

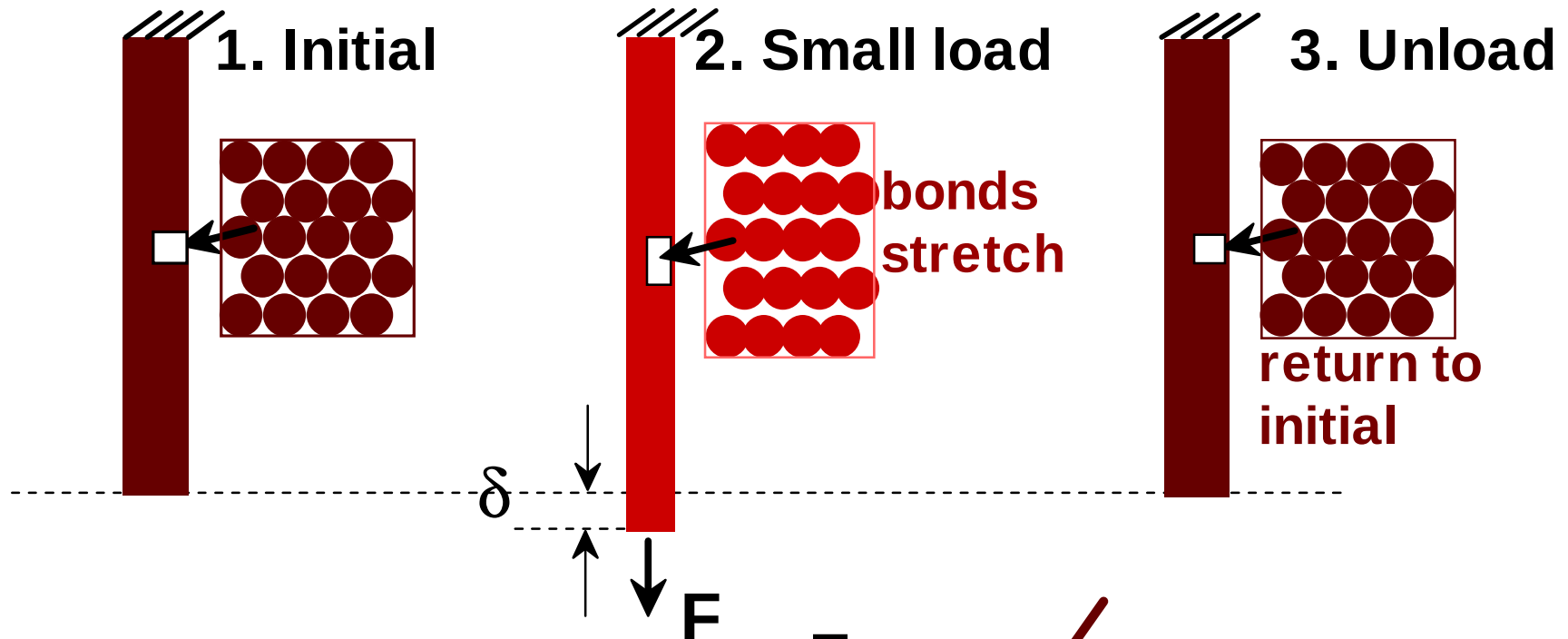
CHAPTER 6:

MECHANICAL PROPERTIES

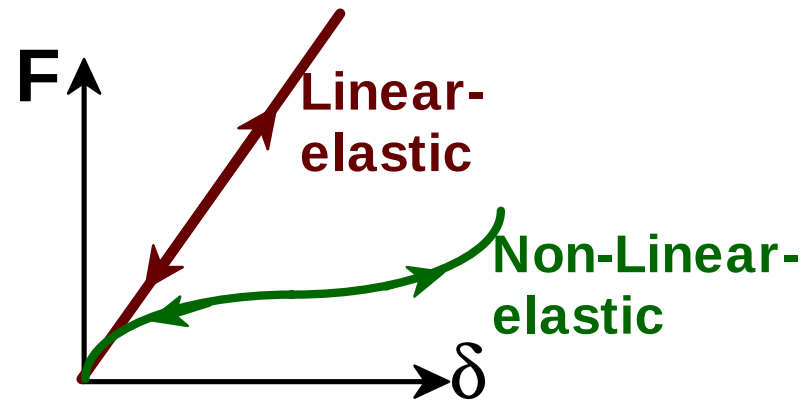
ISSUES TO ADDRESS...

- **Stress** and **strain**: What are they and why are they used instead of load and deformation?
- **Elastic** behavior: When loads are small, how much deformation occurs? What materials deform least?
- **Plastic** behavior: At what point do dislocations cause permanent deformation? What materials are most resistant to permanent deformation?
- **Toughness** and **ductility**: What are they and how do we measure them?

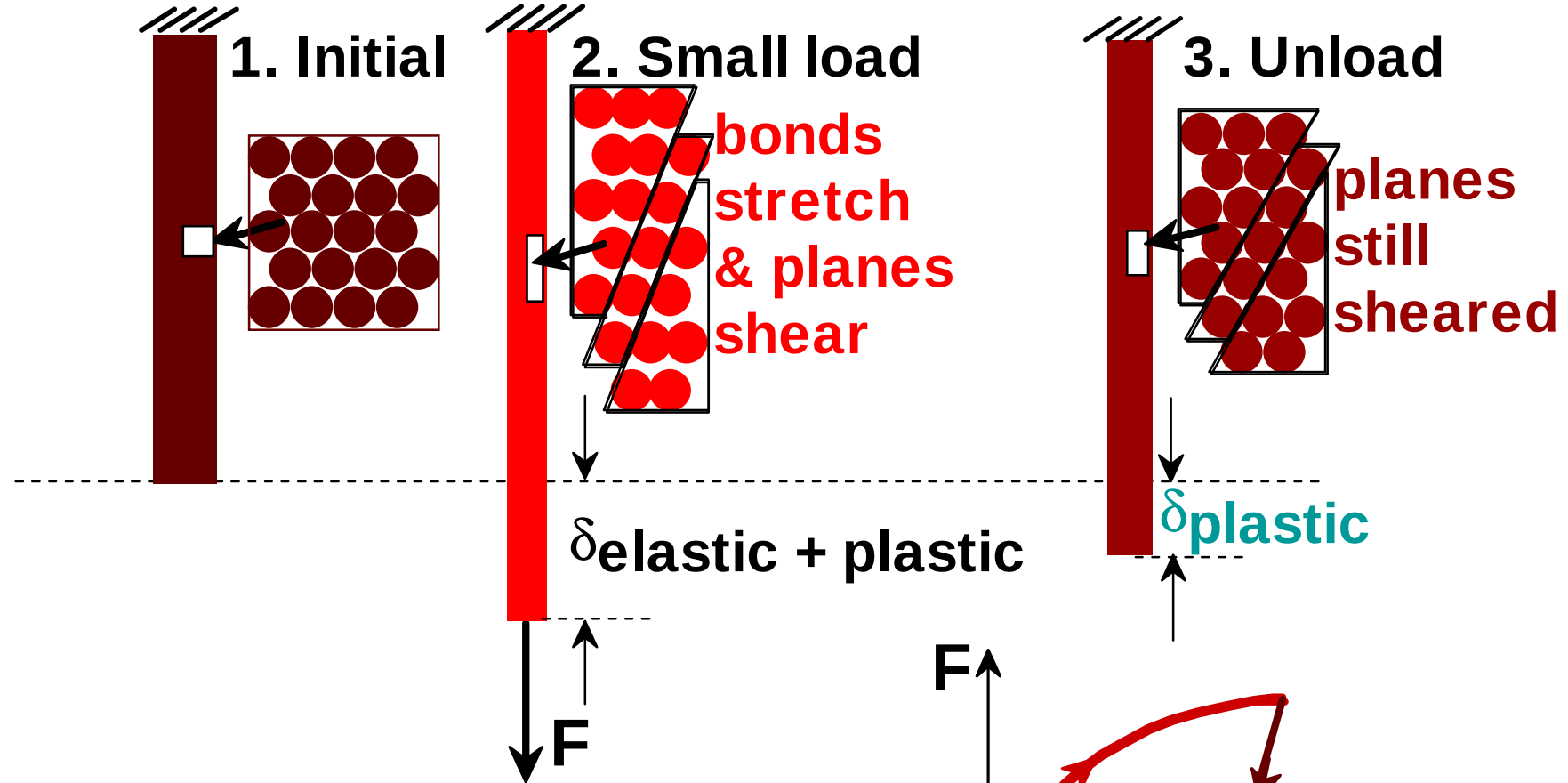
ELASTIC DEFORMATION



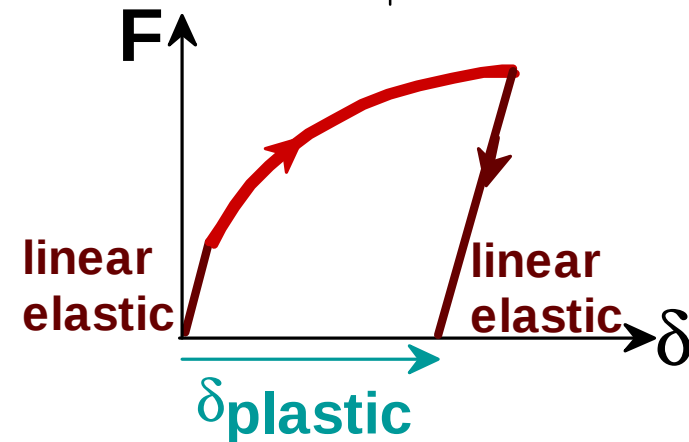
Elastic means **reversible**!



