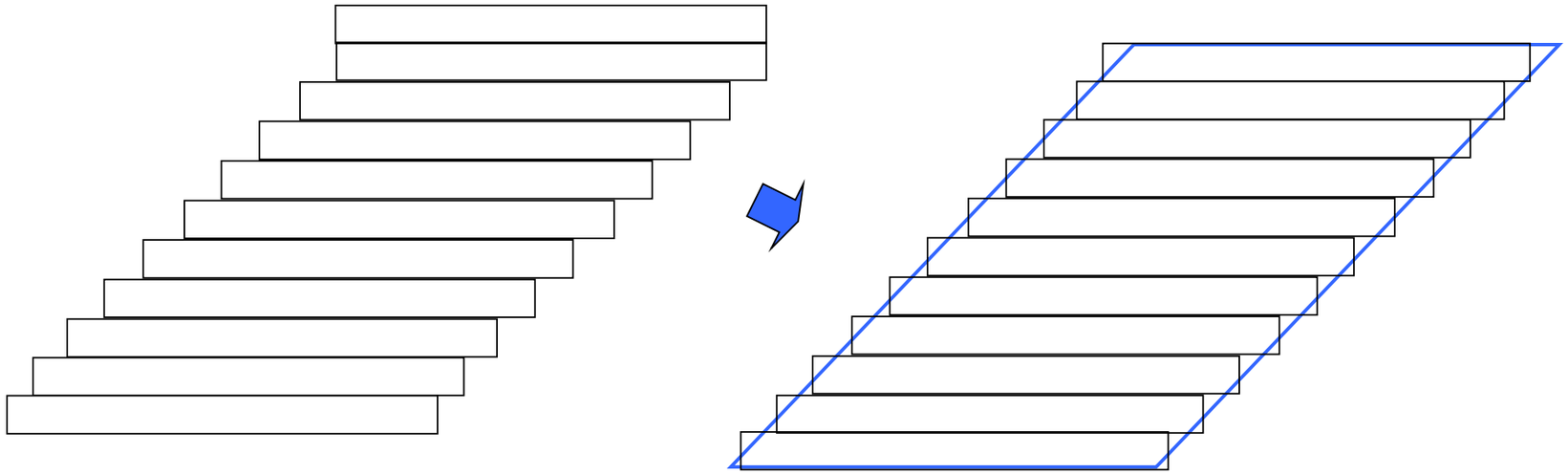


Now visualize dislocations being punched in on successive planes → moving and finally leaving the crystal

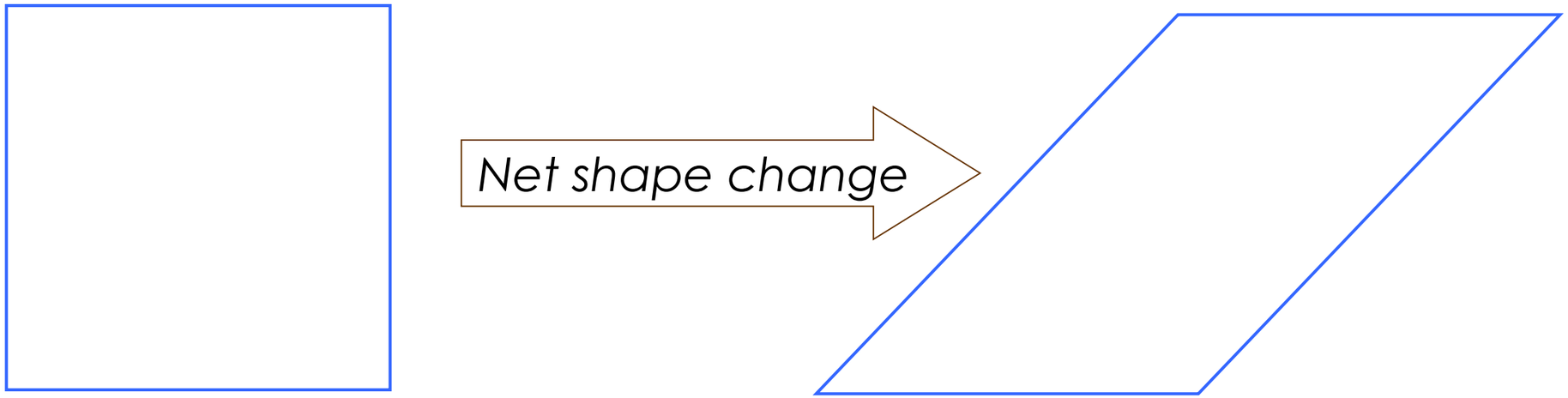
Slip movement



Slip movement



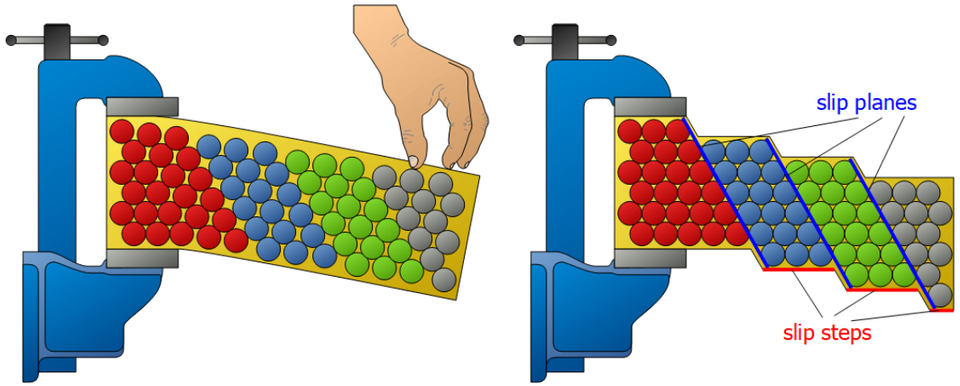
This sequence of events finally leads to deformed shape which can be approximated to a rhombus

