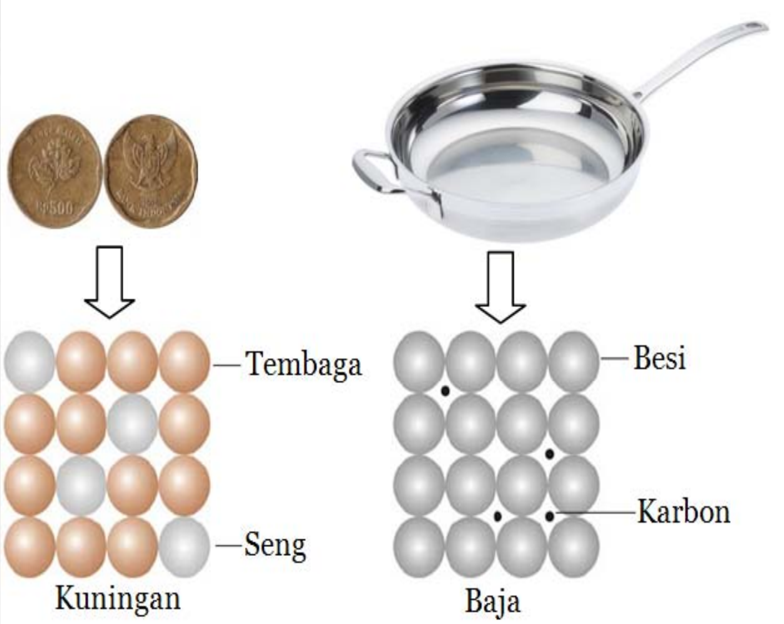
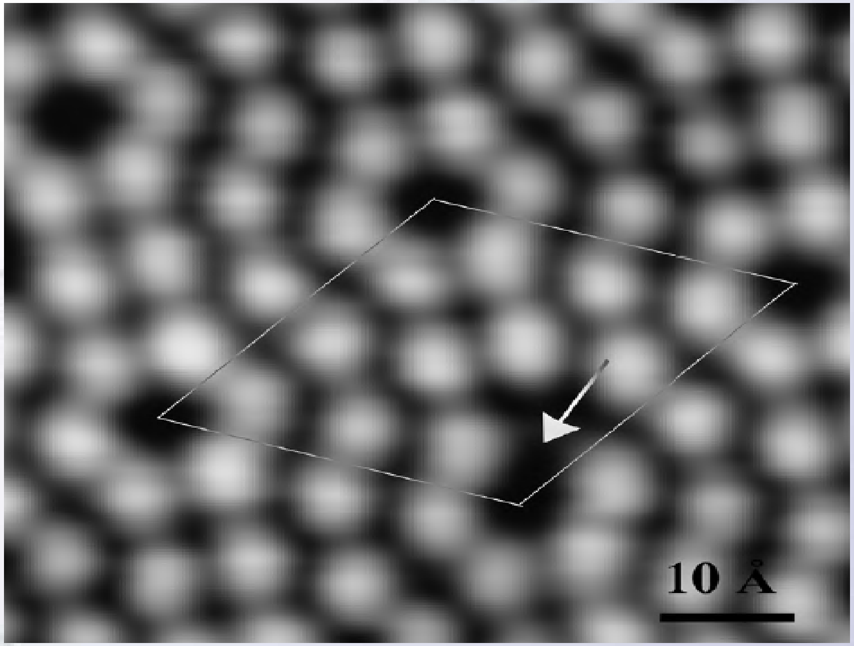
Cacat Kristal





Oleh

Dr. H. Harun Nasrudin, M.S.

Samik, S.Si., M.Si.

OVERVIEW

PENGERTIAN

Classification of Defects

- Point defects: solute atoms (strength, conductivity)
- Line defects: dislocations (plastic deformation)
- Surface defects: external surface (crystal shape)
- Volume defects: voids, inclusions (fracture)

PENGERTIAN

An ideal crystal can be described in terms a three-dimensionally periodic arrangement of points called lattice and an atom or group of atoms associated with each lattice point called motif:

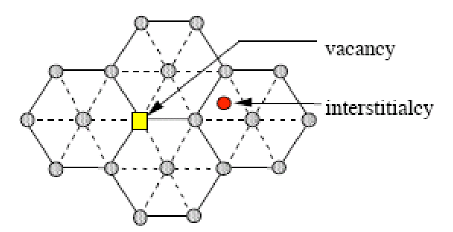
Crystal = Lattice + Motif

However, there can be deviations from this ideality.

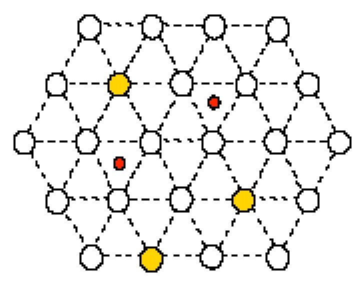
These deviations are known as **CRYSTAL DEFECTS**.

POINT DEFECTS

- Intrinsik defects : Occur in pure substances
  - Schottky defects
  - Frenkel defects

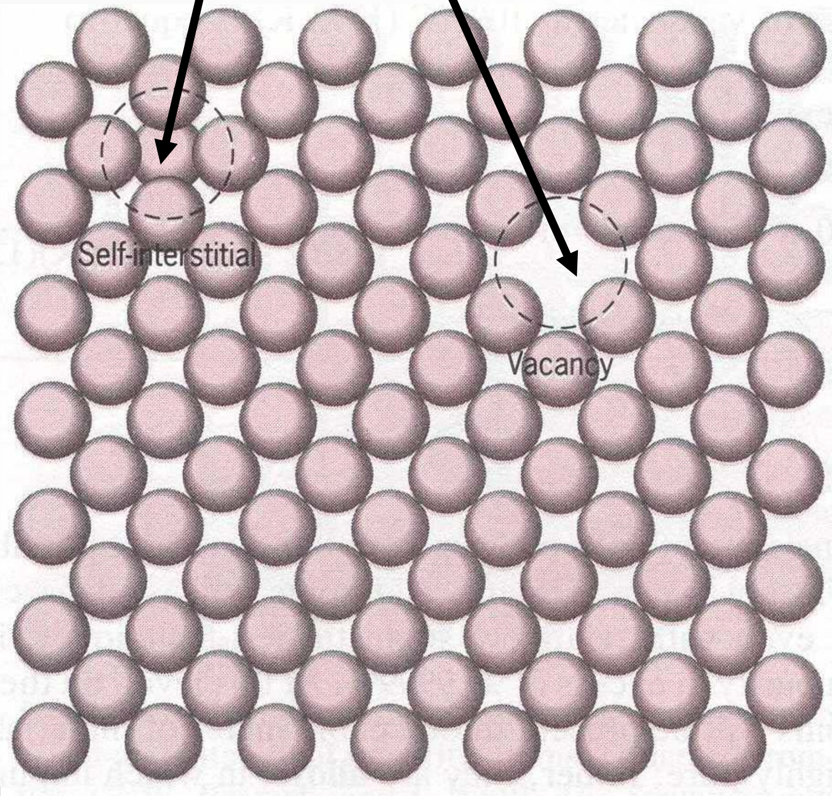


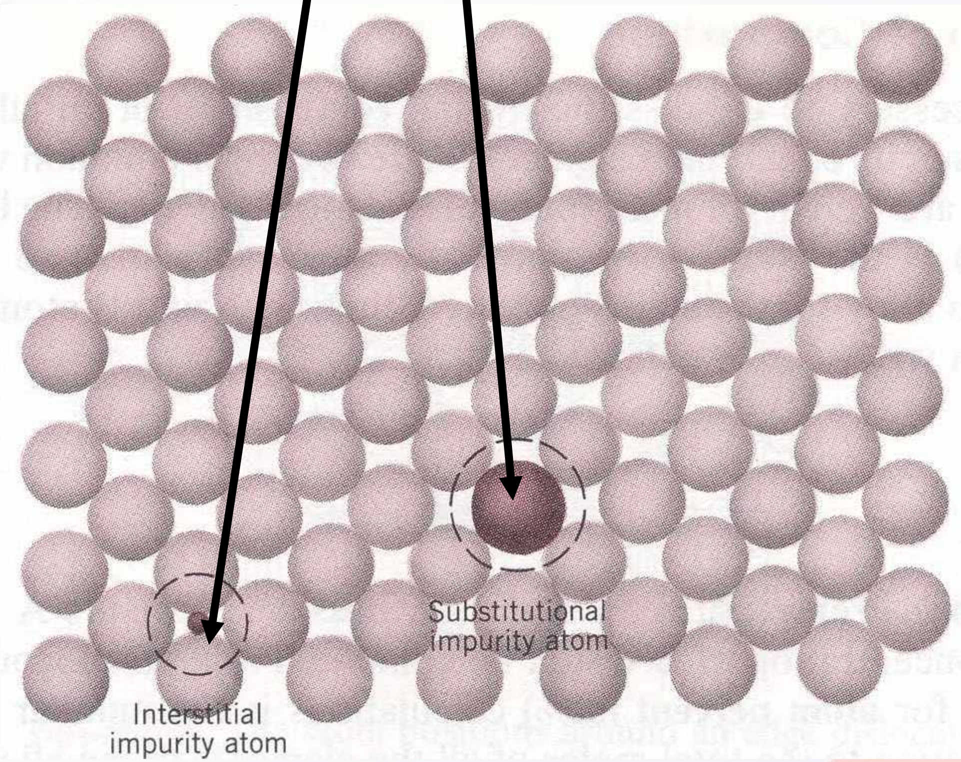
- Extrinsik defects Due to impurities
  - Substitutional solid solutions
  - Interstitial solid solutions



Point Defects

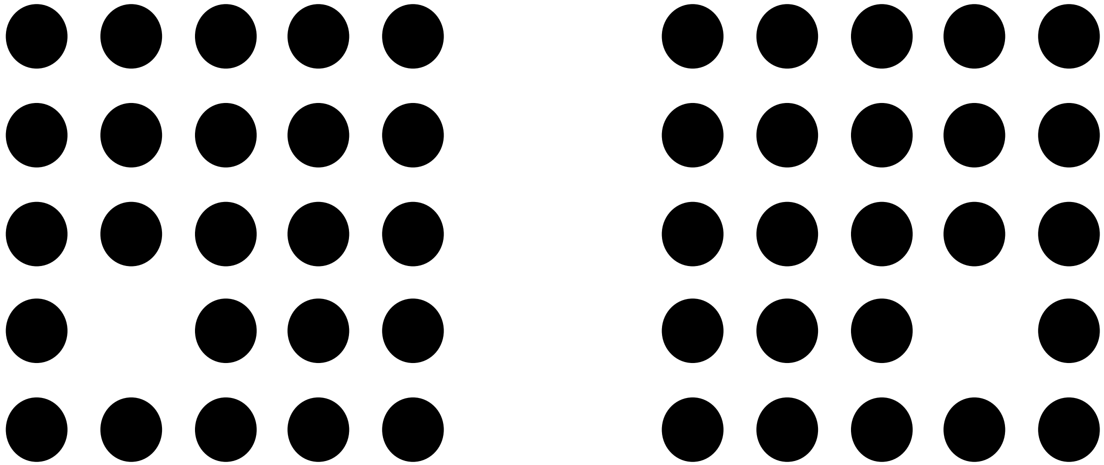
- *Intrinsic* defects
  - *Vacancy*
  - *Self-interstitial*
- *Extrinsic* defects
  - *Substitutional impurity*
  - *Interstitial impurity*





Vacancy

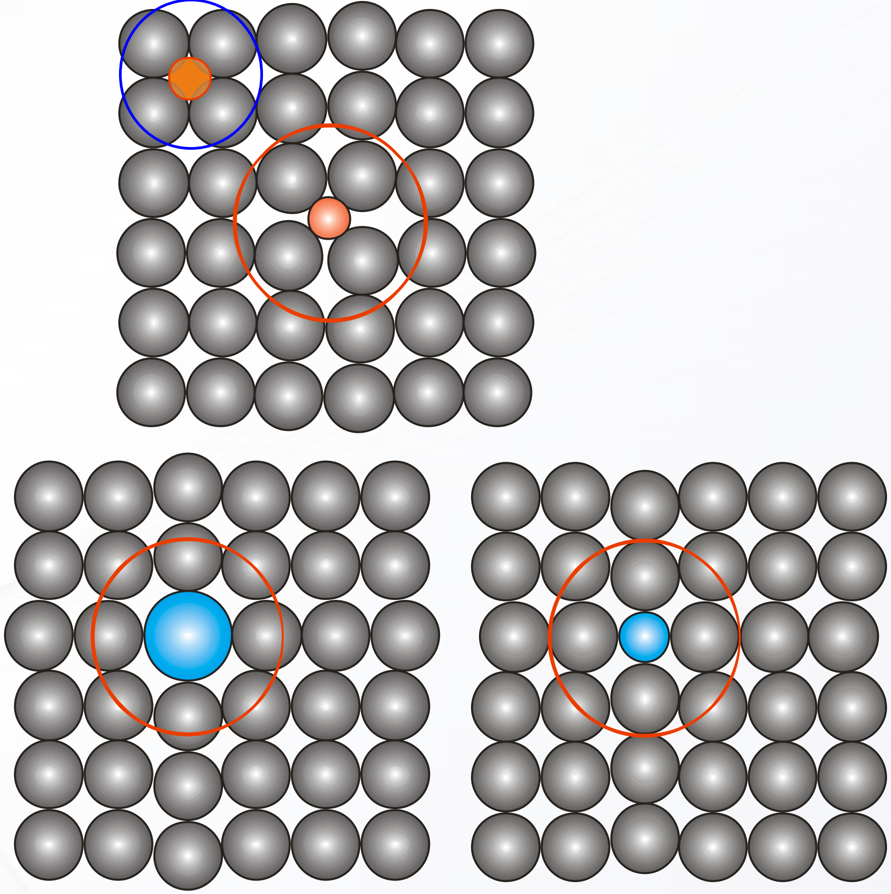
- ☐ Missing atom from an atomic site
- ☐ Atoms around the vacancy displaced
- ☐ Tensile stress field produced in the vicinity



Impurity

Interstitial

Substitutional



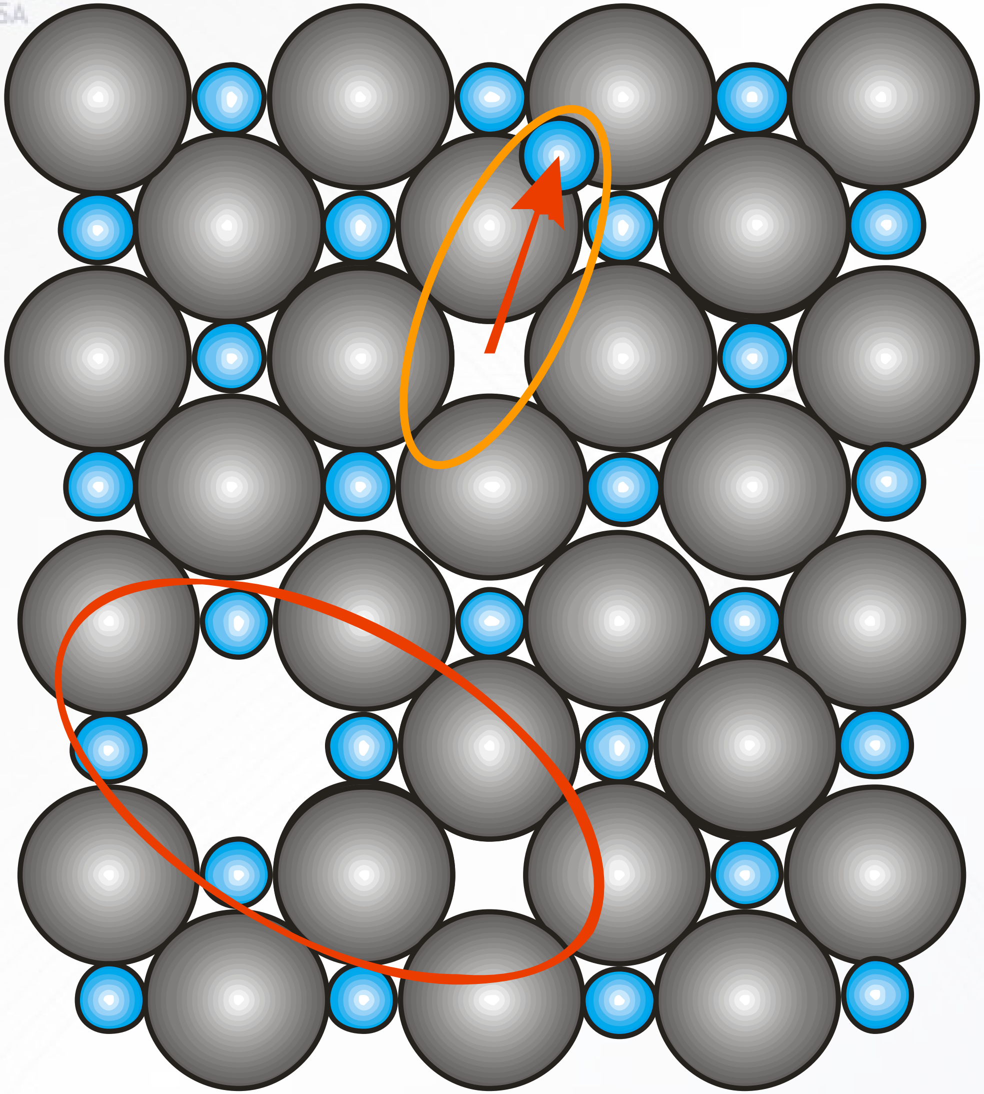
❑ SUBSTITUTIONAL IMPURITY

- Foreign atom replacing the parent atom in the crystal
- E.g. **Cu** sitting in the lattice site of FCC-**Ni**

❑ INTERSTITIAL IMPURITY

- Foreign atom sitting in the void of a crystal
- E.g. **C** sitting in the octahedral void in HT FCC-**Fe**

Defects in ionic solids



Frenkel defect

Cation vacancy
+
cation interstitial

Schottky defect

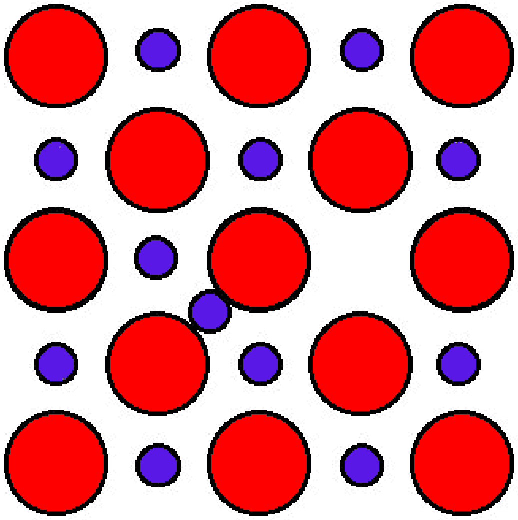
Cation vacancy
+
anion vacancy

Intrinsik Defects -Frenkel

Often a vacancy and interstitial occur together - an ion is displaces from its site into an interstitial position.

This is a **Frenkel Defect** (common in e.g. AgCl) and charge balance is maintained.

Frenkel defects can be induced by irradiation of a sample



Frenkel Defect

Extrinsic defects (due to impurities)

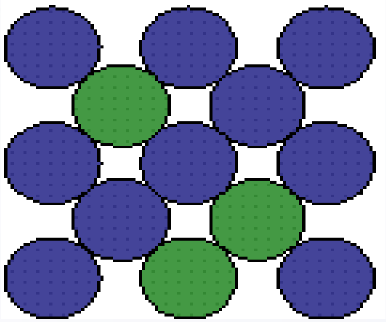
Impurities or *dopants* in a solid are any atom(s) of a type that do not belong in the perfect crystal structure (see ‘extrinsic semiconductors’)

The host crystal with impurities is called a *solid solution*

Substitutional solid solutions

Impurity atoms occupy the same sites of the host atoms

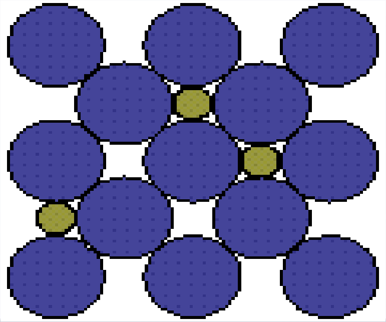
Impurities "substitute" for the host atoms



Interstitial solid solutions

Impurity atoms occupy interstices in the host crystal structure

Impurities usually have a small size compared to the host atoms



Impurity defects

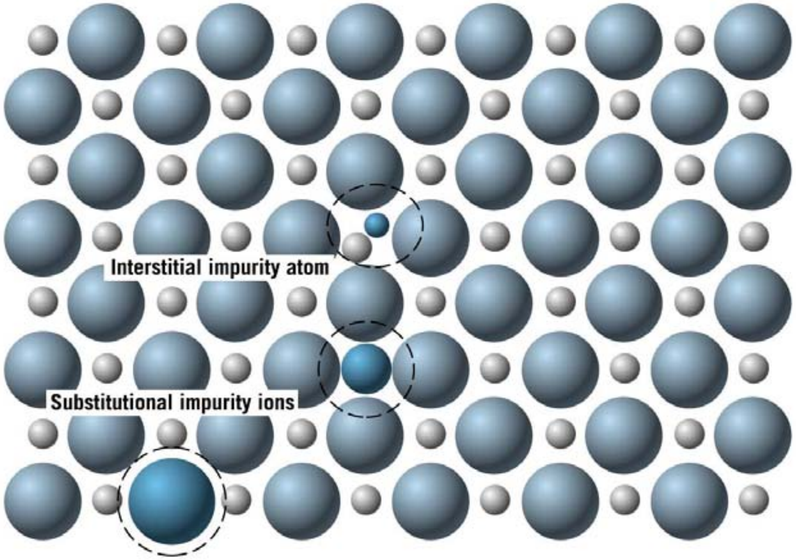


FIGURE 12.23 Schematic representations of interstitial, anion-substitutional, and cation-substitutional impurity atoms in an ionic compound. (Adapted from W. G. Moffatt, G. W. Pearsall, and J. Wulff, *The Structure and Properties of Materials,* Vol. 1, *Structure,* p. 78. Copyright © 1964 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

Charge neutrality must be maintained.

Thus, if a substitutional impurity has a different charge than the substituted ion, another defect (or defects) must be present to balance it out.

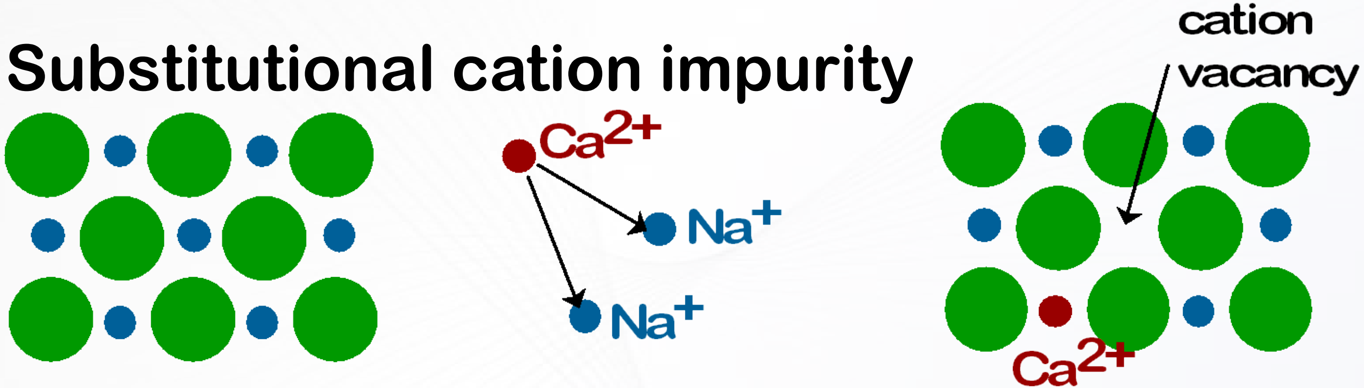
Non-stoichiometry often results.