PLASTIC DEFORMATION (METALS)

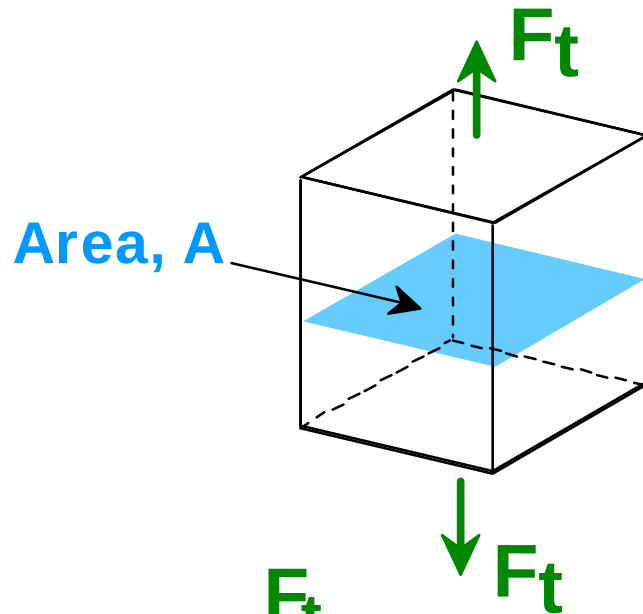


Plastic means **permanent!**



ENGINEERING STRESS

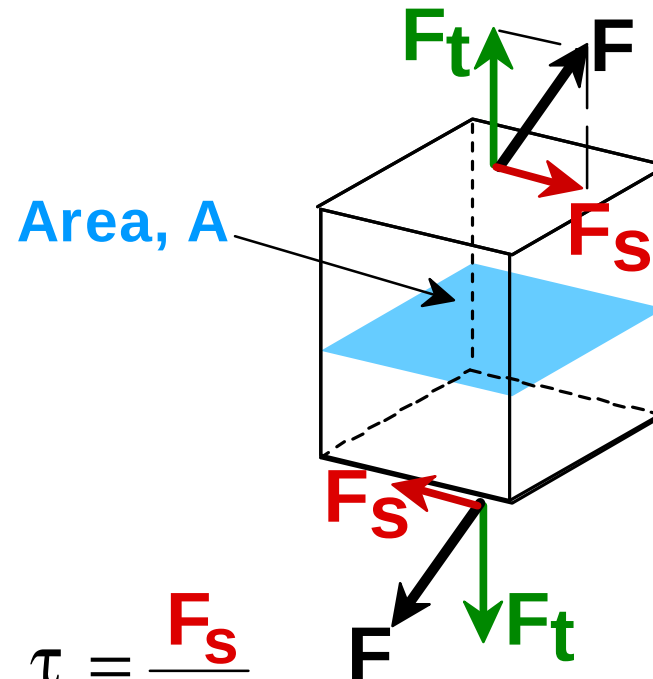
- Tensile stress, σ :



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

A_o
original area
before loading

- Shear stress, τ :



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

Stress has units:
 N/m^2 or lb/in^2

COMMON STATES OF STRESS

- **Simple** tension: cable

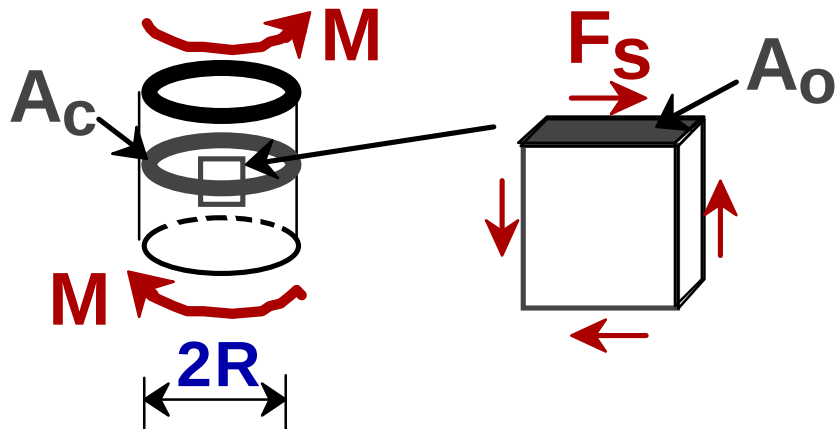


A_0 = cross sectional
Area (when unloaded)

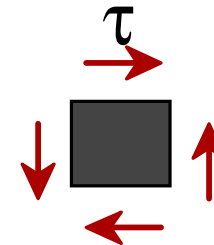
$$\sigma = \frac{F}{A_0}$$



- **Simple** shear: drive shaft



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

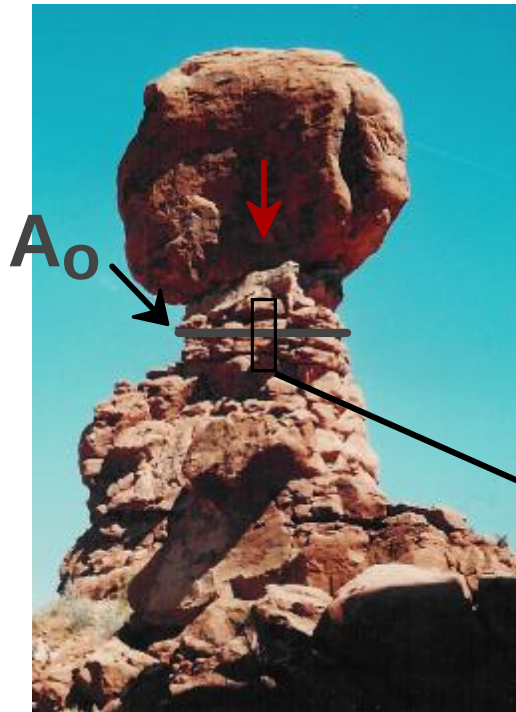


Note: $\tau = M/A_c R$ here.

Ski lift (photo courtesy P.M. Anderson)

OTHER COMMON STRESS STATES (1)

- **Simple** compression:



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



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

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



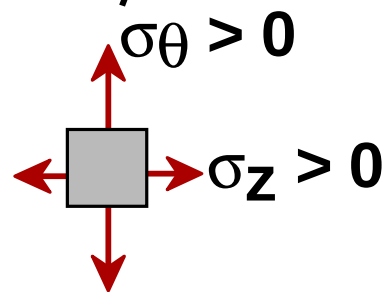
Note: compressive structure member ($\sigma < 0$ here).