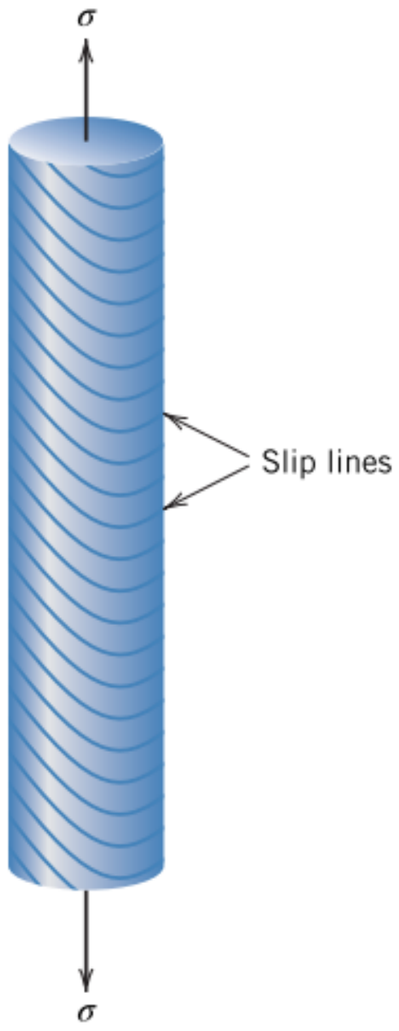


Slip is movement of planes

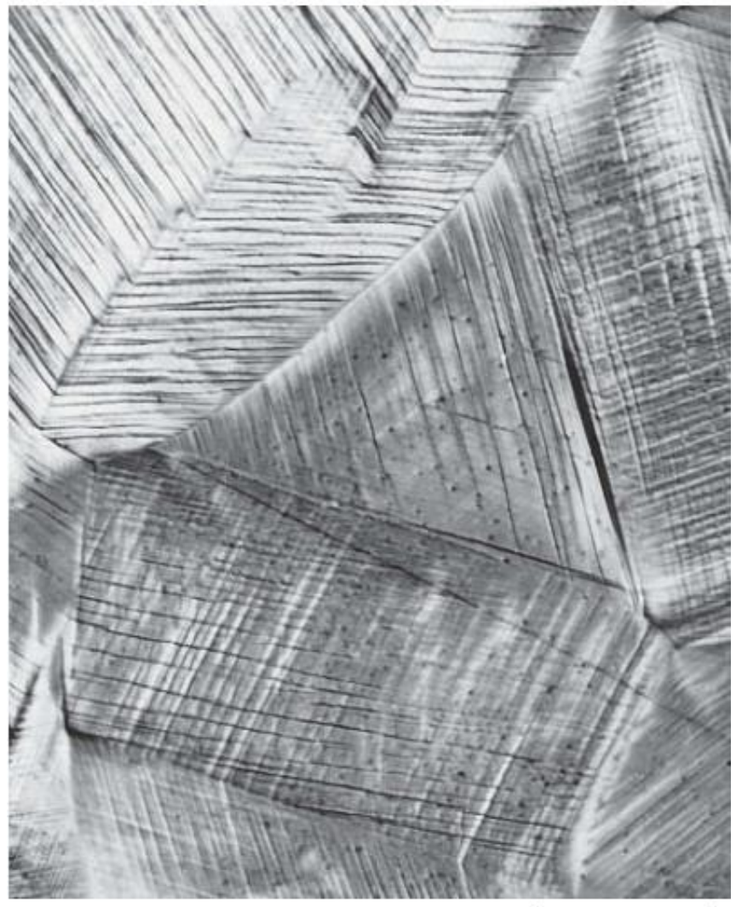
Before slip

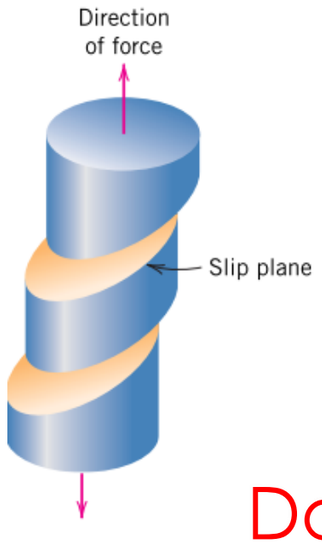
After slip





Visual observation of slip planes





Does this movement takes place in any plane and direction?

Plastic deformation by slip: Recap

Crystallography determines the Burgers vector:

Fundamental lattice translational vector lying on the slip plane.

