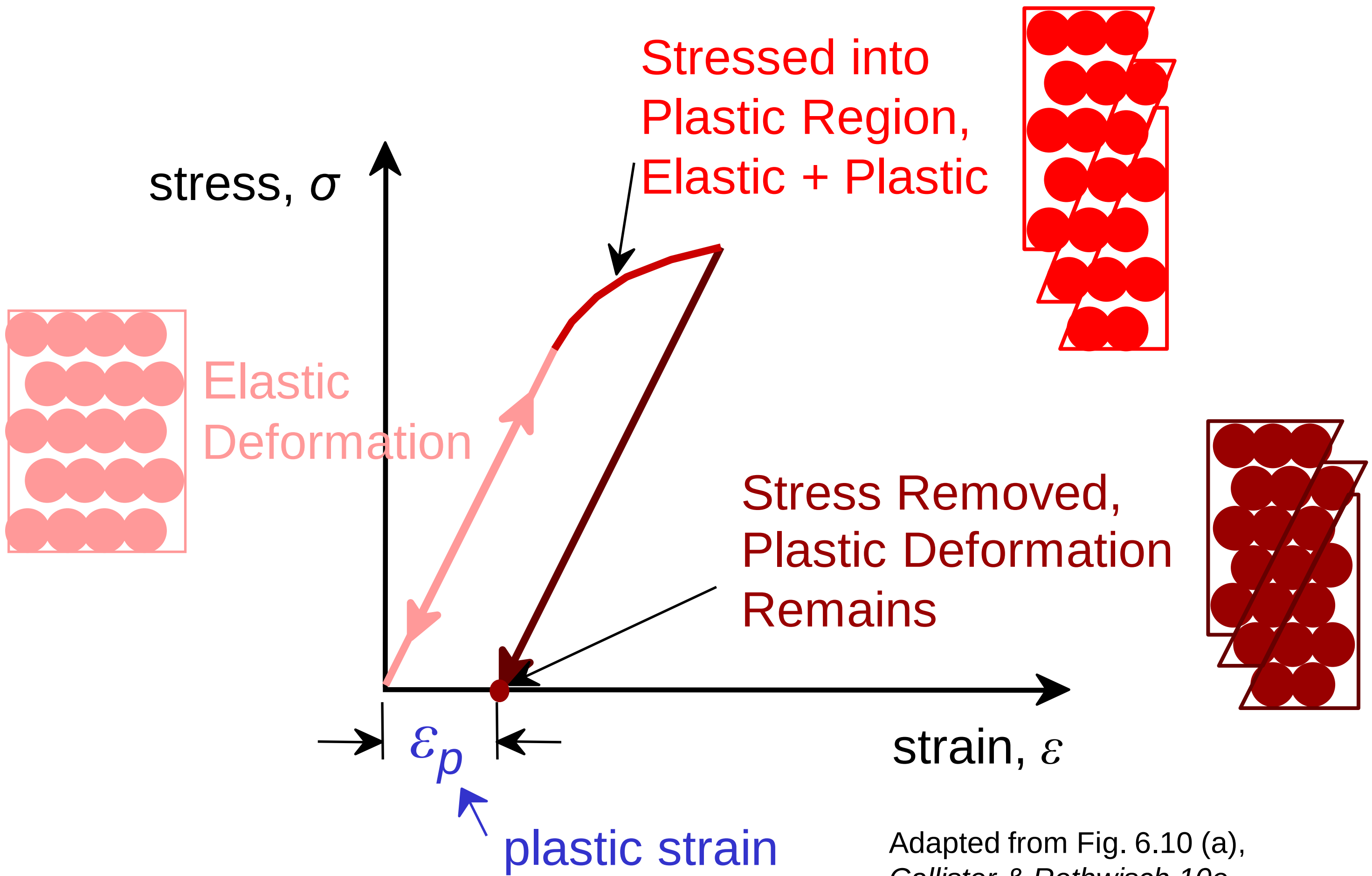
Aalto University
School of Engineering

COE-C2004 - Materials Science and Engineering

Prof. Junhe Lian
Wenqi Liu (Primary Teaching Assistant)
Rongfei Juan (Teaching Assistants)

What happens to the structure during plastic deformation?



Adapted from Fig. 6.10 (a), *Callister & Rethwisch 10e.*

Chapter 4: Dislocations & Strengthening Mechanisms

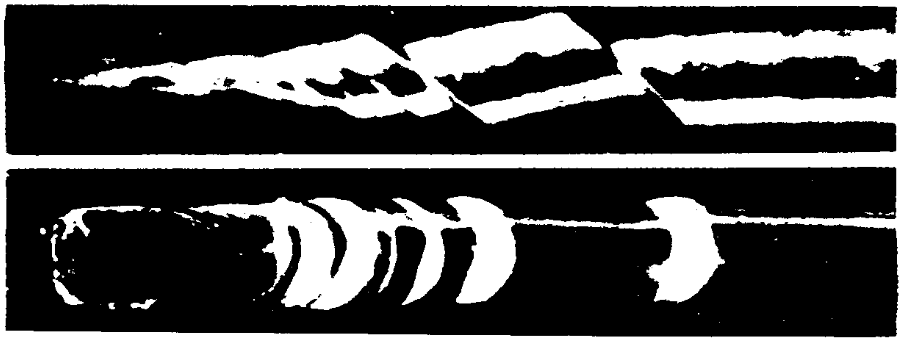
ISSUES TO ADDRESS...

- What are the **underlying mechanisms** of plastic deformation of metals/metal alloys?
- What **structure** of a metal affects its mechanical characteristics? How and why?
- What does **yield strength** mean on the crystal structure scale?
- What techniques are used to increase the **strength/hardness** of metals/alloys?

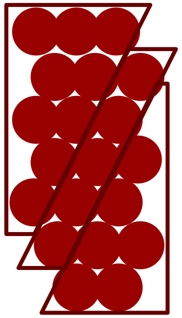
Mechanisms of Plastic deformation of Metals

What happens during plastic deformation?

Single crystal

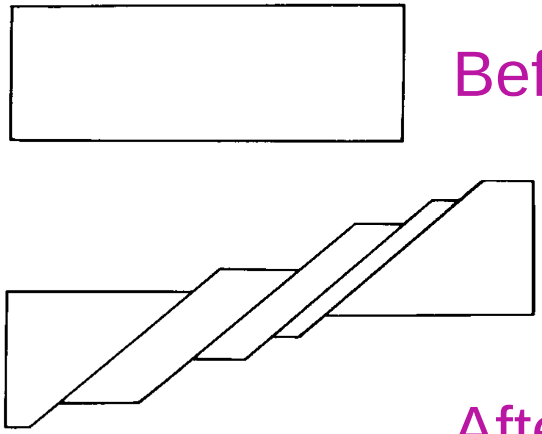


Stress Removed,
Plastic Deformation
Remains



Adapted from Fig. 6.10 (a),
Callister & Rethwisch 10e.

Polycrystal



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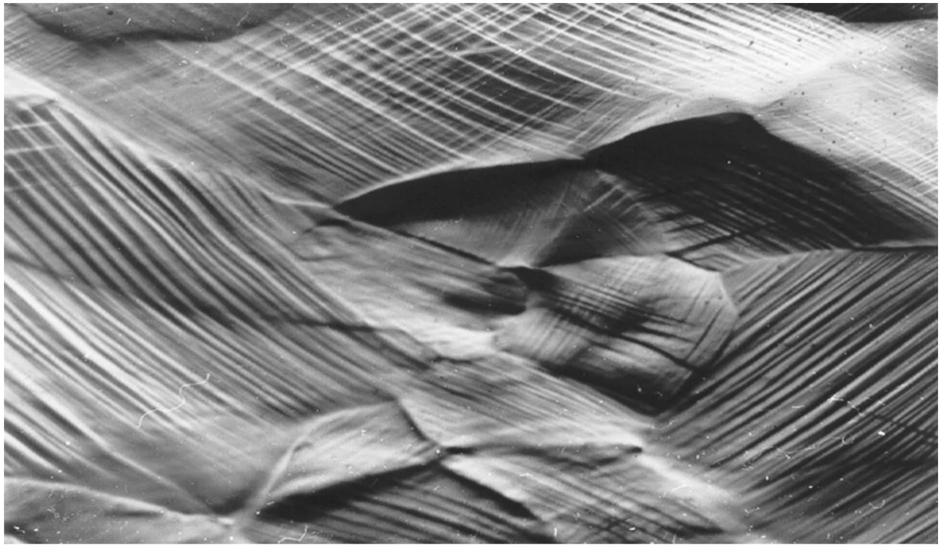