OTHER COMMON STRESS STATES (2)

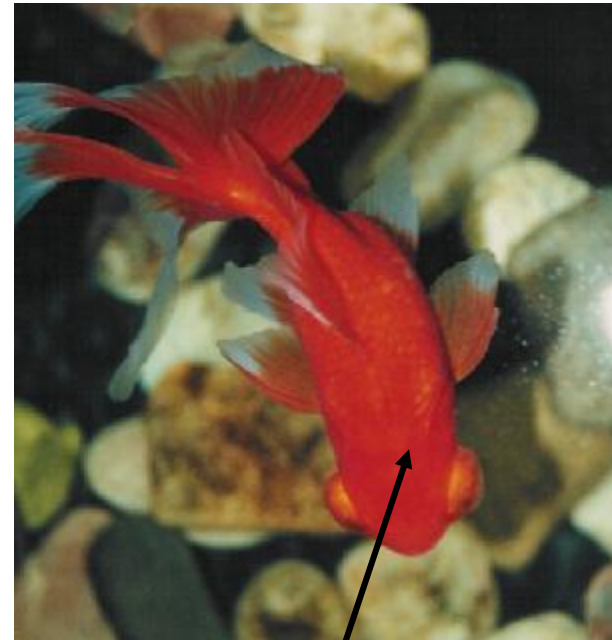
- **Bi-axial** tension:



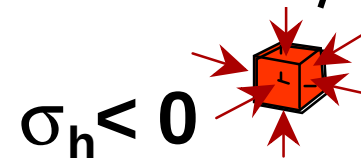
Pressurized tank
(photo courtesy
P.M. Anderson)



- **Hydrostatic** compression:



Fish under water
(photo courtesy
P.M. Anderson)



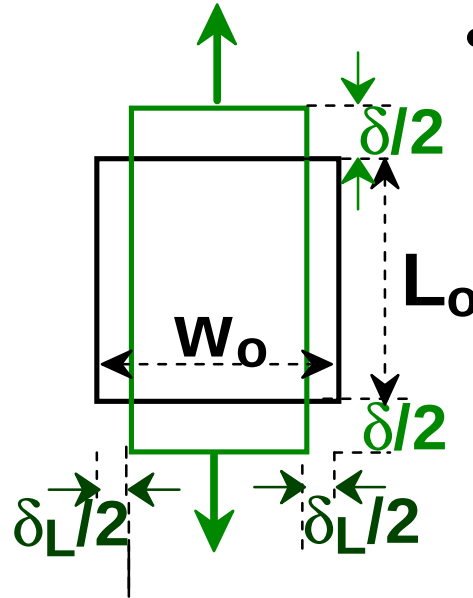
ENGINEERING STRAIN

- **Tensile strain:**

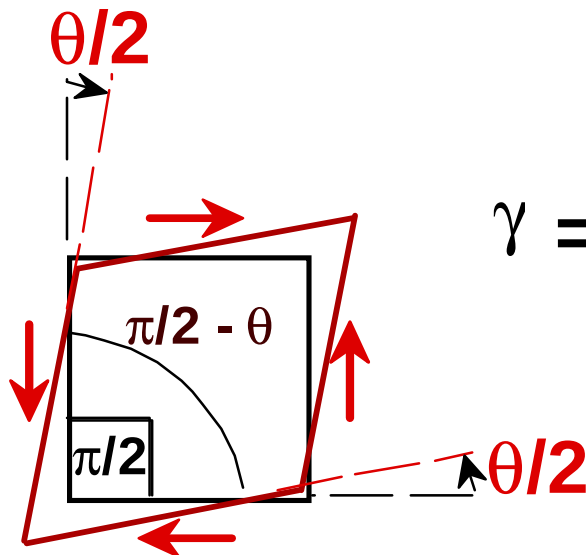
$$\varepsilon = \frac{\delta}{L_o}$$

- **Lateral strain:**

$$\varepsilon_L = \frac{-\delta_L}{W_o}$$



- **Shear strain:**

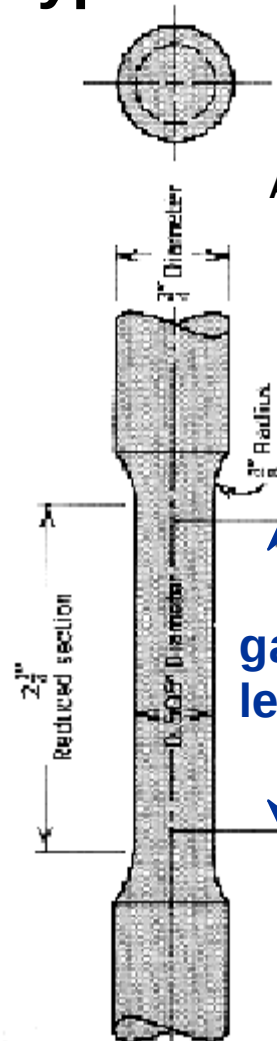


$$\gamma = \tan \theta$$

Strain is always dimensionless.

STRESS-STRAIN TESTING

- Typical tensile specimen



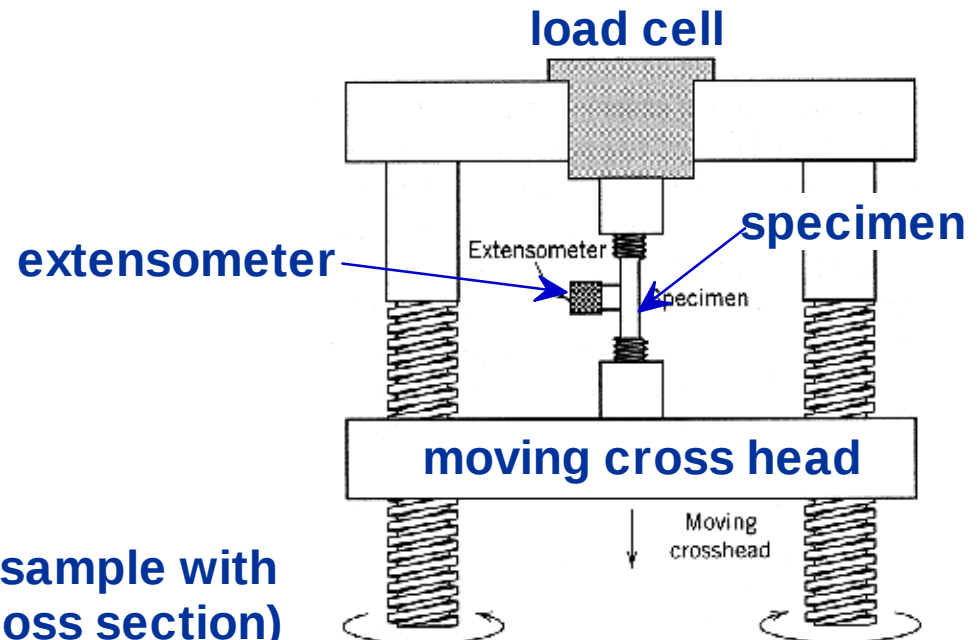
Adapted from Fig. 6.2,
Callister 6e.

gauge length = (portion of sample with reduced cross section)

- Other types of tests:

- compression: brittle materials (e.g., concrete)
- torsion: cylindrical tubes, shafts.

- Typical tensile test machine



Adapted from Fig. 6.3, Callister 6e.
(Fig. 6.3 is 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.)

LINEAR ELASTIC PROPERTIES

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

- **Hooke's Law:**

$$\sigma = E \epsilon$$

- **Poisson's ratio, ν :**

$$\nu = -\frac{\epsilon_L}{\epsilon}$$

metals: $\nu \sim 0.33$

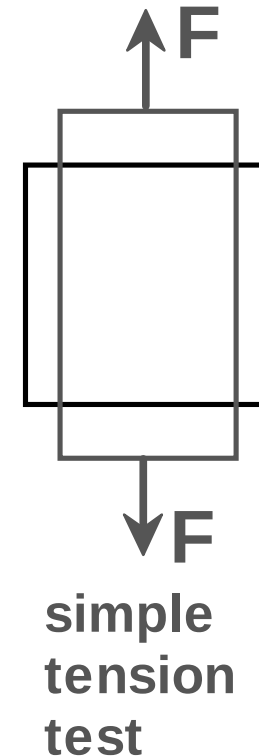
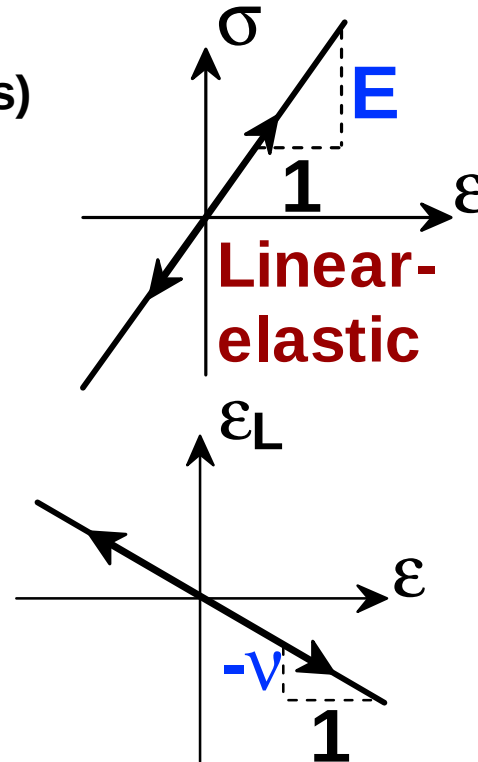
ceramics: ~ 0.25

polymers: ~ 0.40

Units:

