Chemical Engineering 378

Science of Materials Engineering

Lecture 11

Mechanical Properties

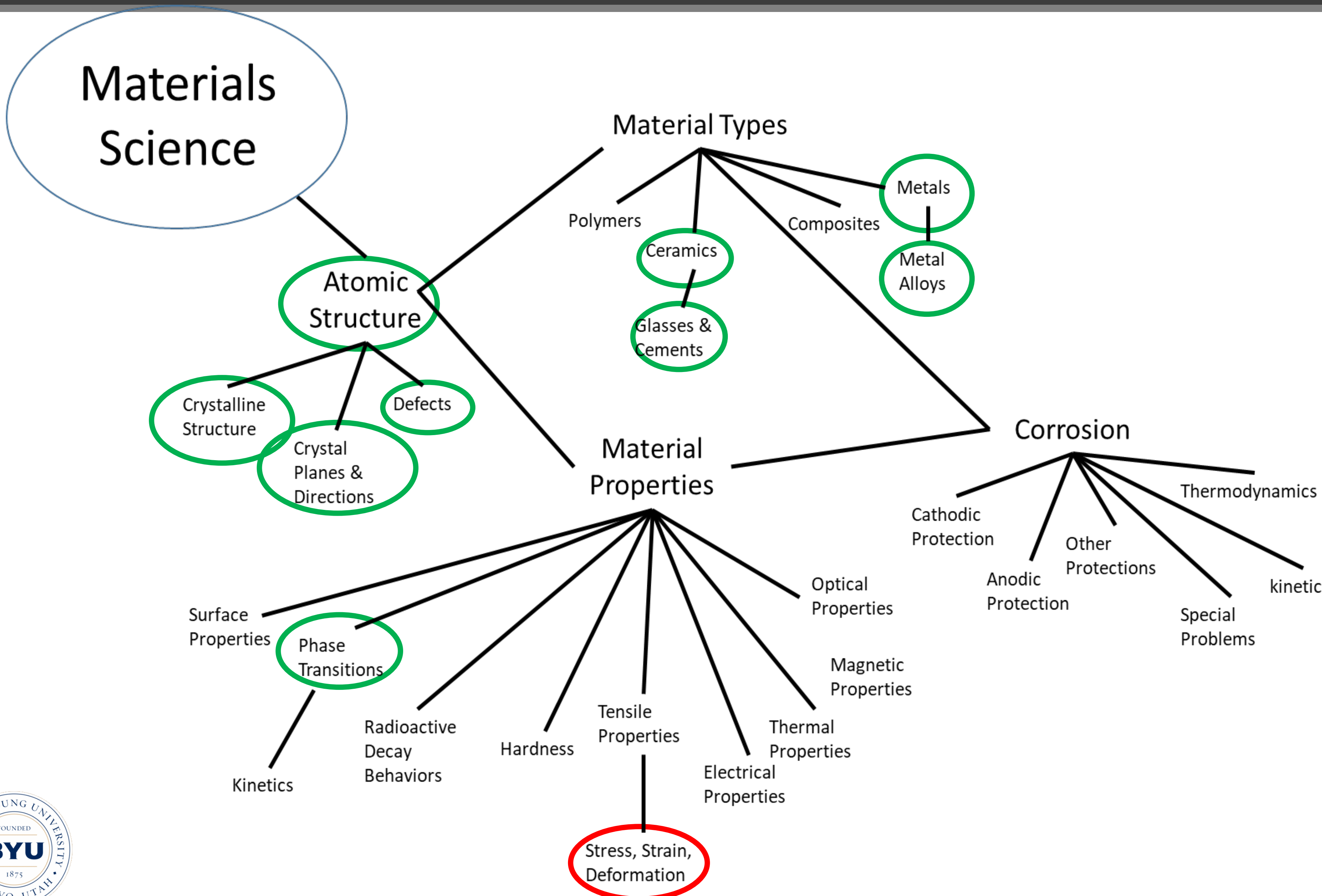
(Stress, Strain, & Elastic Deformation)

Spiritual Thought

"The gift I am thinking of is more important than any of the inventions that have come out of the industrial and technological revolutions. This is a gift of greater value to mankind than even the many wonderful advances we have seen in modern medicine. It is of greater worth to mankind than the development of flight or space travel. I speak of the gift of the Book of Mormon, given to mankind 156 years ago."

-President Ezra Taft Benson

Materials Roadmap

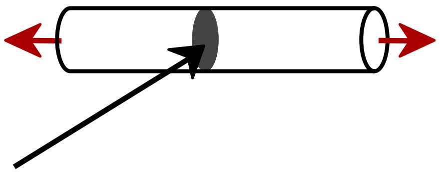


Material Properties

- Material Selection → Properties
  - Optical
  - Electrical
  - Magnetic
  - Thermal
  - Deteriorative
  - Mechanical
- Mechanical Properties – How does a material respond to forces and stresses

Common States of Stress

- **Simple tension:**
  cable

F  *F* = force

A_O = cross-sectional area of cable (with no load)

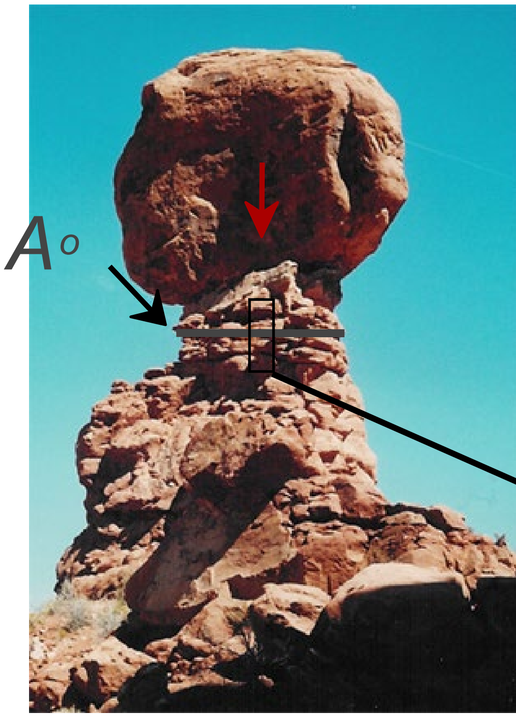
Ski lift (photo courtesy P.M. Anderson)

Tensile stress = σ

$$\sigma = \frac{F}{A_0}$$

OTHER COMMON STRESS STATES (i)

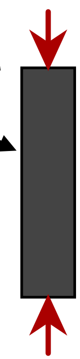
- **Simple compression:**



Balanced Rock, Arches National Park
(photo courtesy P.M. Anderson)

Canyon Bridge, Los Alamos, NM
(photo courtesy P.M. Anderson)

$$\sigma = \frac{F}{A_o}$$

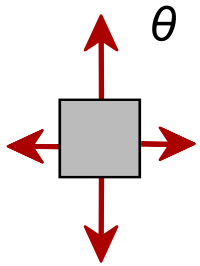


Note: structure members are under compression ($F < 0$ and $\sigma < 0$).