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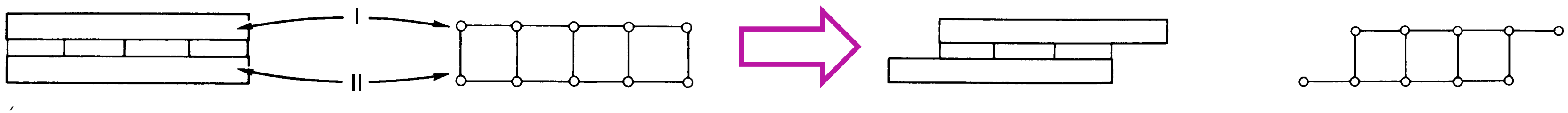
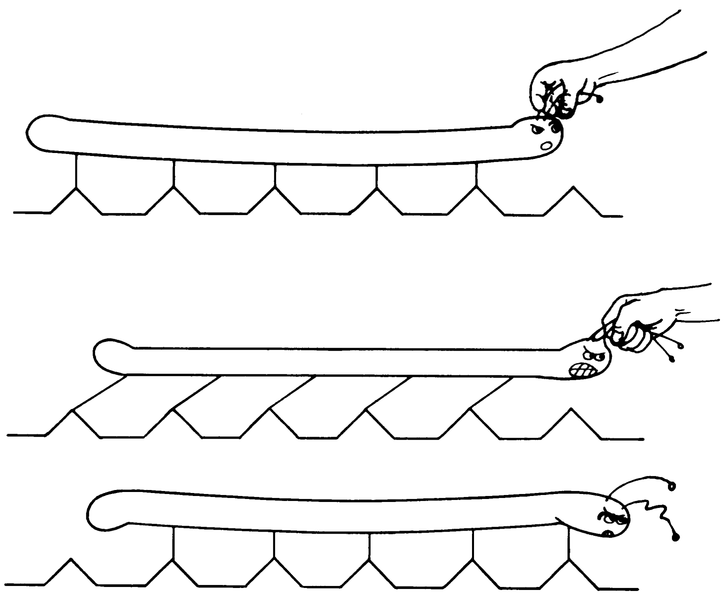
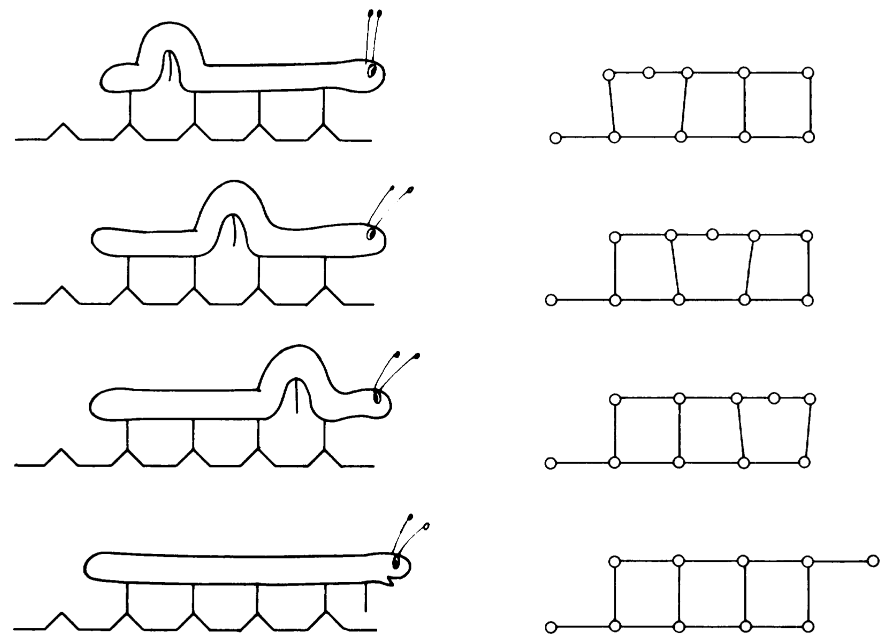
50 µm

Analogy Between Atom Motion and Caterpillar motion





(a)



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Analogy Between Dislocation Motion and Caterpillar Locomotion

- Caterpillar locomotion – hump formed and propelled by lifting and shifting of leg pairs
- Dislocation motion – movement of extra half-plane of atoms by breaking and reforming of interatomic bonds

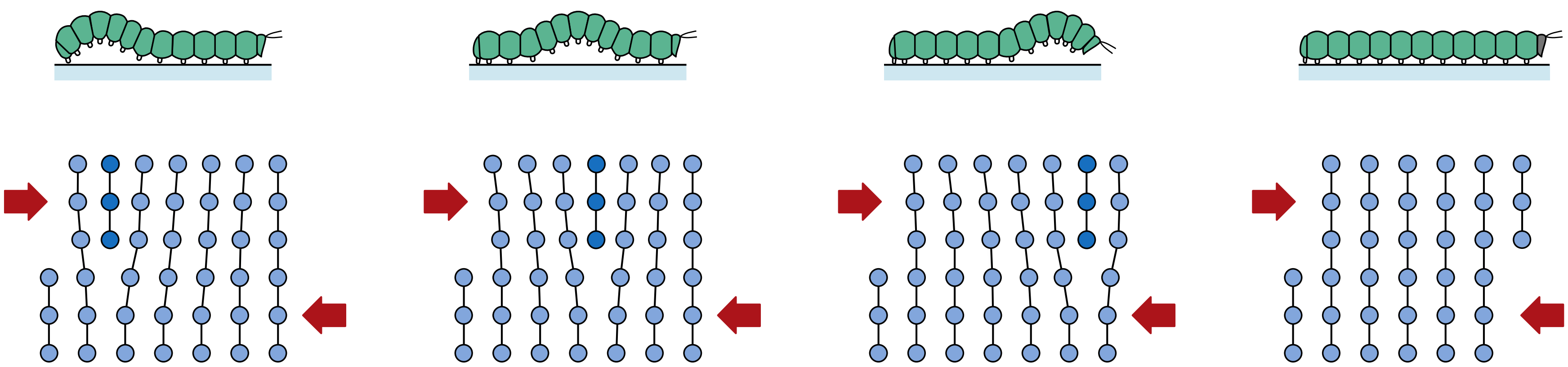
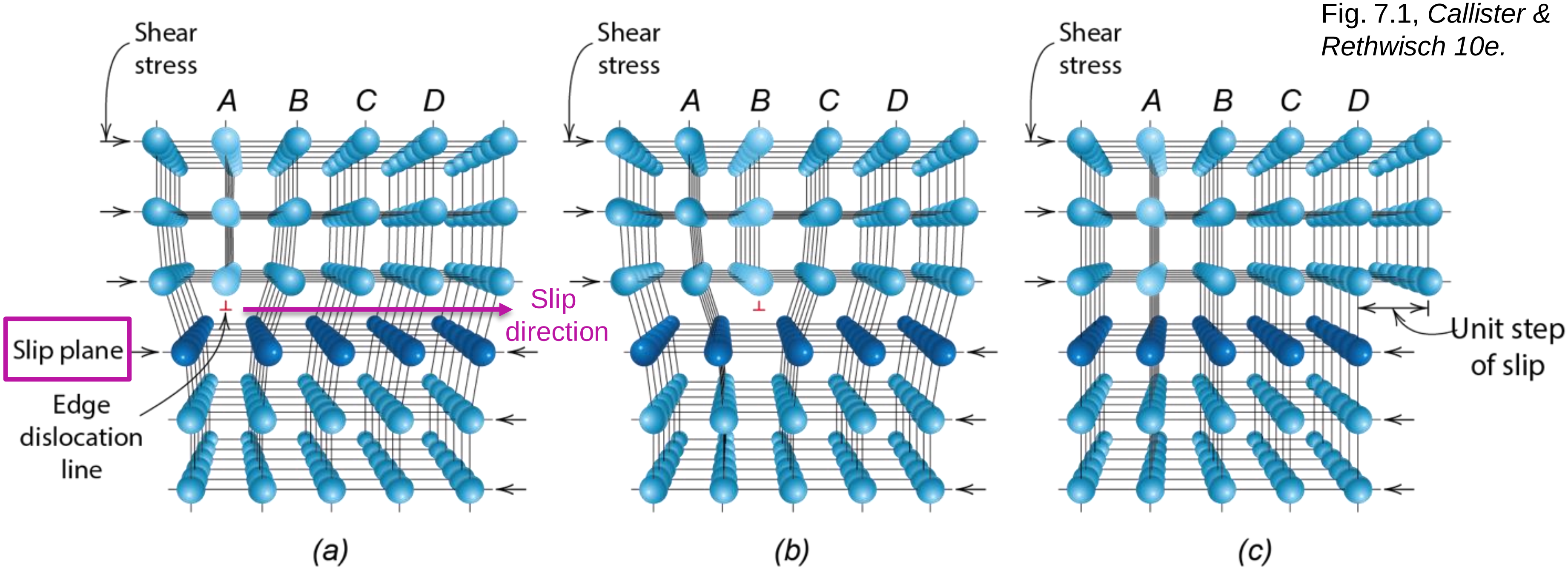


Fig. 7.3, *Callister & Rethwisch 10e.*

Plastic Deformation by Dislocation Motion

- Plastic deformation occurs by **motion of dislocations** (edge, screw, mixed) – process called **slip**
- Applied shear stress can cause extra half-plane of atoms [and edge dislocation line (⊥)] to move as follows:

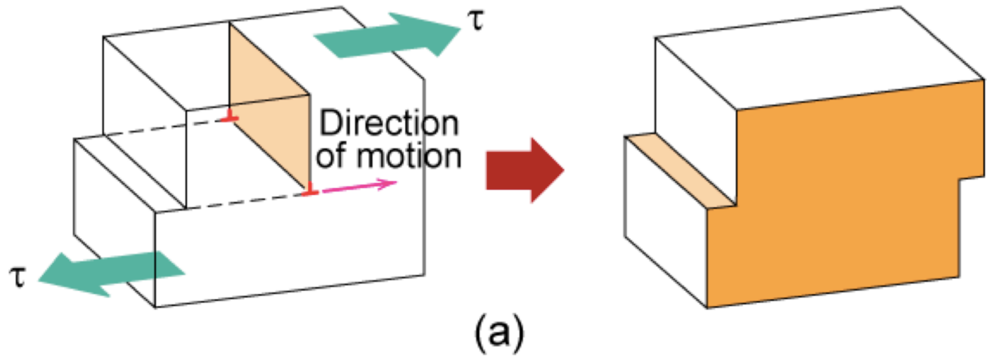
Fig. 7.1, *Callister & Rethwisch 10e.*



- Atomic bonds broken and reformed on the slip plane as dislocation (extra half plane) moves along the slip direction.