E : [GPa] or [psi]

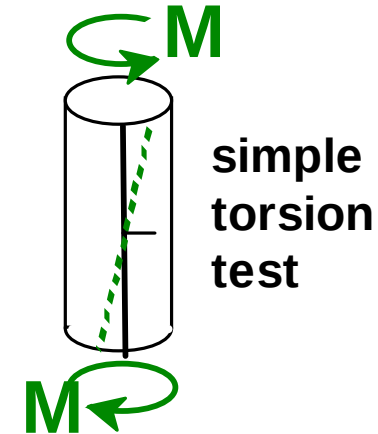
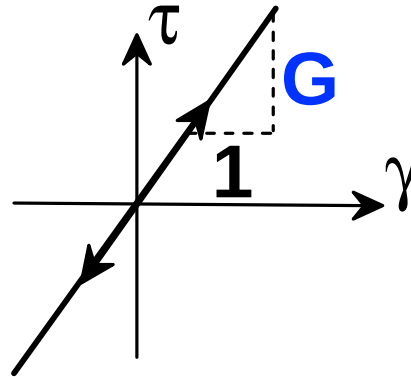
ν : dimensionless



OTHER ELASTIC PROPERTIES

- Elastic Shear modulus, G :

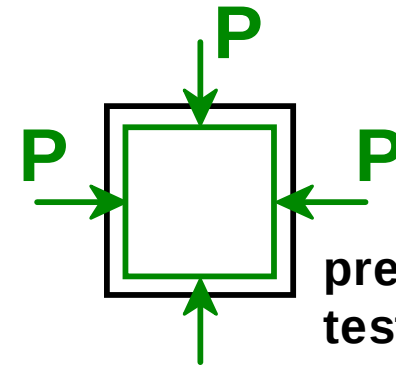
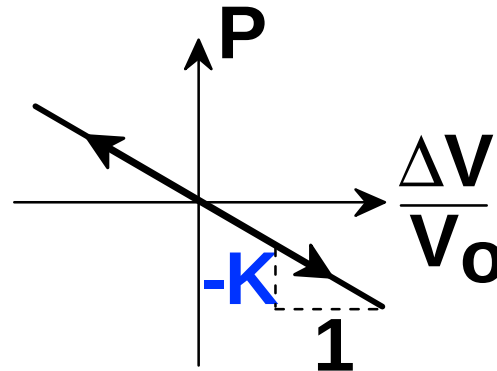
$$\tau = G \gamma$$



simple
torsion
test

- Elastic Bulk modulus, K :

$$P = -K \frac{\Delta V}{V_0}$$

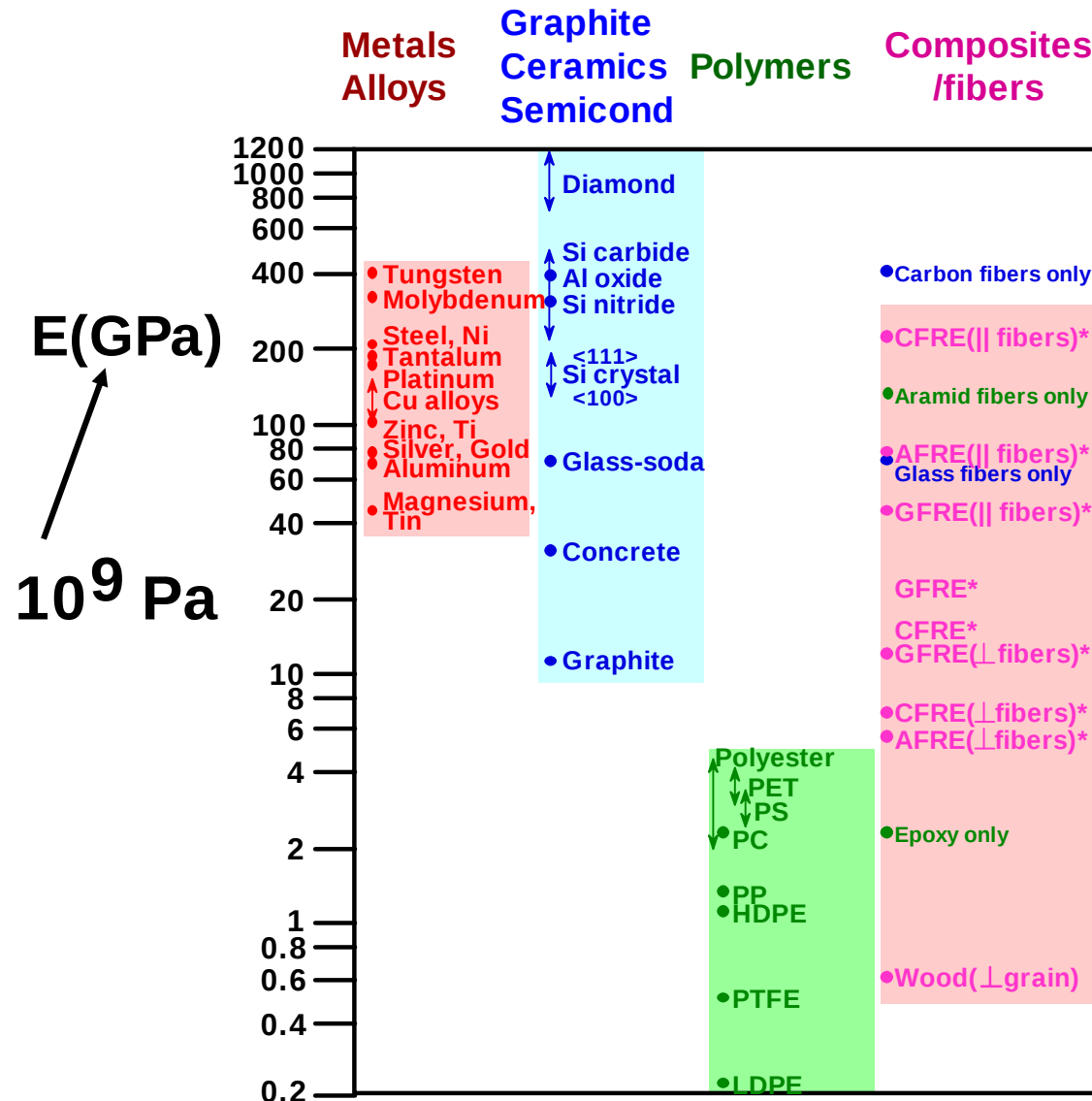


pressure
test: Init.
vol = V_0 .
Vol chg.
= ΔV

- Special relations for isotropic materials:

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

YOUNG'S MODULI: COMPARISON



Eceramics
> Emetals
>> Epolymers

Based on data in Table B2,
Callister 6e.

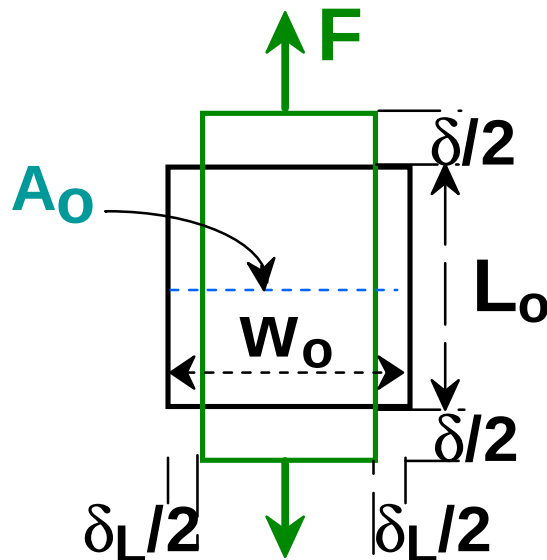
Composite data based on
 reinforced epoxy with 60 vol%
 of aligned
 carbon (CFRE),
 aramid (AFRE), or
 glass (GFRE)
 fibers.