OTHER COMMON STRESS STATES (ii)

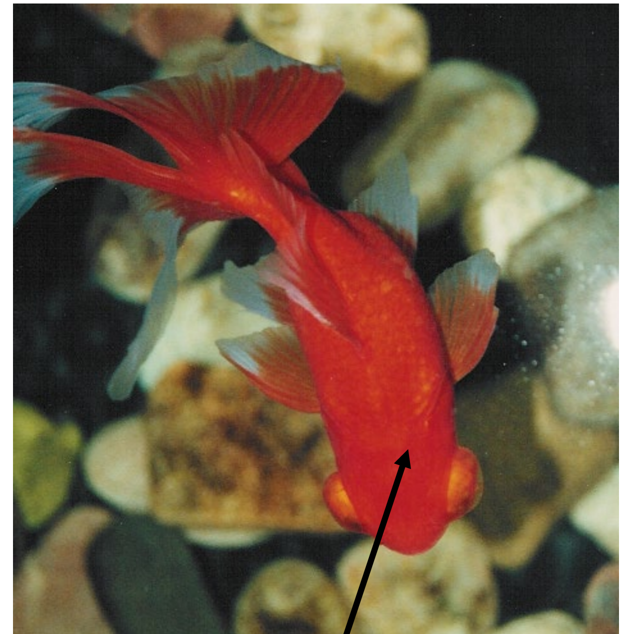
- **Bi-axial tension:**
- **Hydrostatic compression:**

Pressurized tank
(photo courtesy
P.M. Anderson)



$\sigma_\theta > 0$

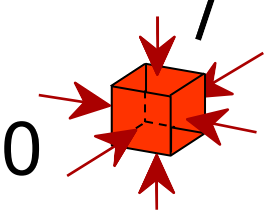
$\sigma_z > 0$



Fish under water

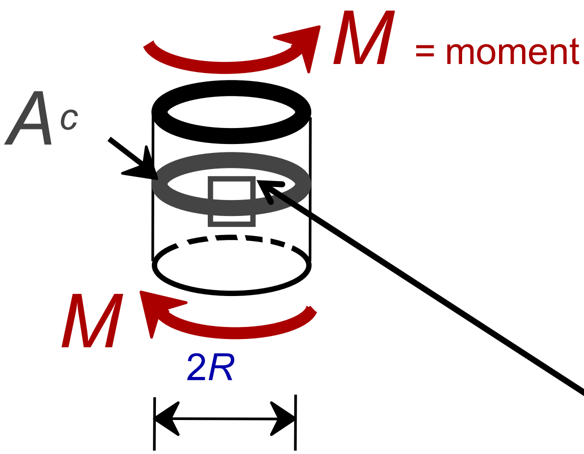
(photo courtesy
P.M. Anderson)

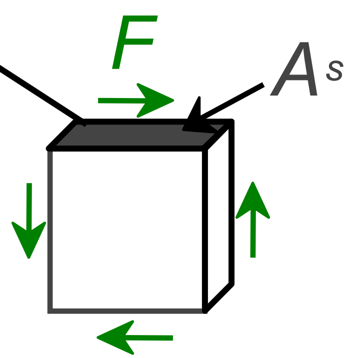
$\sigma_h < 0$



Common States of Stress (cont.)

- **Torsion (a form of shear):**
  drive shaft





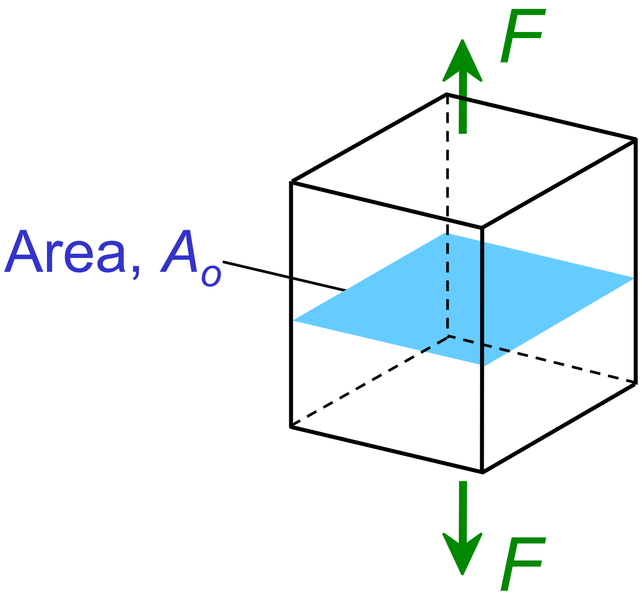
A_C = cross-sectional area of drive shaft (with no load)