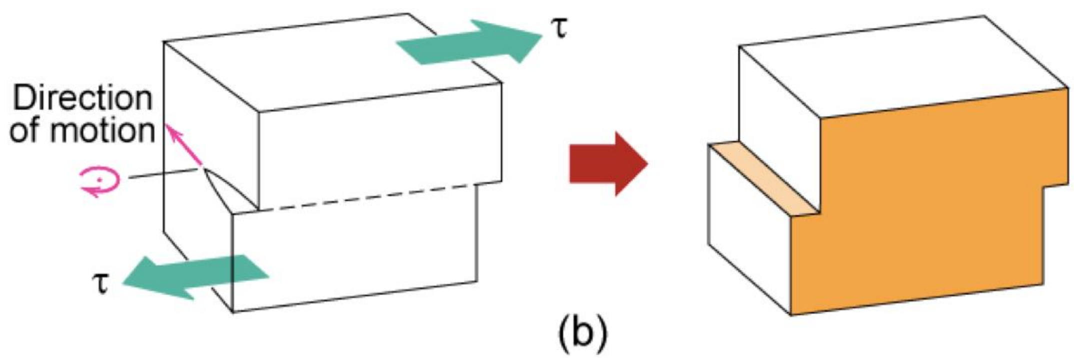
Motion of Edge and Screw Dislocations

- Direction of edge disl. line (⊥) motion—in direction of applied shear stress ***τ.***



Edge dislocation

- Direction of screw disl. line ( ) motion—perpendicular to direction of applied shear stress.



Screw dislocation

Fig. 7.2, *Callister & Rethwisch 10e.*

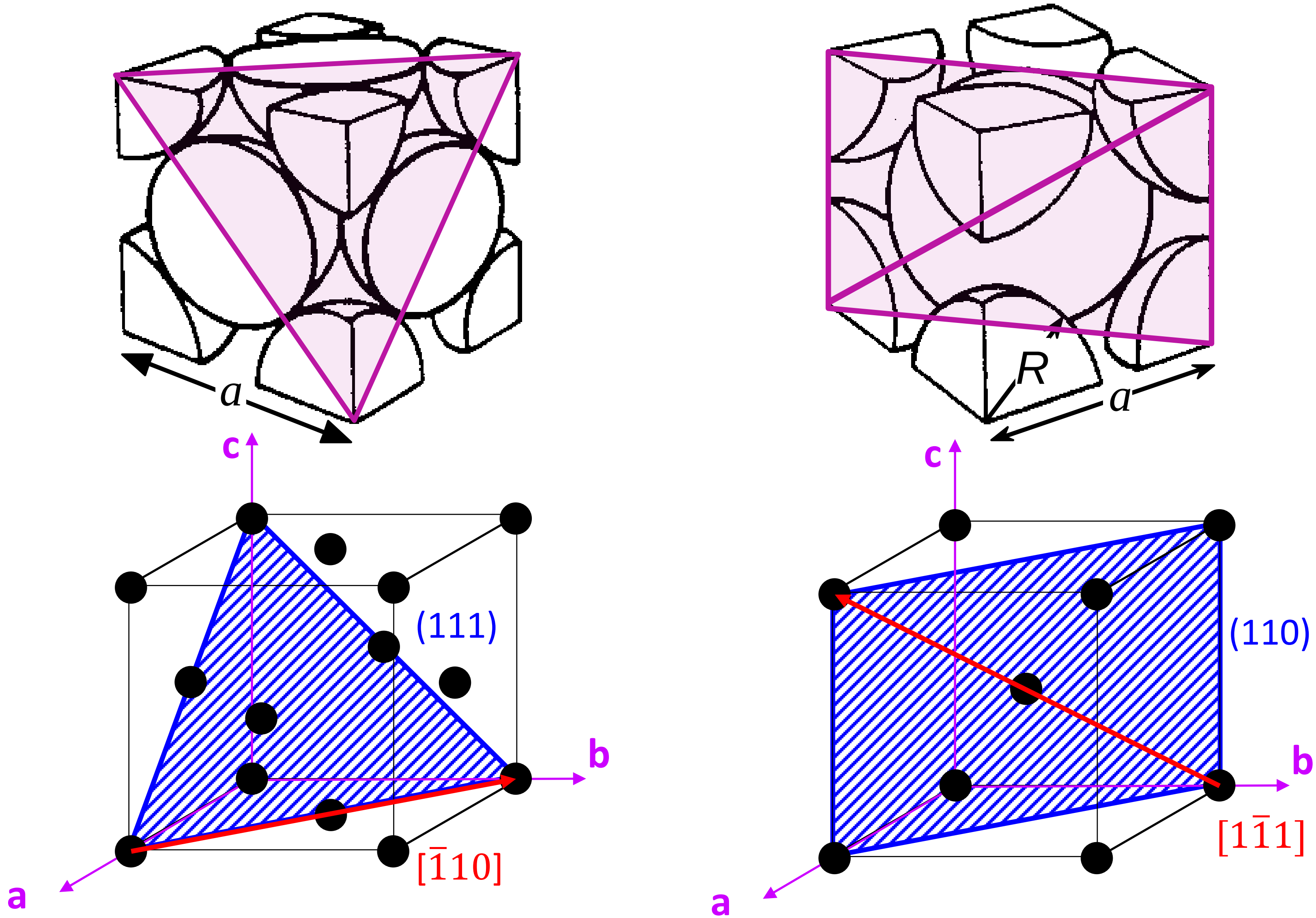
Crystal Structure and Plasticity

Slip Systems

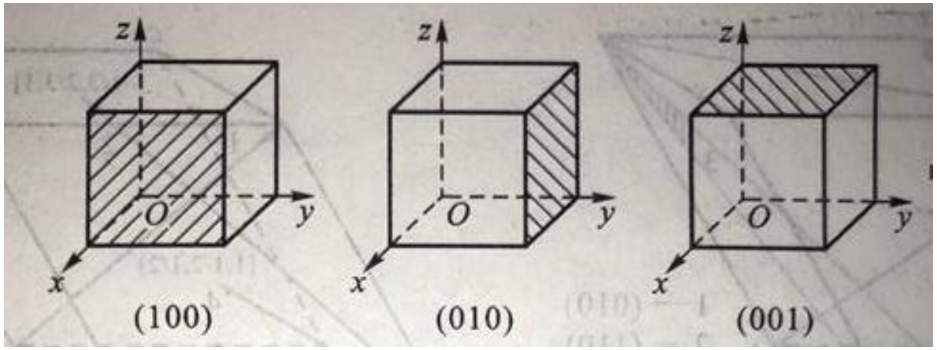
Slip System—Combination of slip plane and slip direction

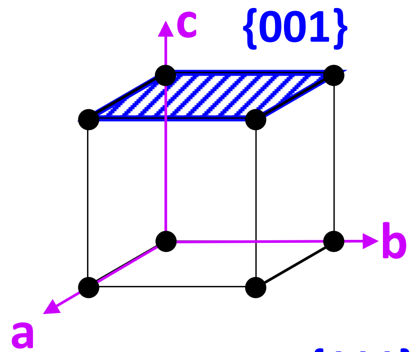
- Slip Plane
  - Crystallographic plane on which slip occurs most easily
  - Close-packed planes
- Slip Direction
  - Crystallographic direction along which slip occurs most easily
  - Close-packed directions

Close-packed planes and directions for FCC & BCC



Family of planes (cube symmetry)

