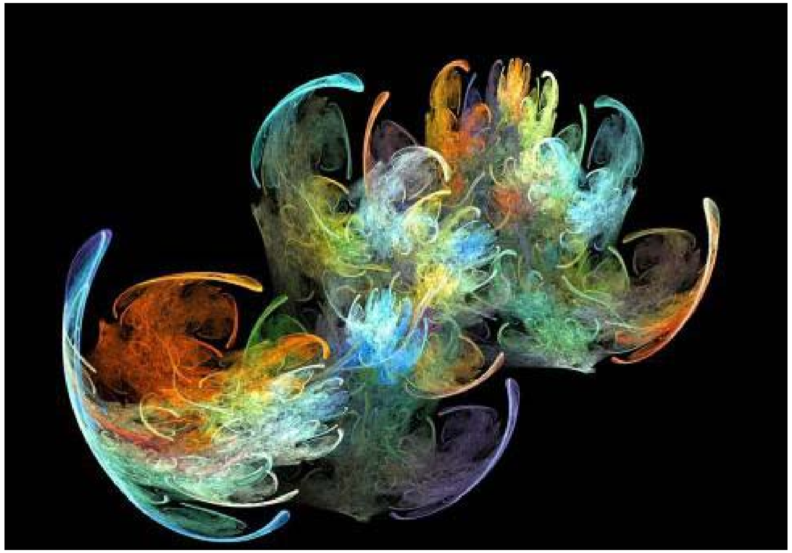


Chapter 5

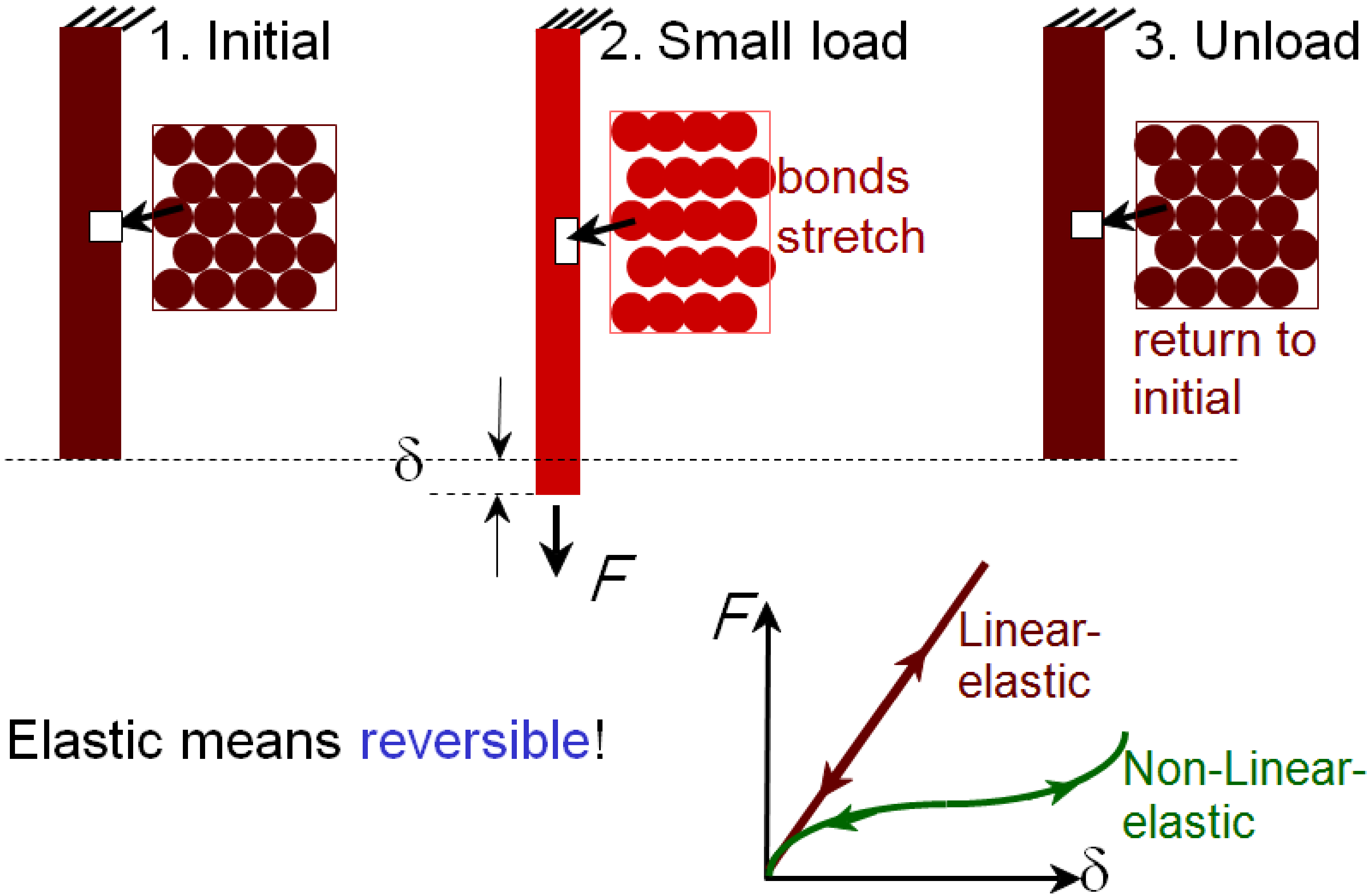
Mechanical Properties

Dr. Mubarak

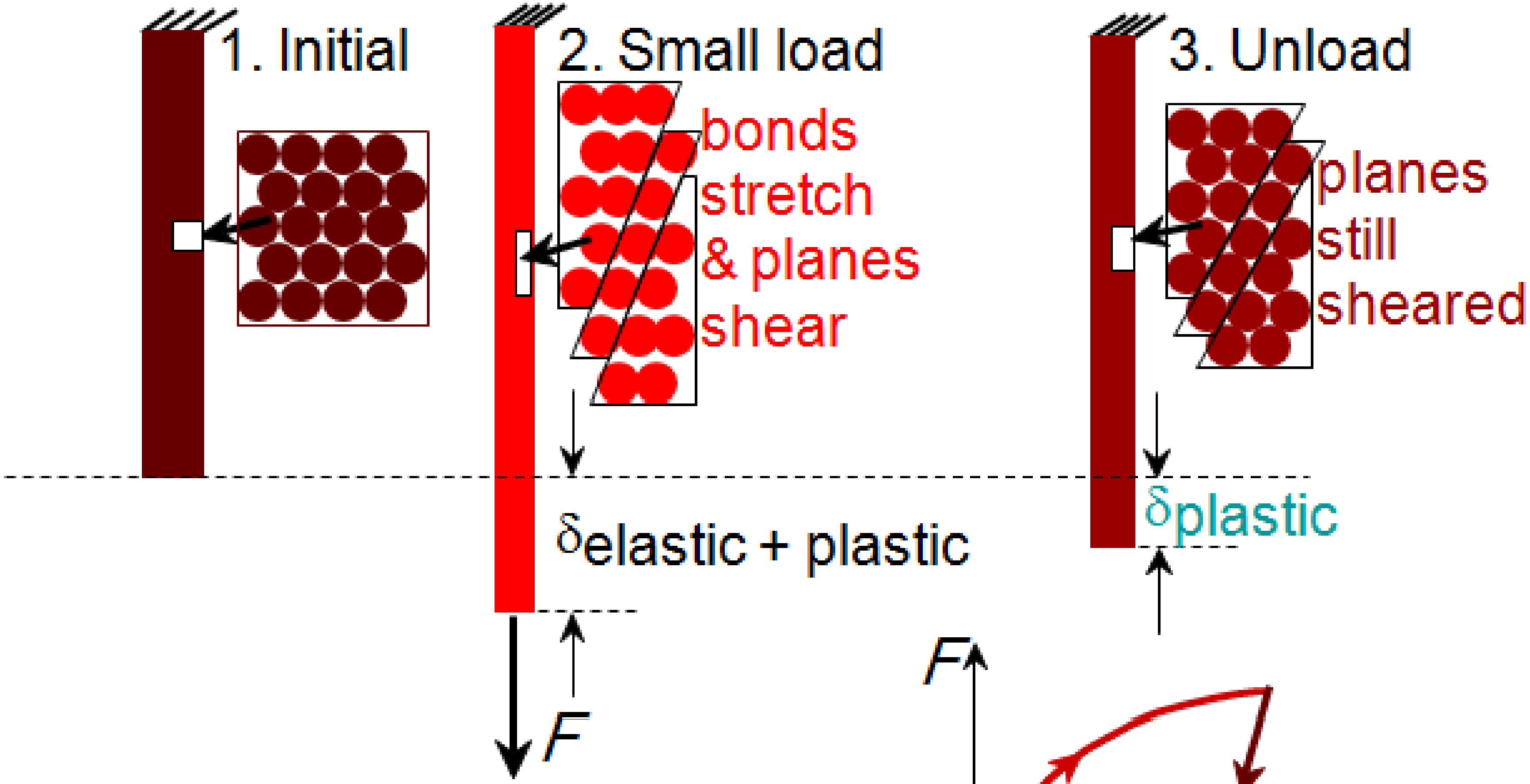
Outline

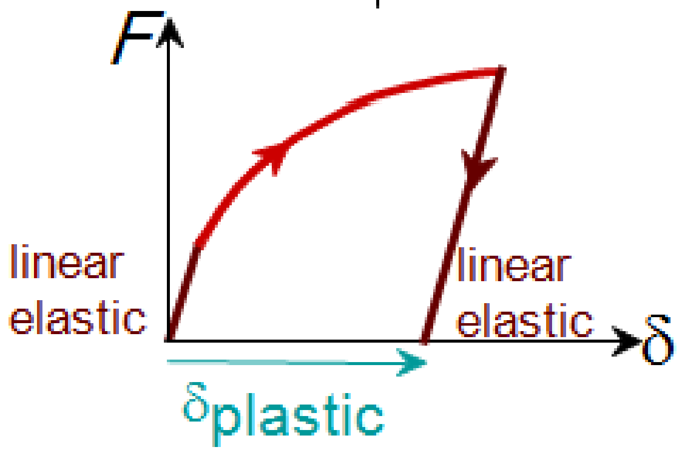
- **Stress and strain:** What are they and why are they used instead of load and deformation?