USEFUL LINEAR ELASTIC RELATIONS

- Simple tension:

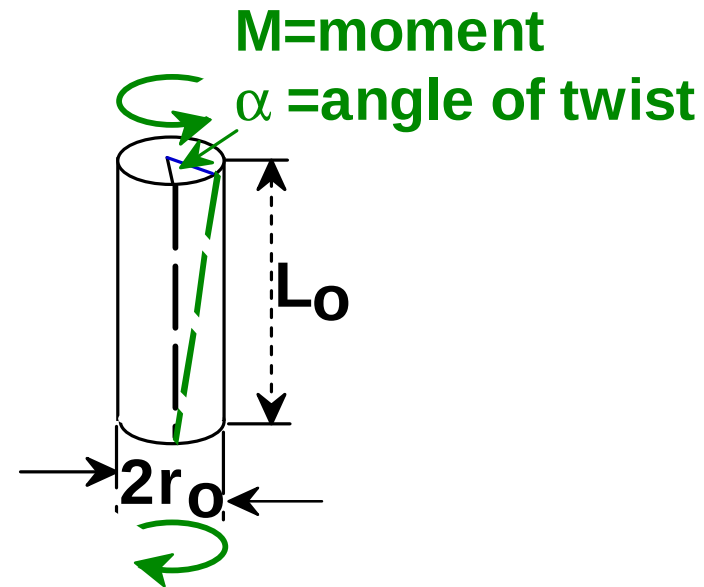
$$\delta = \frac{FL_o}{EA_o}$$

$$\delta_L = -\nu \frac{Fw_o}{EA_o}$$



- Simple torsion:

$$\alpha = \frac{2ML_o}{\pi r_o^4 G}$$

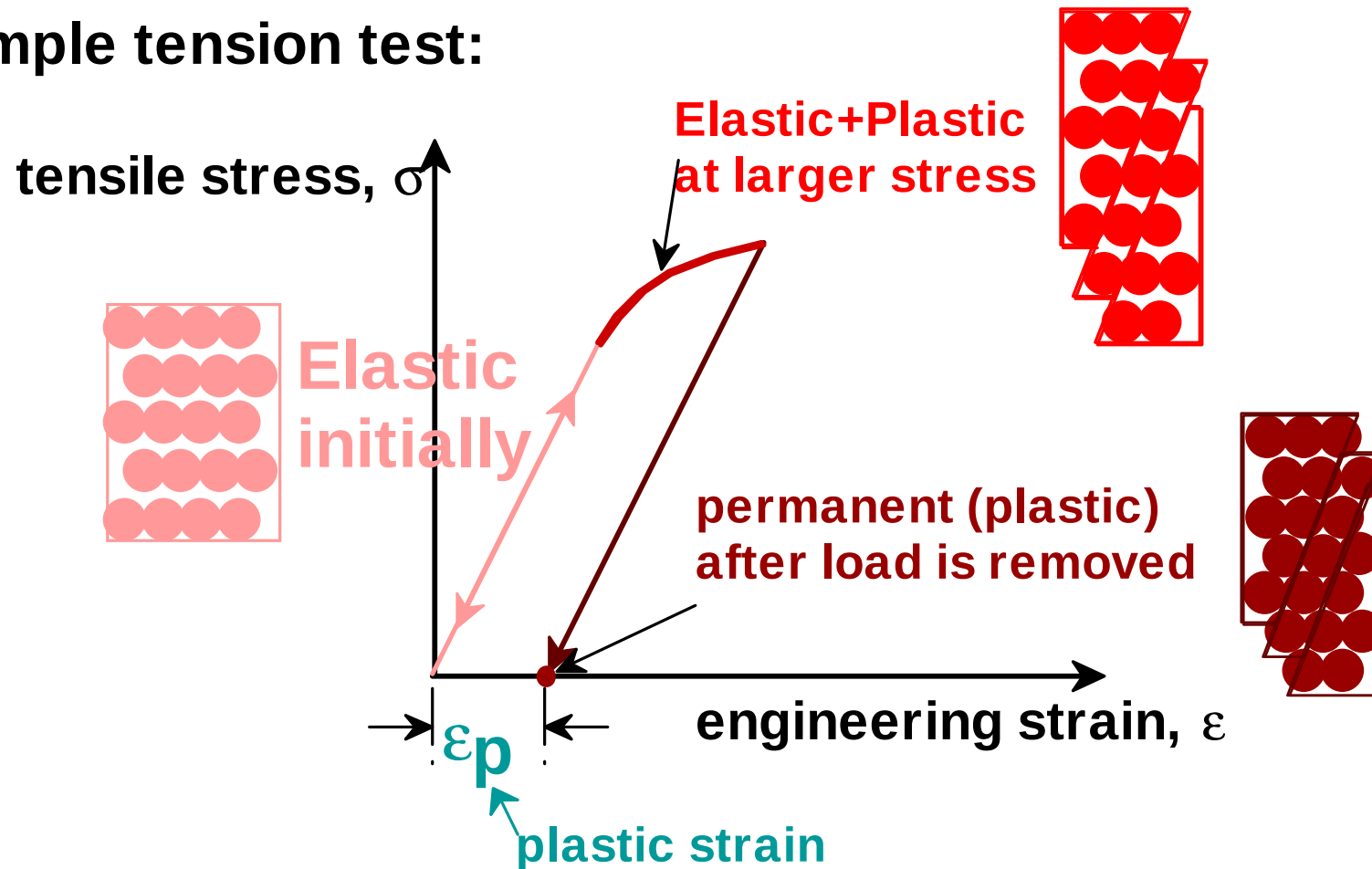


- Material, geometric, and loading parameters all contribute to deflection.
- Larger elastic moduli minimize elastic deflection.

PLASTIC (PERMANENT) DEFORMATION

(at lower temperatures, $T < T_{\text{melt}}/3$)

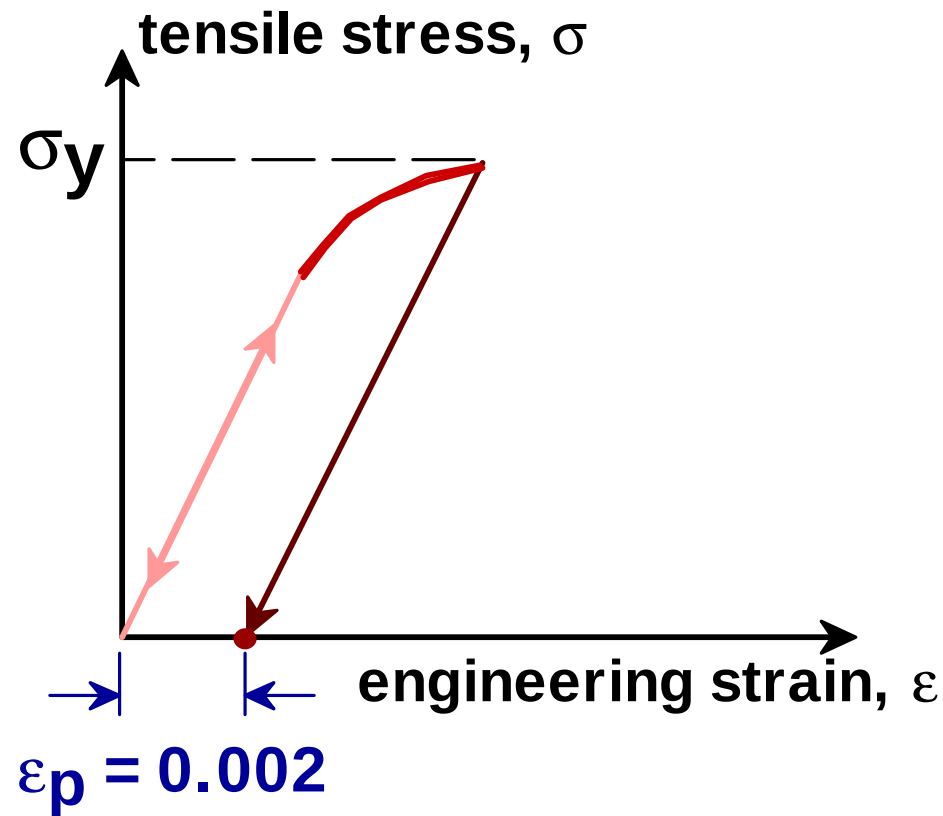
- Simple tension test:



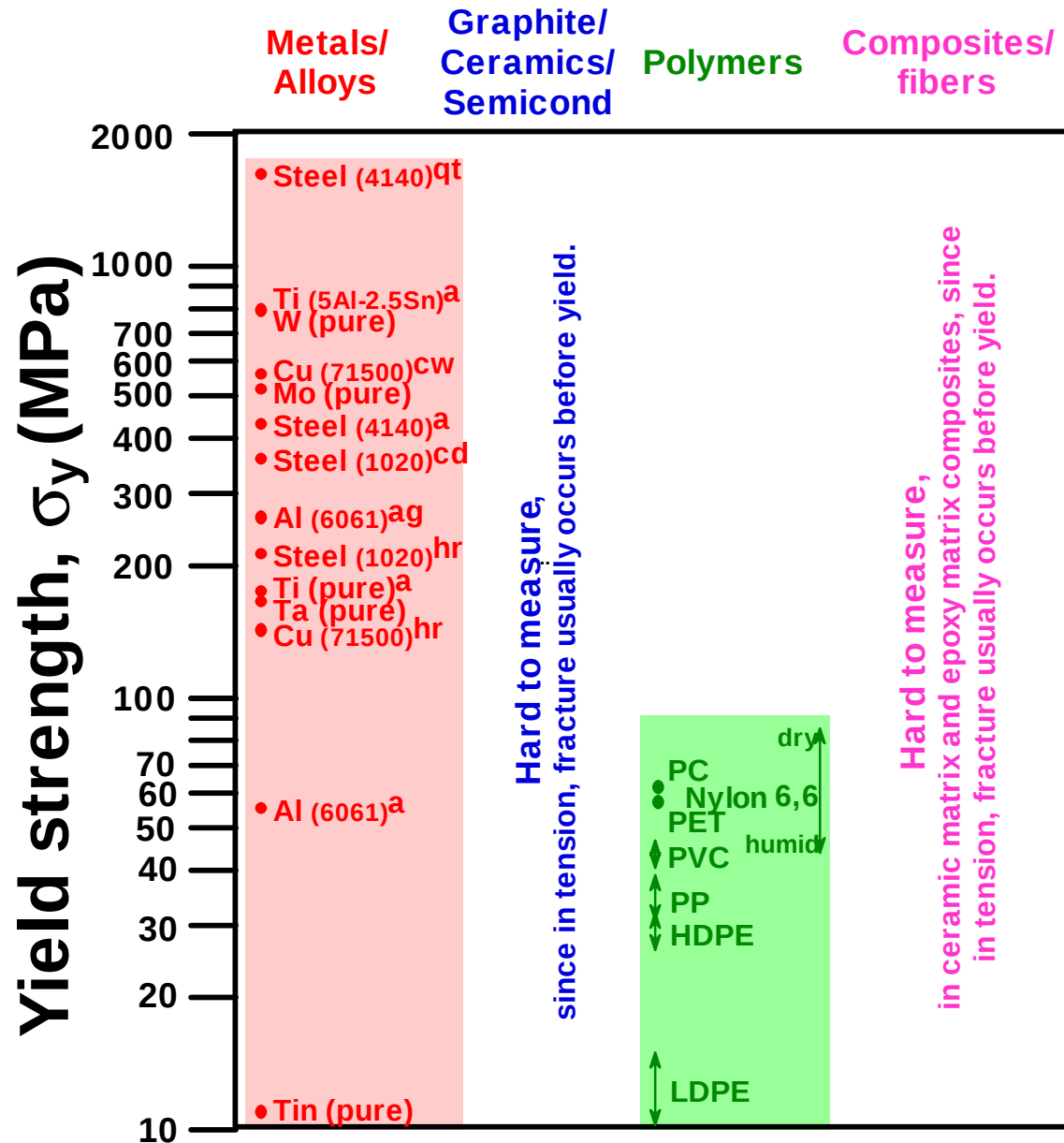
YIELD STRENGTH, σ_y

- Stress at which *noticeable* plastic deformation has occurred.

when $\epsilon_p = 0.002$



YIELD STRENGTH: COMPARISON



$\sigma_y(\text{ceramics})$
 $\gg \sigma_y(\text{metals})$
 $\gg \sigma_y(\text{polymers})$

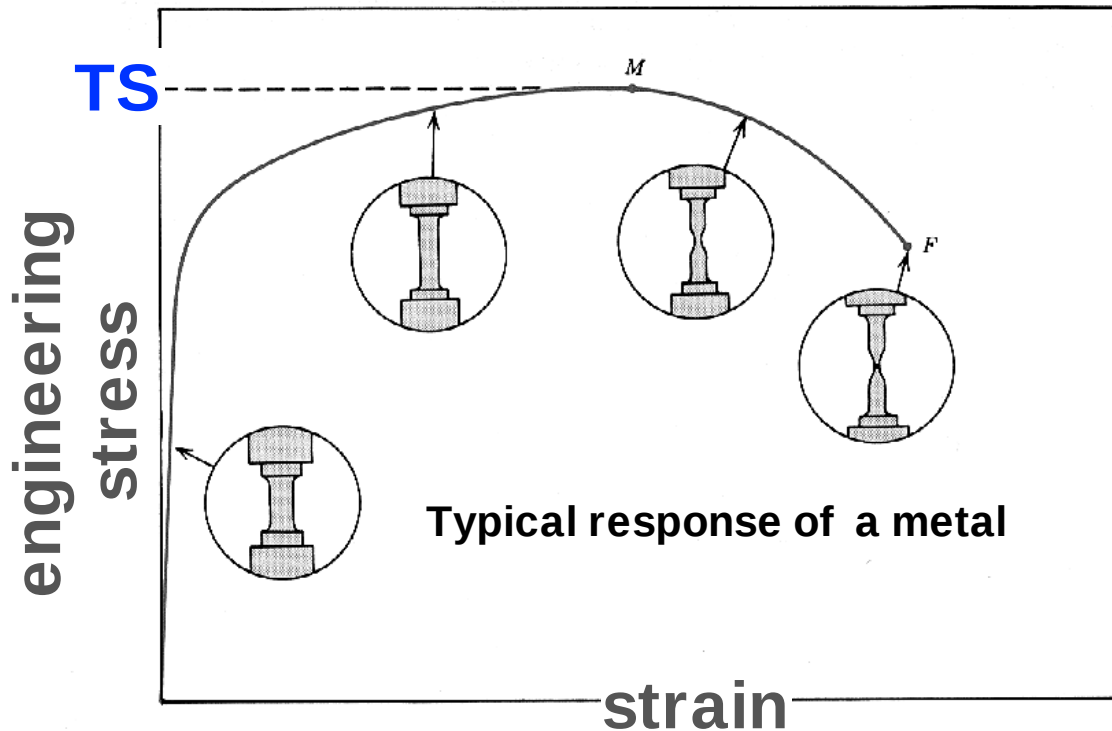
Room T values

Based on data in Table B4, *Callister 6e*.

a = annealed
 hr = hot rolled
 ag = aged
 cd = cold drawn
 cw = cold worked
 qt = quenched & tempered

TENSILE STRENGTH, TS

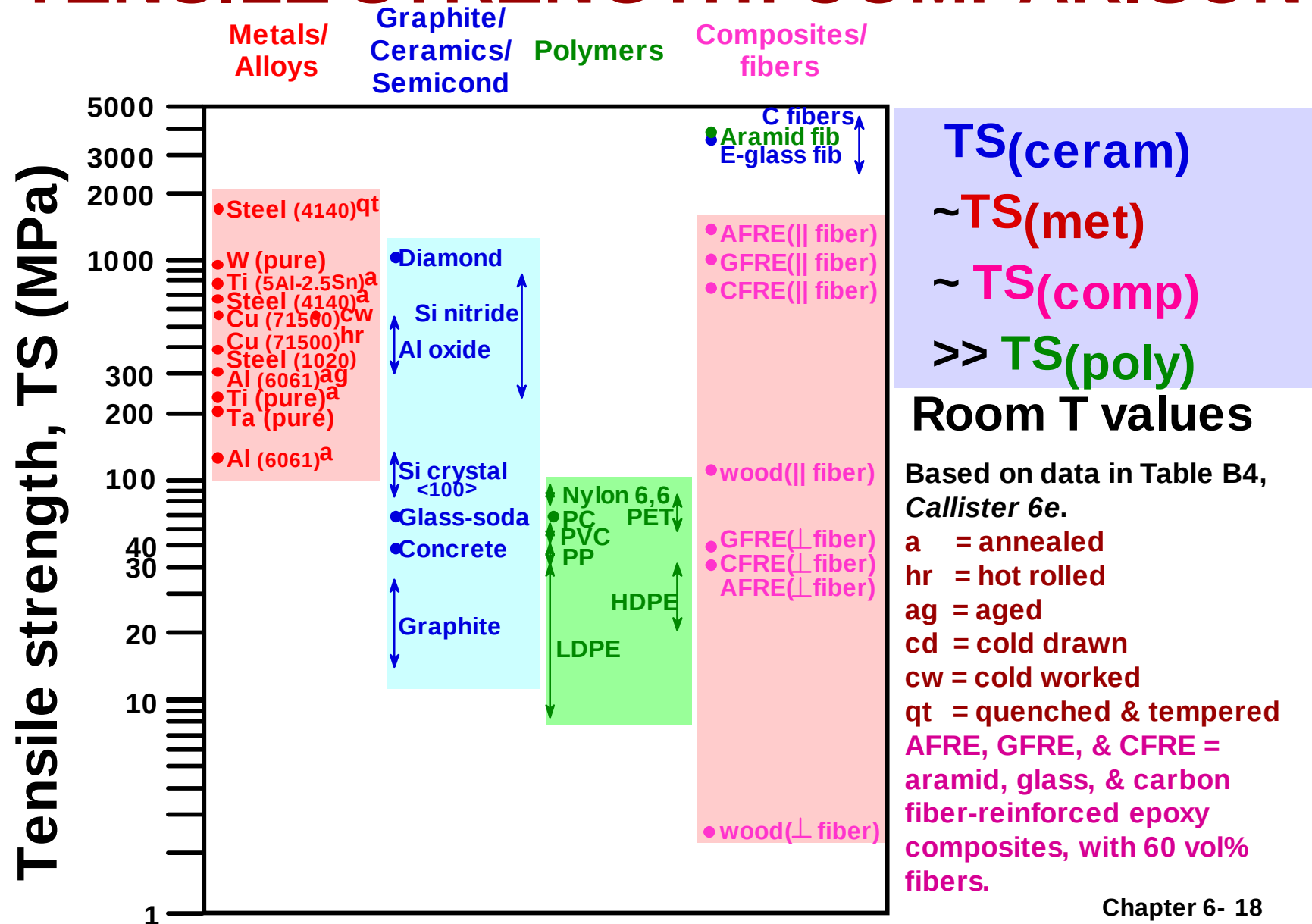
- Maximum possible engineering stress in tension.