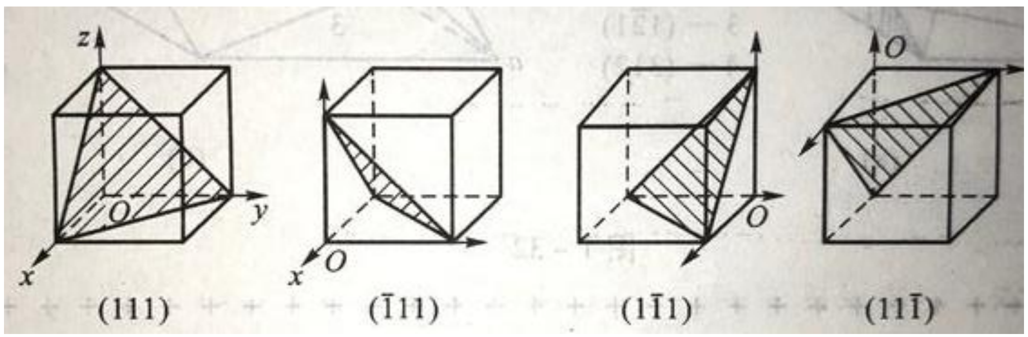


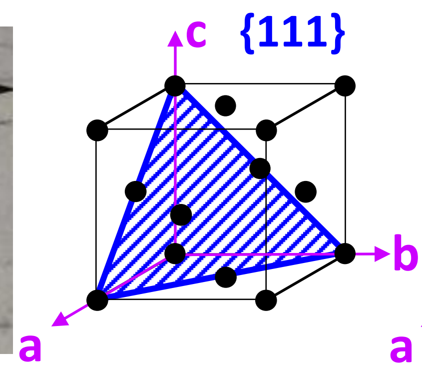


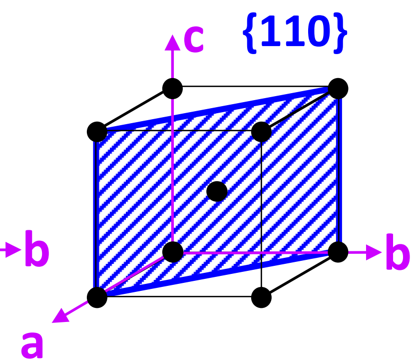
Note:

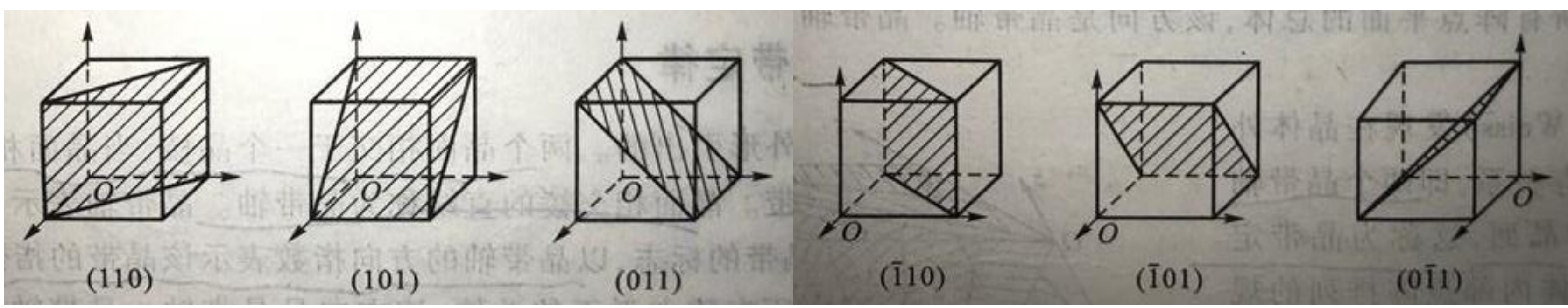
$(001) = (00\bar{1})$

$(111) = (\bar{1}\bar{1}\bar{1})$









Yongning Yu, The fundamentals of Materials Science, 2006

Slip Systems for FCC Crystals

- For FCC crystal structure – slip system is $\{111\}\langle 110\rangle$
  - Dislocation motion on $\{111\}$ planes
  - Dislocation motion in $\langle 110\rangle$ directions
  - A total of 12 independent slip systems for FCC

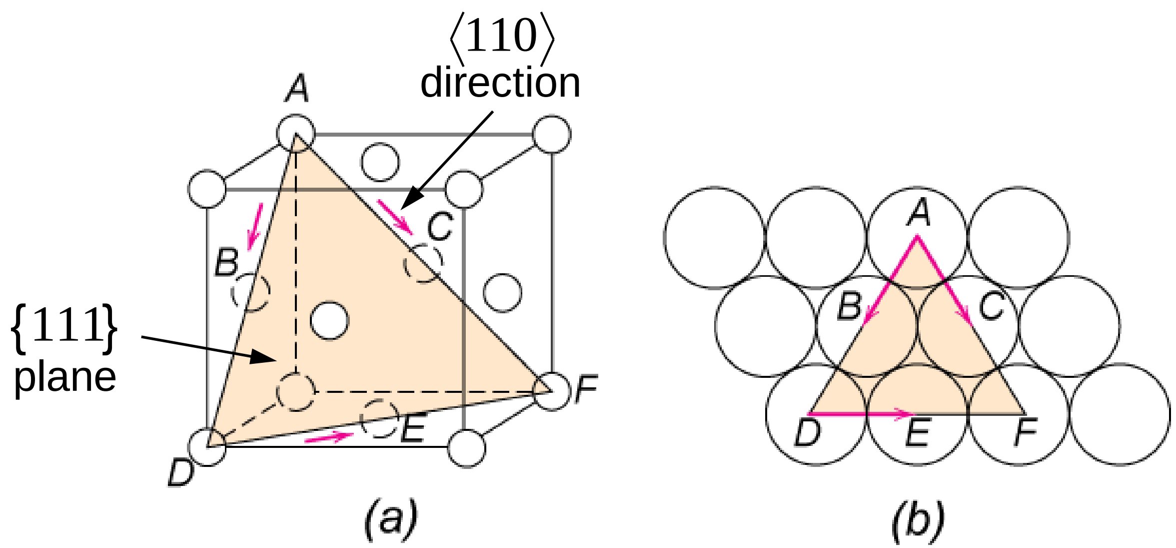
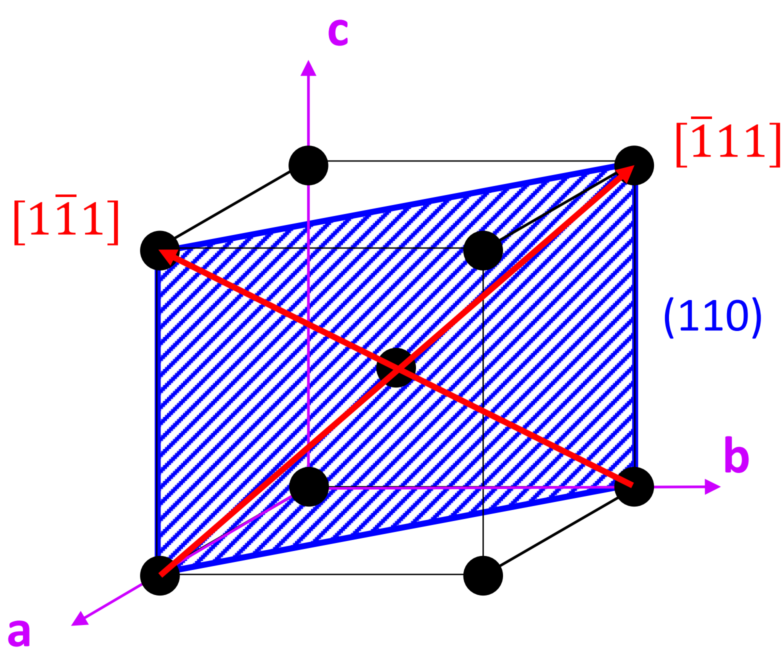
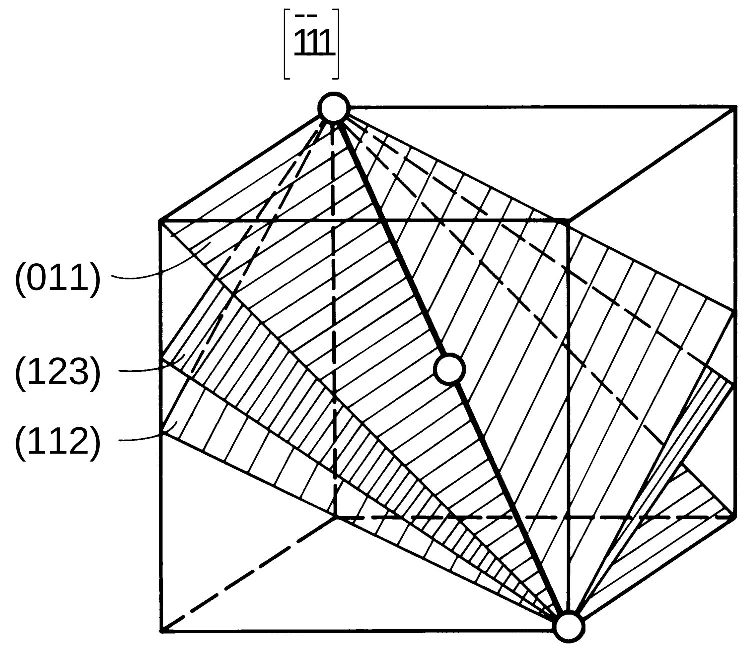