We need to know:

Slip plane (most densely packed plane) → Dislocations move on this plane

Slip direction (Burger vector) → Dislocations move along this direction

Crystal system	Direction of Burger vector (this is the direction of slip)
Monoatomic FCC	½<110>
Monoatomic BCC	½<111>
Monoatomic SC	<100>
NaCl type structure	½<110>
CsCl type structure	<100>
DC type structure	½<110>

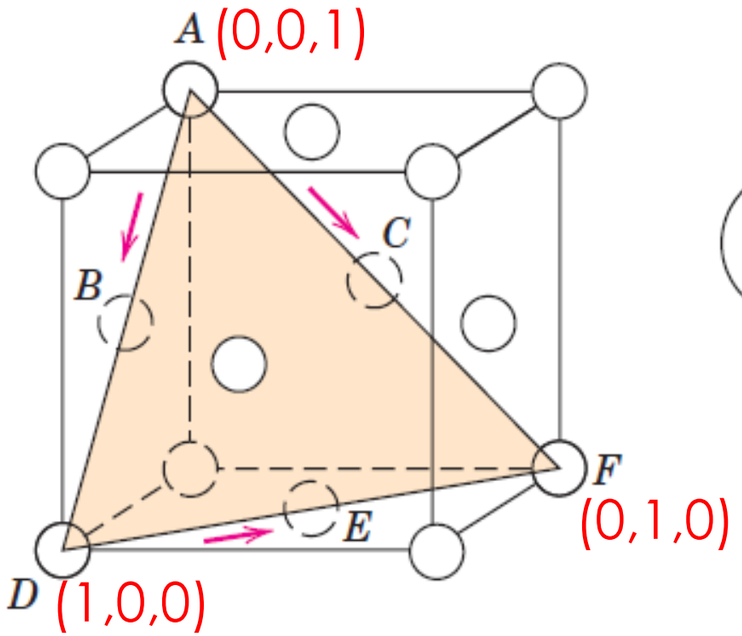
Slip Systems

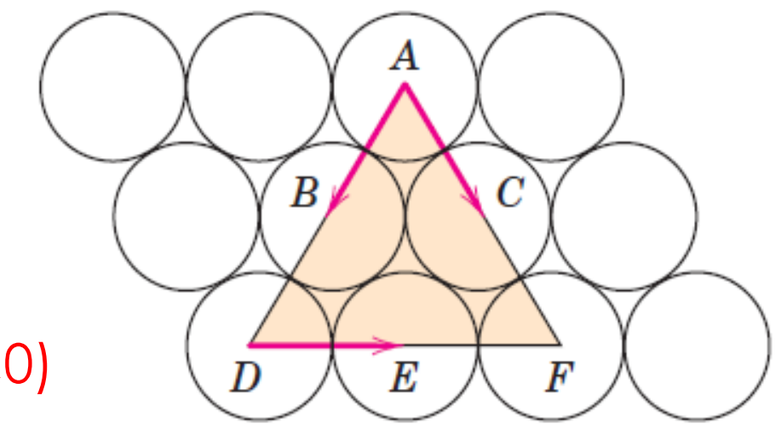
For a FCC system

Slip plane: {111} planes (most densely packed planes)
Slip direction:<110>

Slip system
{111} <110>

Consider (111) plane; On this plane exist $[10\bar{1}], [\bar{1}10]$ and $[0\bar{1}1]$ directions.





Three possible slip directions on same slip plane

{111} planes: There are 4 unique members.
On each plane three possible <110> type directions.
Total 12 possible combinations.

Slip Systems

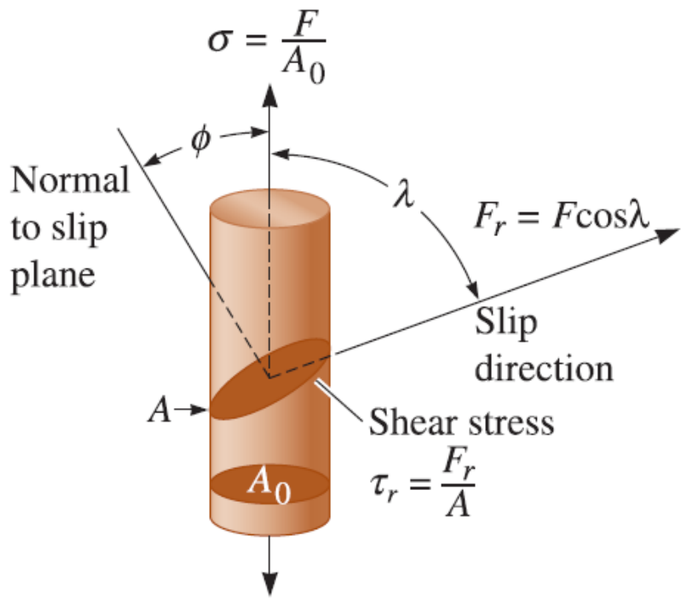
A combination of a slip direction lying on a slip plane is called a slip system.

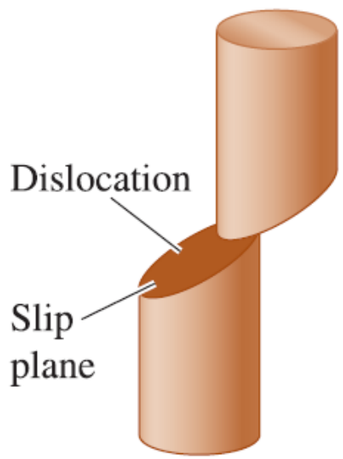
This is described in terms of a family of directions and a family of planes.