Cationic	**Anionic**
Ca instead of Na in NaCl	O instead of Cl in NaCl
B instead of Si in SiO_2	O instead of N in GaN

IMPURITIES

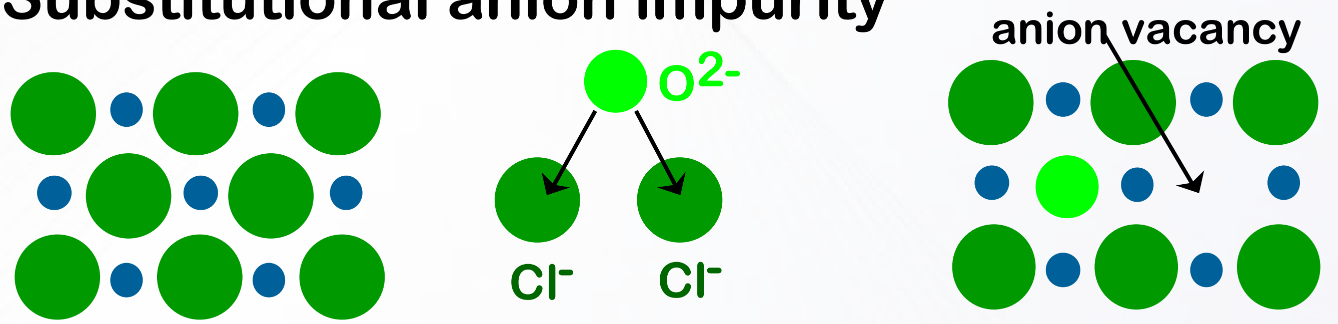
- Impurities must satisfy charge balance
- Ex: NaCl

- Substitutional cation impurity



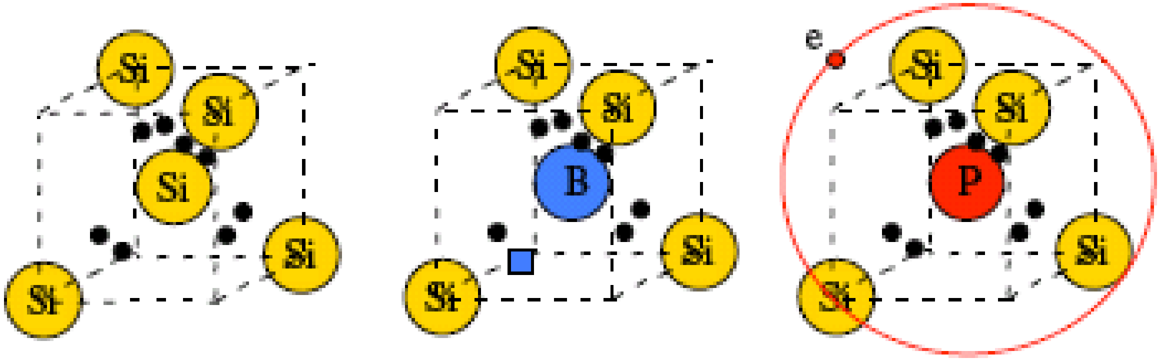
initial geometry | Ca^{2+} impurity | resulting geometry

- Substitutional anion impurity



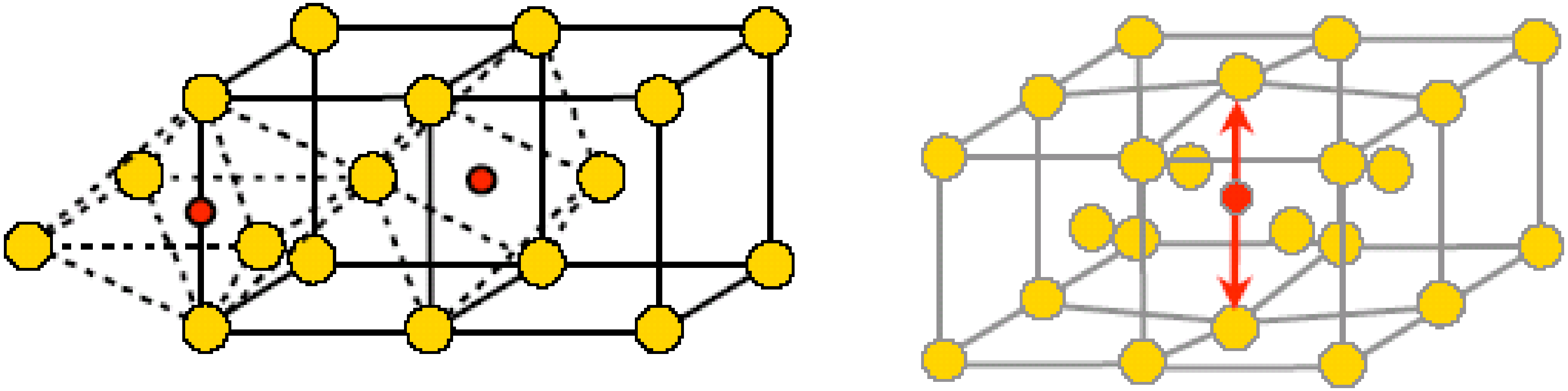
initial geometry | O^{2-} impurity | resulting geometry

Substitutional Solutes: Electrical Defects in Semiconductors



- Solutes can control the number and type of carriers in Si
- P (z = 5) introduces an electron in an excited state
  - Electron can be liberated to conduct electricity
  - "Donor" solutes create "n-type" extrinsic semiconductors
- B (z = 3) leaves a hole in a bonding state
  - Hole can "accept" an electron to create a mobile positive charge
  - "Acceptor" solutes create "p-type" extrinsic semiconductors

Interstitial Solutes: Carbon in Steel



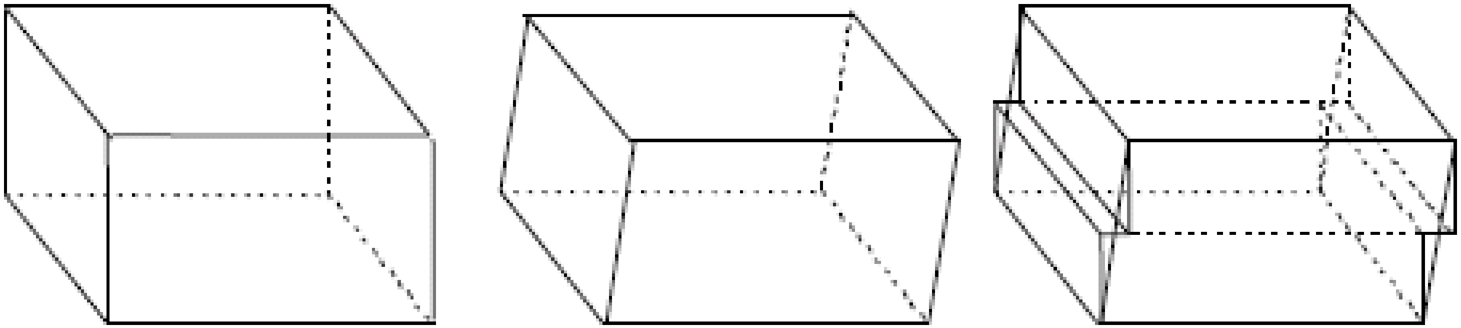
- Carbon interstitials fill octahedral sites in bcc Fe
  - Octahedral has larger volume (smaller radius) than tetrahedral
- Octahedral sites are asymmetric
  - Sites distort, creating local strain
  - Makes deformation difficult, strengthens material

LINE DEFECTS

(DISLOCATIONS)

- Plastic deformations by Slip
- Edge Dislocations
- Screw Dislocations
- Mixed Dislocation

Line Defects:
Plastic Deformation by Slip



- Plastic deformation is a change in shape
  - Changes in shape happen by shear
  - Equivalent to simple shear shown
- Shear happens by “slip”
  - Planes of atoms slip over one an other like cards in a deck
  - Slip is accomplished by linear defects - “dislocations”

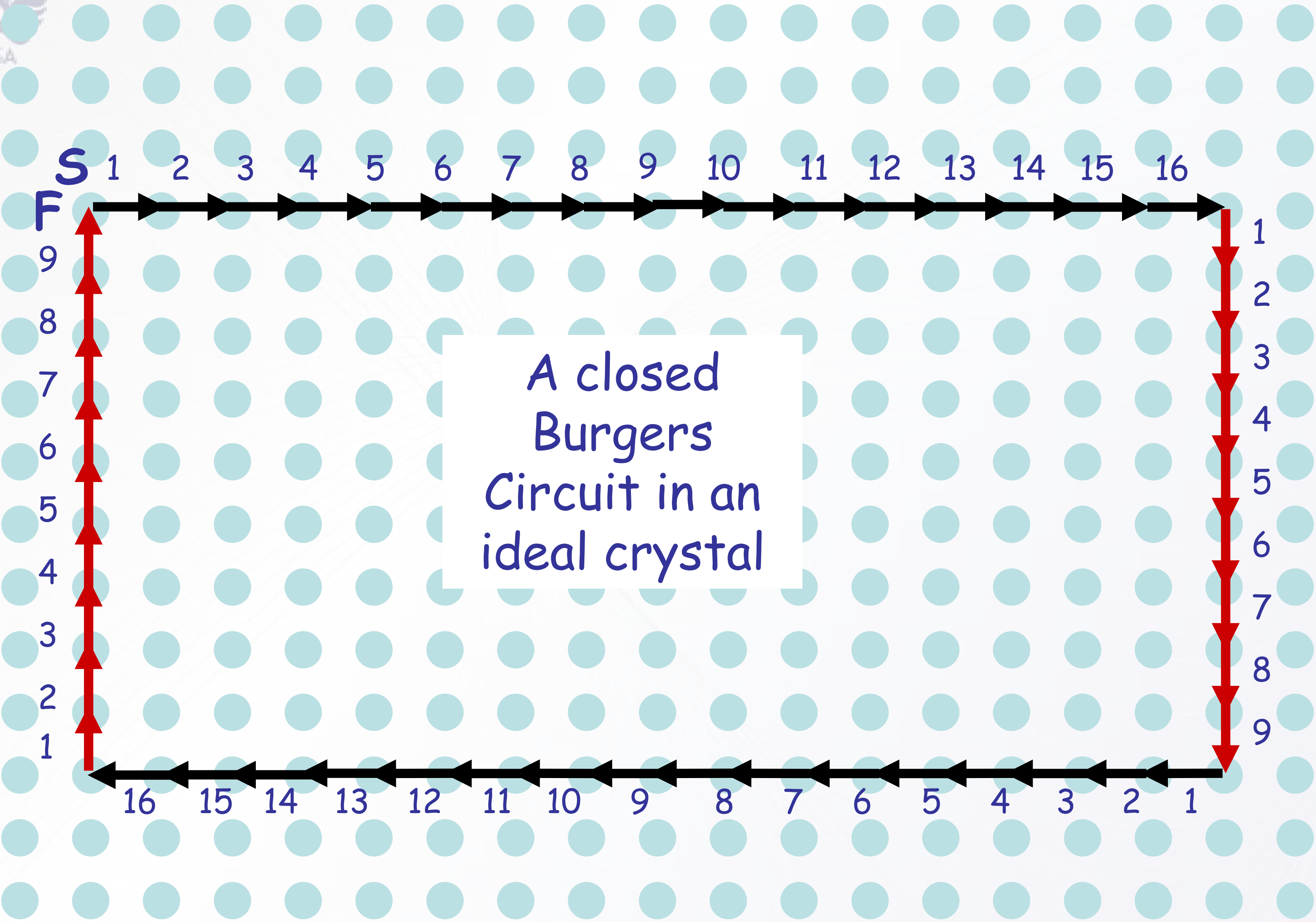
Mechanism of plastic deformation in crystals: <u>dislocation glide</u>, or slip of atomic planes (atomic planes move one by one via the formation and movement of dislocations, rather than all the planes move simultaneously)

Burgers vector

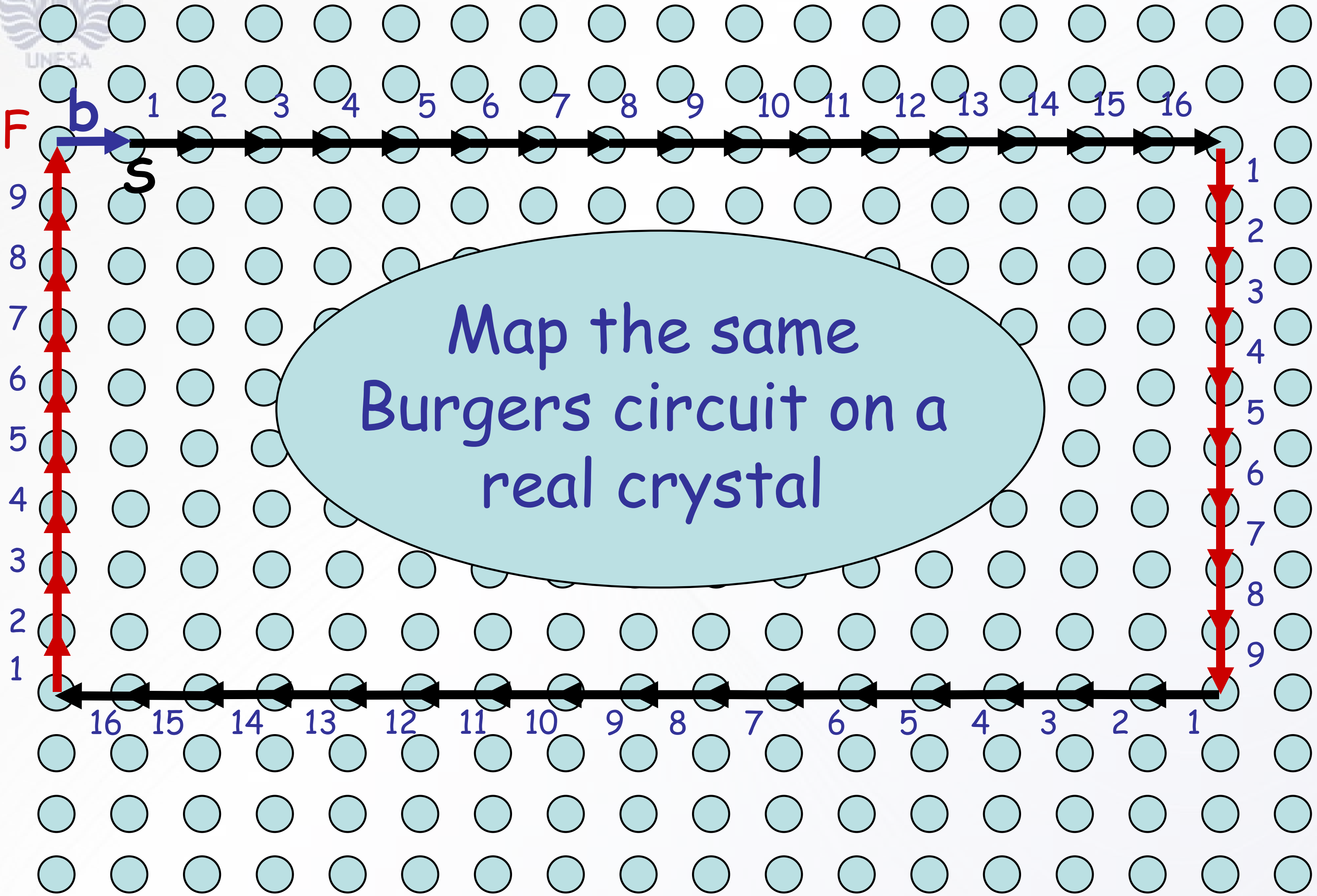
Johannes Martinus
BURGERS

✗ Burger's vector

✓ Burgers vector



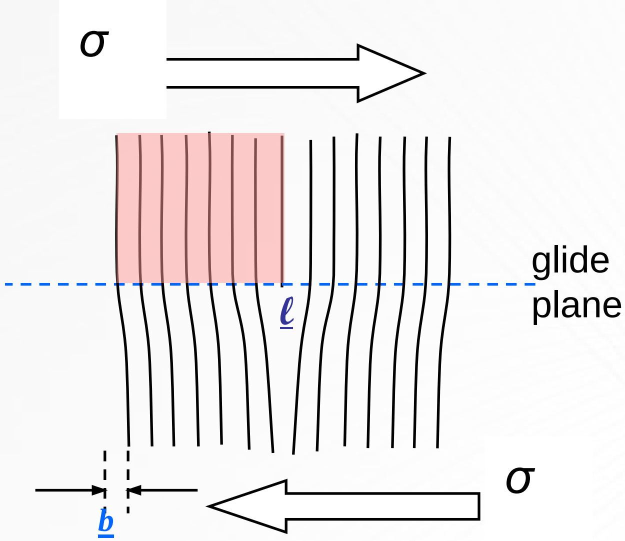
A closed Burgers Circuit in an ideal crystal



Map the same Burgers circuit on a real crystal

RHFS convention

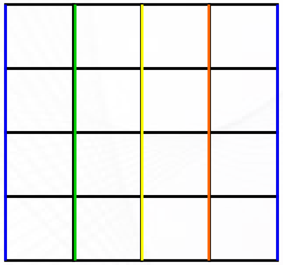
Definitions



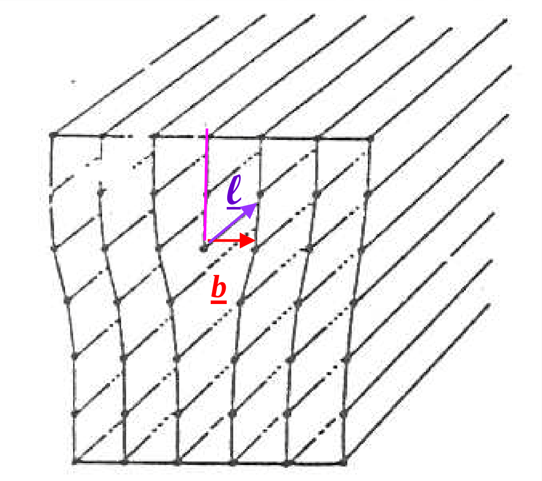
- The boundary plane across which shear occurs is the glide plane
- The boundary line that separates slipped (red) and unslipped regions is the dislocation line or axis ***ℓ***
- The direction and magnitude of slip = Burger's vector, ***b***
- *b* is in general a lattice vector, so there is no long range mismatch between slipped and unslipped planes
- If *b* is parallel to *ℓ* dislocation is 'screw'
- If *b* is perpendicular to *ℓ* dislocation is 'edge'

Edge and Screw Dislocations

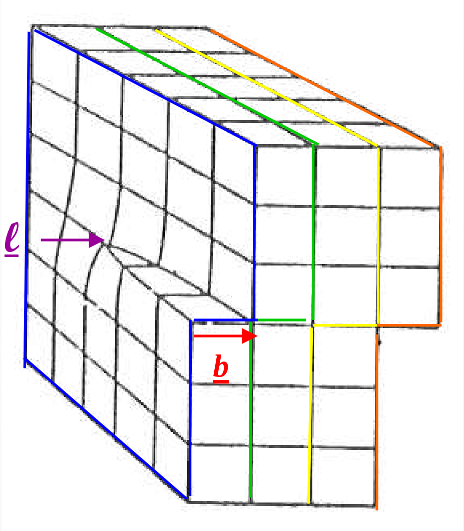
Perfect crystal lattice

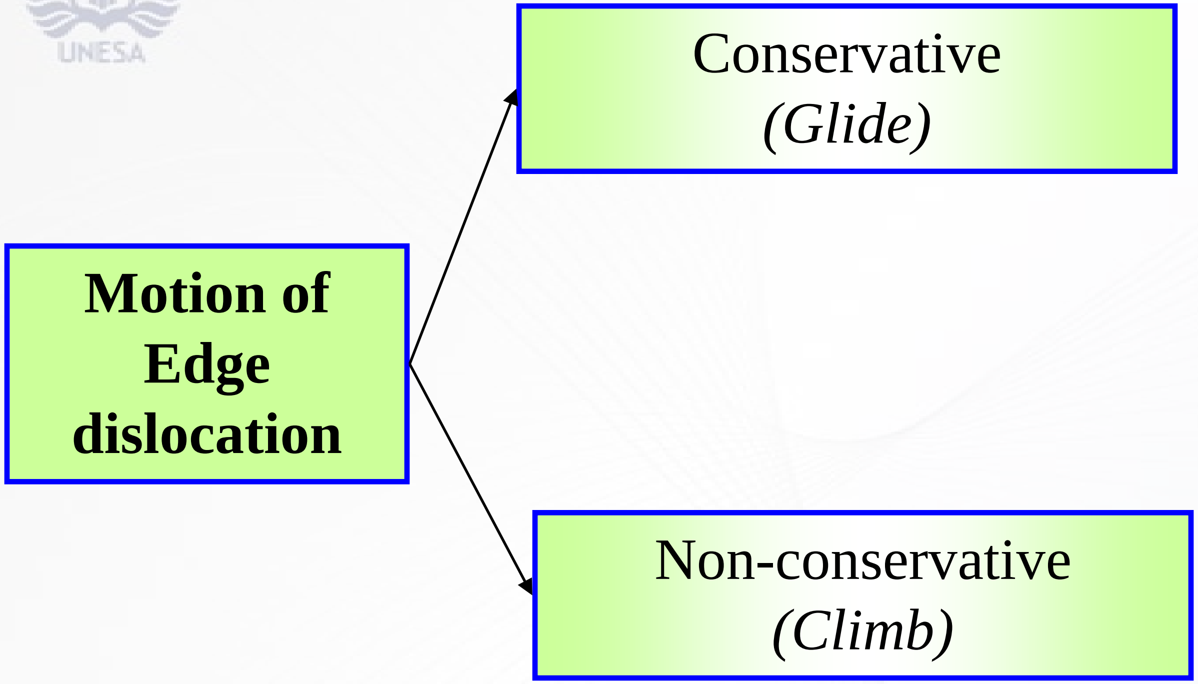


Edge dislocation:
“extra plane”



Screw dislocation
(distortion of the
crystal)





Motion of Edge dislocation

Conservative
(Glide)

Motion of dislocations
On the slip plane

Non-conservative
(Climb)

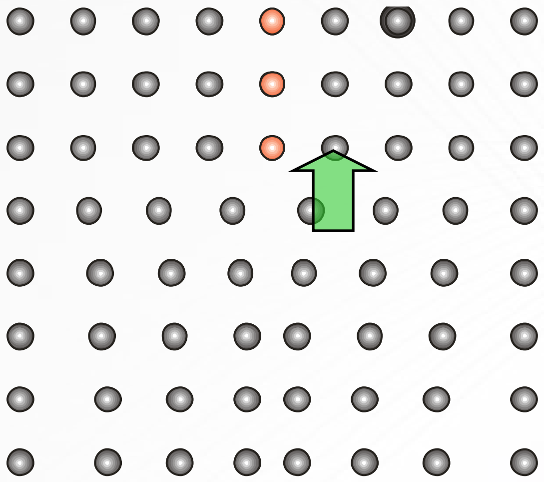
Motion of dislocation
⊥ to the slip plane

- For edge dislocation: as **b** ⊥ **l**
- Climb involves addition or subtraction of a row of atoms below the half plane

  positive climb = climb up → removal of a plane of atoms

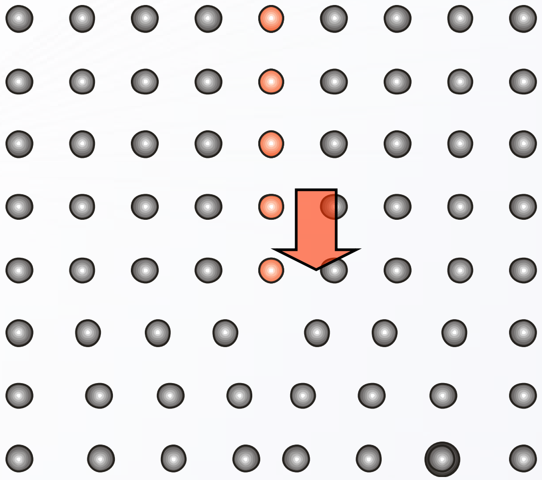
  negative climb = climb down → addition of a plane of atoms