Ski lift (photo courtesy P.M. Anderson)

$$\tau = \frac{F}{A_s} = \frac{M}{A_C R}$$

Engineering Stress

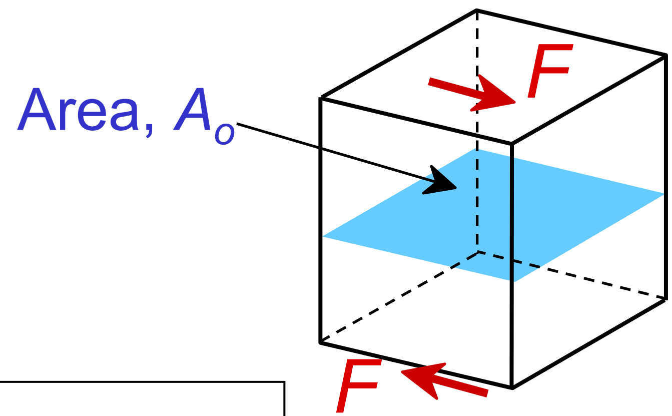
- Tensile stress, σ:



$$\sigma = \frac{F}{A_o}$$

original cross-sectional area before loading

- Shear stress, τ:



$$\tau = \frac{F}{A_o}$$

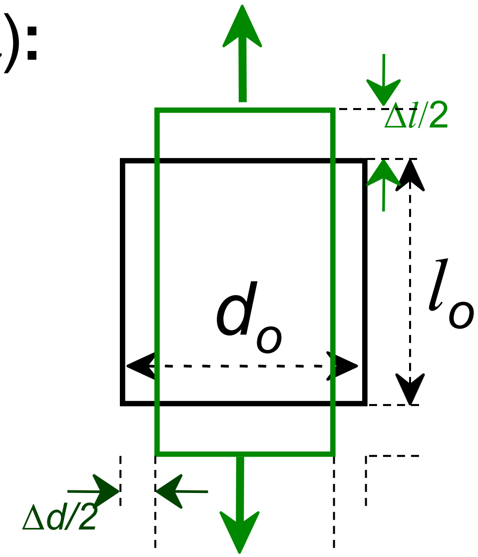
Units for stress:

MPa = 10^6 Pa = 10^6 N/m^2 or lb$_f$/in^2

Engineering Strain

- **Tensile strain** (ε_z):

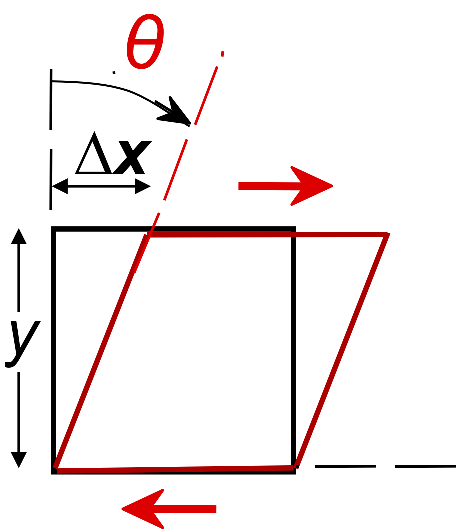
$$\varepsilon_z = \frac{\Delta l}{l_o}$$



- **Lateral strain** (ε_x):

$$\varepsilon_x = \frac{-\Delta d}{d_0}$$

- **Shear strain** (γ):



$$\gamma = \Delta x / y = \tan\theta$$

Both tensile and shear strain are dimensionless

Stress-Strain Testing

- **Typical tensile test machine**

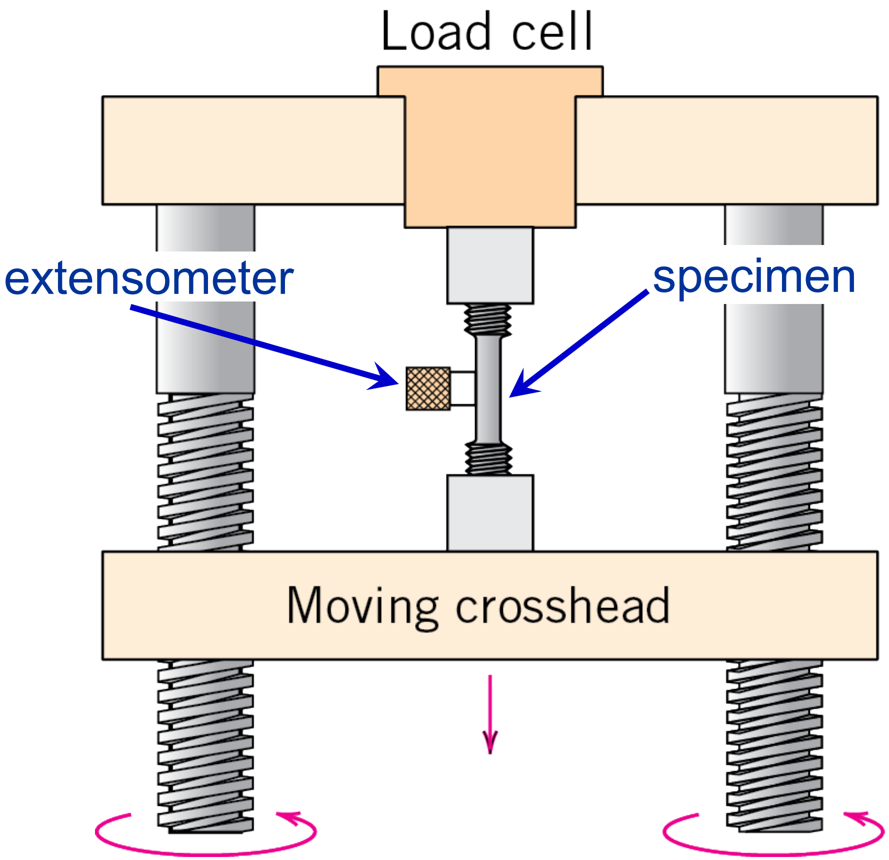


Fig. 6.3, *Callister & Rethwisch 10e.*
(Taken from H.W. Hayden, W.G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*, p. 2, John Wiley and Sons, New York, 1965.)