Fig. 7.6, *Callister & Rethwisch 10e.*

Slip Systems for BCC Crystals

- For BCC crystal structure – main slip system is $\{110\}\langle 111\rangle$
  - Dislocation motion mainly on $\{110\}$ planes
  - Dislocation motion in $\langle 111\rangle$ directions
  - A total of 12 main independent slip systems for BCC





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Slip Systems for FCC & BCC Crystals

crystal structure	slip plane	slip direction	number of non-parallel planes	slip directions per plane	number of slip systems
fcc	{111}	$\langle 1\bar{1}0\rangle$	4	3	12 = (4x3)
bcc	{110}	$\langle 11\bar{1}\rangle$	6	2	12 = (6x2)
	{112}	$\langle 11\bar{1}\rangle$	12	1	12 = (12x1)
	{123}	$\langle 111\rangle$	24	1	24 = (24x1)

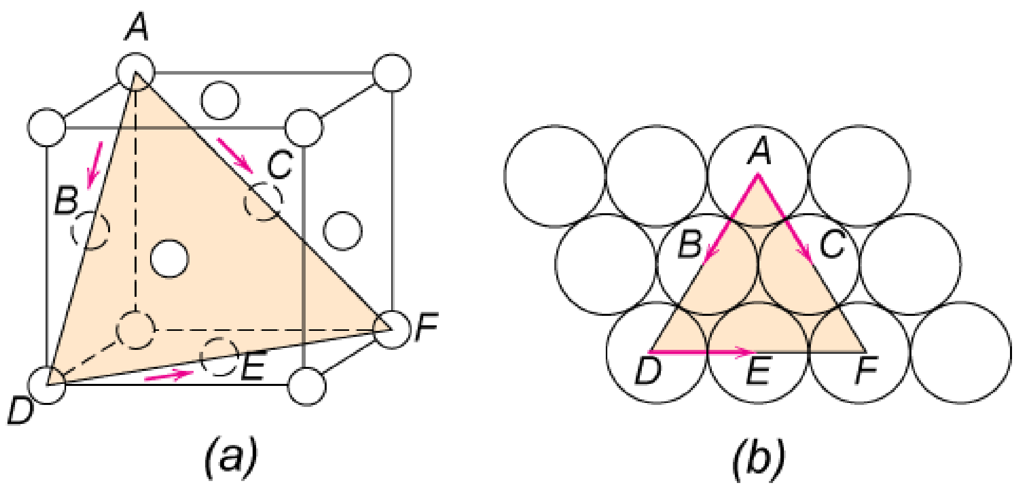
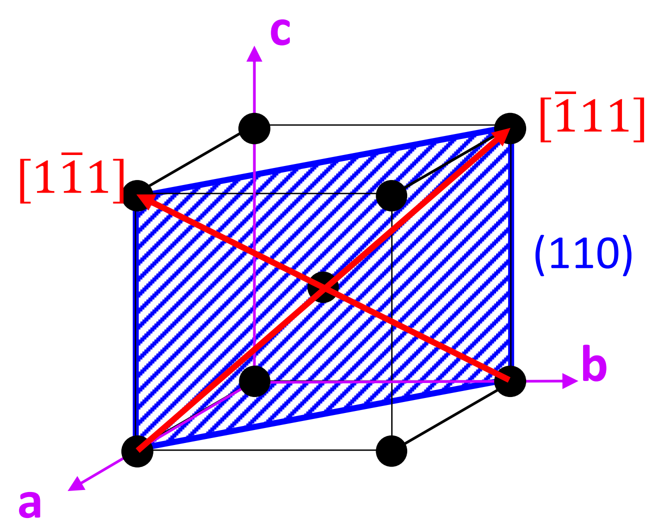


Fig. 7.6, *Callister & Rethwisch 10e.*



Slip in Single Crystals
- Resolved Shear Stress

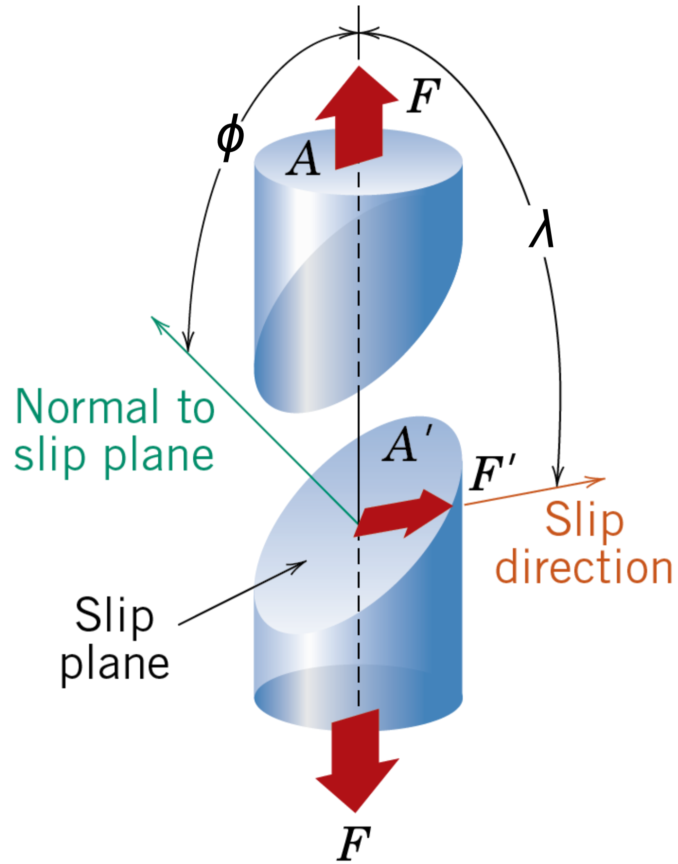
- Applied tensile stress—shear stress component when slip plane oriented neither perpendicular nor parallel to stress direction
- From figure, resolved shear stress, τ_R

$$t_R = \frac{F'}{A'}$$

- τ_R depends on orientation of normal to slip plane and slip direction with direction of tensile force F:

$$F' = F \cos /$$

$$A' = \frac{A}{\cos f}$$



Slip in Single Crystals
- Resolved Shear Stress (cont.)

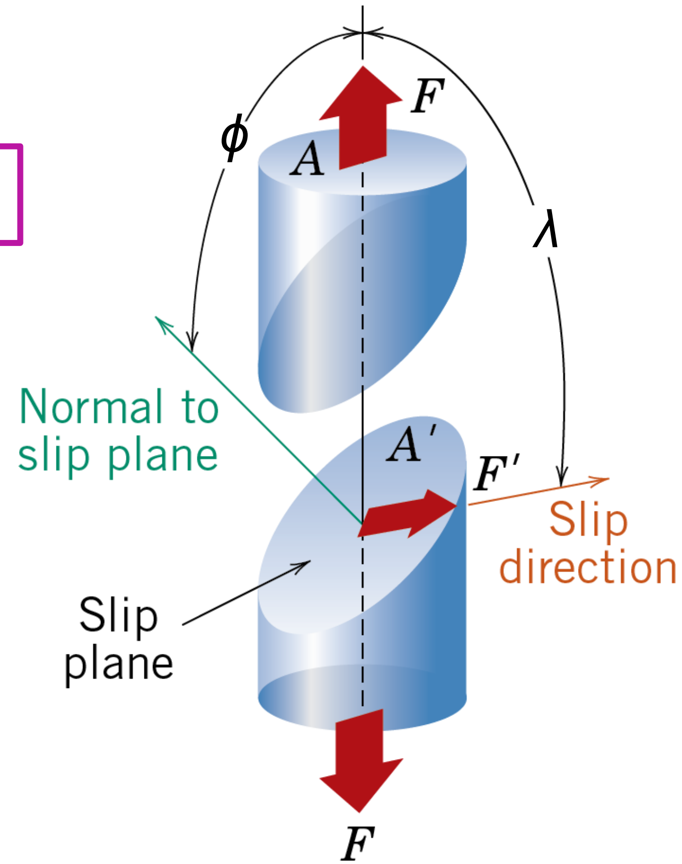
- Relationship between tensile stress, σ, and τ_R:

Schmid's Law

$$t_R = \frac{F'}{A'} = \frac{F\cos /}{\dfrac{A}{\cos f}} = \frac{F}{A}\cos / \cos f$$

$$= s\,\boxed{\cos / \cos f}$$

Schmid Factor



Slip in Single Crystals
- Critical Resolved Shear Stress

- Dislocation motion—on specific slip system—when τ_R reaches critical value:
  - -- "Critical resolved shear stress", τ_{CRSS}
  - -- Slip occurs when $\tau_R > \tau_{\mathrm{CRSS}}$
  - -- Typically 0.1 MPa < τ_{CRSS} < 10 MPa
- In a single crystal there are
  - -- multiple slip systems
  - -- a variety of orientations
- One slip system for which τ_R is highest: $\tau_R(\mathrm{max}) > \sigma\,(\cos\lambda\,\cos\phi\,)_{\mathrm{max}}$
  - -- Most favorably oriented slip system
- Yield strength of single crystal, σ_y, when

$$s_y = \frac{t_{\mathrm{CRSS}}}{\left(\cos / \cos f\right)_{\mathrm{max}}}$$

Deformation of Single Crystals Example Problem

A single crystal of some metal has a τ_{crss} of 20.7 MPa and is exposed to a tensile stress of 45 MPa.