Edge Climb



Positive climb

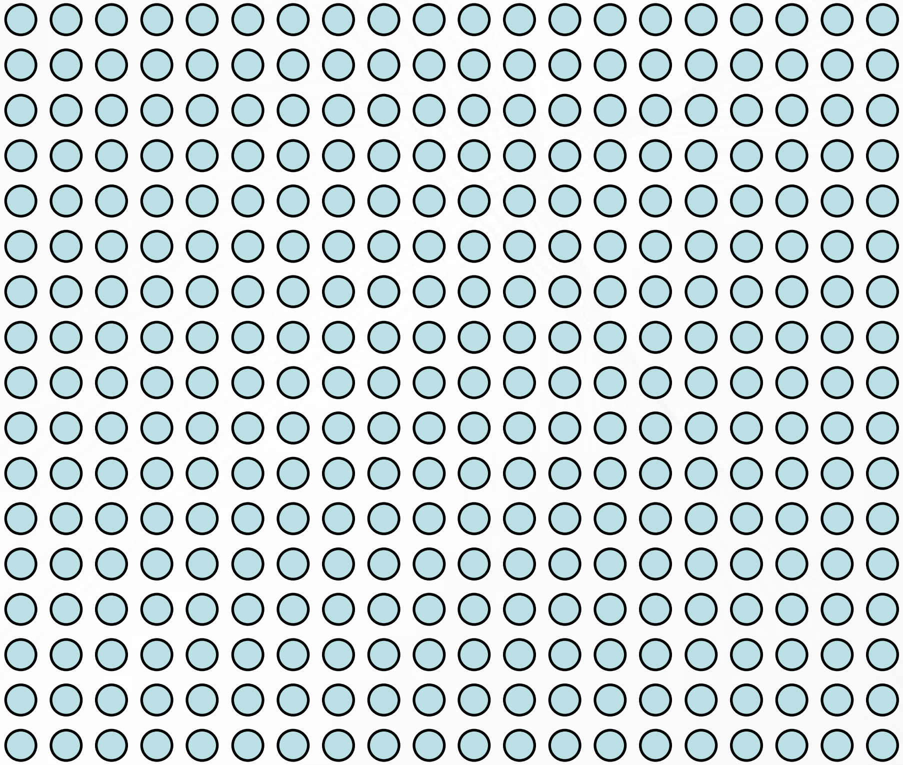
Removal of a row of atoms



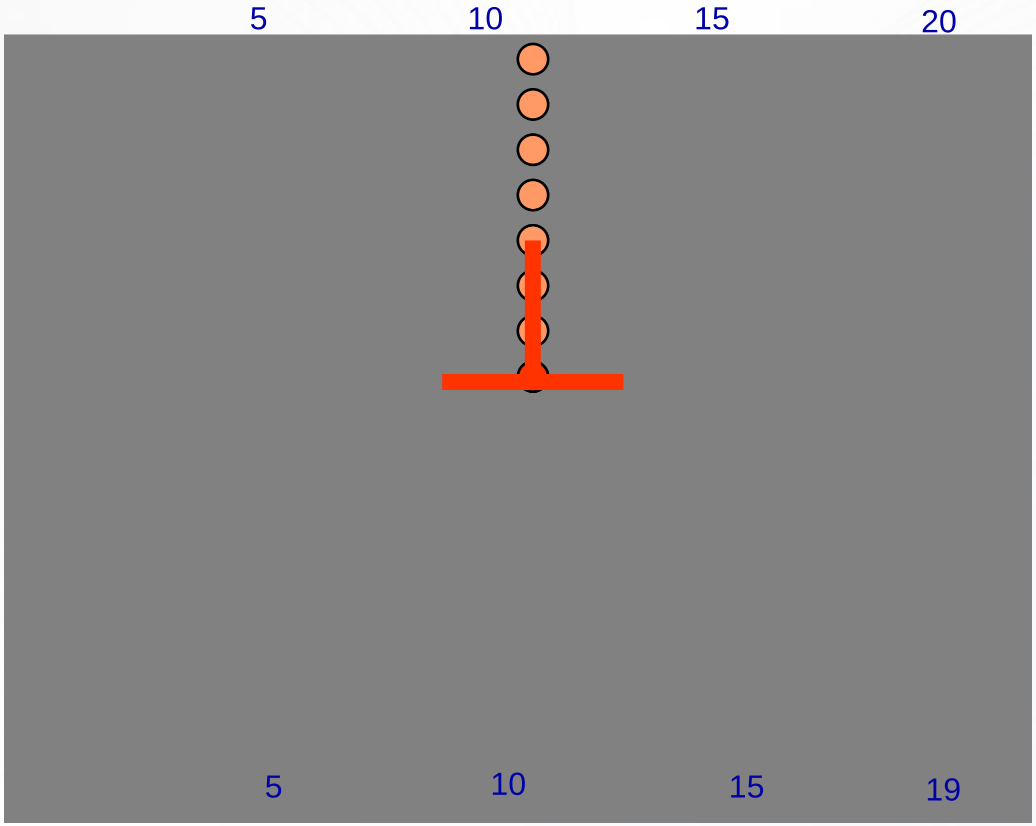
Negative climb

Addition of a row of atoms

Let’s look at the atoms in a perfect crystal

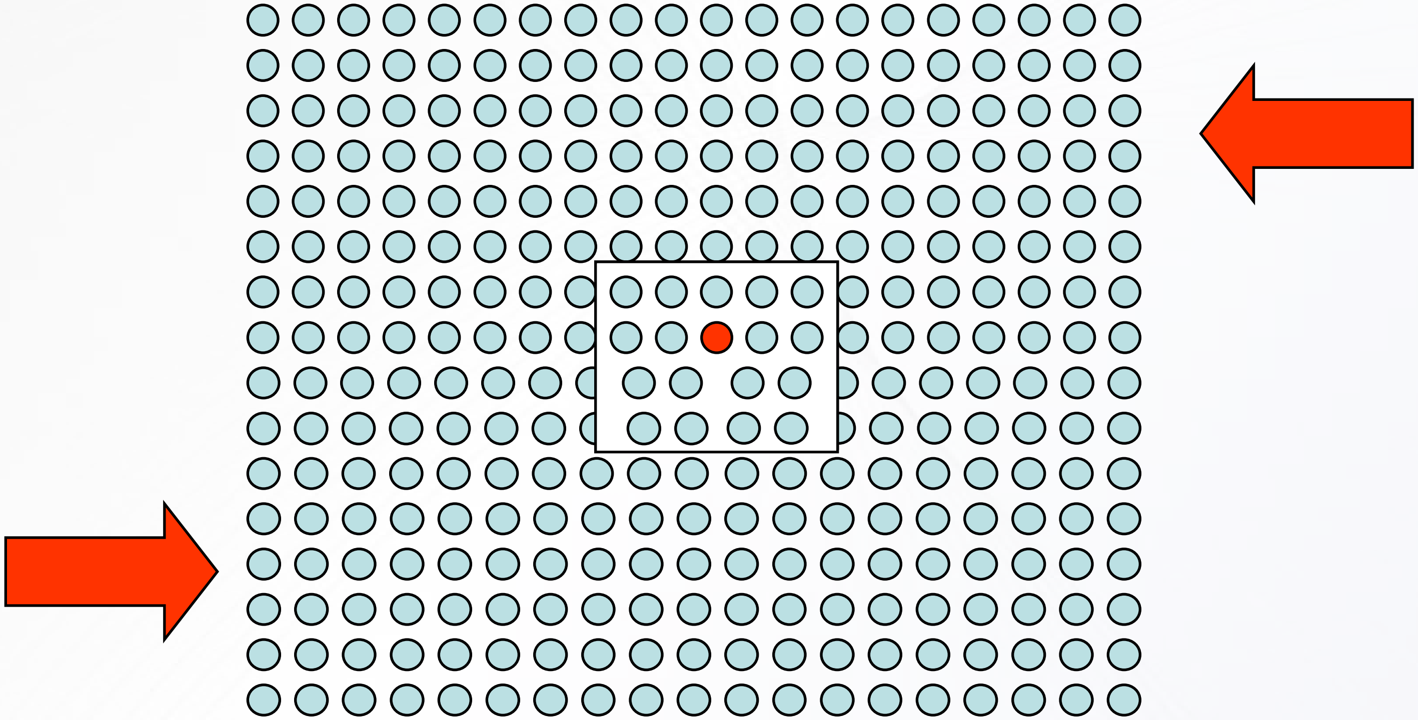


Let’s look at the atoms in a <u>realistic</u> crystal

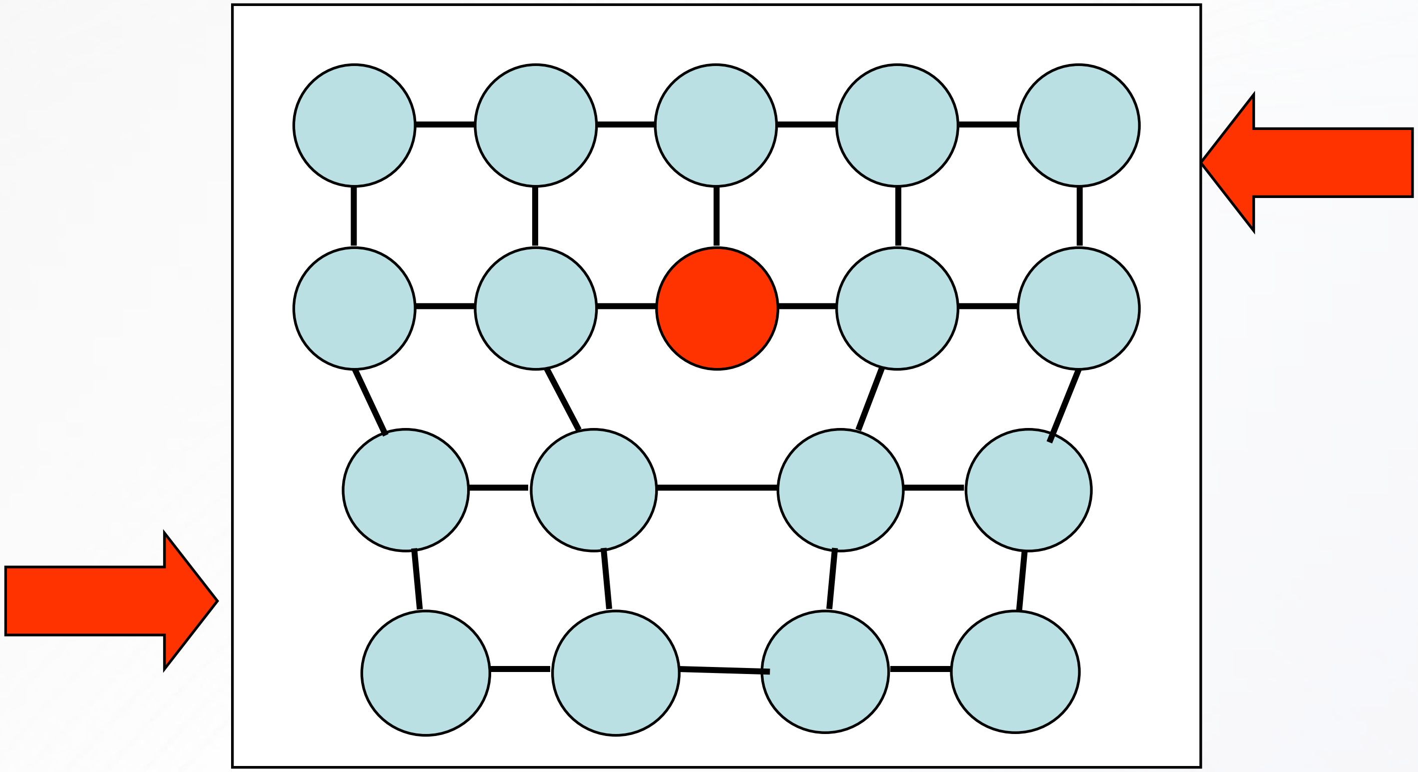


⊥ = **“Edge dislocation”**

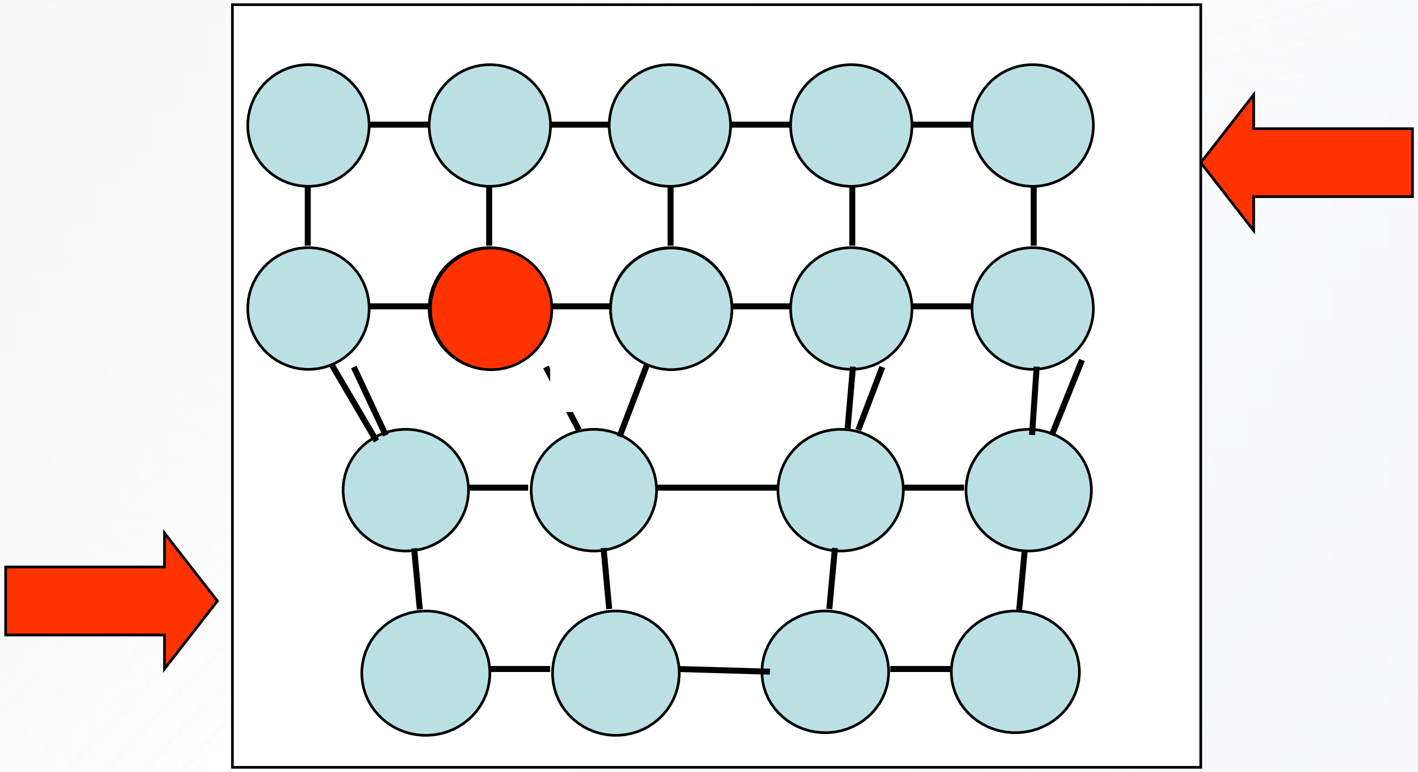
“glide”edge dislocations



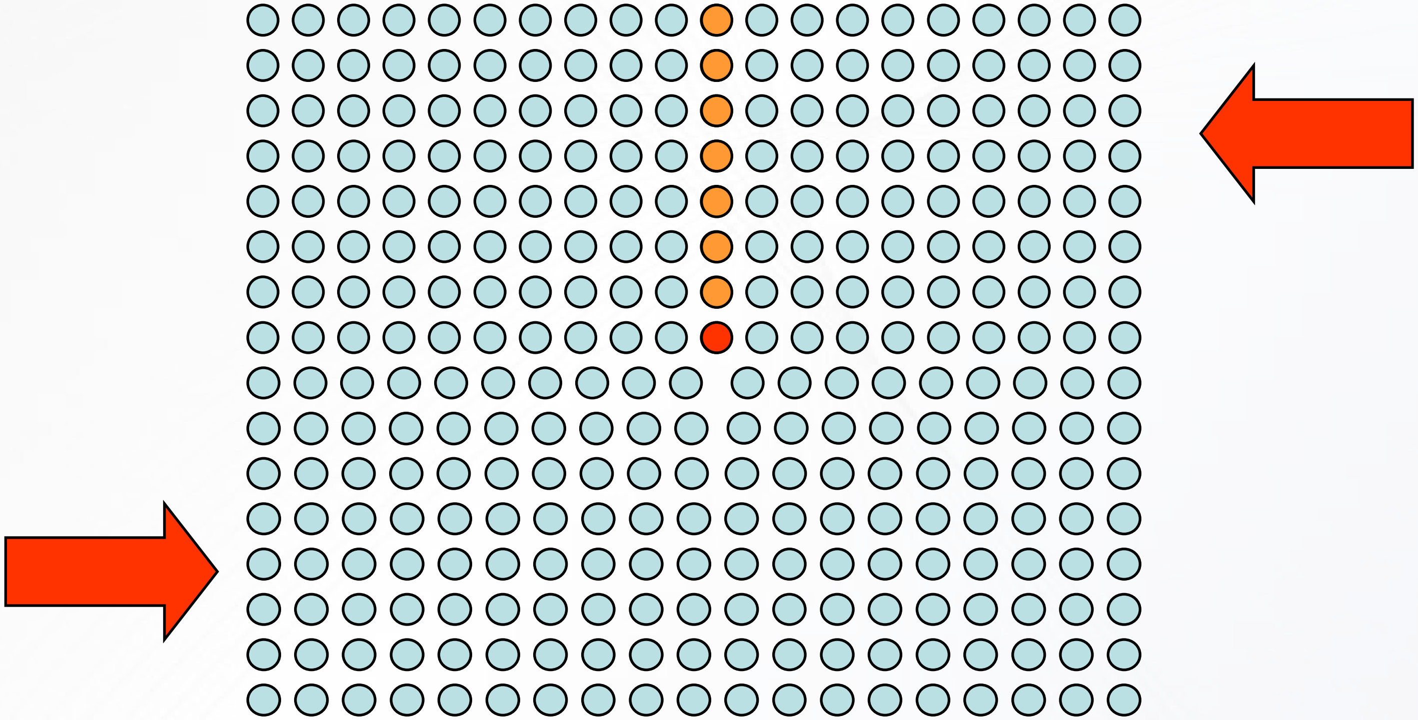
“glide”edge dislocations



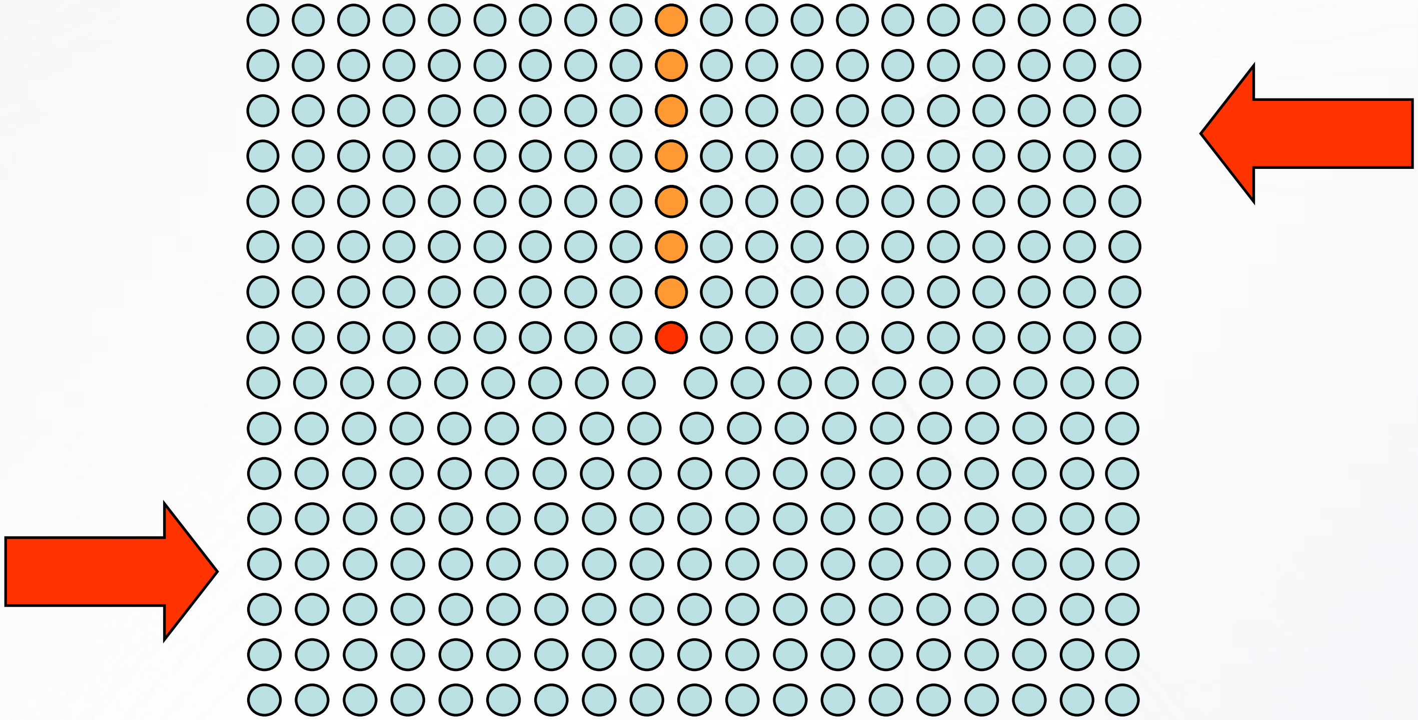
“glide”edge dislocations



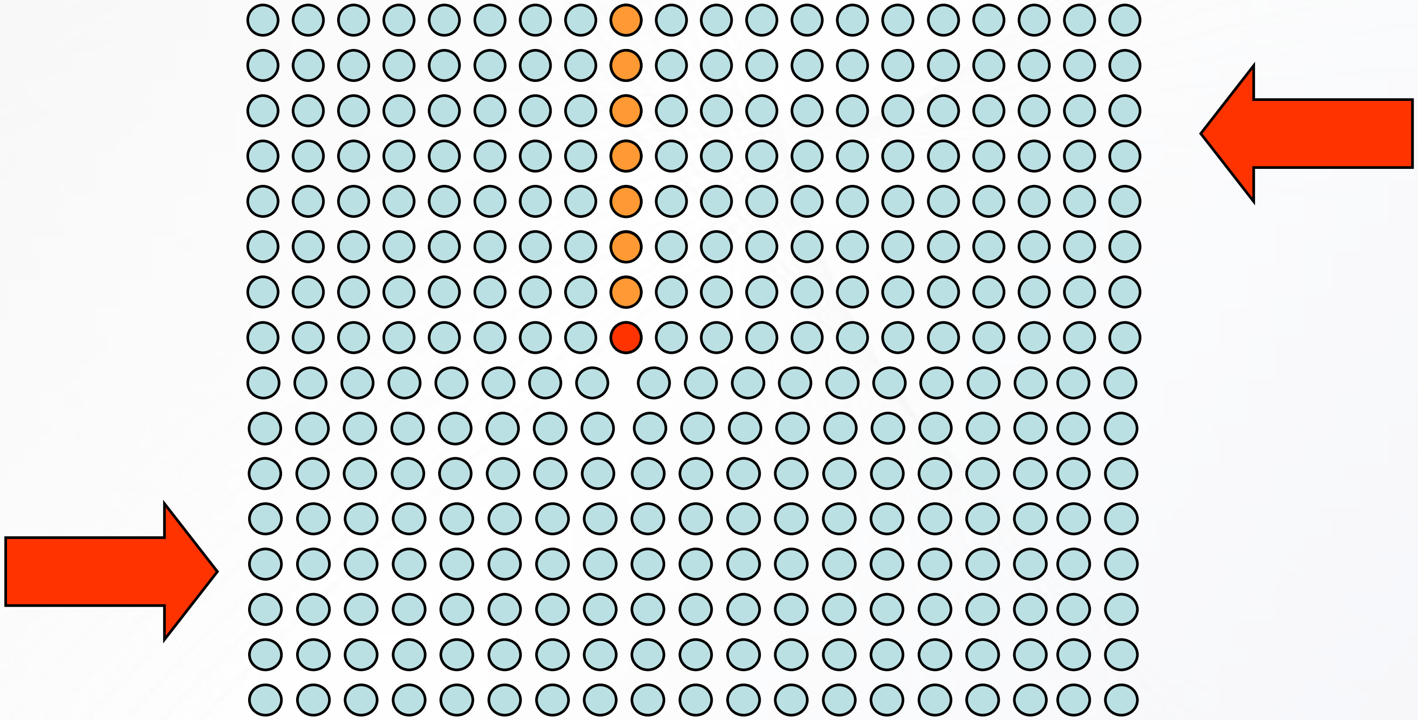
“glide”edge dislocations



“glide”edge dislocations



“glide”edge dislocations



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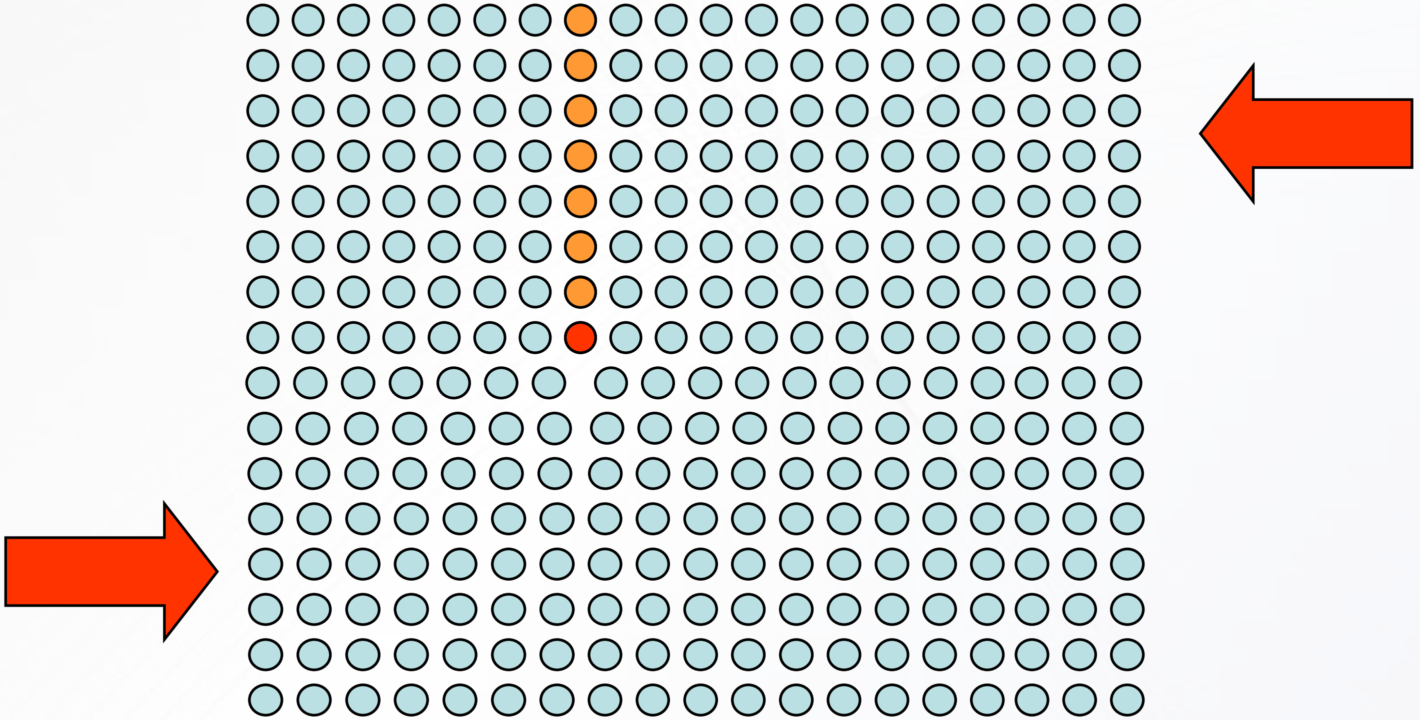