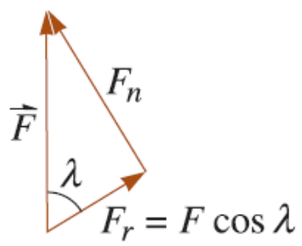
Metals	*Slip Plane*	*Slip Direction*	*Number of Slip Systems*
	Face-Centered Cubic		
Cu, Al, Ni, Ag, Au	{111}	⟨110⟩	12
	Body-Centered Cubic		
α-Fe, W, Mo	{110}	⟨111⟩	12
α-Fe,W	{211}	⟨111⟩	12
α-Fe, K	{321}	⟨111⟩	24
	Hexagonal Close-Packed		
Cd, Zn, Mg, Ti, Be	{0001}	$\langle 11\bar{2}0 \rangle$	3
Ti, Mg, Zr	$\{10\bar{1}0\}$	$\langle 11\bar{2}0 \rangle$	3
Ti, Mg	$\{10\bar{1}1\}$	$\langle 11\bar{2}0 \rangle$	6

HCP metals have fewer active slip systems and hence, are normally quite brittle.

Slip in single crystals – Schmid's law







Full amount of force is not used to move the dislocation along slip direction on the slip plane.

Although tensile stress is σ,

The shear stress responsible to move the dislocation is τ_r (Resolved shear stress).

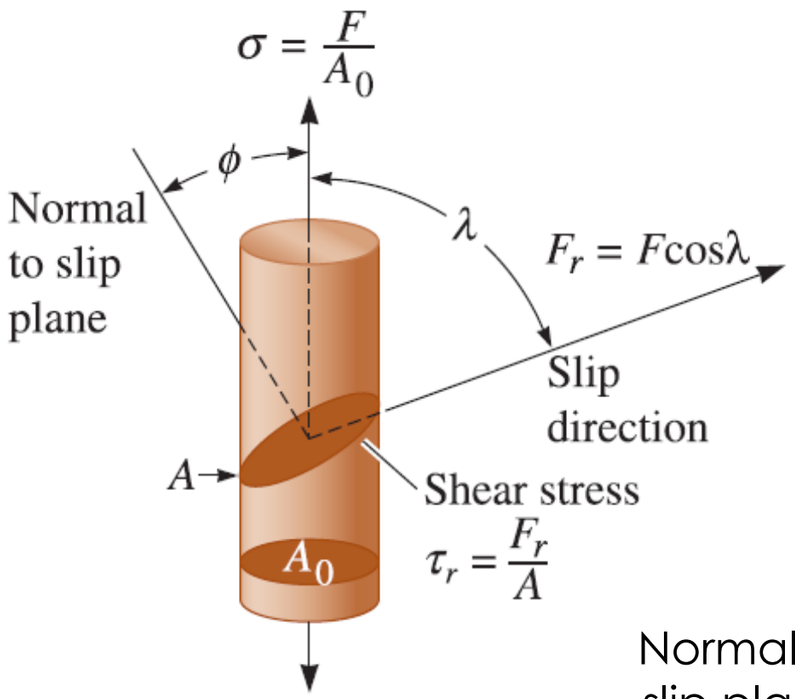
$$\tau_r = \frac{F_r}{A} = \frac{\mathrm{F}\cos\lambda}{\frac{A_0}{\cos\phi}} = \frac{F}{A_o}\cos\lambda\cos\phi$$

$$\boldsymbol{\tau_r = \sigma\cos\lambda\cos\phi}$$

Resolved shear stress

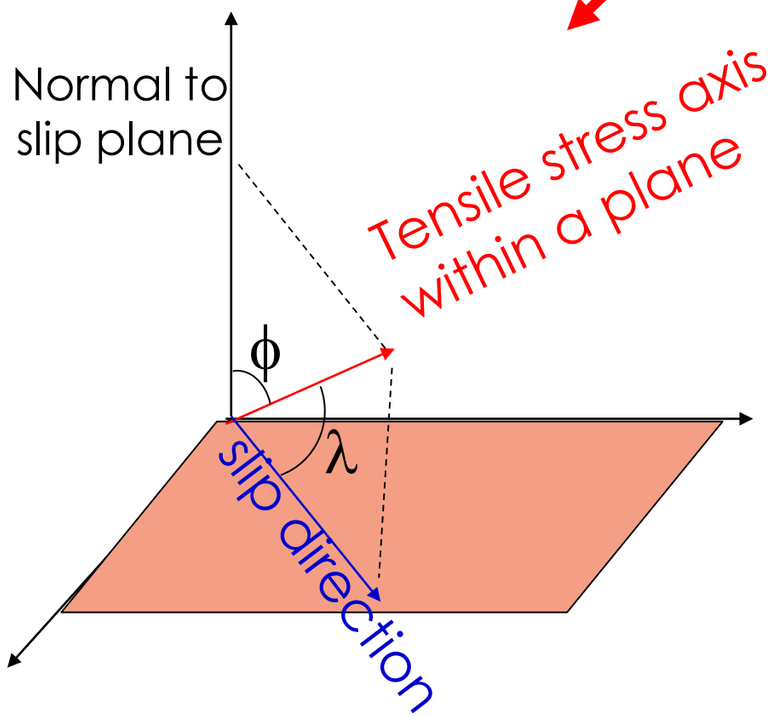
Minimum amount of shear stress capable of moving a dislocation is critical resolved shear stress τ_{CRSS}