(a) Will yielding occur when $\phi = 60°$ and $\lambda = 35°$?

(b) If not, what stress is necessary?

Solution:

(a) First calculate τ_R

$$t_R = s \cos / \cos f$$

$$t_R = (45\ \text{MPa})\left[\cos(35°)\cos(60°)\right]$$

$$= 18.4\ \text{MPa}$$

Since $t_R (18.4\ \text{MPa}) < t_{crss} (20.7\ \text{MPa})$ -- no yielding

Deformation of Single Crystals Example Problem (cont.)

(b) To calculate the required tensile stress to cause yielding use the equation:

$$\sigma_y = \frac{\tau_{CRSS}}{\cos\lambda \cos\phi}$$

With specified values

$$\sigma_y = \frac{20.7\ \text{MPa}}{\cos(35°)\cos(60°)}$$

$$= 50.5\ \text{MPa}$$

Therefore, to cause yielding, $\boxed{\sigma \geq 50.5\ \text{MPa}}$

Single Crystals Slip—Macroscopic Scale

- Parallel slip steps form on surface of single crystal
- Steps result from motion of large numbers of dislocations on same slip plane
- Sometimes on single crystals appear as "slip lines" (see photograph)

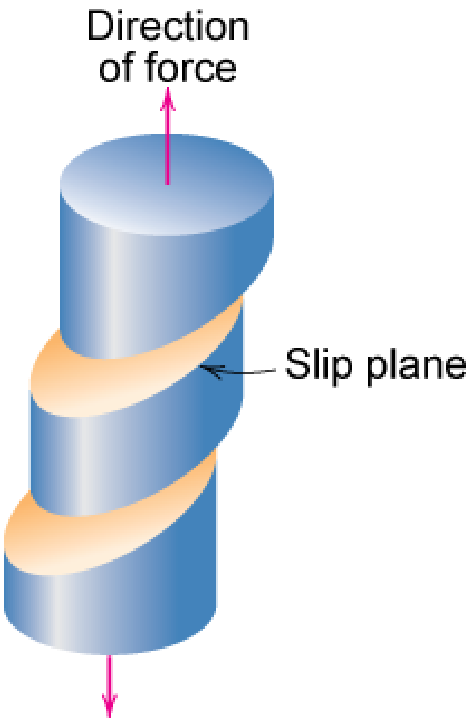
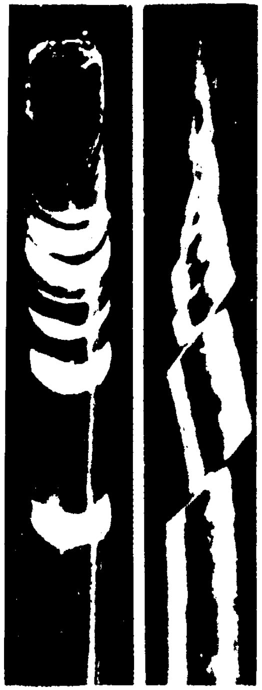


Fig. 7.8, *Callister & Rethwisch 10e.*



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Slip in Polycrystalline Materials

- Polycrystalline materials— many grains, often random crystallographic orientations

- Orientation of slip planes, slip directions (ϕ, λ)—vary from grain to grain.

- On application of stress—slip in each grain on most favorable slip system.
  - with largest τ_R
  - when $\tau_R > \tau_{crss}$

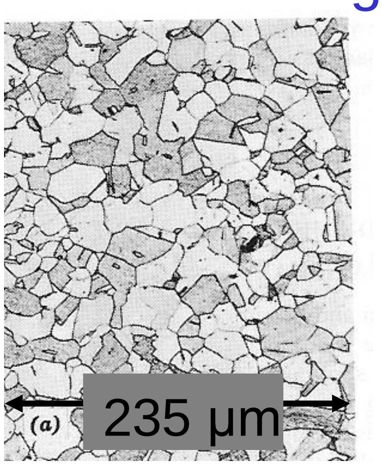
- In photomicrograph—note slip lines in grains have different orientations.

Adapted from Fig. 7.10, *Callister & Rethwisch 10e.* (Photomicrograph courtesy of C. Brady, National Bureau of Standards [now the National Institute of Standards and Technology, Gaithersburg, MD].)

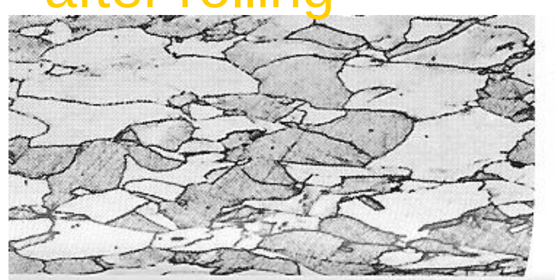
Slip in Polycrystalline Materials (cont.)

- Grains change shape (become distorted)—during plastic deformation—due to slip
- Manner of grain distortion similar to gross plastic deformation
  - Grain structures before and after deformation (from rolling)
  - Before rolling—grains equiaxed & randomly oriented
    - ➢ Properties isotropic
  - After rolling (deformation)—grains elongated in rolling direction
    - ➢ Also preferred crystallographic orientation of grains
    - ➢ Properties become somewhat anisotropic

- before rolling



- after rolling



rolling direction

Adapted from Fig. 7.11, *Callister & Rethwisch 10e.* (from W.G. Moffatt, G.W. Pearsall, and J. Wulff, *The Structure and Properties of Materials*, Vol. I, *Structure*, p. 140, John Wiley and Sons, New York, 1964.)

Strengthening mechanisms

Strengthening Mechanisms for Metals

- For a metal to plastically deform—dislocations must move
- Strength and hardness—related to **mobility of dislocations**
  -- Reduce disl. mobility—metal strengthens/hardens
  -- Greater forces necessary to cause disl. motion
  -- Increase disl. mobility—metal becomes weaker/softer
- Mechanisms for strengthening/hardening metals—
  decrease disl. mobility
- 3 mechanisms discussed
  -- Grain size reduction
  -- Solid solution strengthening
  -- Strain hardening (cold working)

Strengthening Mechanisms for Metals
Mechanism I – Reduce Grain Size

- Grain boundaries act as barriers to dislocation motion
- At boundary
  - — Slip planes change directions (note in illustration)
  - — Discontinuity of slip planes
- Reduce grain size
  - — increase grain boundary area
  - — more barriers to dislocation motion
  - — increase yield strength, tensile strength & hardness

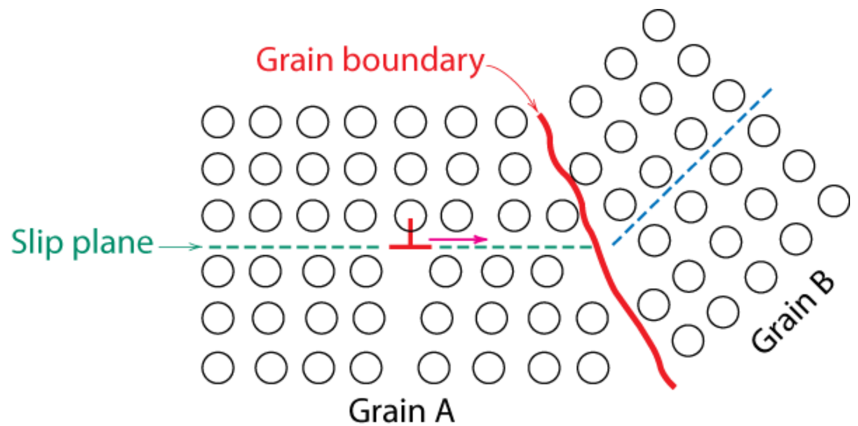


Fig. 7.14, *Callister & Rethwisch 10e.*
(From L. H. Van Vlack, *A Textbook of Materials Technology*, Addison-Wesley Publishing Co., 1973. Reproduced with the permission of the Estate of Lawrence H. Van Vlack.)