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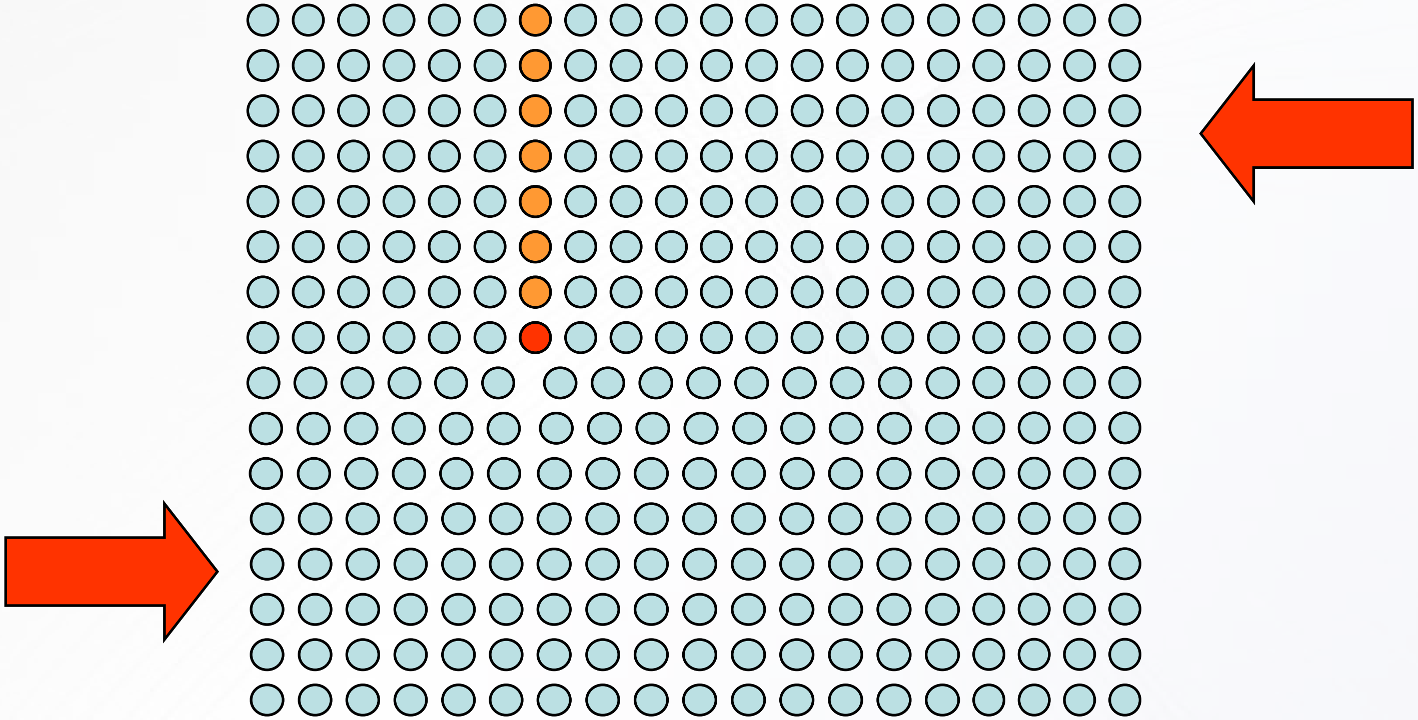
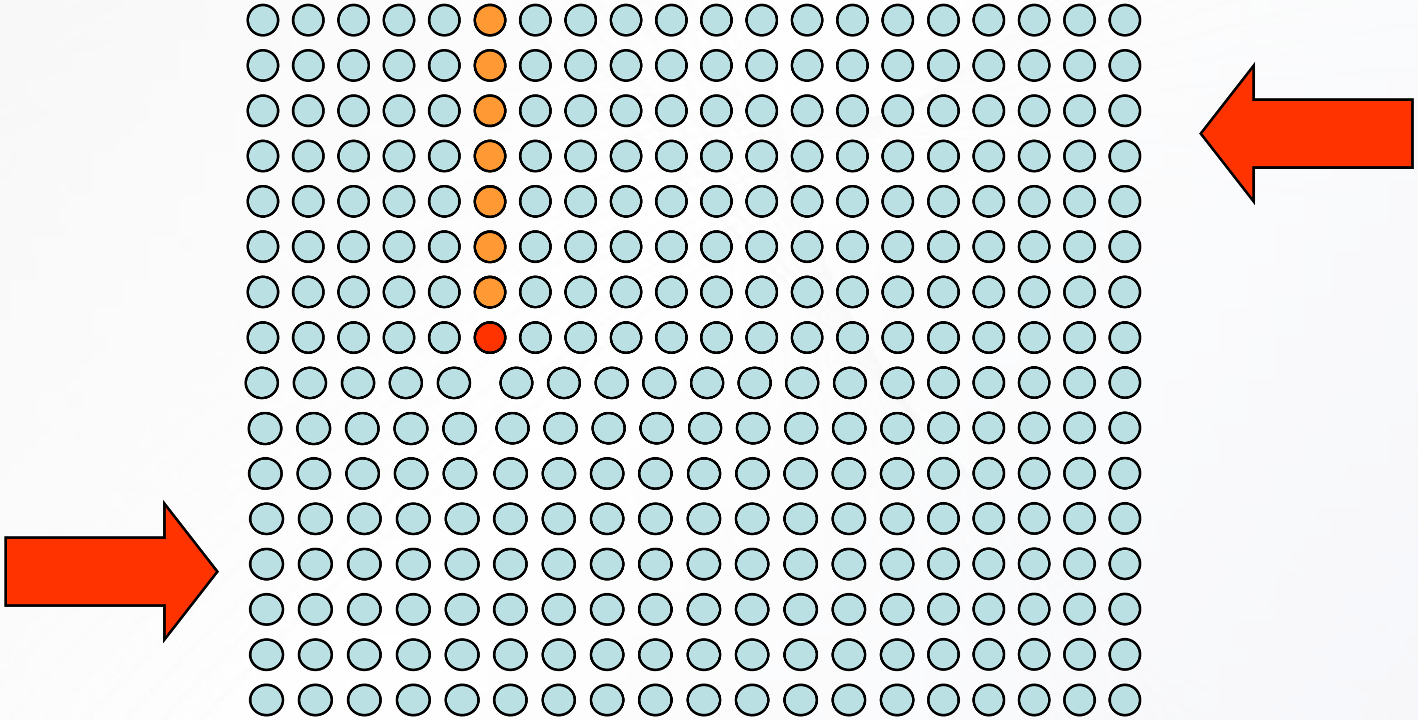


“glide”edge dislocations



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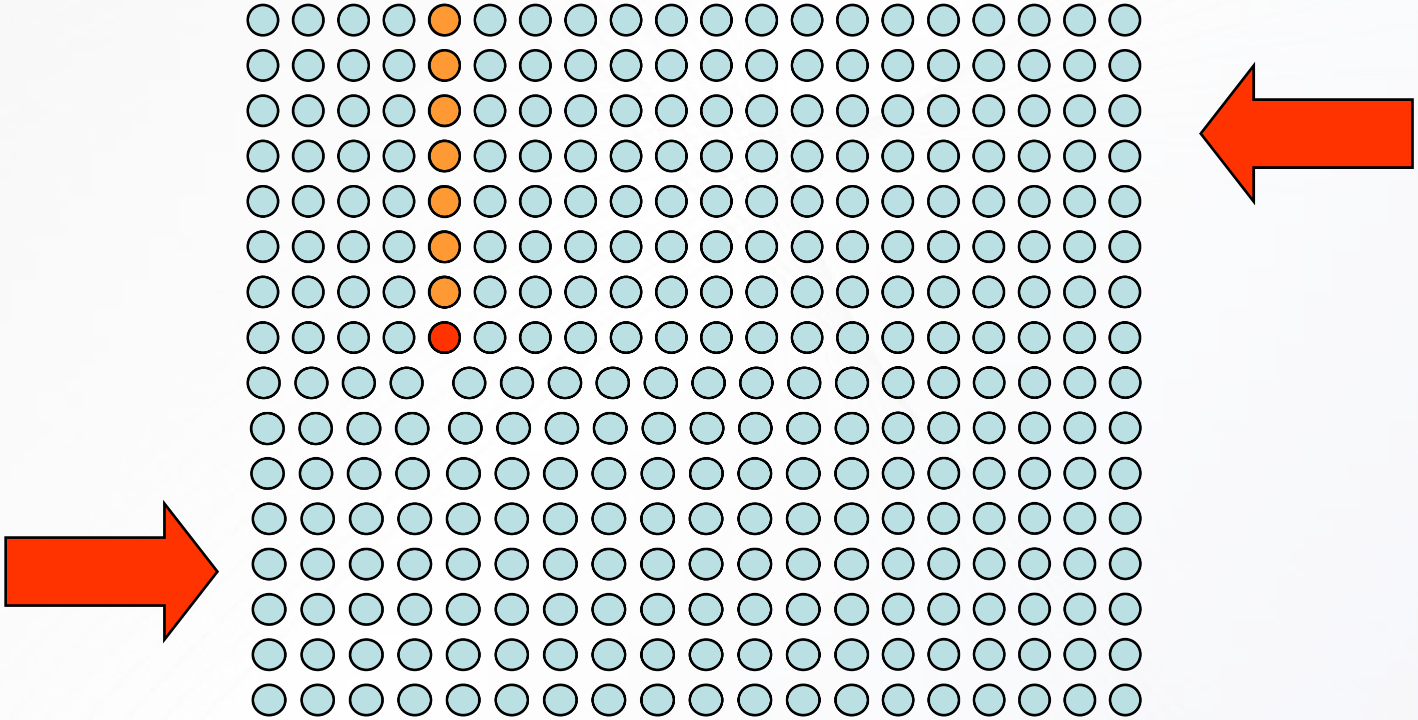
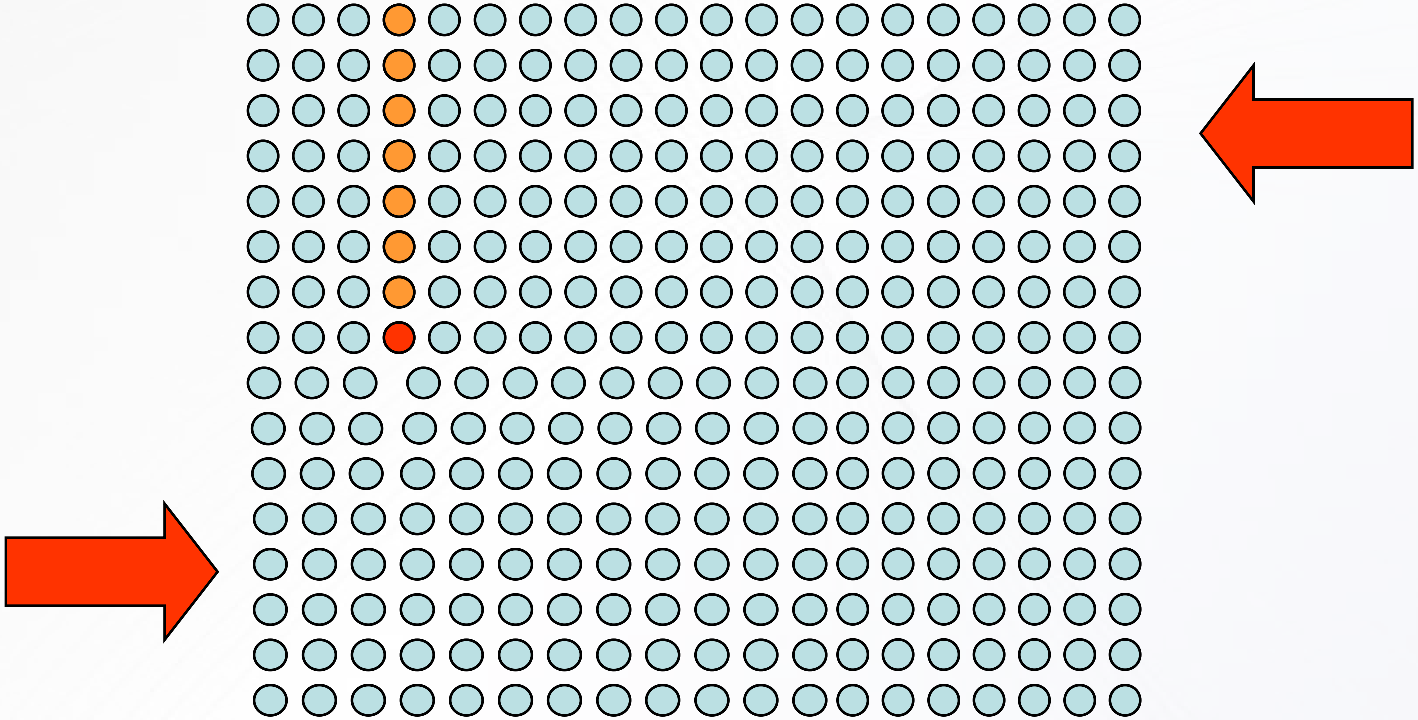


“glide”edge dislocations



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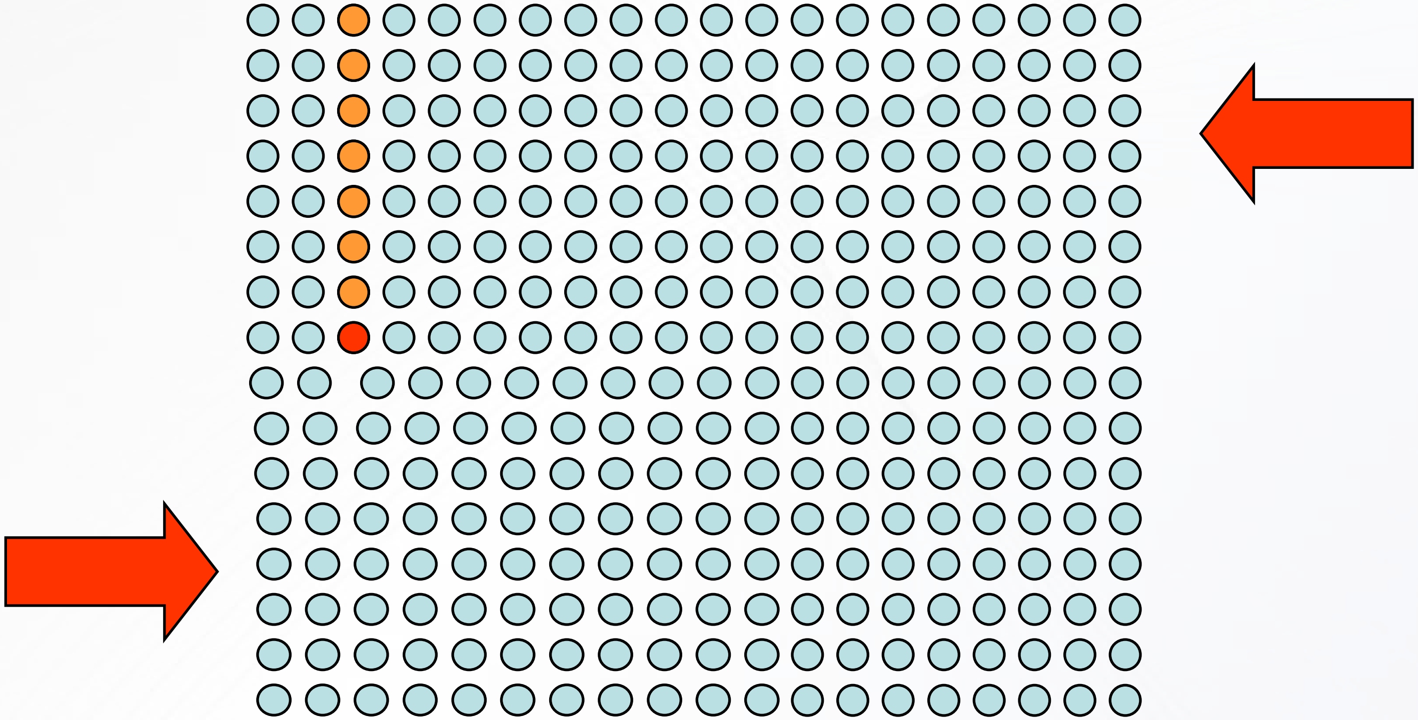
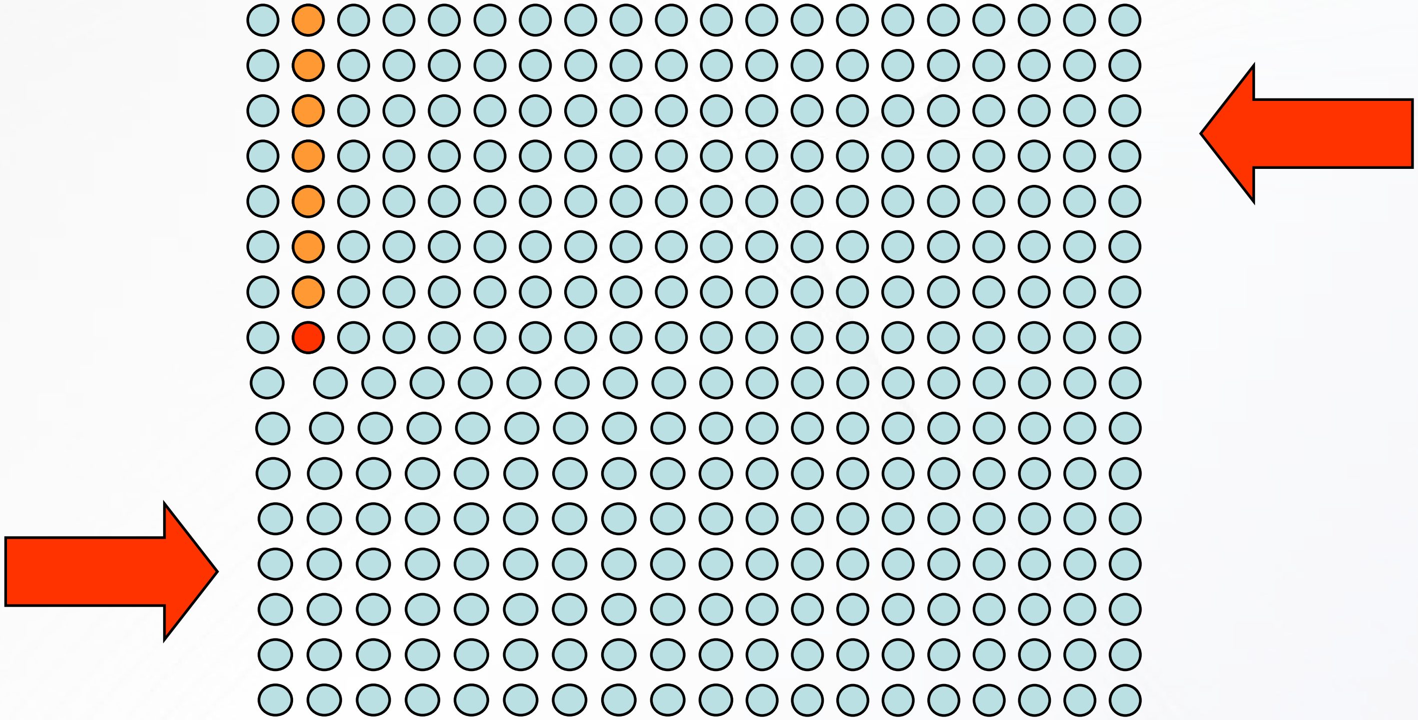


“glide”edge dislocations



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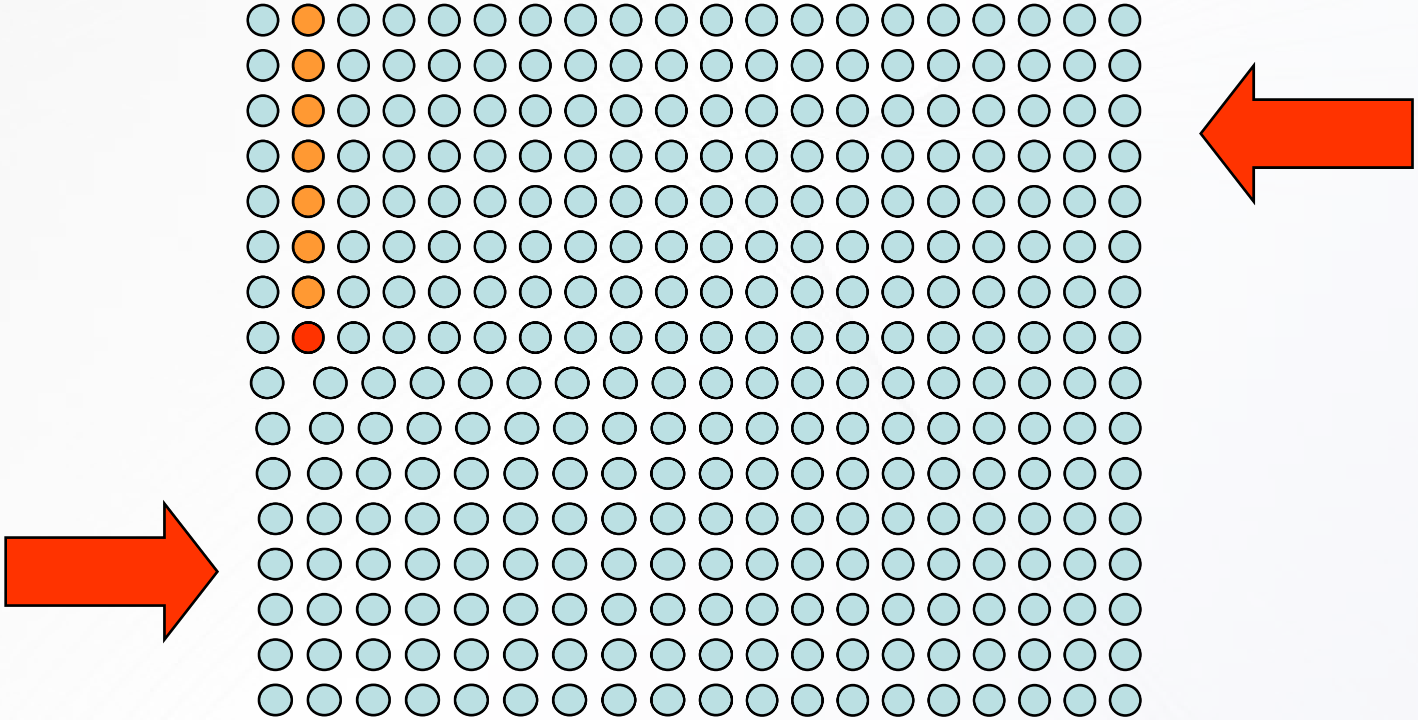
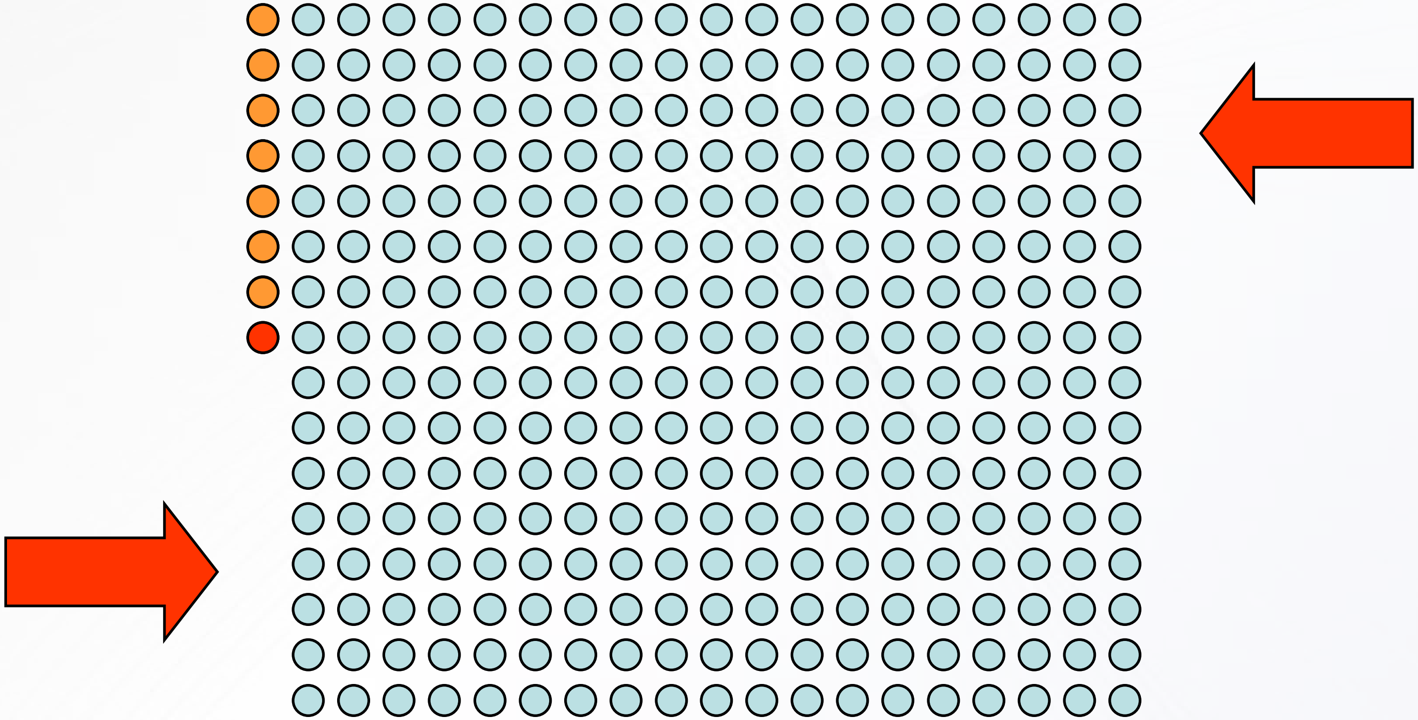
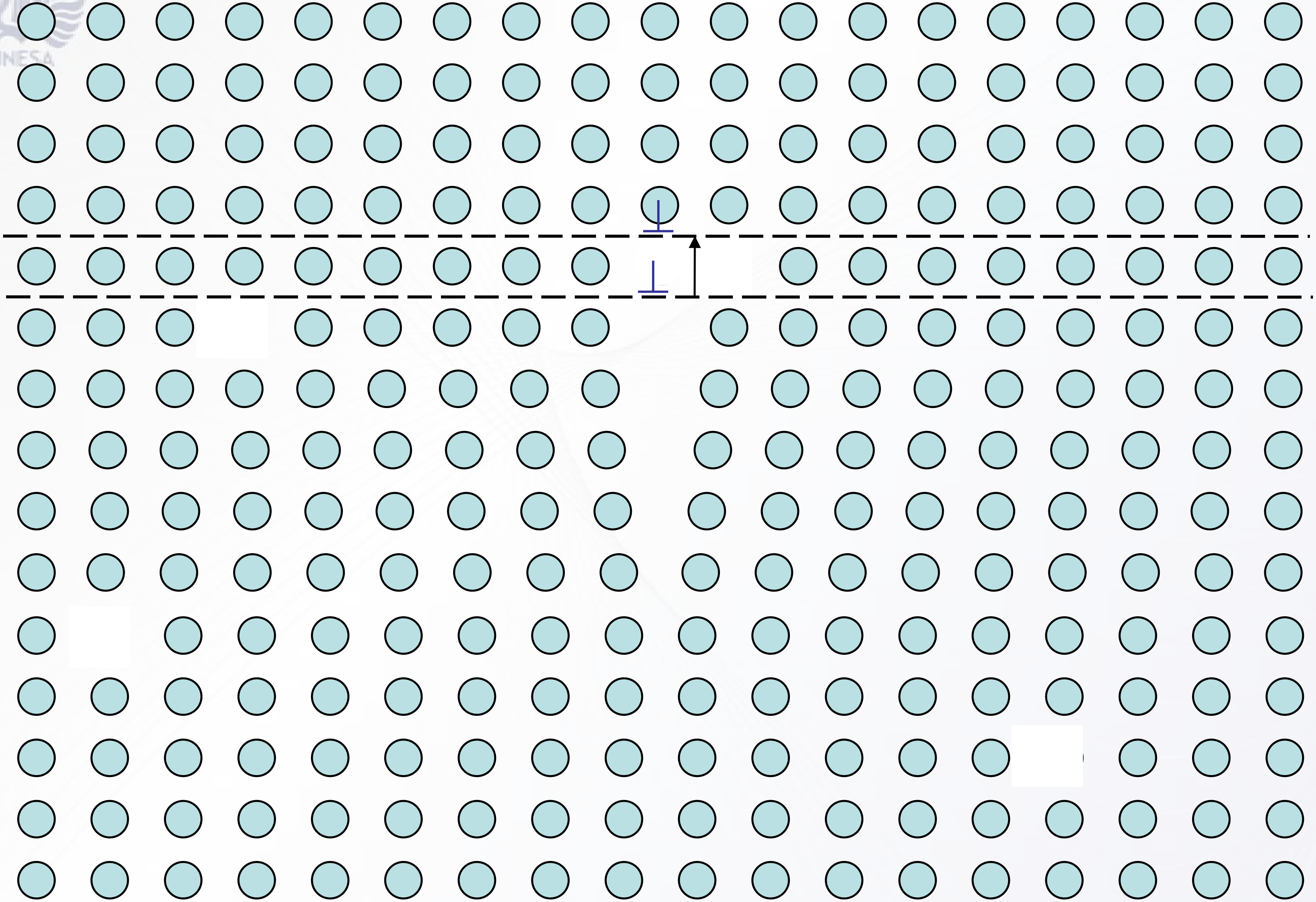