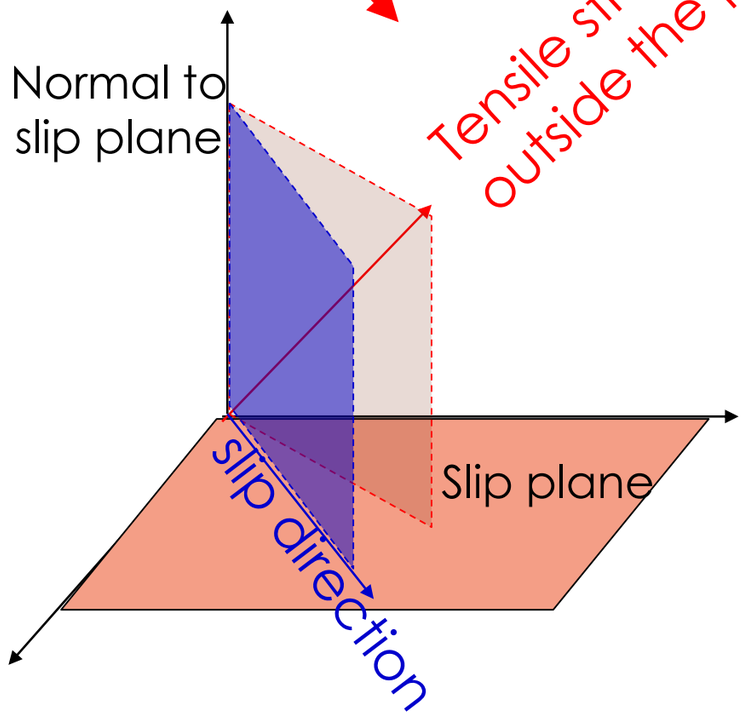
Slip in single crystals – Schmid's law



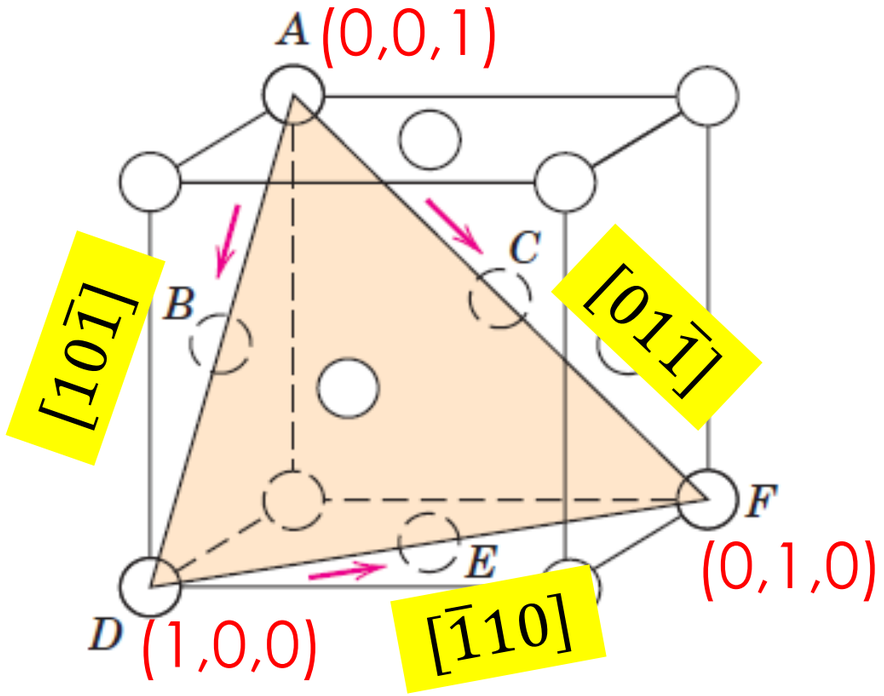
Is ALWAYS ($\phi + \lambda$) = 90°?

No, not necessarily.





Slip in single crystals – Schmid's law



If we apply a tensile stress, the amount of shear stress along these possible slip directions is not same.