Adapted from Fig. 6.11,
Callister 6e.

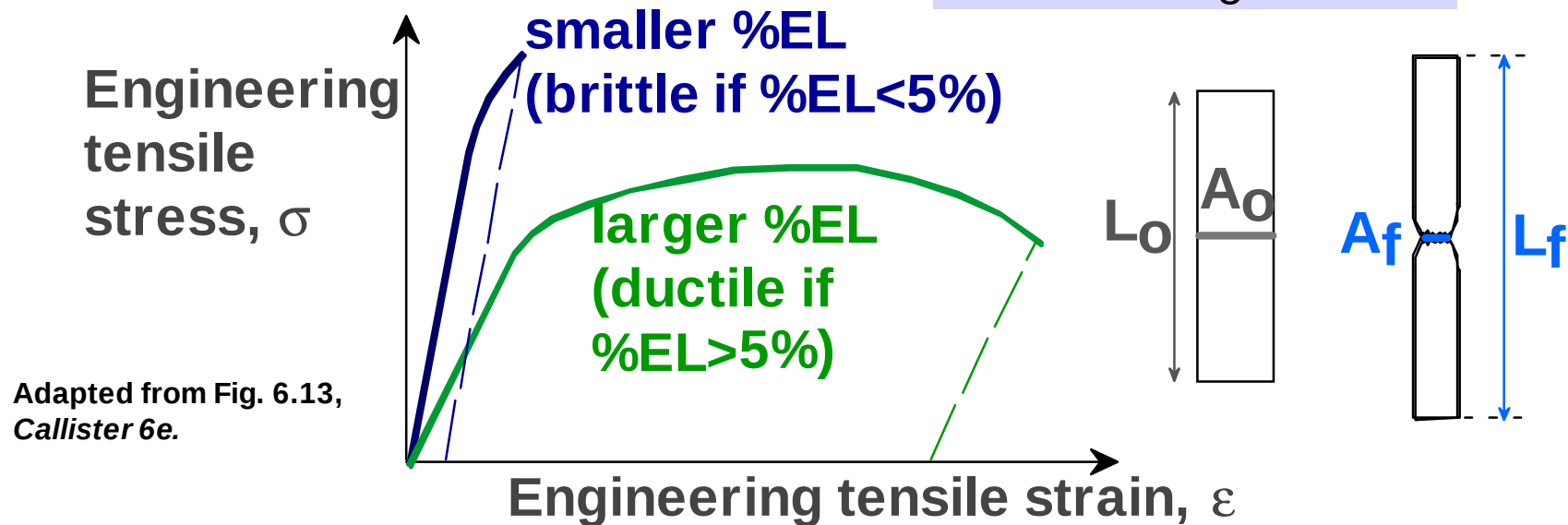
- Metals: occurs when noticeable **necking** starts.
- Ceramics: occurs when **crack propagation** starts.
- Polymers: occurs when **polymer backbones** are aligned and about to break.

TENSILE STRENGTH: COMPARISON



DUCTILITY, %EL

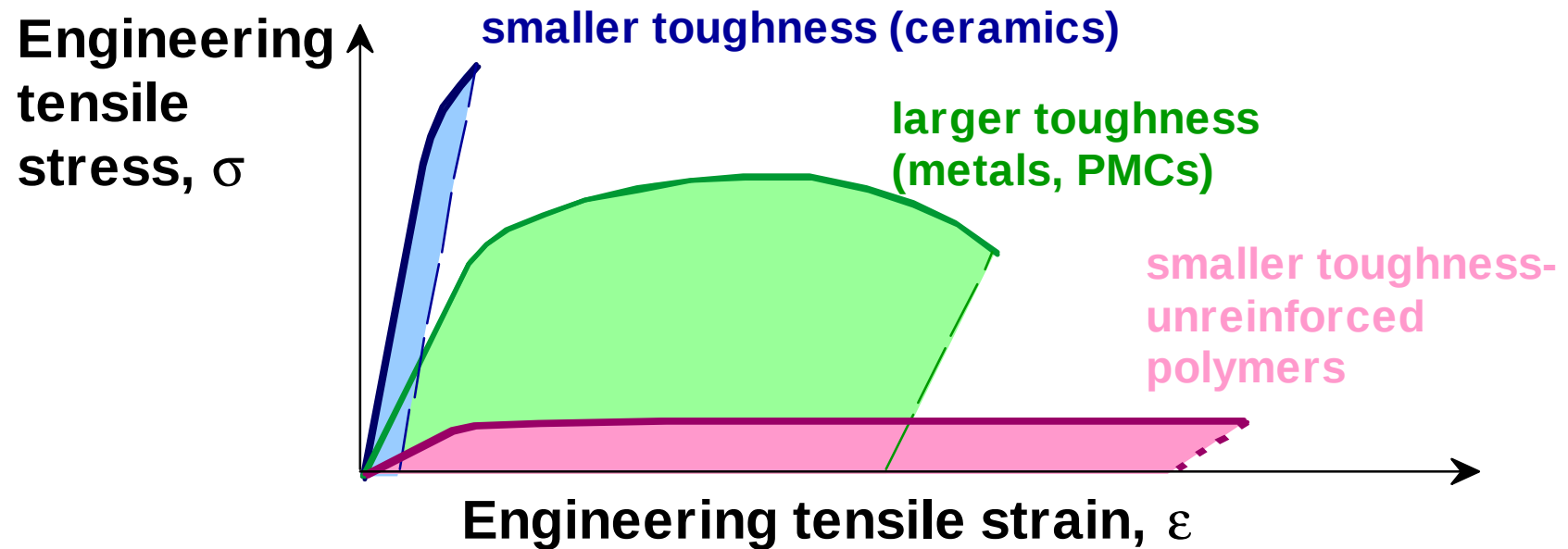
- Plastic tensile strain at failure:
$$\%EL = \frac{L_f - L_o}{L_o} \times 100$$



- Another ductility measure:
$$\%AR = \frac{A_o - A_f}{A_o} \times 100$$
- Note: %AR and %EL are often comparable.
 - Reason: crystal slip does not change material volume.
 - %AR > %EL possible if internal voids form in neck.