- Dependence of σ_y on average grain diameter, *d:*

$$\sigma_{yield} = \sigma_0 + k_y d^{-1/2}$$

—σ_0, k_y = material constants

Strengthening Mechanisms for Metals
Mechanism II – Solid-Solution Strengthening

- Lattice strains around dislocations
  - Illustration notes locations of tensile, compressive strains around an edge dislocation

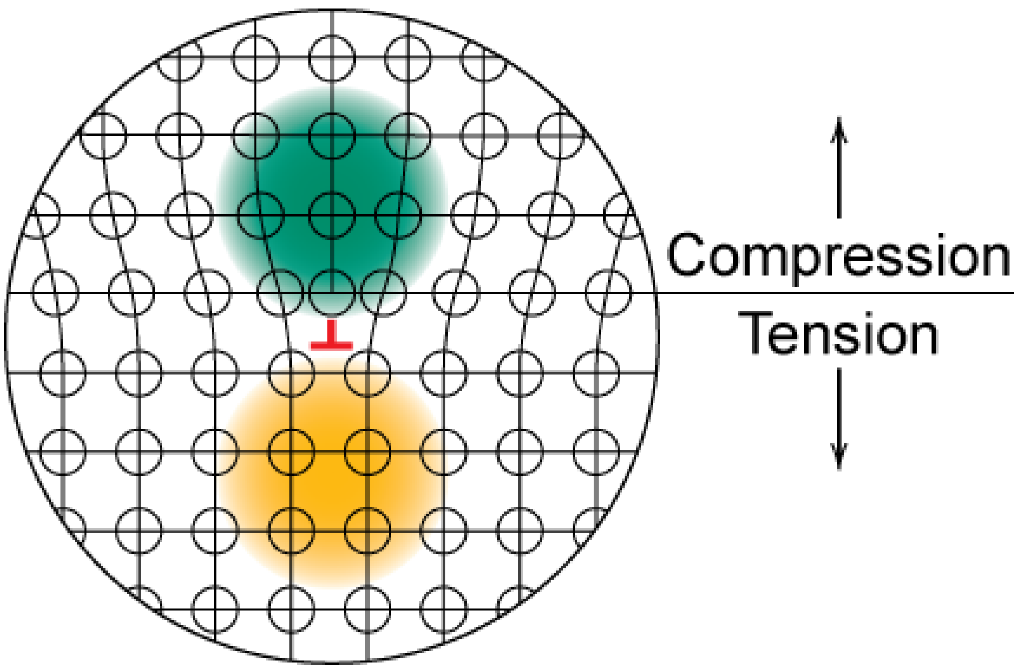


Fig. 7.4, *Callister & Rethwisch 10e.* (Adapted from W.G. Moffatt, G.W. Pearsall, and J. Wulff, *The Structure and Properties of Materials*, Vol. I, *Structure*, p. 140, John Wiley and Sons, New York, 1964.)

Solid Solution Strengthening (cont.)

- Large substitutional impurities introduce compressive strains
- When located below slip line for edge dislocation as shown:
  - partial cancellation of impurity (compressive) and disl. (tensile) strains
  - higher shear stress required to cause disl. motion

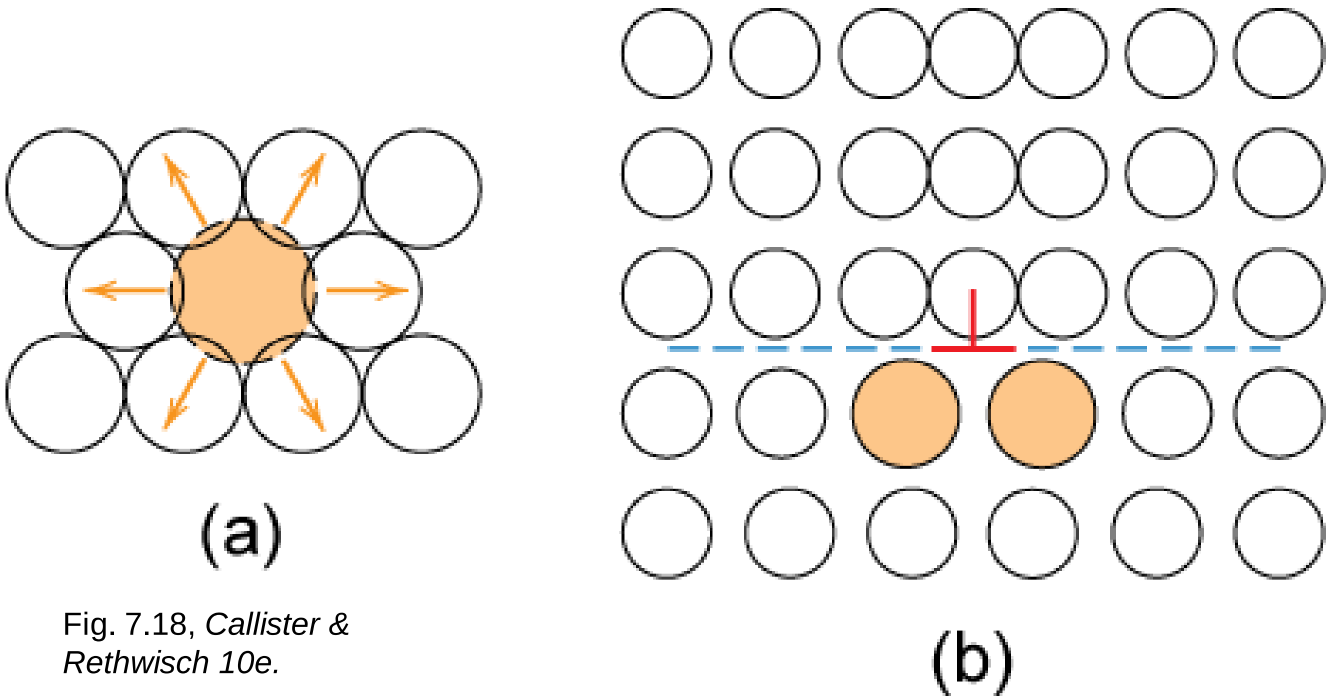
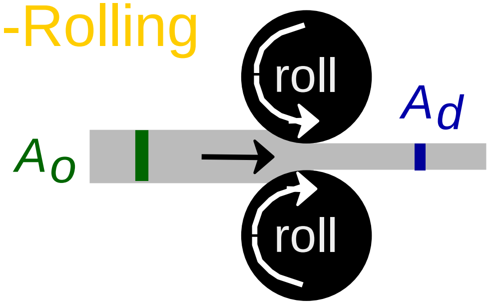


Fig. 7.18, *Callister & Rethwisch 10e.*

Strengthening Mechanisms for Metals
Mechanism III – Strain Hardening

- Plastically deforming most metals at room temp. makes them harder and stronger
- Phenomenon called "Strain hardening (or cold working)”
- Deformation—often reduction in cross-sectional area.

-Rolling



- Deformation amt. = percent coldwork (%CW)

$$\%CW = \frac{A_o - A_d}{A_o} \times 100$$

Summary

- Plastic deformation occurs by **motion of dislocations**.
- Dislocation slip happens on the **close-packed planes** and **directions** of different crystal structures.
- Dislocation slip is triggered when the **critical resolved shear stress** is reached.
- Strength is increased by decreasing **dislocation mobility**.
- Strengthening techniques for metals:
  - grain size reduction
  - solid solution strengthening
  - strain hardening (cold working)

Announcements

Reading: Textbook **Ch. 6-7**

Assignment: Open; DL: **18:00 Sunday**

Q&A time: **Tuesday 16:30**

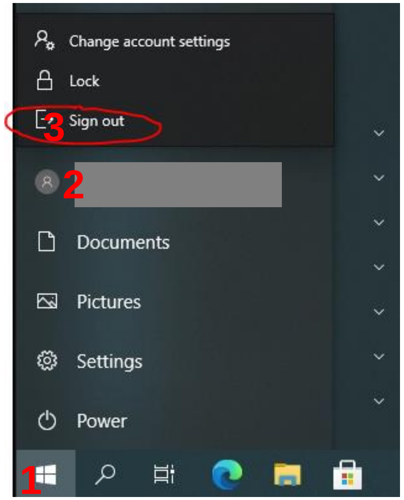
Exercise: **Thursday 10:15 – 12:00**

Preparation of your computational environment is needed before the exercise sessions.

DREAM.3D & ParaView preparation

Software preparation

DREAM.3D: open-source/freeware software
http://dream3d.bluequartz.net
ParaView: freeware software https://www.paraview.org/download/
Aalto VDI system: **mfavdi.aalto.fi**, or VMware Horizon Client **vdi.aalto.fi**, for more information, please refer to Remote access to Windows classroom computers.
IMPORTANT! Please remember to do '**Sign Out**' after the session (NOT Disconnect). Click your username in Start and click 'Sign Out'.
Basic Rule: Please use DOT as the decimal separator, NO COMMA!



Please download and extract the zip file of DREAM.3D and ParaView,
and copy it to your work direction. It might take 1-2 h for download/unzip/ installation.
For DREAM.3D, No installation needed, just unzip package and start.
For ParaView, you can choose the package or installation version.

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Choose the version according to your operating system.

Prebuilt Binaries

The current version is 6.5.160 and is available in prebuilt binaries for MacOS, Windows and Linux operating systems:

Operating System	Notes
MacOS - DREAM3D-6.5.160-OSX.dmg	MacOS 10.14 and greater required, including macOS 11.0. Download is a Disk Image
MacOS - DREAM3D-6.5.160-OSX.zip	MacOS 10.14 and greater required, including macOS 11.0. Download is a Zip file
Windows - DREAM3D-6.5.160-Win64.zip	Windows version 8 or 10
Linux - DREAM3D-6.5.160-Linux-x86_64.tar.gz	Ubuntu 18.04 or Equivelant. Self contained tar archive.