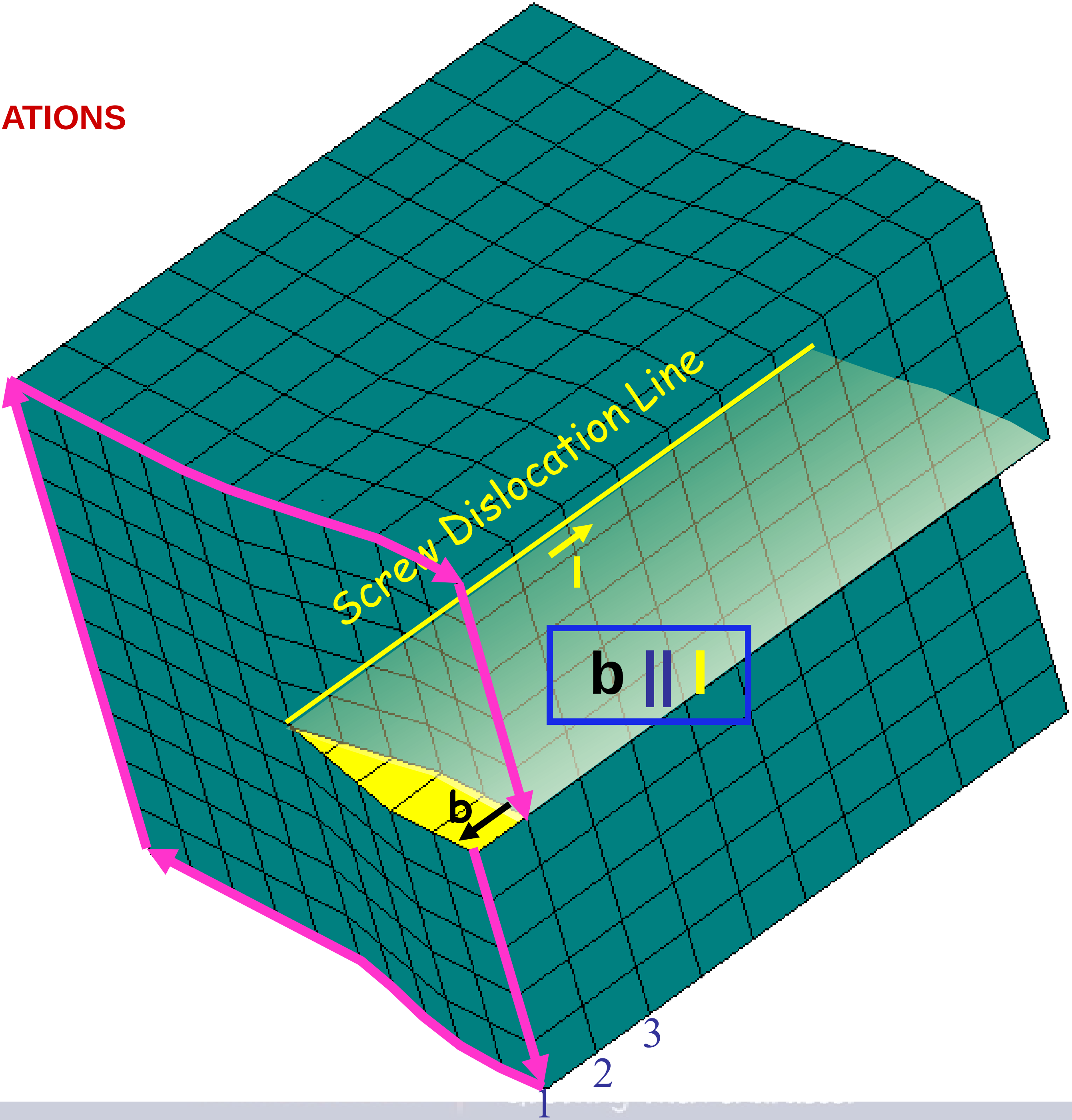
“glide”edge dislocations



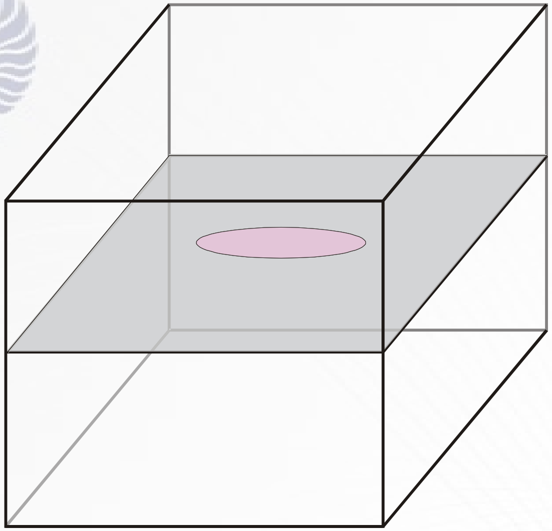
Atomistic mechanism of climb



SCREW DISLOCATIONS

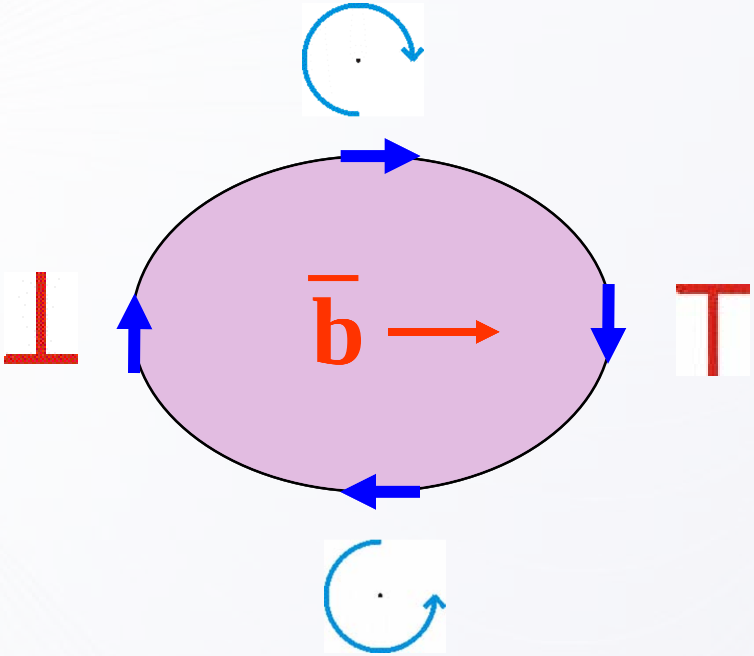


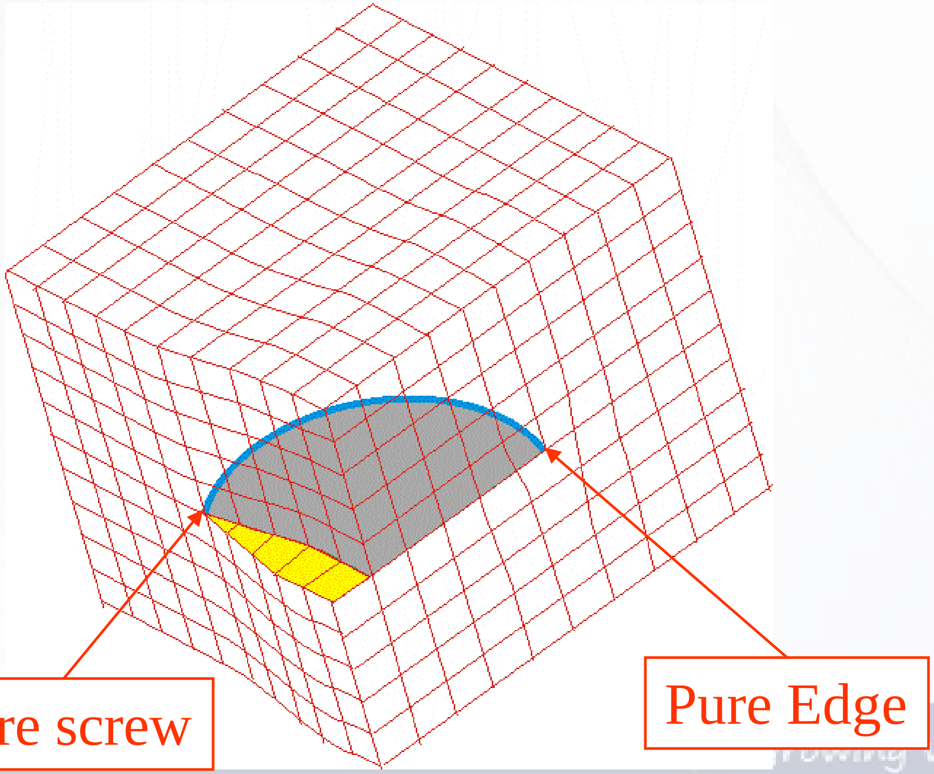
Mixed dislocations



$\vec{\bar{b}}$

$\vec{\bar{l}}$





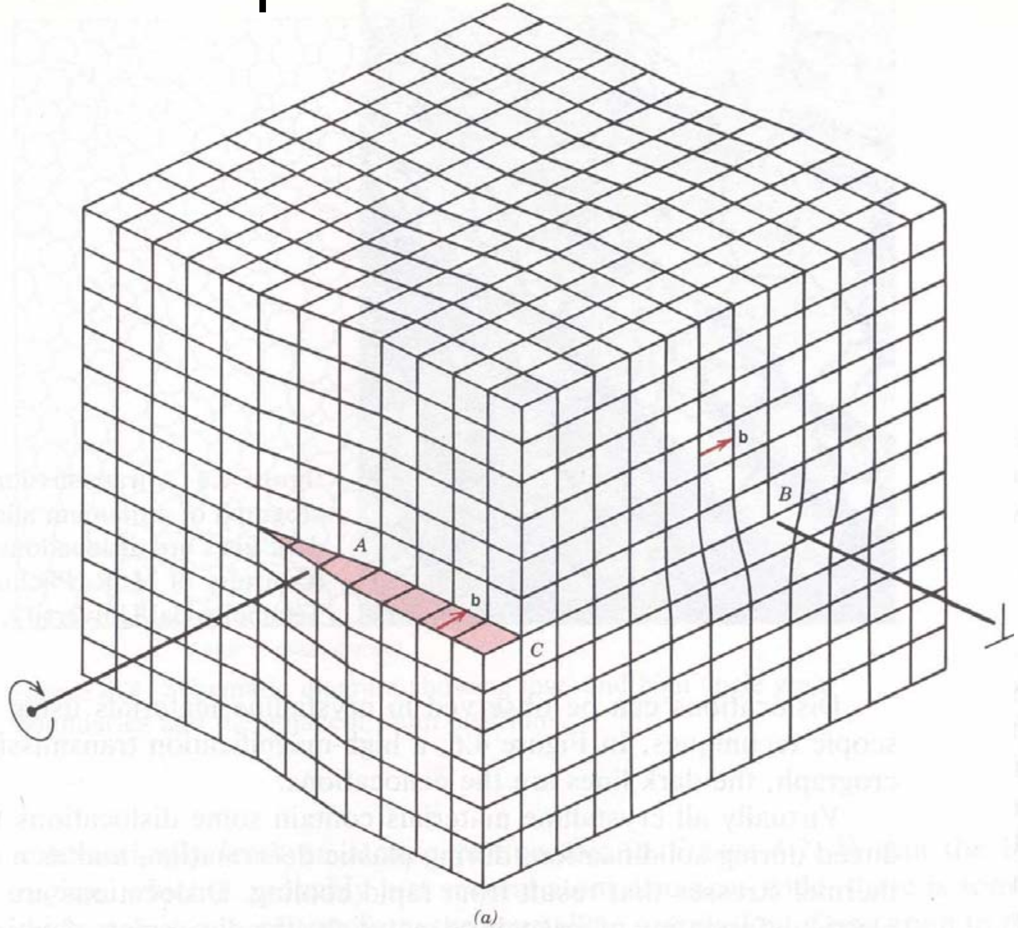
Pure screw

Pure Edge

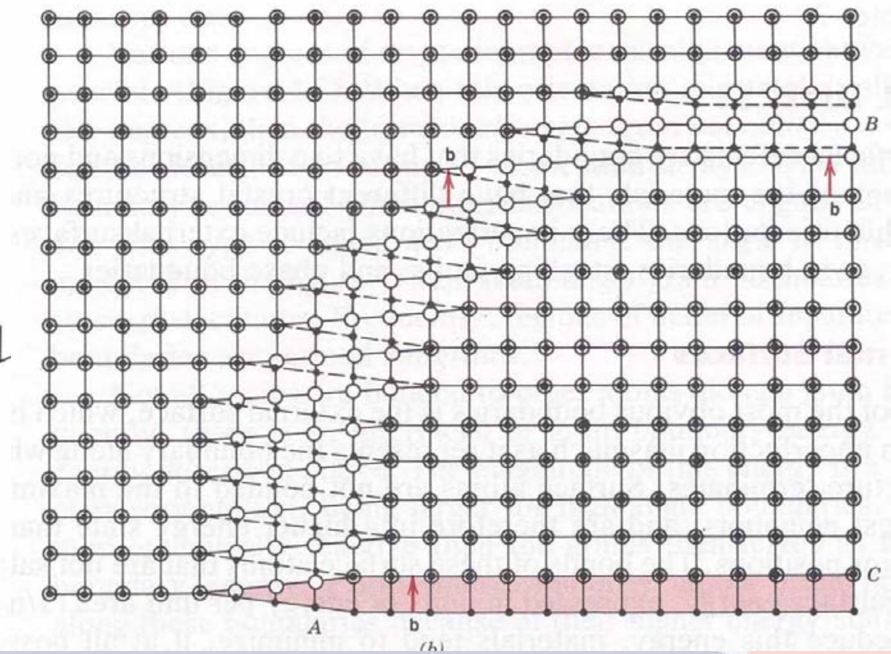
Mixed Dislocations

- *Mixed dislocations* have edge & screw components

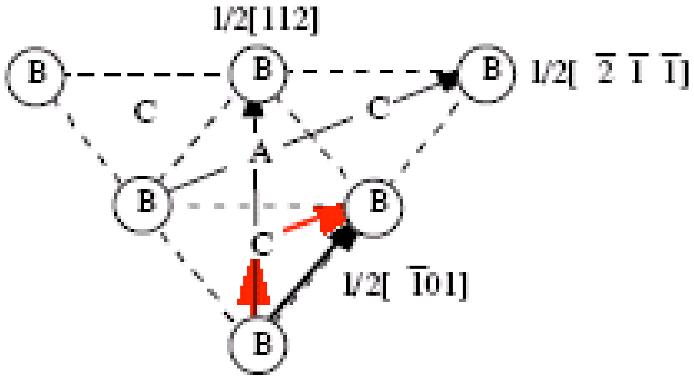
Orientation of line
w.r.t. fault vector ***b***
varies along dislocation

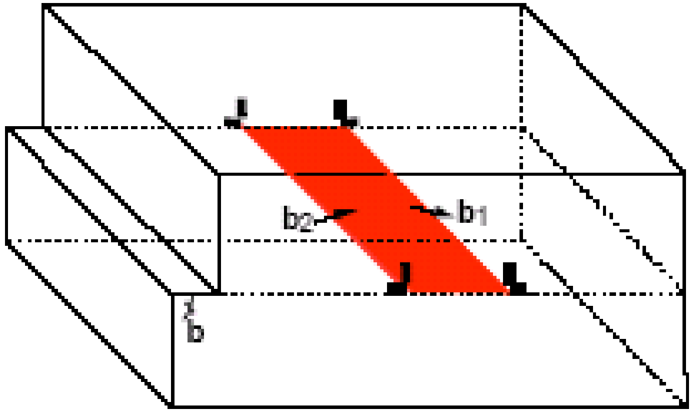


top view



PARTIAL DISLOCATIONS

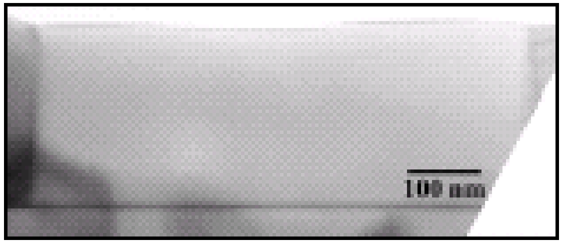




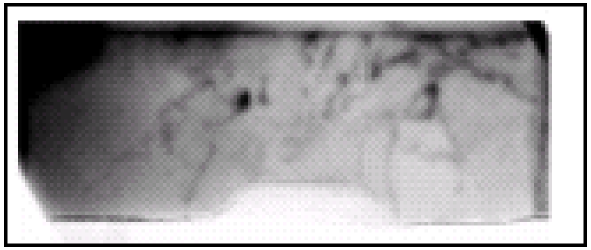
- Sometimes dislocations are split into “partials”
  - Separated by a “stacking fault”
- Common in fcc
  - “Total” dislocation B → B
  - Splits into “partial” dislocations B → C and C → B
  - Separated by “stacking fault” …ABCABC… → …A|CABCA…

Dislocations Created on Indenting Al

- *Minor, Stach and Morris, Appl. Phys. Lett., 79, 1625-27 (2001)*

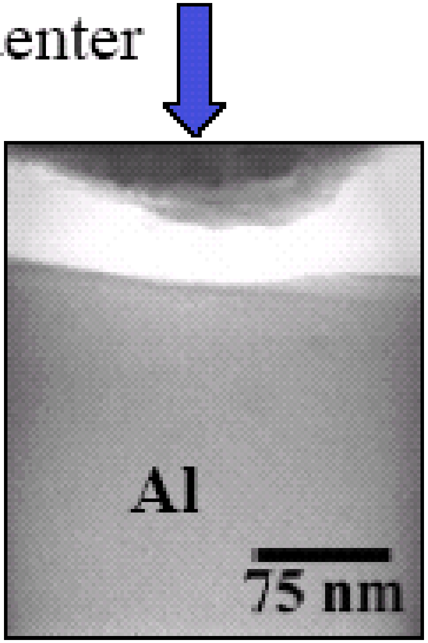


Before



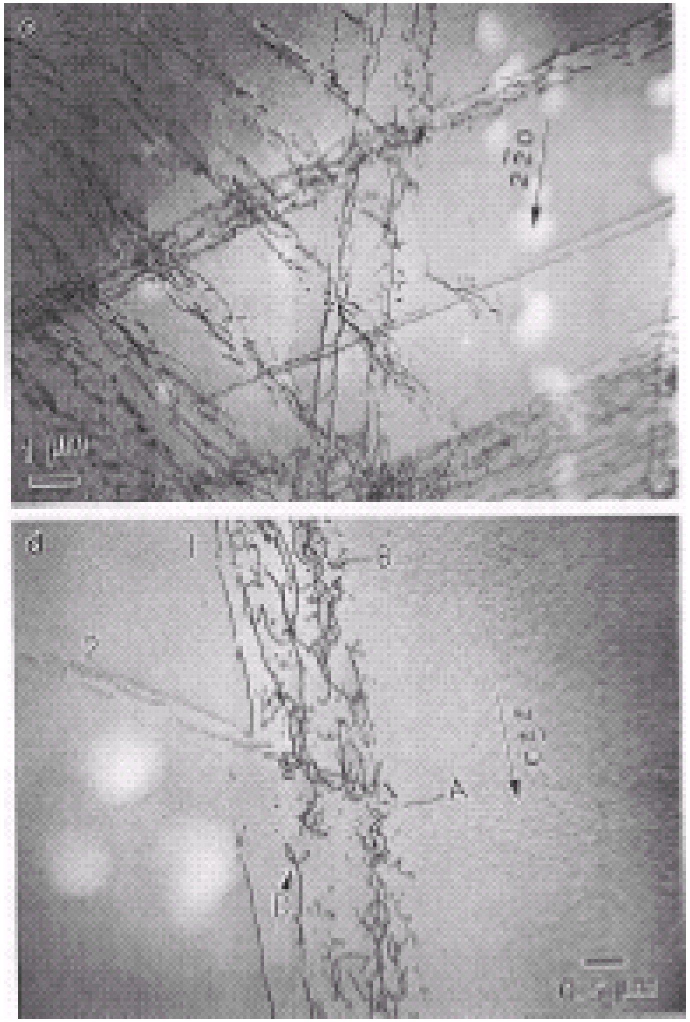
After

Diamond Nanoindenter



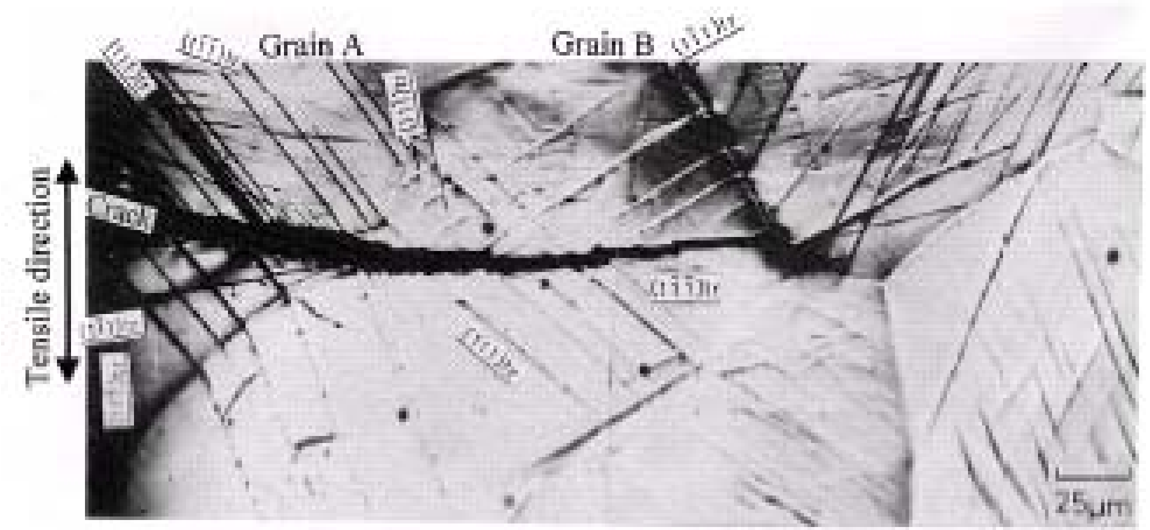
Dislocations in TiC

- Chien, Ning and Heuer, Acta Mater., 44, 2265 (1996)