- **Typical tensile specimen**

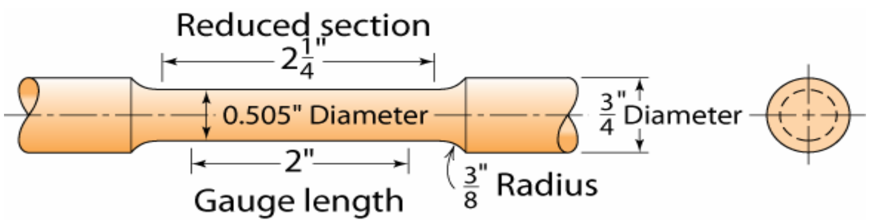


Fig. 6.2, *Callister & Rethwisch 10e.*

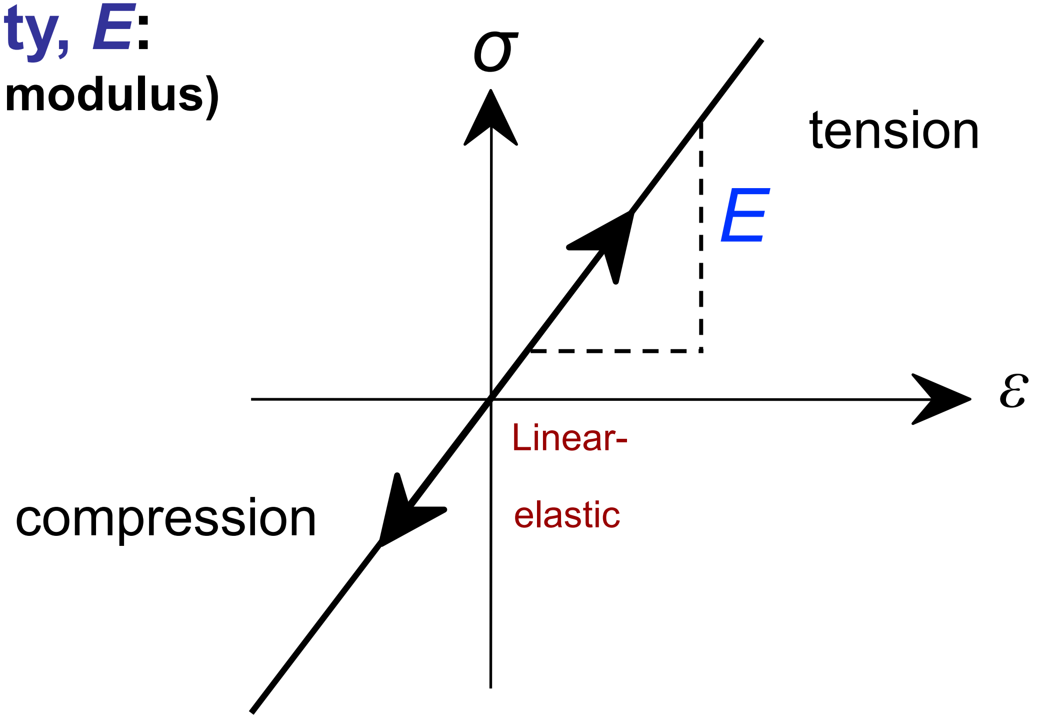
Linear Elastic Properties

- **Elastic deformation** is nonpermanent and reversible!
  - generally valid at small deformations
  - linear stress strain curve

- **Modulus of Elasticity, *E*:**
  (also known as Young's modulus)