- Depends on the angles λ and ϕ

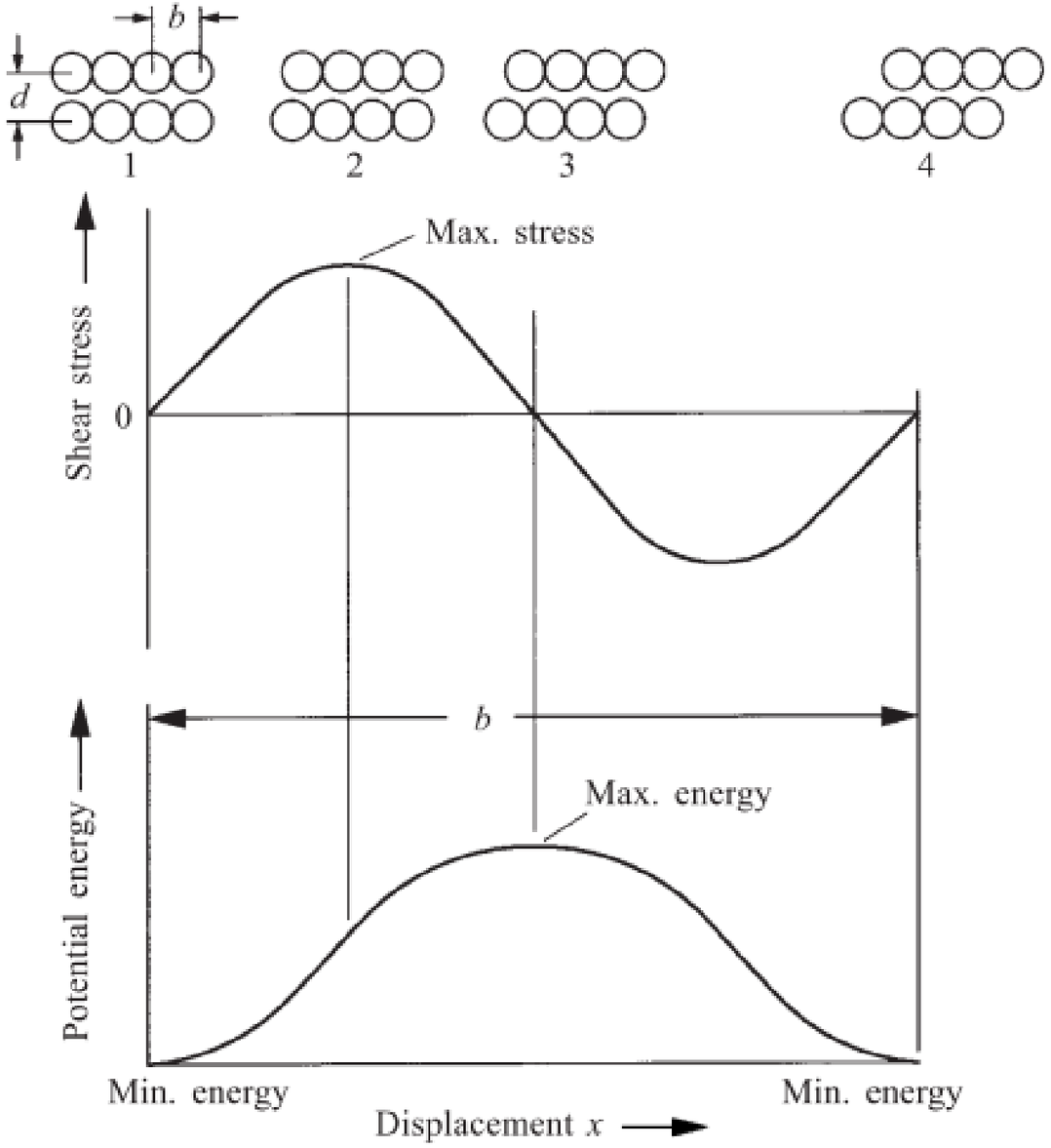
$(\tau_r = \sigma \cos\lambda \cos\phi)$

Dislocations will move along the direction which has the maximum of the resolved shear stress among all possible directions.

$$\tau_{CRSS} = \sigma_y \left(\cos\lambda \cos\phi\right)_{max}$$

A single crystal of aluminum is oriented for a tensile test such that its slip plane normal makes an angle of 28.18° with the tensile axis. Three possible slip directions make angles of 62.48°, 72.08°, and 81.18° with the same tensile axis. (a) Which of these three slip directions is most favored? (b) If plastic deformation begins at a tensile stress of 1.95 MPa, determine the critical resolved shear stress for aluminum.

Stress to move a dislocation in ideal crystals



$$\tau = k\sin\left(\frac{2\pi x}{b}\right)$$

K= constant
b= interatomic distance
d=interplanar spacing

$$\frac{2\pi x}{b} << 1$$

$$\therefore \sin(\theta) = \theta \ \textit{if}\ \theta\ \textit{is very small}$$

$$\tau = k\left(\frac{2\pi x}{b}\right)$$

Now,

$$\mu = \frac{\tau}{\theta}\ ;\ \theta = \frac{x}{d}$$

$$\Rightarrow \tau = \frac{\mu x}{d}$$

$$\Rightarrow k = \frac{\mu b}{2\pi d}$$

$$\tau = \frac{\mu b}{2\pi d}\sin\left(\frac{2\pi x}{b}\right)$$

Now for maximum τ

$$\tau_{CRSS} = \frac{\mu}{6}$$

b=d for many crystals

Do real crystals follow the above theoretical prediction?

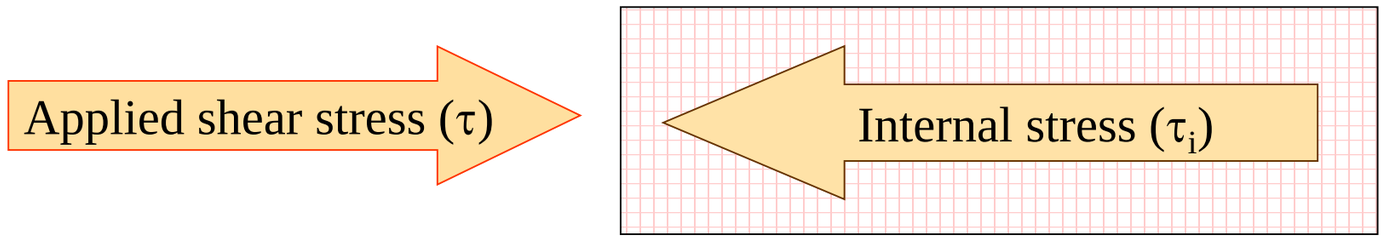
Stress to move a dislocation in real crystals

Crystal	Structure	Shear Modulus μ (MN/m^2)	Theoretical τ (MN/m^2)	CRSS, τ (MN/m^2)	μ/τ **(This should be 6)**
Copper	FCC	44000	7300	0.5	88000
Aluminum	FCC	25000	4100	0.75	33000
Gold	FCC	26000	4300	0.5	52000
Nickel	FCC	70000	11600	5	14000
Silver	FCC	26000	4300	0.5	52000
Iron	BCC	70000	11600	15	4700
Zinc	HCP	33000	5500	0.3	110000

Real crystal do not follow the above result and deforms at much lower stress.