Slip Lines Across Grains in Stainless Steel

- *Tomota, et al., Acta Mater., 46, 3099-3108 (1998)*



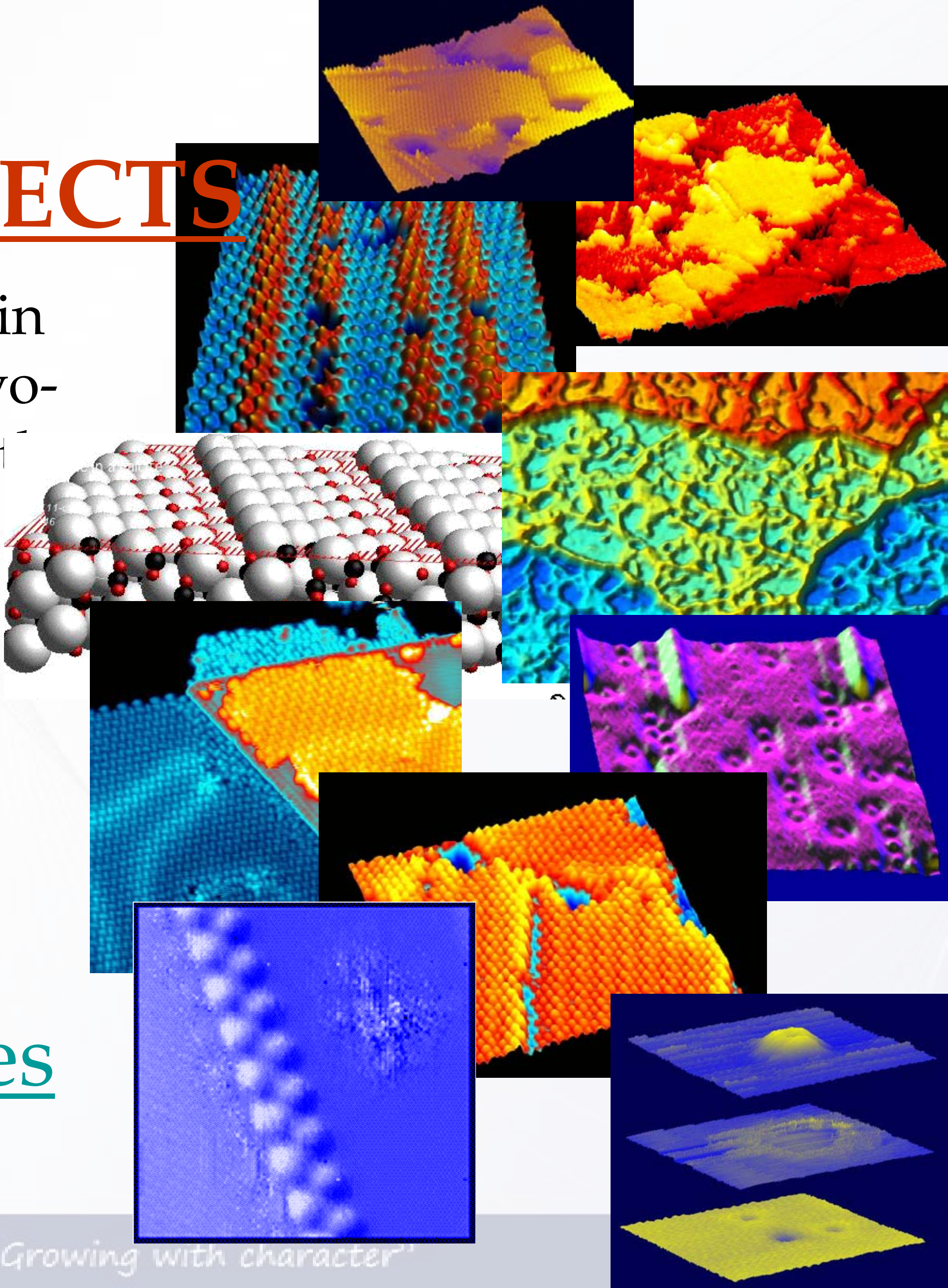
Defects	*Dimensionality*	*Examples*
Point	0	Vacancy
Line	1	Dislocation
Surface	2	Free surface, Grain boundary
Volume	3	Voids, Inclusions, Precipitates

SURFACE DEFECTS

Imperfections, such as grain boundaries, that form a two-dimensional plane within t
crystal.

classifications

- free surface
- twin boundary
- stacking faults
- grain boundaries



VOLUME DEFECTS

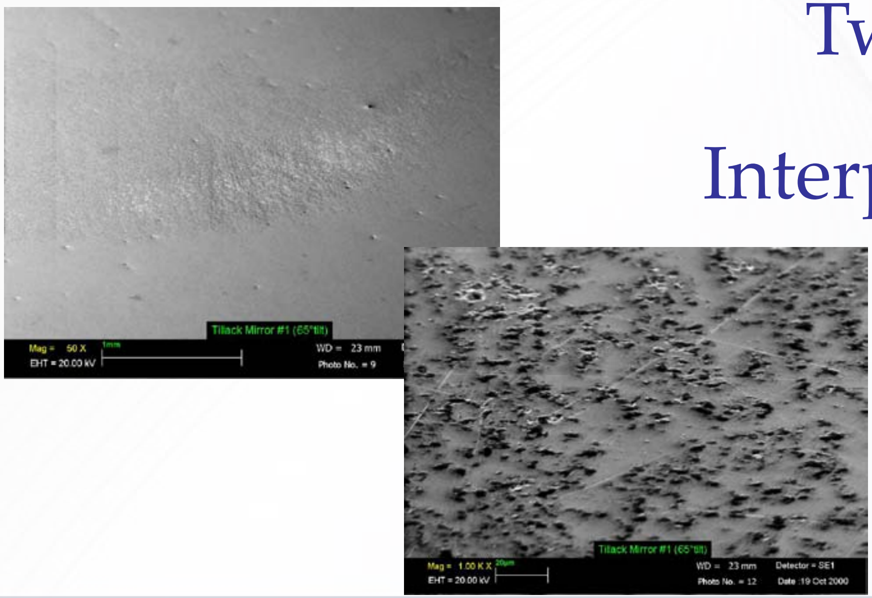
Three-dimensional defects in solids
Volume defects play an important role in corrosion mechanisms

Always involve a second phase
- Porosity (solid – vapor)
- Inclusions (solid – solid)
- Precipitates (solid – solid)
- Cracks (solid – vapor)

- voids
- inclusions
- precipitates

enter

External	**Internal**	
Free surface	Grain boundary Stacking fault	*Same phase*
	Twin boundary Interphase boundary	*Different phases*

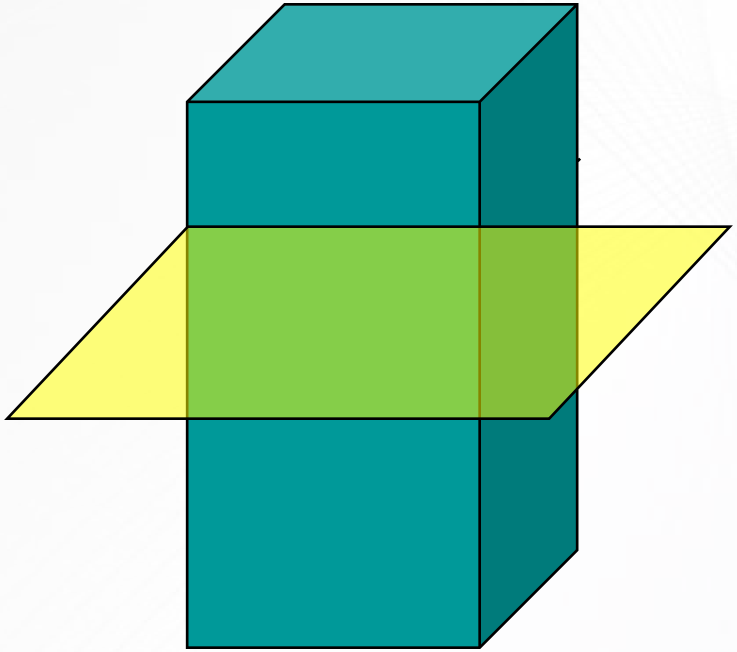


SEM photos of damaged Al

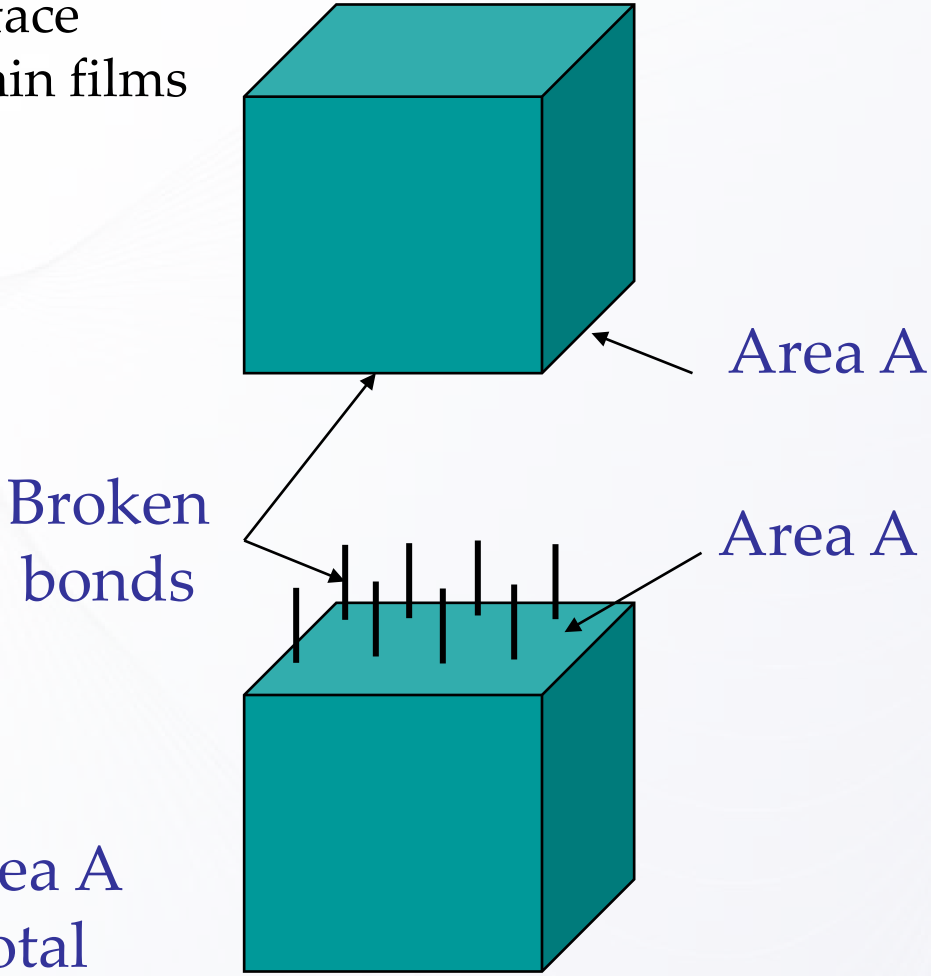
bome

free surface

Surface grooving where grain boundaries intersect free surfaces leads to surface roughness, possibly break-up of thin films



If bond are broken over an area A then two free surfaces of a total area 2A is created



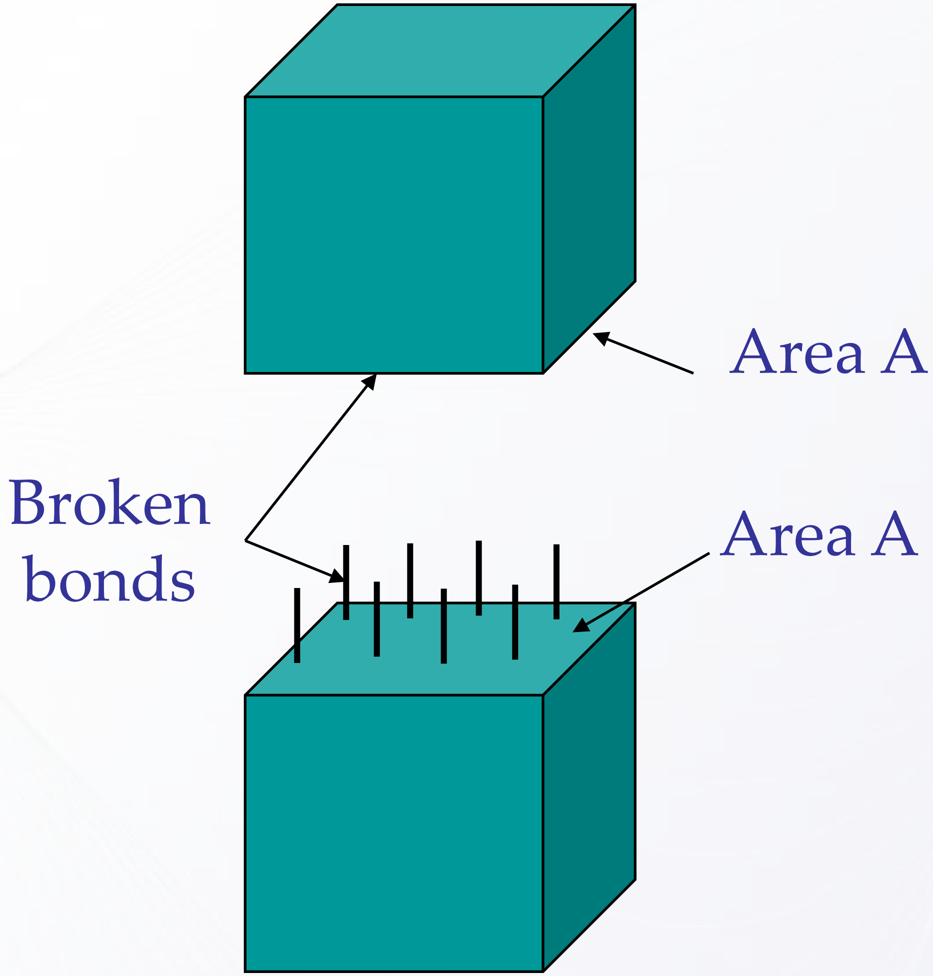
n_A = no. of surface atoms per unit area

n_B = no. of broken bonds per surface atom

ε = bond energy per atom

$$\boxed{\gamma = \frac{1}{2} n_A \, n_B \, \varepsilon}$$

Surface energy per unit area

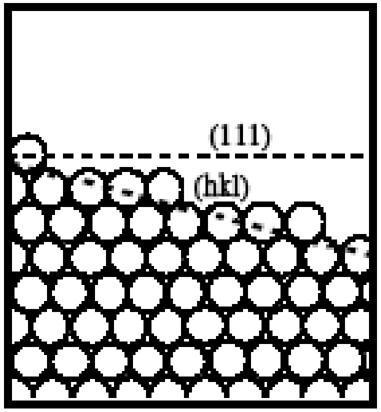


If bond are broken over an area A then two free surfaces of a total area 2A is created

Surface energy is anisotropic

Surface energy depends on the orientation, i.e., the Miller indices of the free surface

n_A, n_B are different for different surfaces

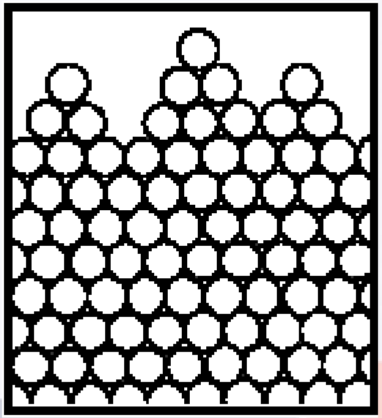


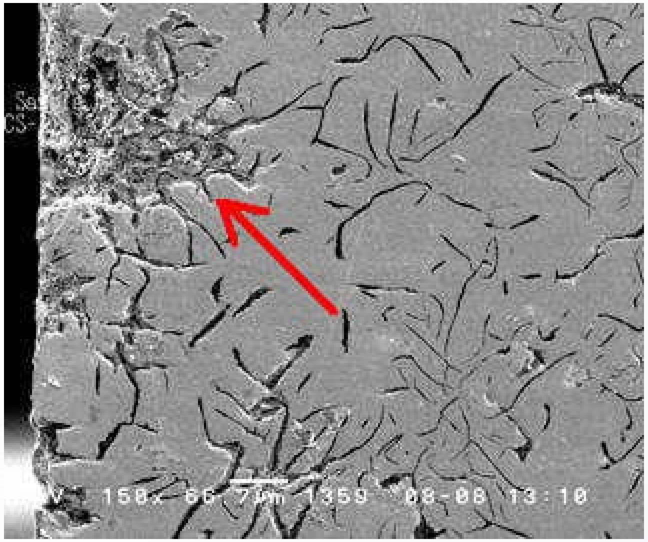
Free Surfaces of Metals

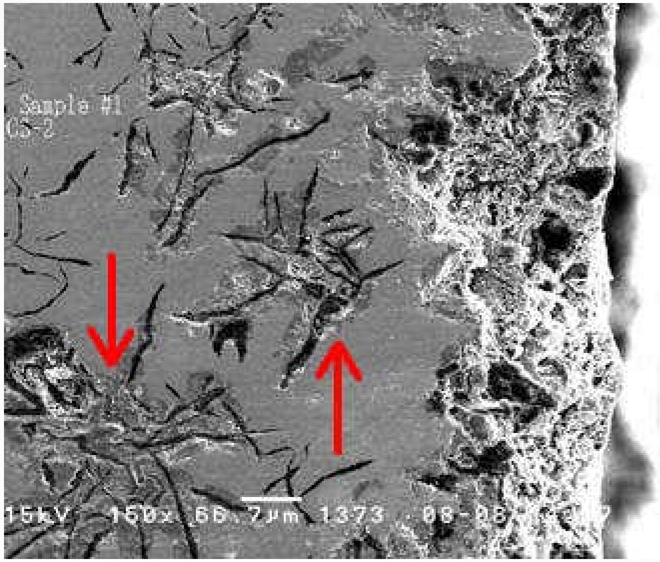
Surface tension (σ) lowest for low-index planes

Diffuse Interface

At high T, metal surfaces tend to be rough, diffuse







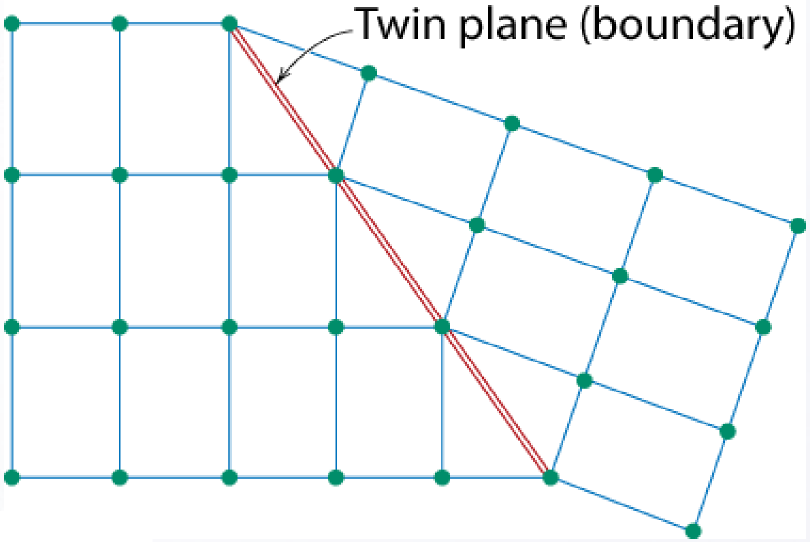
free surface

bome

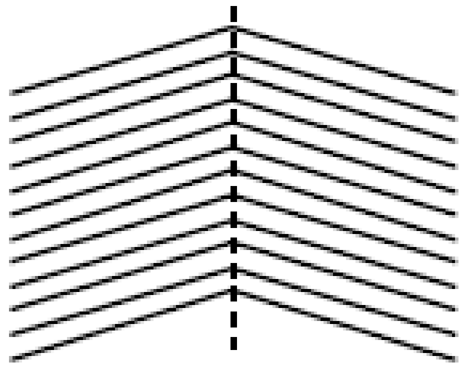
twin boundary (plane)

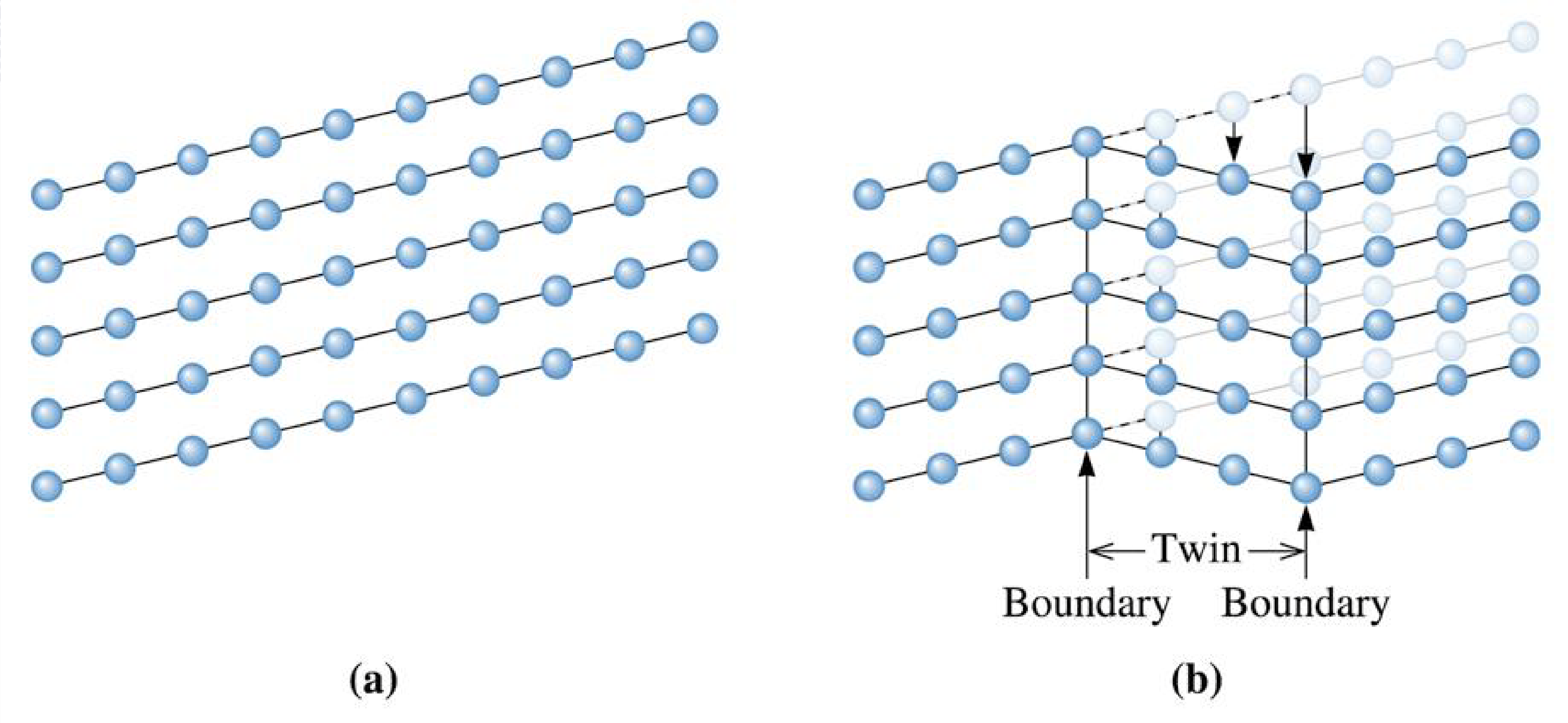
Essentially a reflection of atom positions across the twin plane

Twining is very common in minerals (result of phase transition during cooling)