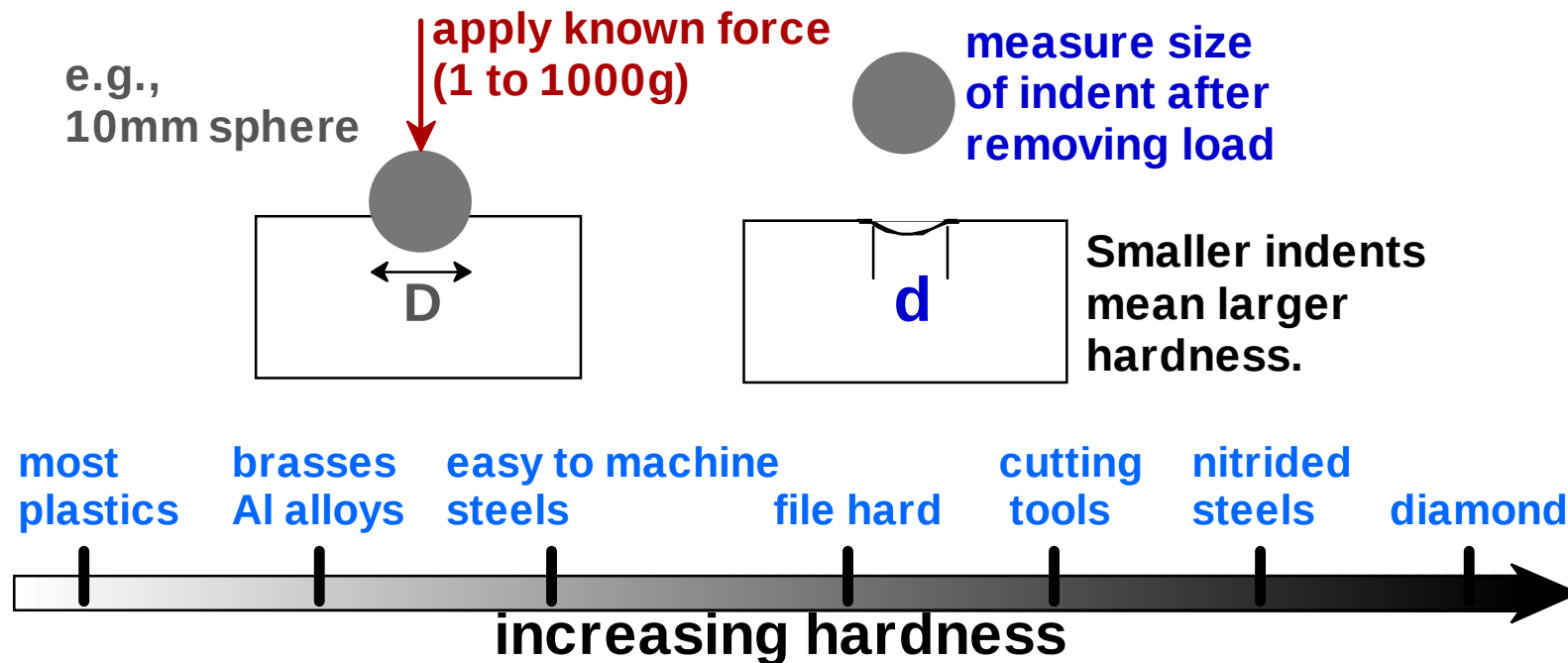
TOUGHNESS

- Energy to break a unit volume of material
- Approximate by the area under the stress-strain curve.



HARDNESS

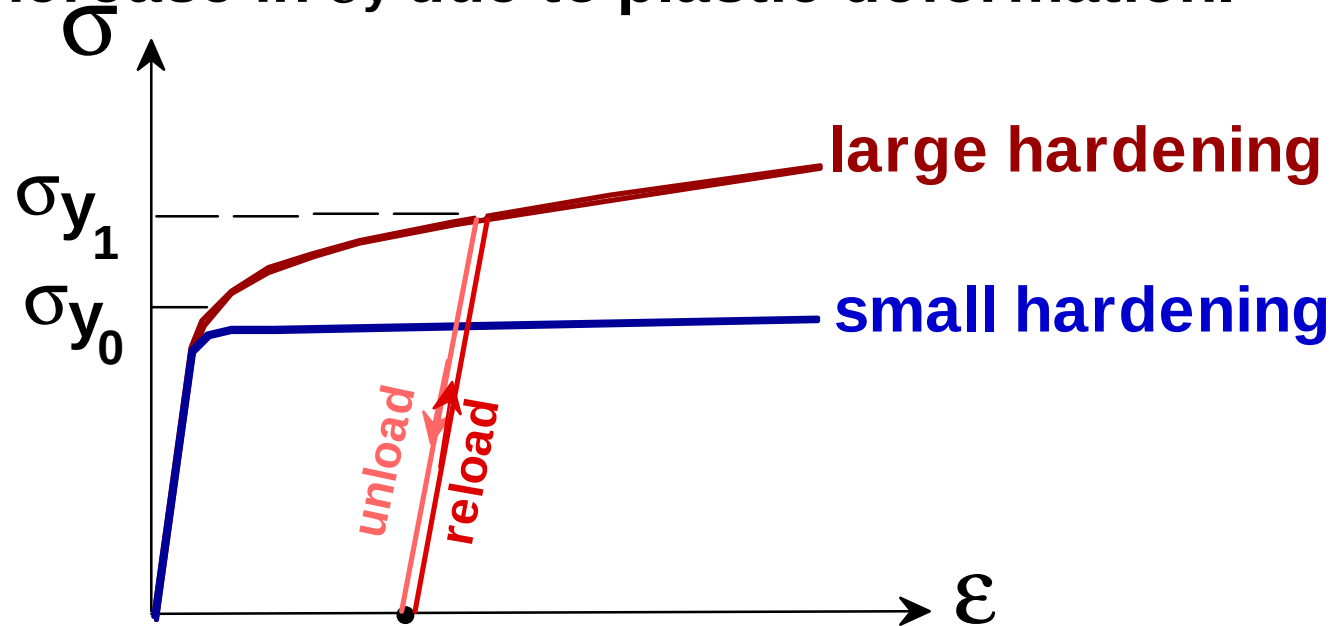
- Resistance to permanently indenting the surface.
- Large hardness means:
 - resistance to plastic deformation or cracking in compression.
 - better wear properties.



Adapted from Fig. 6.18, *Callister 6e*. (Fig. 6.18 is adapted from G.F. Kinney, *Engineering Properties and Applications of Plastics*, p. 202, John Wiley and Sons, 1957.)

HARDENING

- An increase in σ_y due to plastic deformation.



- Curve fit to the stress-strain response:

$$\sigma_T = C(\epsilon_T)^n$$

hardening exponent:
 $n=0.15$ (some steels)
to $n=0.5$ (some copper)

“true” stress (F/A)

“true” strain: $\ln(L/L_0)$

DESIGN OR SAFETY FACTORS

- Design uncertainties mean we do not push the limit.
- **Factor of safety, N**

$$\sigma_{\text{working}} = \frac{\sigma_y}{N}$$

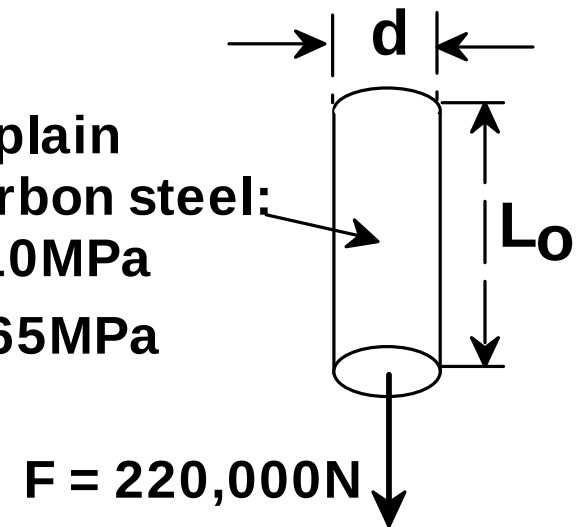
Often N is
between
1.2 and 4

- **Ex: Calculate a diameter, d, to ensure that yield does not occur in the 1045 carbon steel rod below. Use a factor of safety of 5.**

$$\frac{220,000\text{N}}{\pi(d^2/4)} = \frac{\sigma_y}{N}$$

5

1045 plain
carbon steel:
 $\sigma_y=310\text{MPa}$
 $\text{TS}=565\text{MPa}$



SUMMARY

- **Stress** and **strain**: These are size-independent measures of load and displacement, respectively.
- **Elastic** behavior: This reversible behavior often shows a linear relation between stress and strain. To minimize deformation, select a material with a large elastic modulus (E or G).
- **Plastic** behavior: This permanent deformation behavior occurs when the tensile (or compressive) uniaxial stress reaches σ_y .
- **Toughness**: The energy needed to break a unit volume of material.
- **Ductility**: The plastic strain at failure.

Note: For materials selection cases related to mechanical behavior, see slides 22-4 to 22-10.