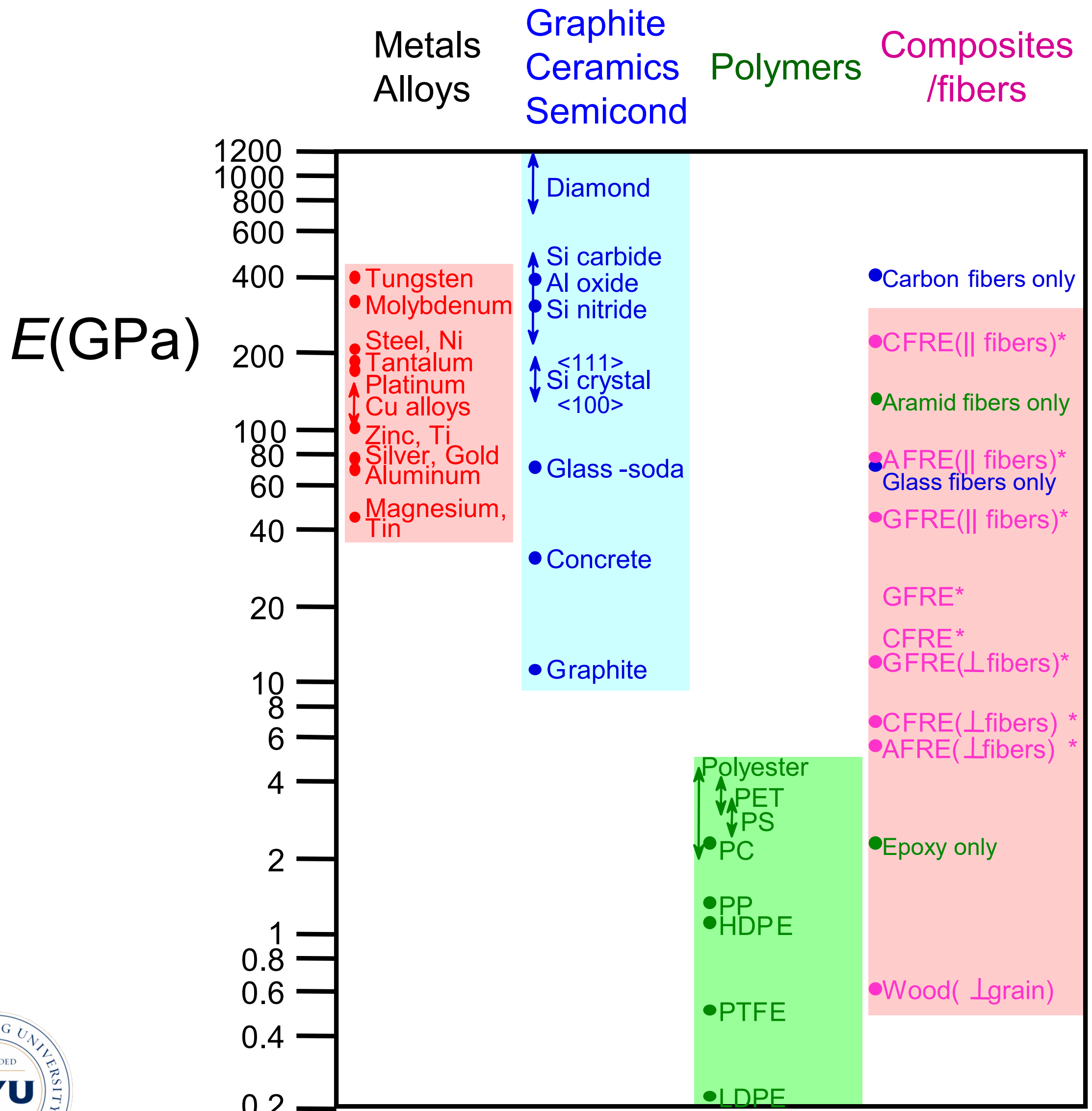
- **Hooke's Law:**

$$\sigma = E\,\varepsilon$$



Units:
E: [GPa] or [psi]
1 GPa = 10^9 Pa

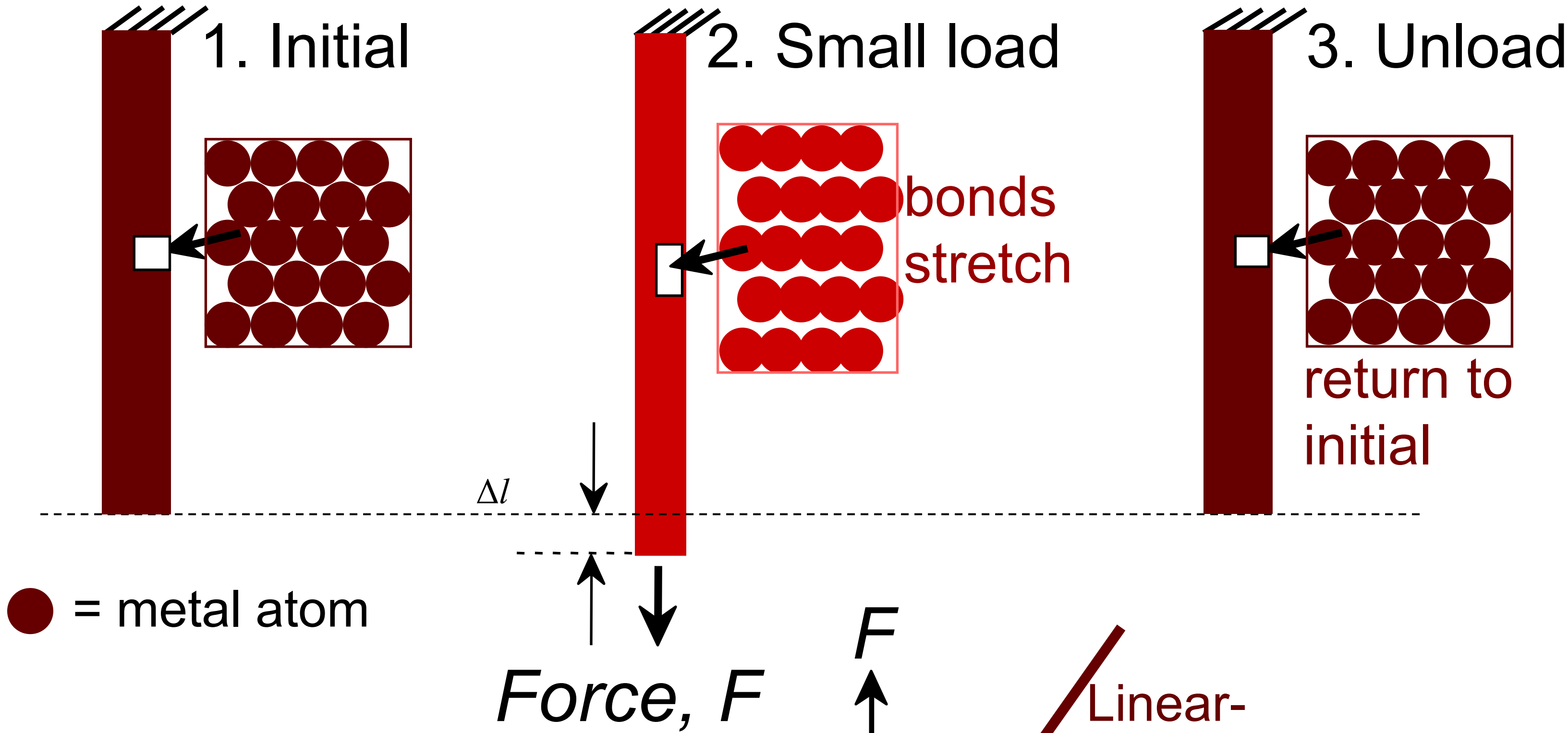
Elastic Modulus – Comparison of Material Types



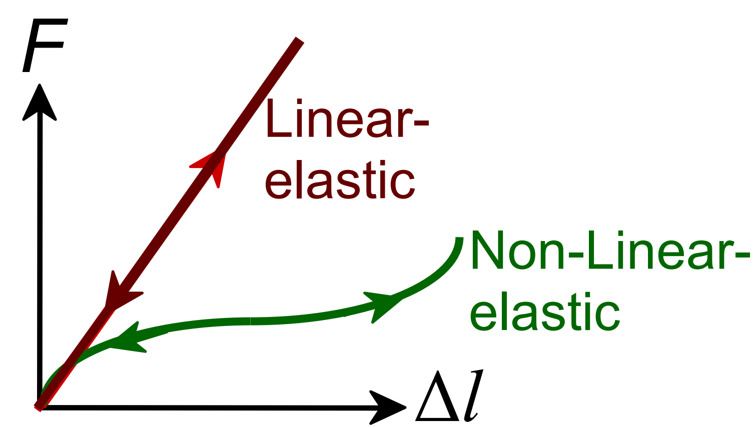
Based on data in Table B.2, *Callister & Rethwisch 10e.*
Composite data based on reinforced epoxy with 60 vol% of aligned carbon (CFRE), aramid (AFRE), or glass (GFRE) fibers.

Elastic Deformation

Atomic configurations—before, during, after load (force) application



Elastic deformation is nonpermanent and reversible!