Stress to move a dislocation in real crystals

- Ideal crystal assumes no dislocations, but real crystal have dislocations present in the crystal.
- The dislocations does not move simultaneously.
- They move by small adjustment in the bond lengths in the dislocation region.
- Dislocations already have stress field and helps for movement.



We need to consider a model which uses stress field already present in the crystal

Stress to move a dislocation in real crystals

- Peierls & Nabarro consider presence of dislocations and calculate the stress to move it called as Peierls-Nabarro stress (PN stress).
- Width of the dislocation is considered as a basis for the ease of motion of a dislocation in the model which is a function of the bonding in the material.

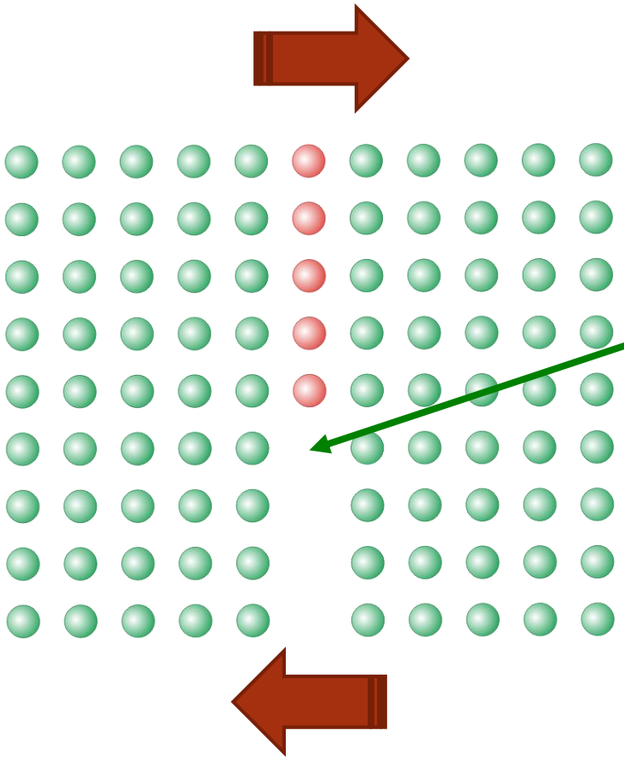
$$\tau_{PN} = \mu e^{-\left(\frac{2\pi w}{b}\right)}$$

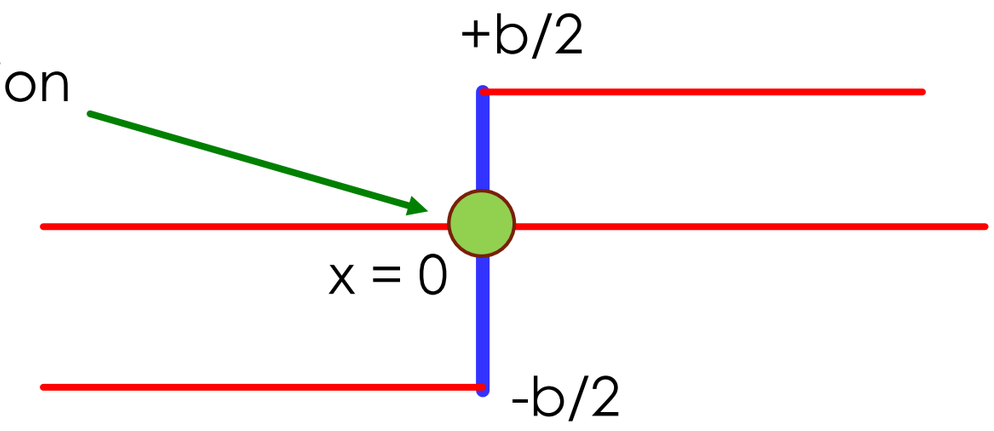
- μ → Shear modulus of the crystal
- b → |**b**|
- w → Width of the dislocation !!!

(dimension over which dislocation is relaxed)