Table of contents

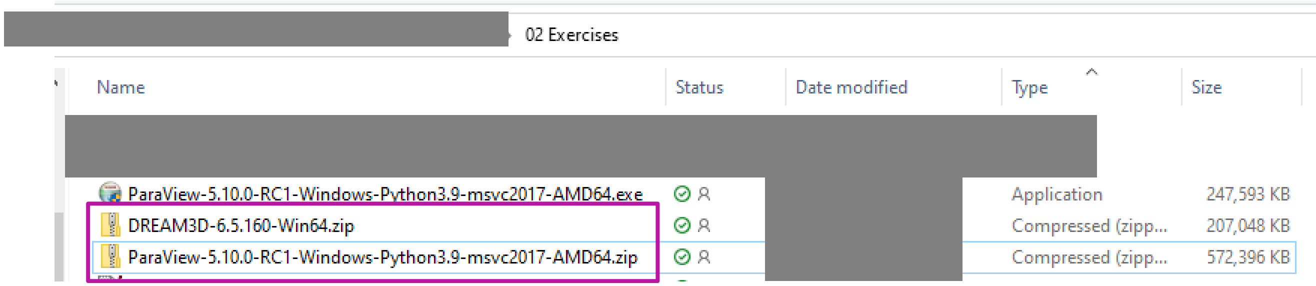
ParaView Download

https://www.paraview.org/download/

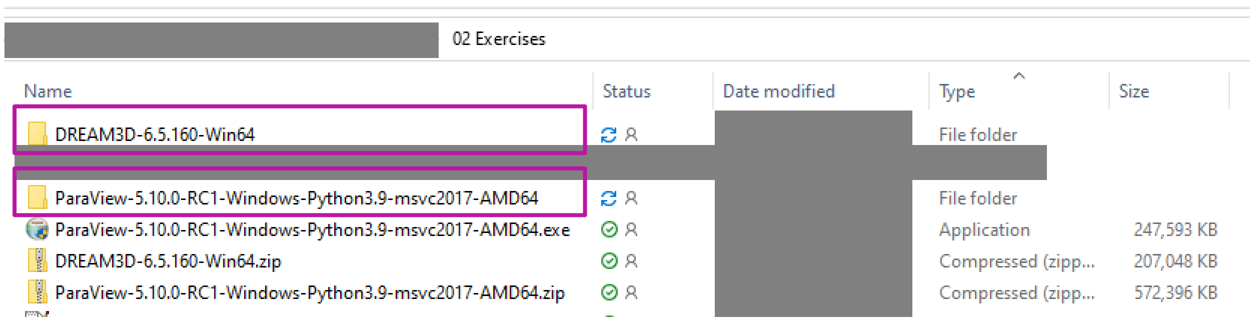
Choose the version according to
(1)your operating system
(2).zip or .exe type as you want.

Documentation files

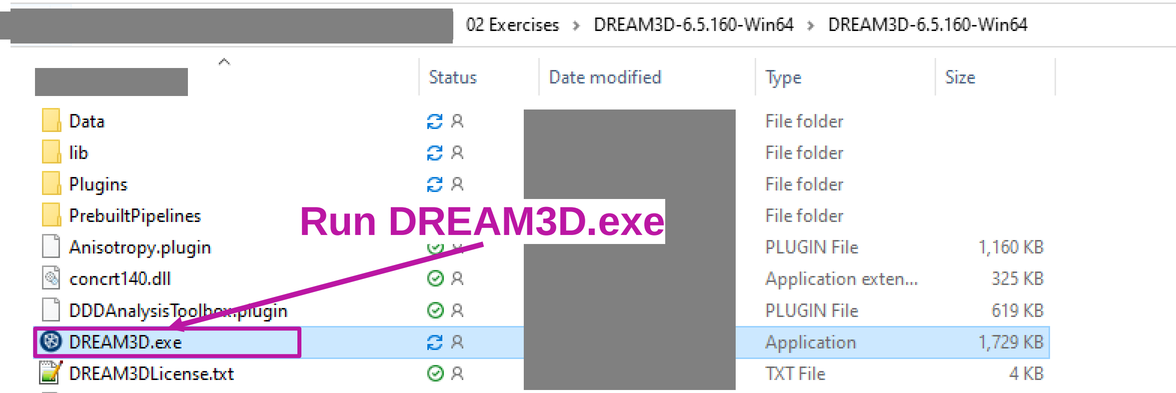
DREAM.3D & ParaView Extraction



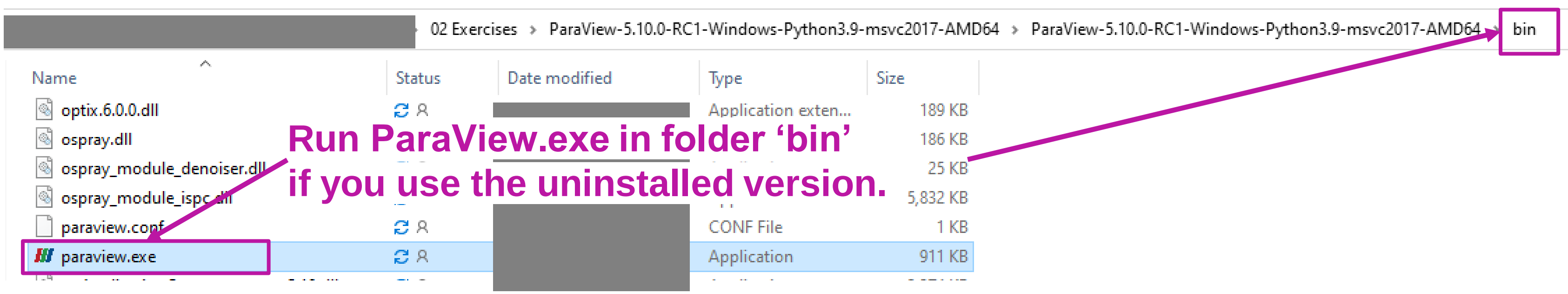
Extract the DREAM.3D/ParaView .zip file



DREAM.3D & ParaView running

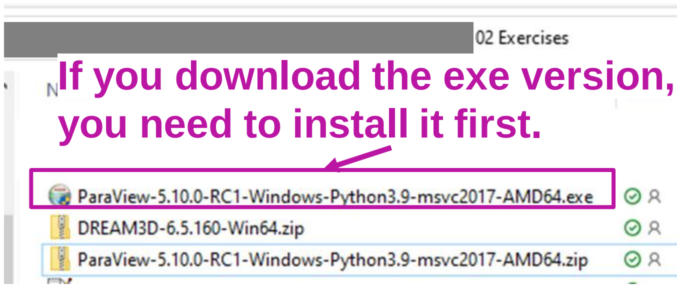


Run DREAM3D.exe

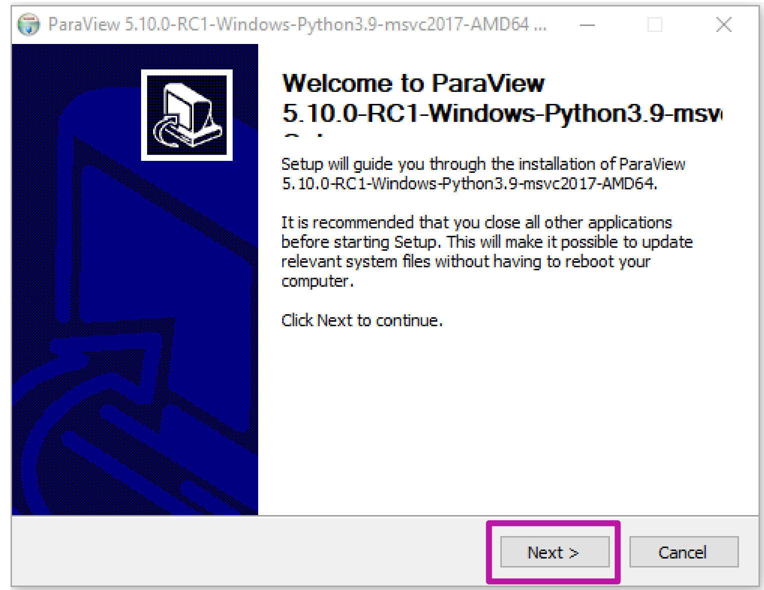


Run ParaView.exe in folder ‘bin’
if you use the uninstalled version.

ParaView installation

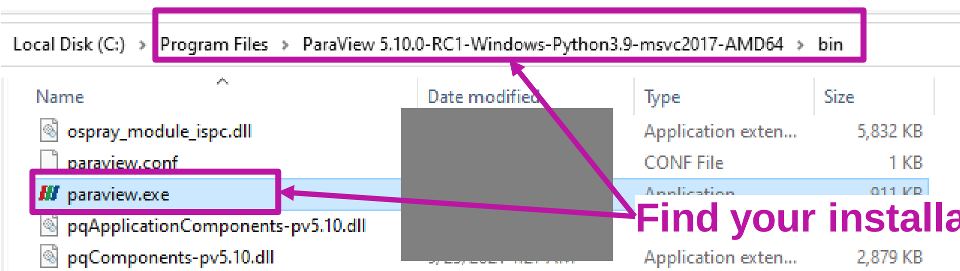


If you download the exe version, you need to install it first.



You are probably asked for the confirmation to run an .exe application in windows system.

Click 'Yes', then step by step to install ParaView on your computer.



Find your installation folder and run ParaView.exe

Questions?