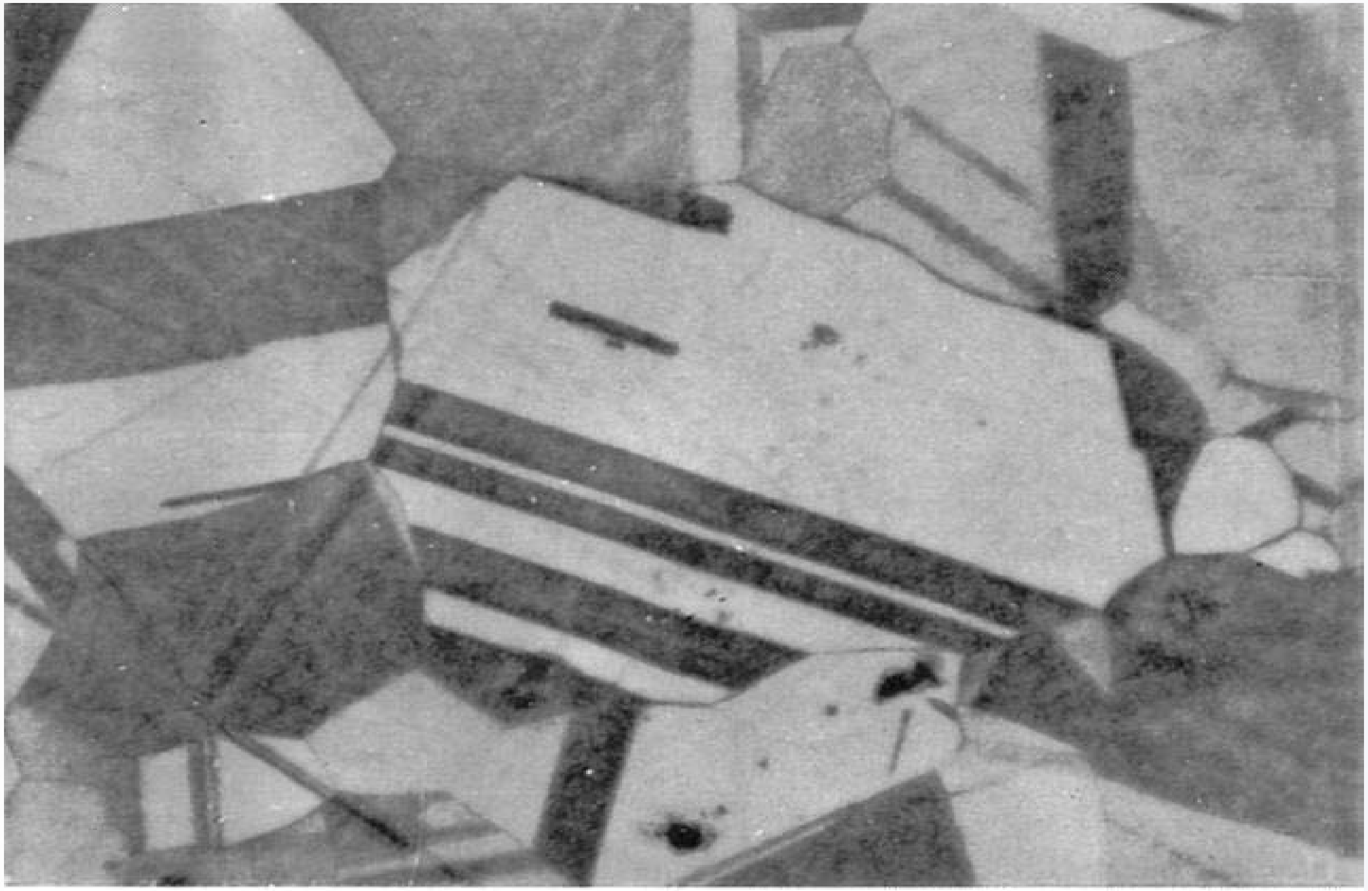


Twinning is an important deformation mechanism
Sn, Mg, high-N austenitic (FCC) steel, Cu at low T





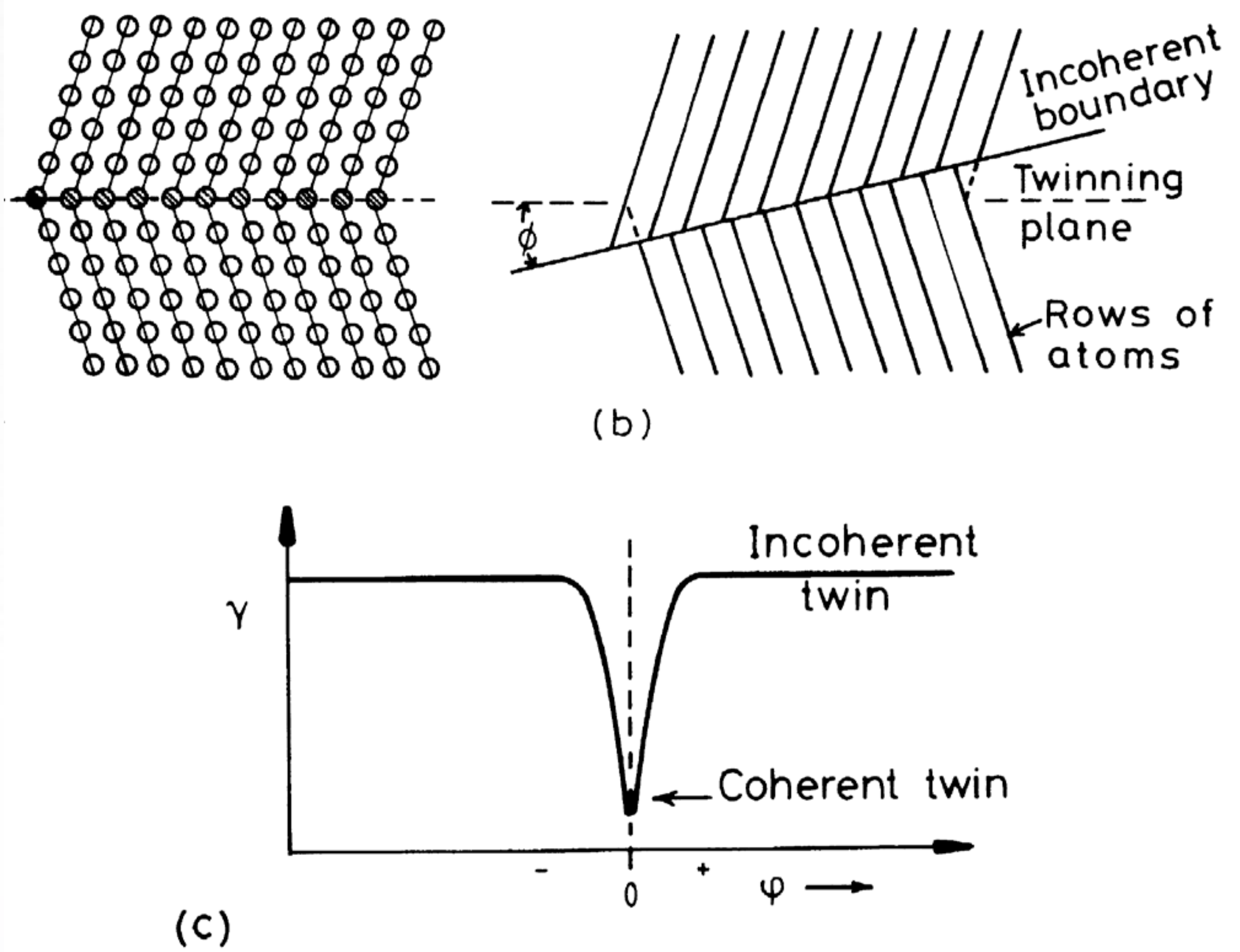
Formation of twin (b) may be caused by application of stress to the perfect crystal (a)



(c)

Figure (c) : A micrograph of twins within a grain of brass (x250)

Twin: coherent vs. incoherent



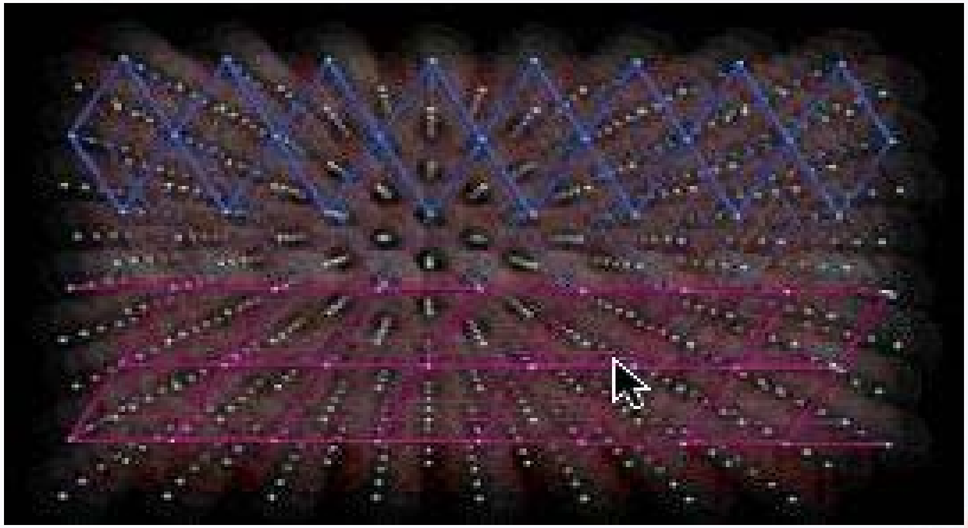
(Porter & Easterling - fig.3.12/p123)

stacking faults

- Stack close-packed planes in wrong sequences
  Create extra or missing plane inside the crystal

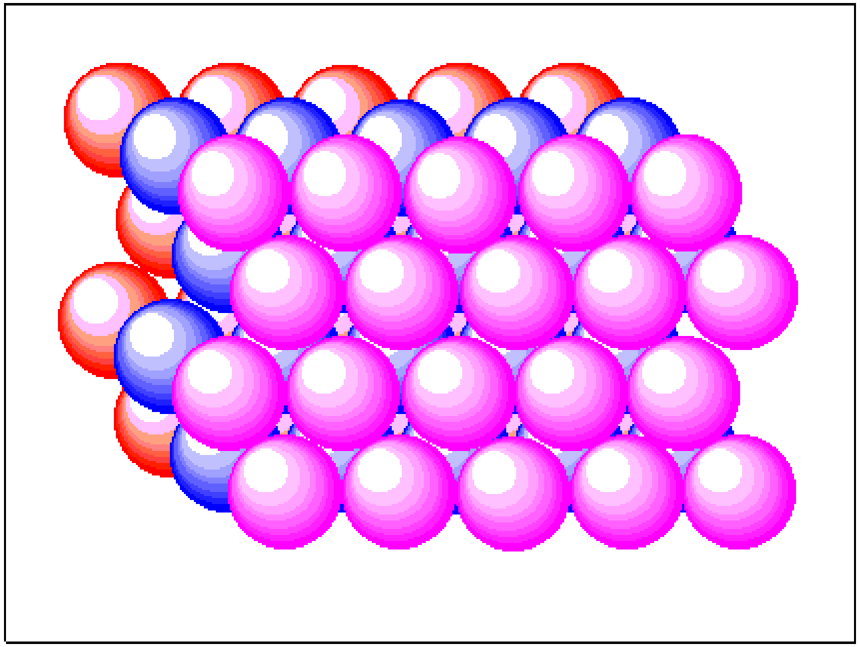
It may occur during

(1) crystallization from the melt or solid state,
(2) solid state processes or recrystallization,
phase transition, and crystal growth, and
(3) deformations.

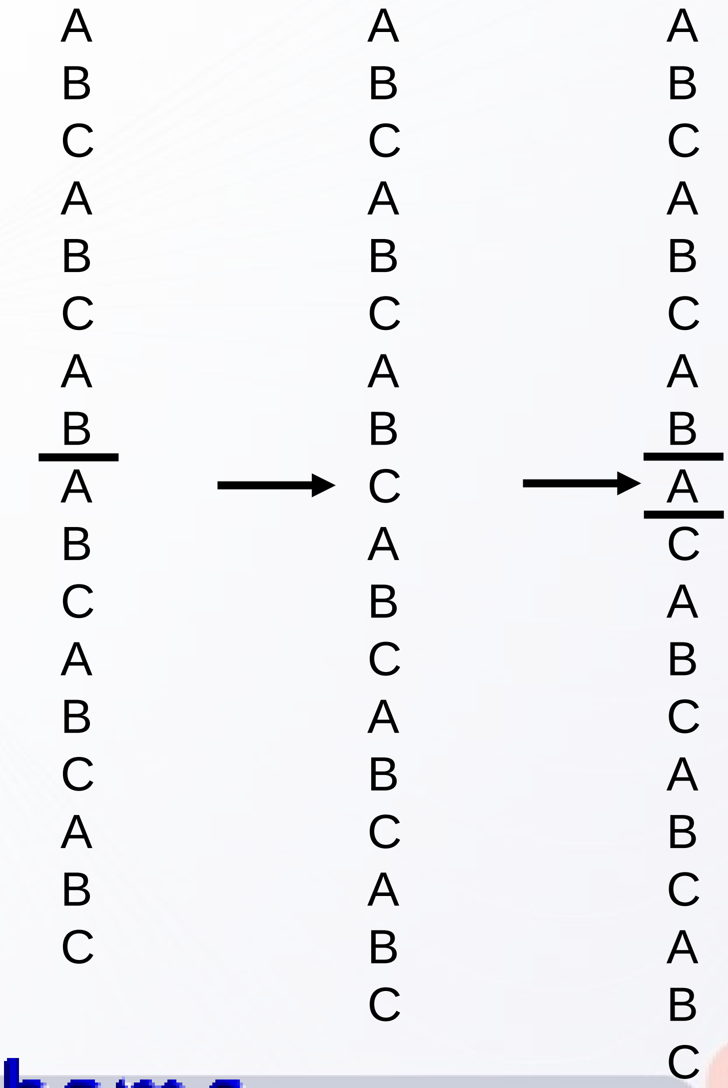


- For FCC metals an error in ABCABC packing sequence

- Intrinsic : Remove a plane (C)
- Extrinsic : Insert an extra plane (A)

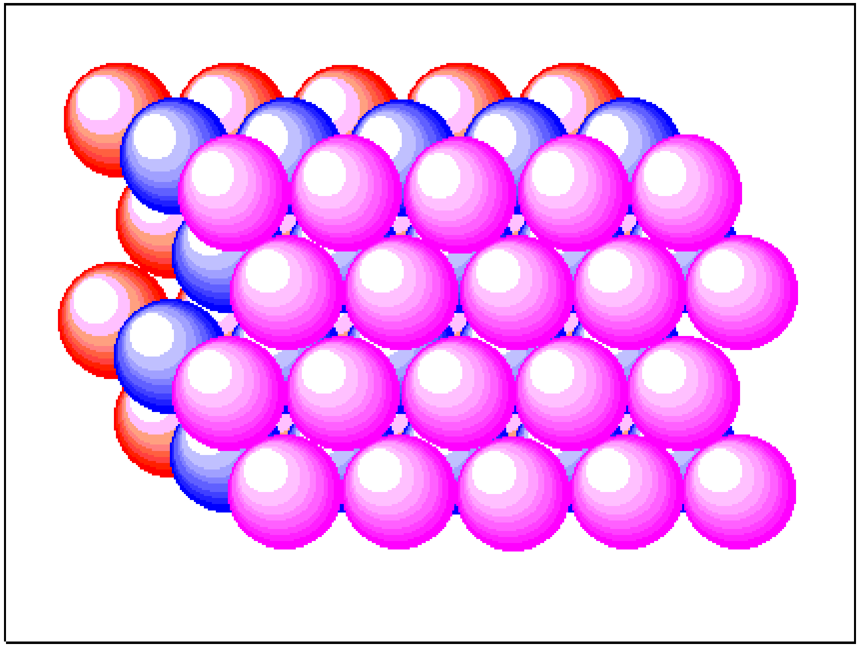


ABCABCABCABC

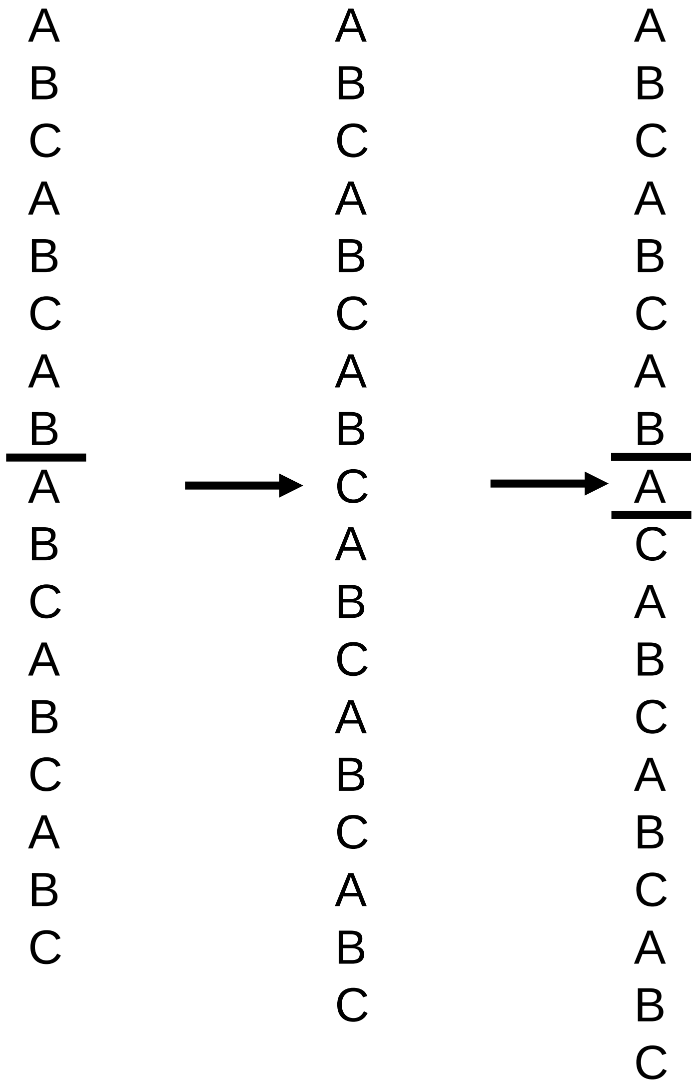


A		A		A
B		B		B
C		C		C
A		A		A
B		B		B
C		C		C
A		A		A
B		B		B
A	→	C	→	A
B		A		C
C		B		A
A		C		B
B		A		C
C		B		A
A		C		B
B		A		C
C		B		A
		C		B
				C

- Intrinsik : menghilangkan bidang C
- Extrinsik : Memasukkan bidang tambahan A
- Kristal sempurna



ABCABCABC

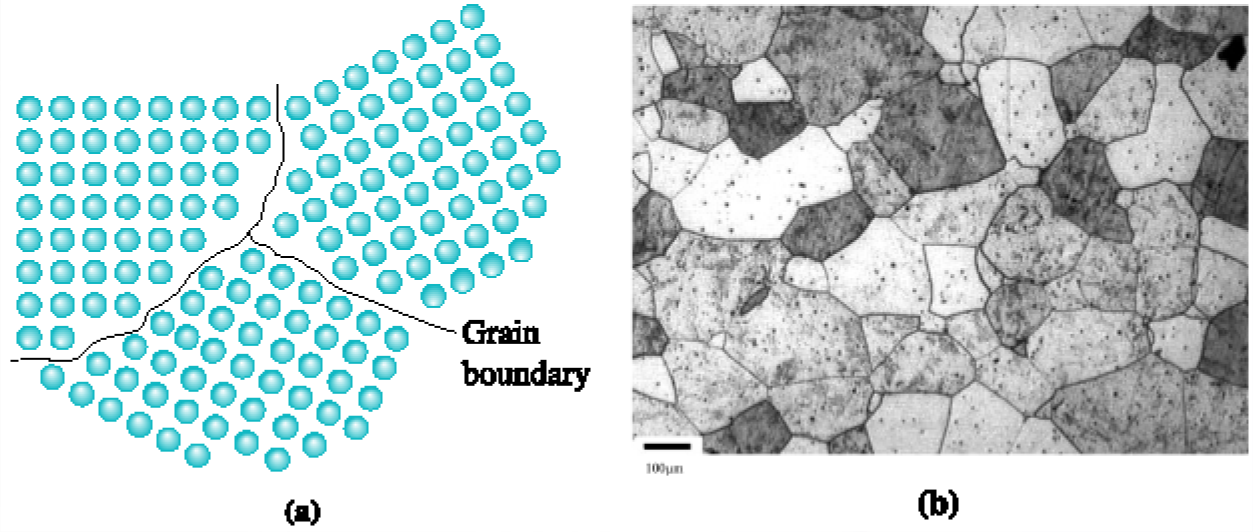


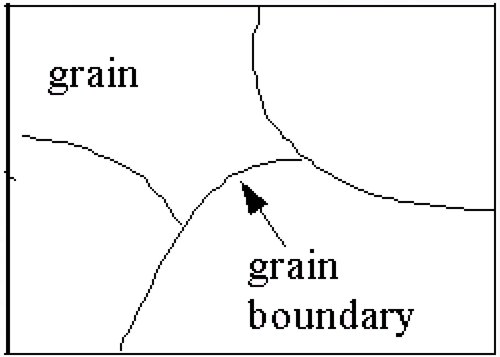
A B C A B C A B A B C A B C A B C

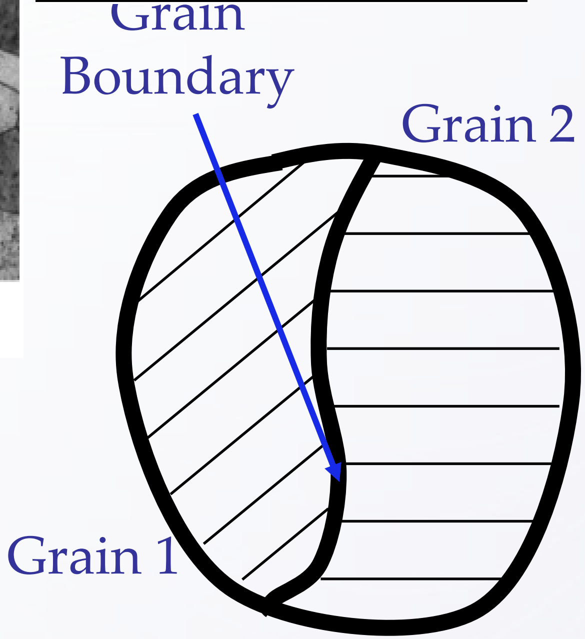
A B C A B C A B C A B C A B C A B C

A B C A B C A B A C A B C A B C A B C

grain boundaries





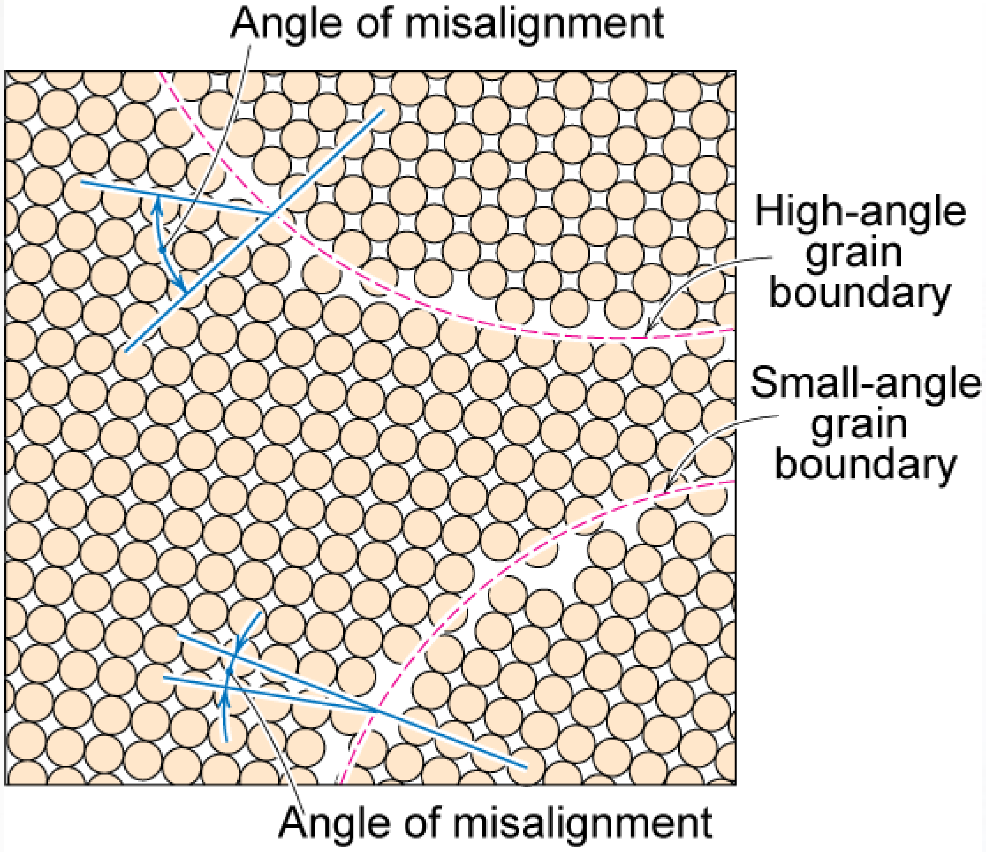


<u>See Figure :</u>

(a) The atoms near the boundaries of the three grains
(b) Grains and grain boundaries in a stainless steel sample.