Influence of Bonding Forces

- Elastic modulus depends on interatomic bonding forces
- Modulus proportional to slope of interatomic force-interatomic separation curve $\left(\frac{dF}{dr}\right)_{r_o}$

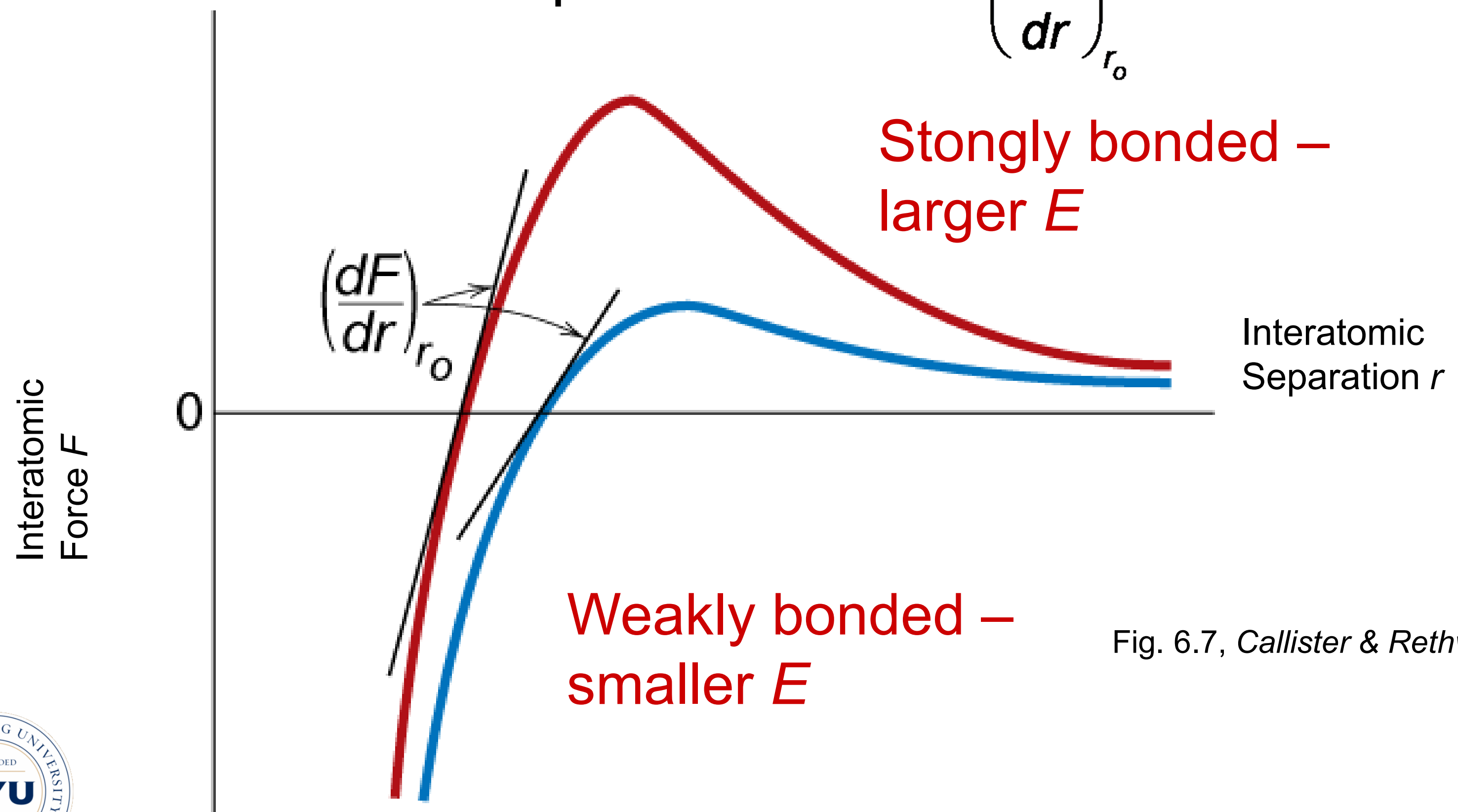
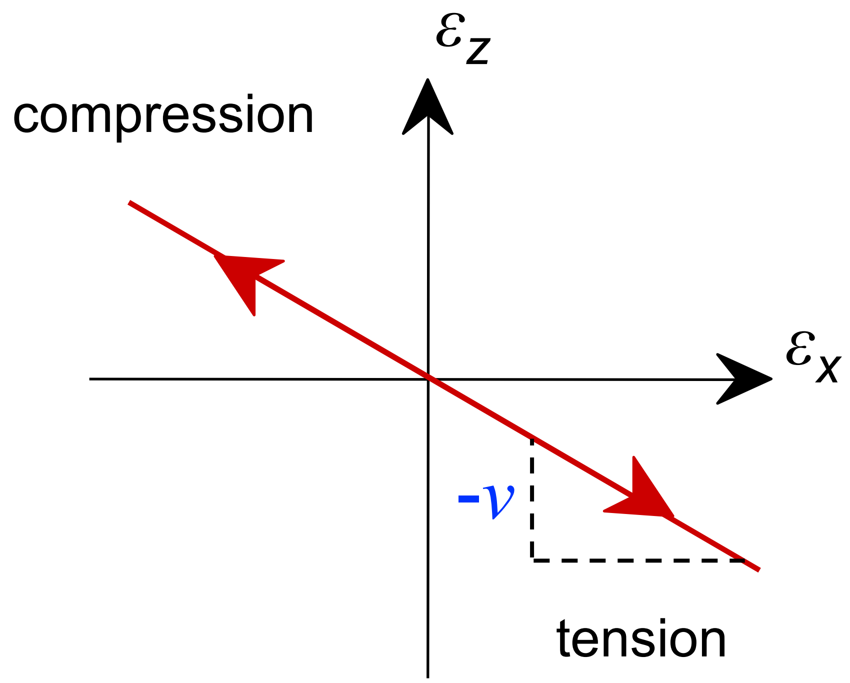


Fig. 6.7, *Callister & Rethwisch 10e.*

Poisson's ratio

- Poisson's ratio, ν:

$$\nu = -\frac{\varepsilon_x}{\varepsilon_z}$$



metals: ν ~ 0.33
ceramics: ν ~ 0.25
polymers: ν ~ 0.40

Units:
ν: dimensionless

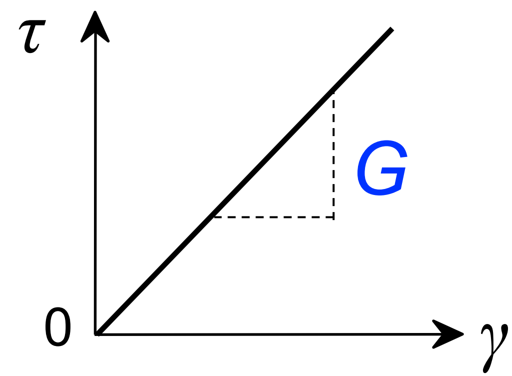
For most metals, ceramics and polymers:

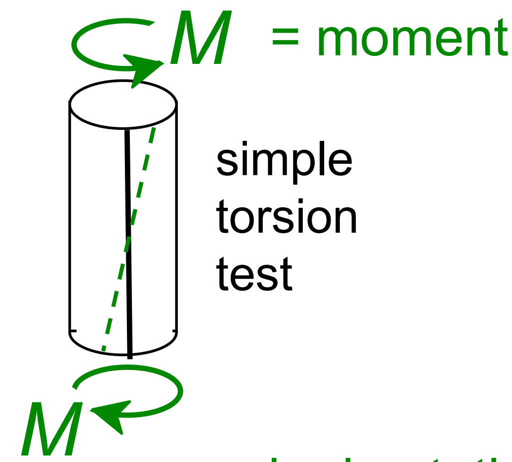
$$0.15 < \nu \leq 0.50$$

Other Elastic Properties

- Elastic Shear modulus, G:

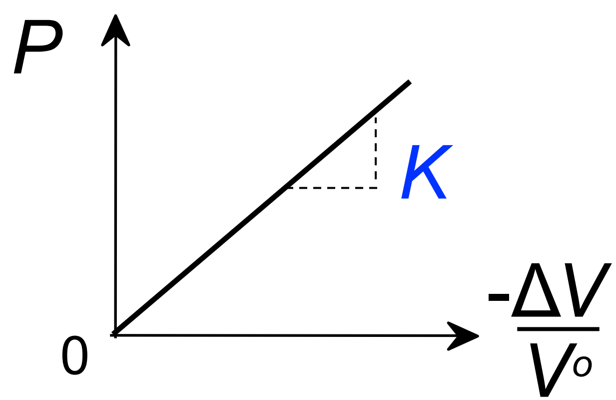
$$\tau = G\,\gamma$$

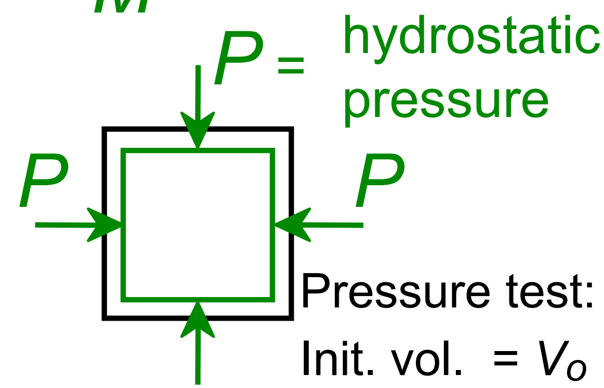




- Elastic Bulk modulus, K:

$$P = -K\frac{\Delta V}{V_o}$$



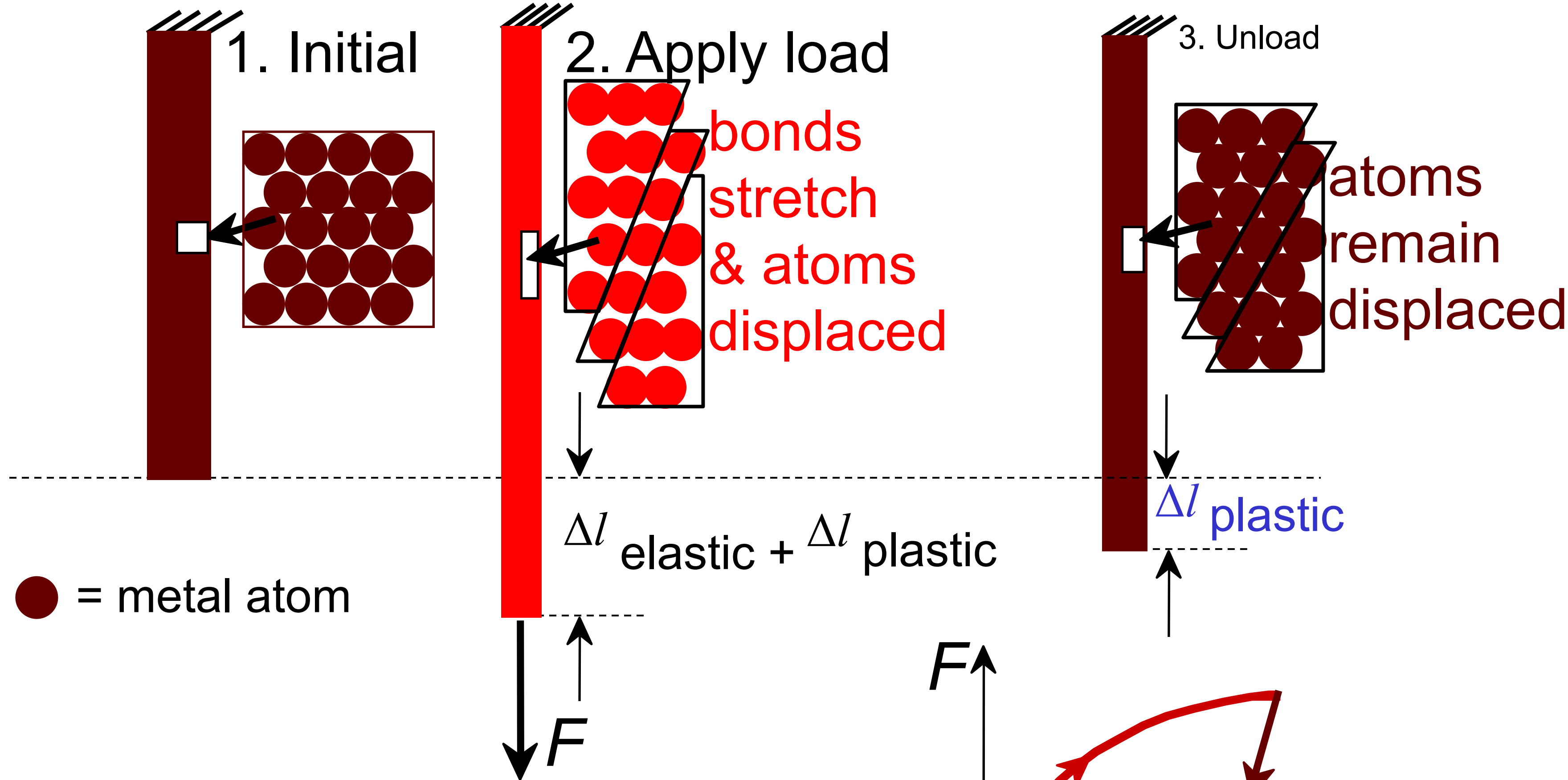


Pressure test:
Init. vol. = V_o
Vol. chg. = ΔV

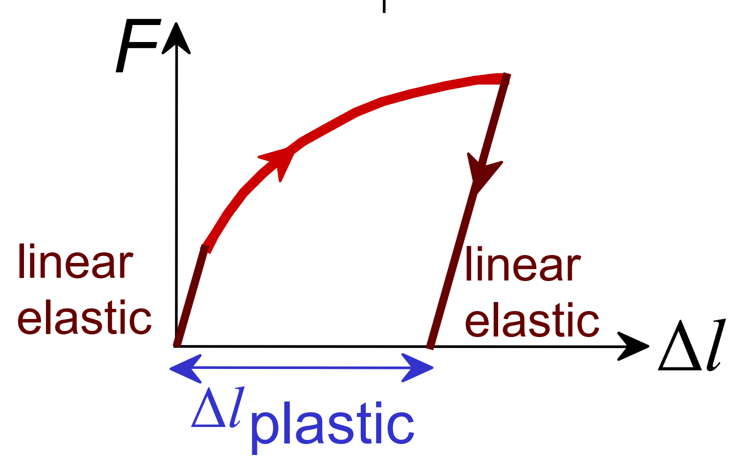
- Elastic constant relationships for isotropic materials:

$$G = \frac{E}{2(1+\nu)} \qquad K = \frac{E}{3(1-2\nu)}$$

Plastic Deformation (Metals)

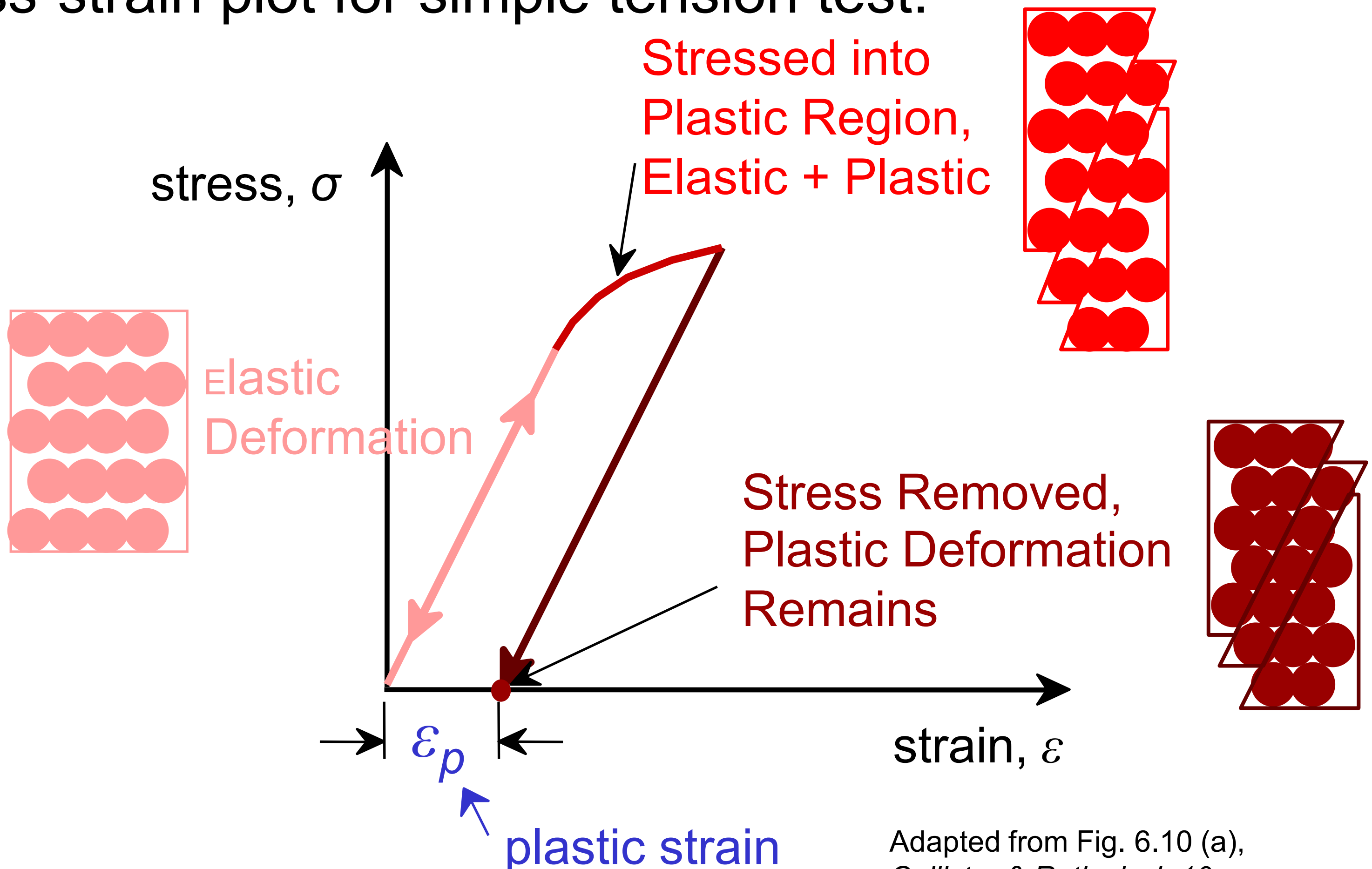


Plastic deformation is permanent and nonrecoverable.



Plastic Deformation

- Plastic Deformation is permanent and nonrecoverable
- Stress-strain plot for simple tension test:



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