Stress to move a dislocation in real crystals

Width of dislocation: Few atomic distance
e.g. 10-20 planes, Diamond



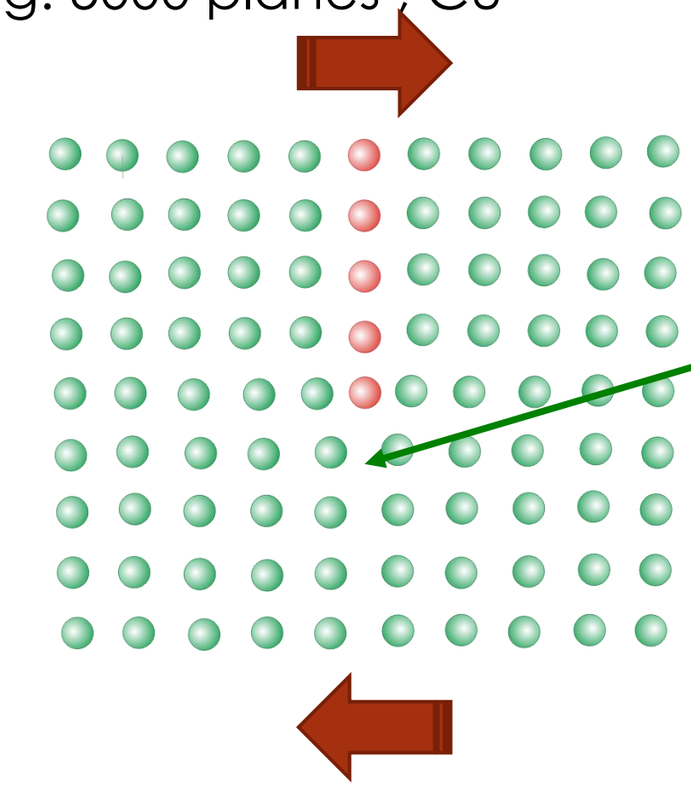


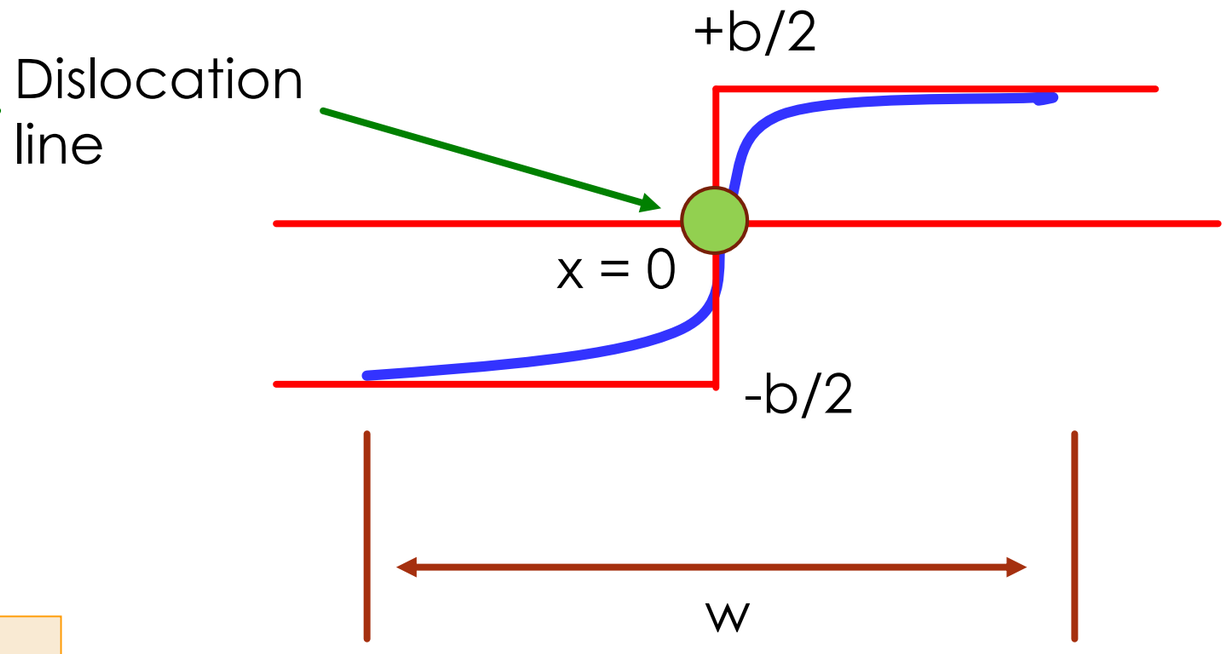
w is almost zero here

- Unrelaxed condition- *stiff*
- Narrow width *of displacement fields*
- ⇒ atomic adjustments required *(for any one atom)* for dislocation motion are large

Stress to move a dislocation in real crystals

Width of dislocation: Many interatomic distance
e.g. 5000 planes , Cu





- 'Relaxed' condition
- Large width *of displacement fields*
- ⇒ atomic adjustments required for dislocation motion are small

Stress to move a dislocation in real crystals

Effect of w on τ_{PN}				
w	0	b	5b	10b
τ_{PN}	μ	μ / 400	μ / 10^{14}	μ / 10^{27}

Hence,

- Narrow dislocations are more difficult to move than wide ones
- Dislocations with larger b are more difficult to move

Width of the dislocation & bonding of crystals

Nature of chemical bonding in the crystal determines the → extent of relaxation & the width of the dislocation

Covalent crystals

- Strong and directional bonds → small relaxation (low w) → high τ_{PN}
- Usually fail by brittle fracture before τ_{PN} is reached

Metallic crystals

- Weaker and non-directional bonds → large relaxation (high w) → low τ_{PN}
- E.g. Cu can be cold worked to large strains

Ionic crystals

- Moderate and non- directional bonds
- Surface cracks usually lead to brittle fracture
- Large b (NaCl: b = 3.95Å) → more difficult to move

Summary

1. Plastic deformation takes place by the movement of slip planes.
2. Dislocation movement takes place along a specific direction and plane called as slip system.
3. Stress to move dislocations is affected by the presence of dislocations.
4. Narrow (stiff) dislocations are difficult to move.
5. Wide (relaxed) dislocations are easy to move.