(*Courtesy Dr. A. Deardo.*)

A grain boundary is a boundary between two regions of identical crystal structure but different orientation



Grains: individual crystals
Grain boundaries: zones between any two grains

- regions between crystals
- transition from lattice of one region to that of the other
- slightly disordered
- low density in grain boundaries
  - high mobility
  - high diffusivity
  - high chemical reactivity

Grain Boundary: *low* and *high angle*

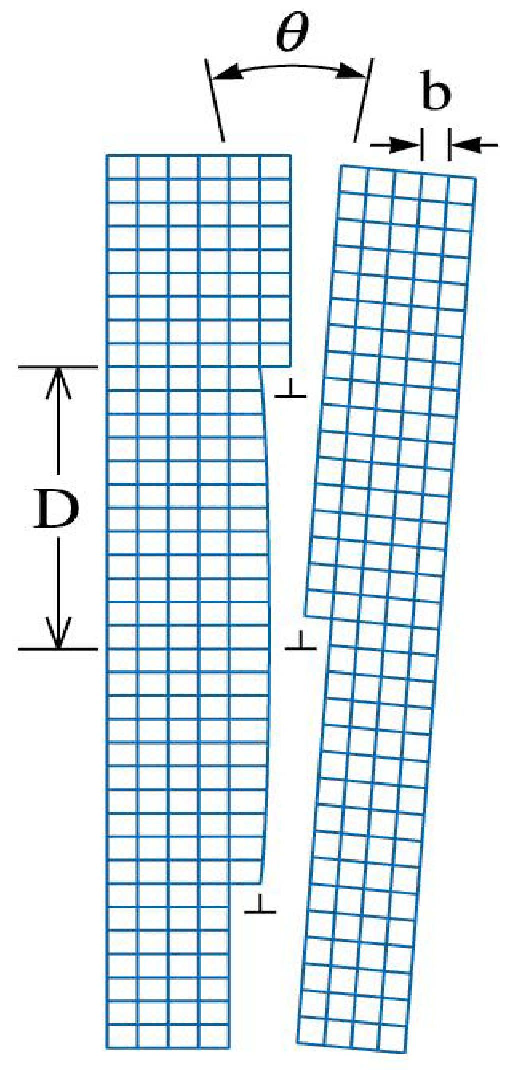
One grain orientation can be obtained by rotation of another grain across the grain boundary about an axis through an **angle**

If the angle of rotation is high, it is called a **high angle grain boundary**

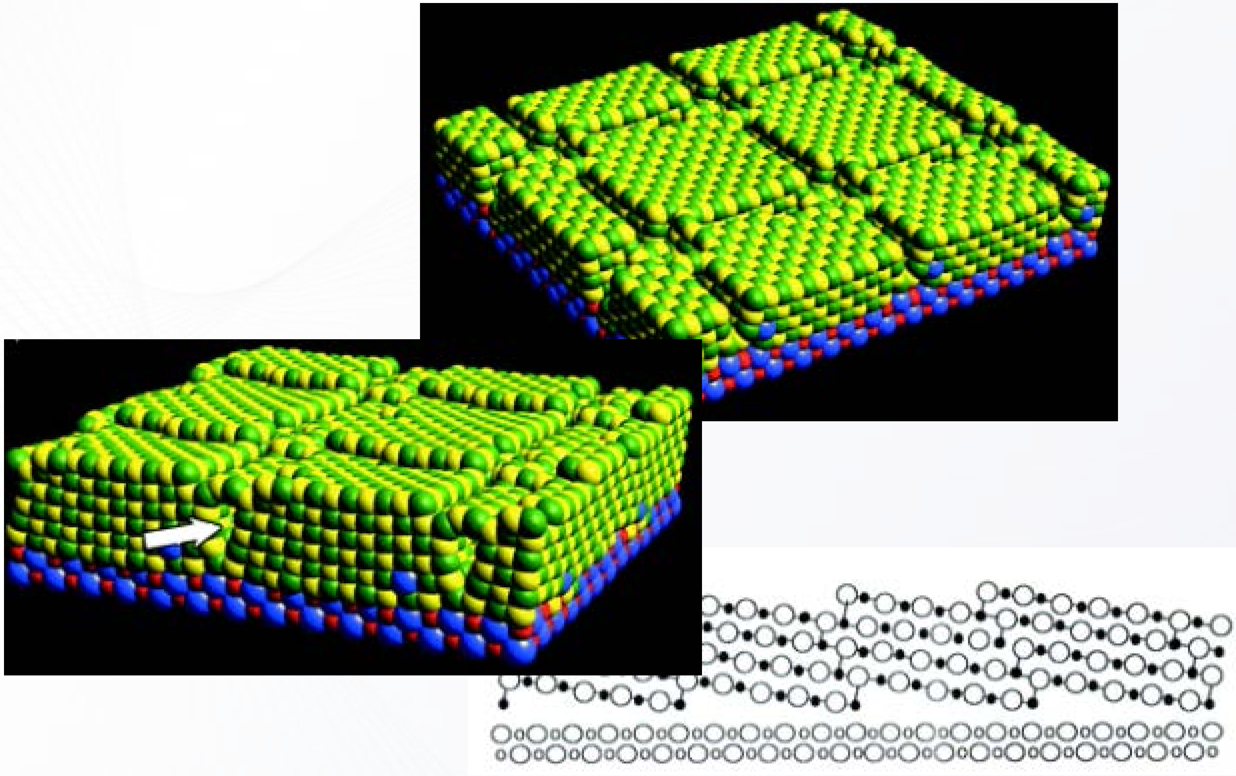
If the angle of rotation is low it is called a **low angle grain boundary**

Low-angle grain boundary

- An array of dislocations causing a small misorientation of the crystal across the surface of the imperfection.



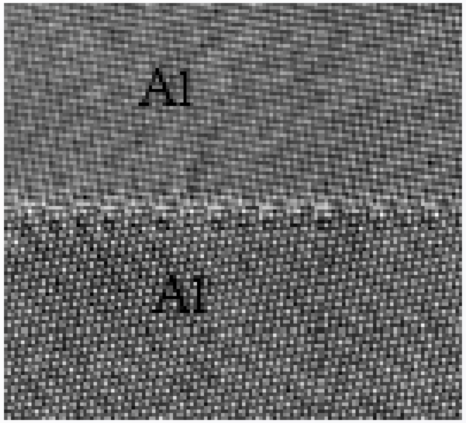
(c) 2003 Brooks/Cole Publishing / Thomson Learning



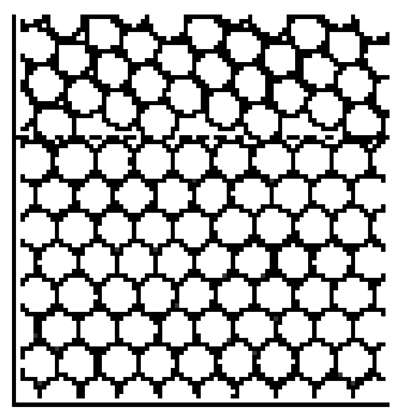
The low angle grain boundary is produced by an array of dislocations, causing an angular mismatch θ between lattices on either side of the boundary.

High-angle grain boundary

High-angle boundaries are likely sites for chemical segregation



A simple high-angle boundary where two crystals meet



Grain Boundary: *tilt* and *twist*

One grain orientation can be obtained by rotation of another grain across the grain boundary about an **axis** through an angle

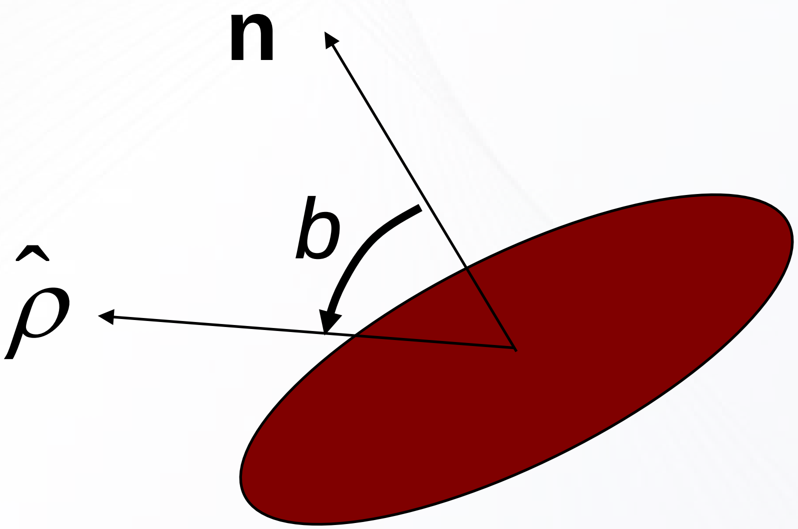
If the axis of rotation lies in the boundary plane it is called **tilt boundary**

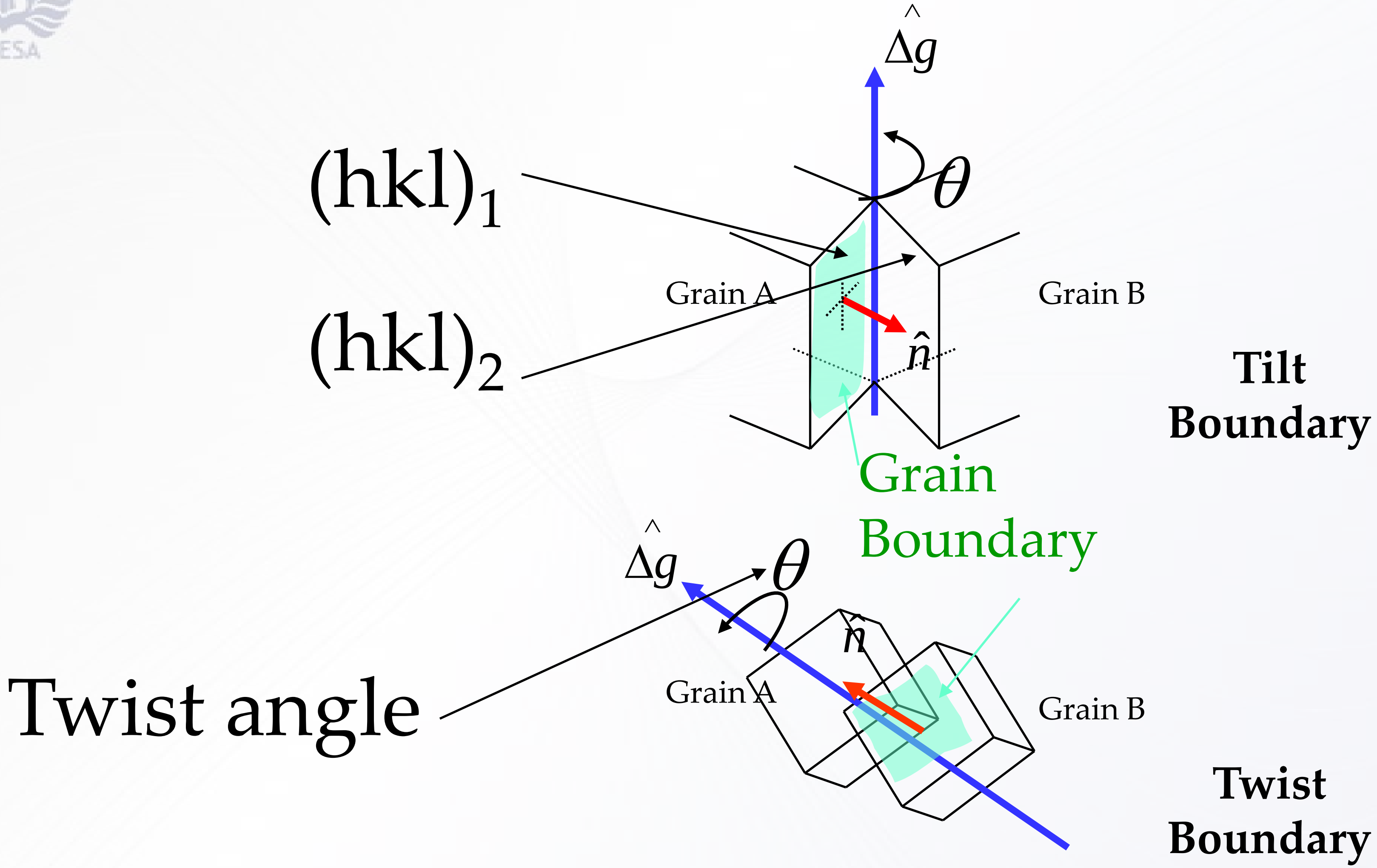
If the angle of rotation is perpendicular to the boundary plane it is called a **twist boundary**

Tilt-twist character

If $\cos^{-1}(b)=0°$, boundary is pure twist;

If $\cos^{-1}(b)=90°$, boundary is pure tilt.





$(hkl)_1$

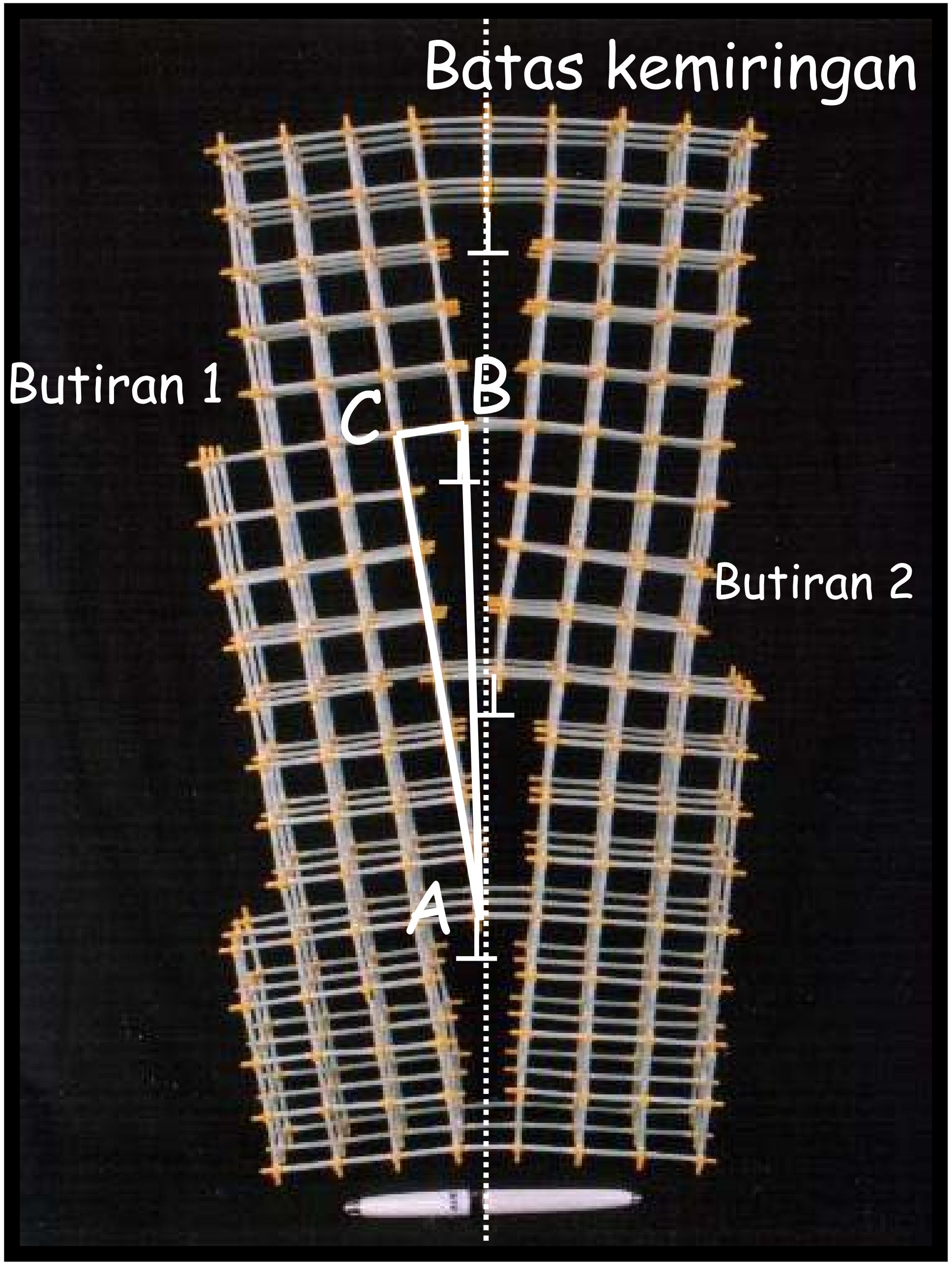
$(hkl)_2$

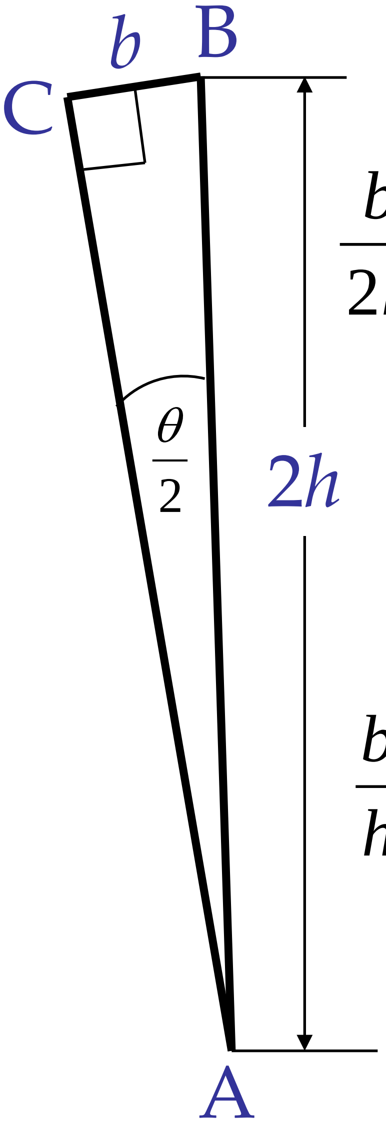
Tilt Boundary

Grain Boundary

Twist angle

Twist Boundary



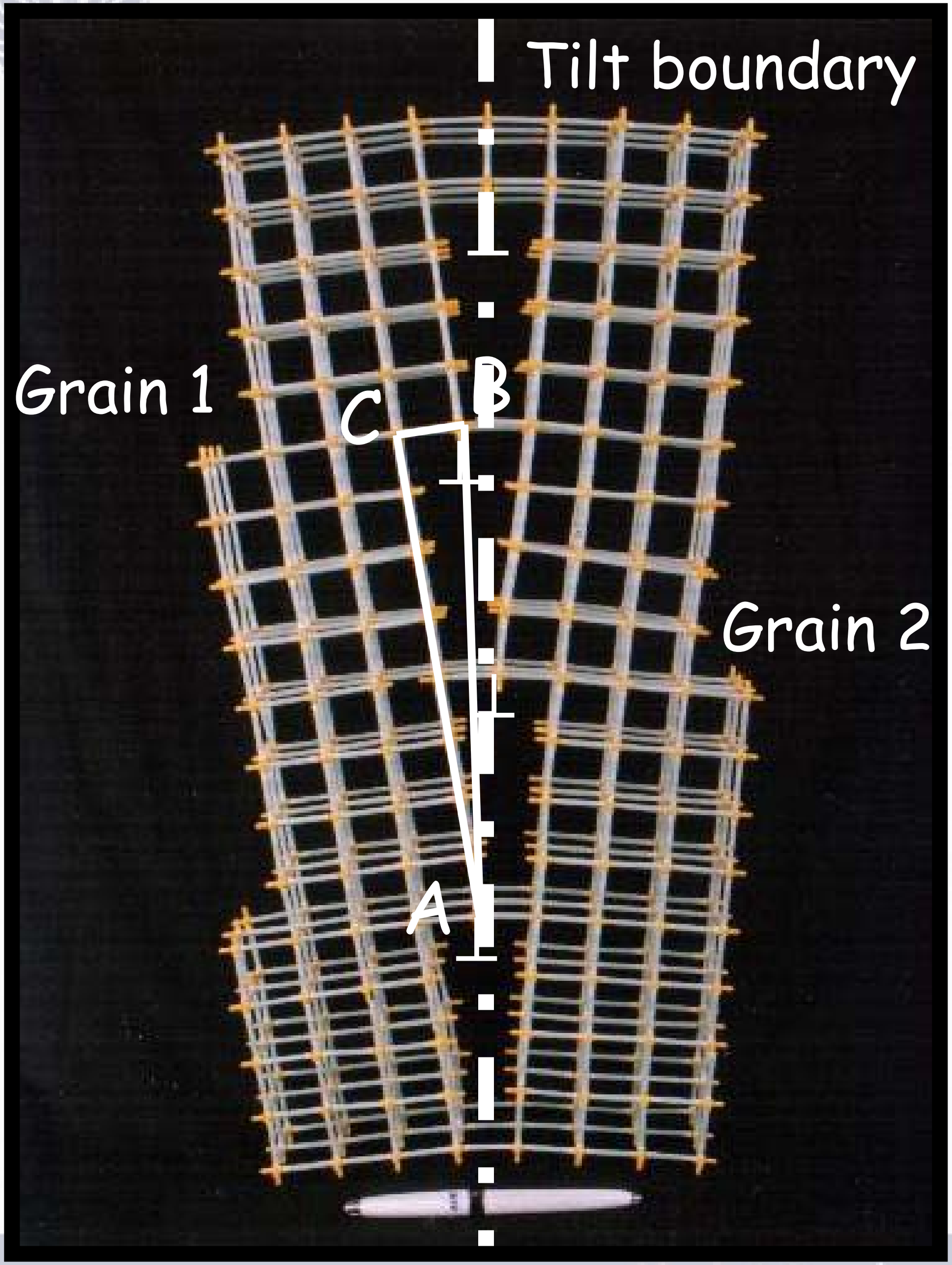


$$\frac{b}{2h} = \sin\frac{\theta}{2}$$

Atau

$$\frac{b}{h} = \tan\theta$$

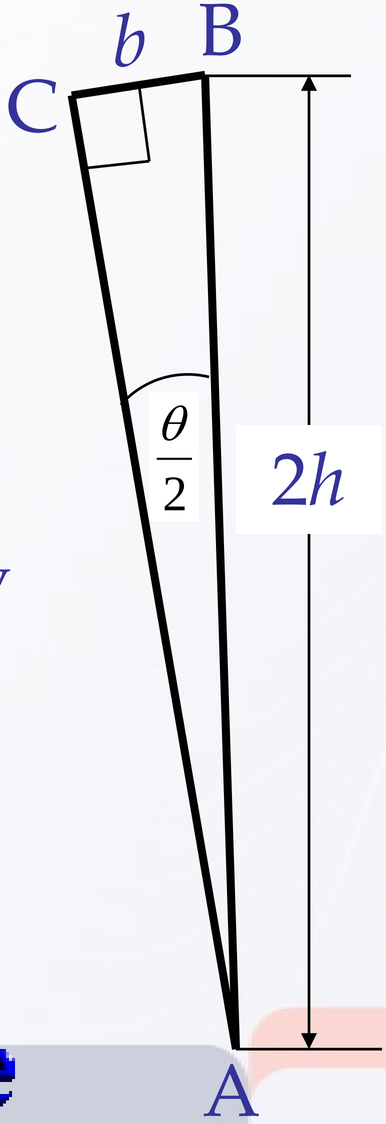
Edge dislocation model of a small angle tilt boundary



$$\frac{b}{2h} = \sin\frac{\theta}{2}$$

Or approximately

$$\frac{b}{h} = \tan\theta$$



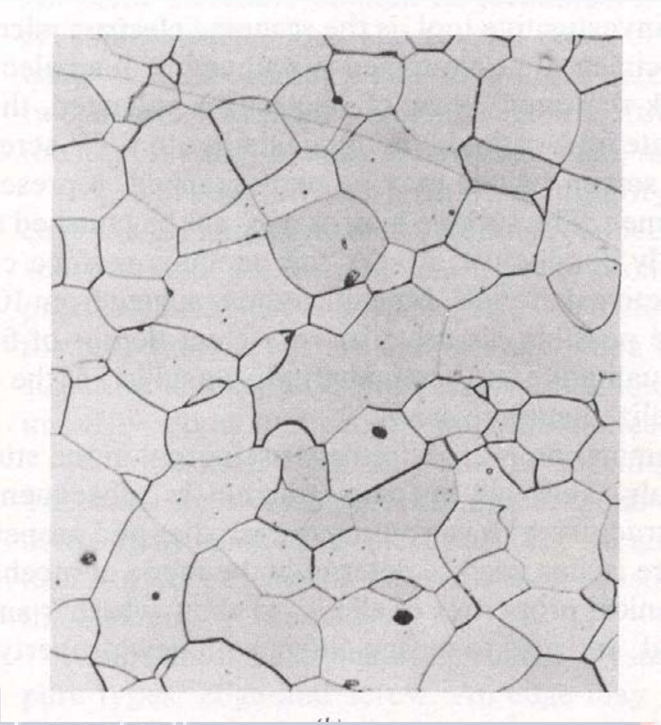
voids (porosity)

- holes in the materials

Voids are small regions where there are no atoms, and can be thought of as clusters of vacancies

inclusions

inclusions particles of foreign matter embedded in the solid



precipitations

Every impurity introduced into a crystal has a certain level of solubility, which defines the concentration of that impurity that the solid solution of the host crystal can accommodate.

Impurity solubility usually decreases with decreasing temperature.

If an impurity is introduced into a crystal at the maximum concentration allowed by its solubility at a high temperature,

the crystal will become supersaturated with that impurity once it is cooled down.

A crystal under such supersaturated conditions seeks and achieves equilibrium by **precipitating** the excess impurity atoms into another phase of different composition or structure.

PRECIPITATES

Impurities cluster together to form small regions of a different phase

Precipitates are considered undesirable because they have been known to act as sites for the generation of dislocations

Precipitates induced during silicon wafer processing come from oxygen, metallic impurities, and dopants like boron

Importance of Defects

- Effect on Mechanical Properties via Control of the Slip Process
- Strain Hardening
- Solid-Solution Strengthening
- Grain-Size Strengthening
- Effects on Electrical, Optical, and Magnetic Properties

Defectoscope

Defectoscope

Detect fine surface defects
The system can detect flaws as fine as 30 microns on polished surfaces

Electron microscopy

Optical microscopy