- **Elastic behavior:** When loads are small, how much deformation occurs? What materials deform least?
- **Plastic behavior:** At what point does permanent deformation occur? What materials are most resistant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

Elastic Deformation



Elastic means reversible!

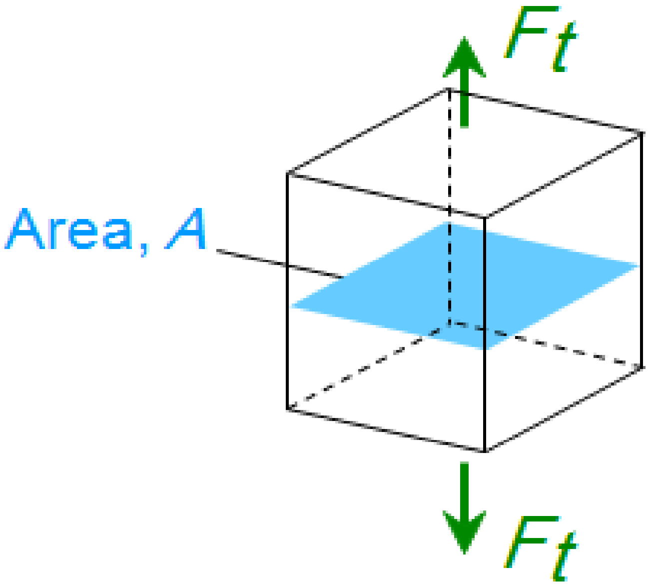




Plastic means permanent!

Engineering Stress

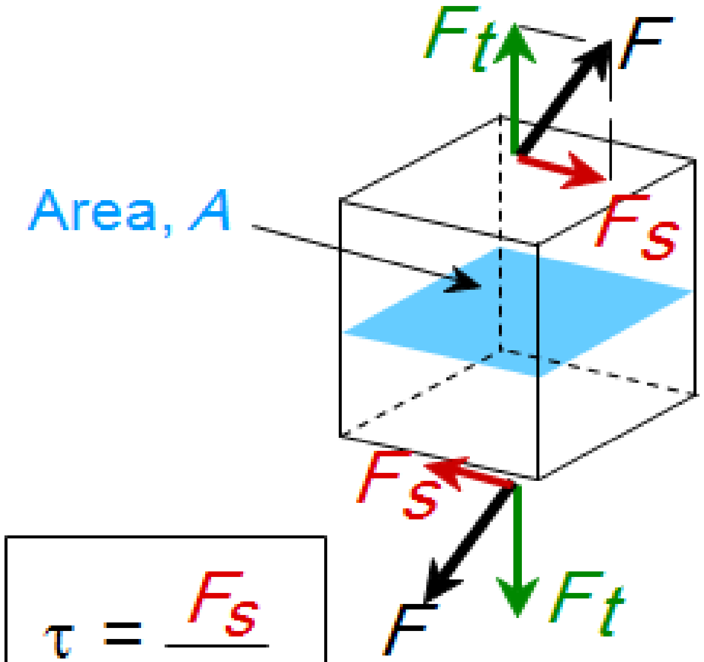
- Tensile stress, σ:



$$\sigma = \frac{F_t}{A_o} = \frac{lb_f}{in^2} \text{ or } \frac{N}{m^2}$$

original area before loading

- Shear stress, τ:

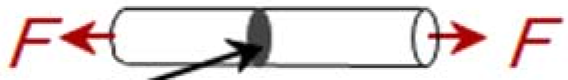


$$\tau = \frac{F_s}{A_o}$$

∴ Stress has units:
N/m^2 or $lb_f/in2$

Common States of Stress

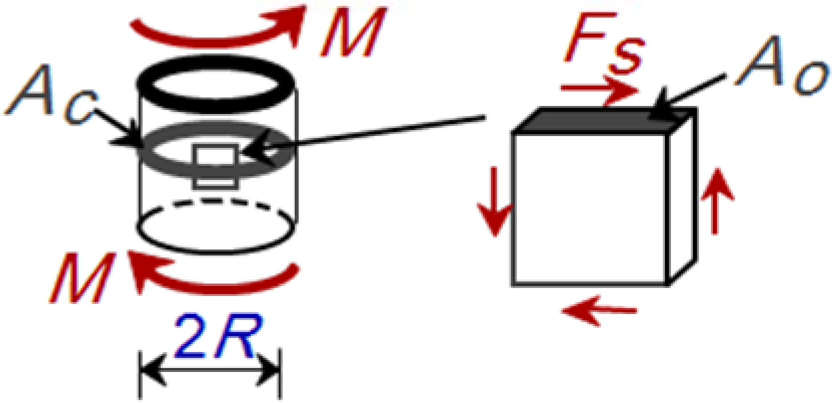
- **Simple tension: cable**



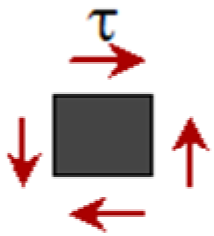
A_o = cross sectional area (when unloaded)

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

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



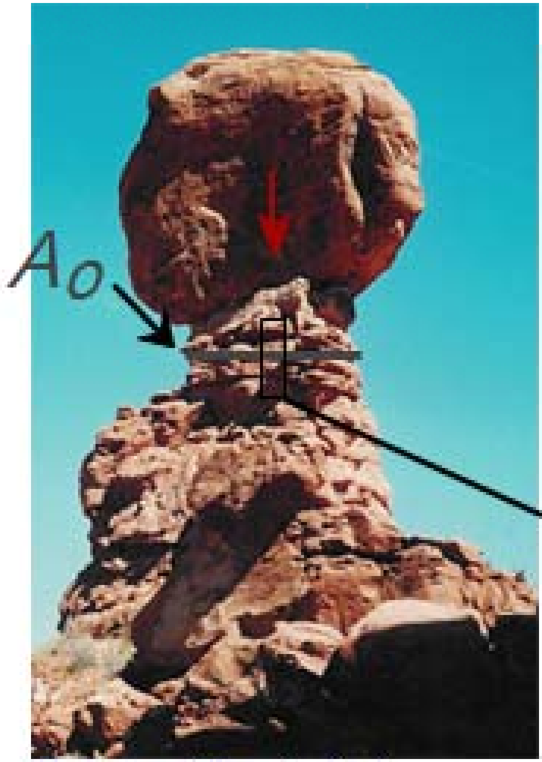
$$\tau = \frac{F_s}{A_o}$$



Note: $\tau = M/A_cR$ here.

Other Common Stress States (1)

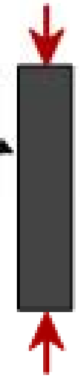
- **Simple compression:**



Balanced Rock, Arches National Park

Canyon Bridge, Los Alamos, NM

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

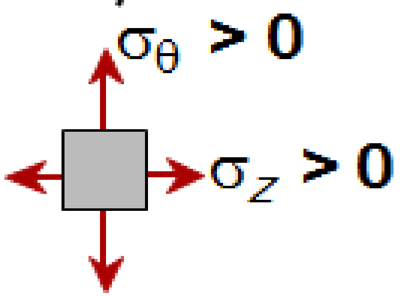


Note: compressive structure member ($\sigma < 0$ here).

Other Common Stress States (2)

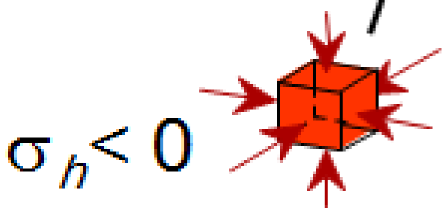
- **Bi-axial tension:**

Pressurized tank



- **Hydrostatic compression:**

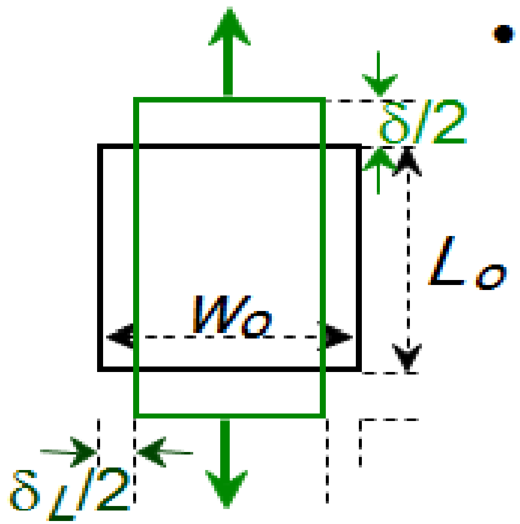
Fish under water



Engineering Strain

- **Tensile strain:**

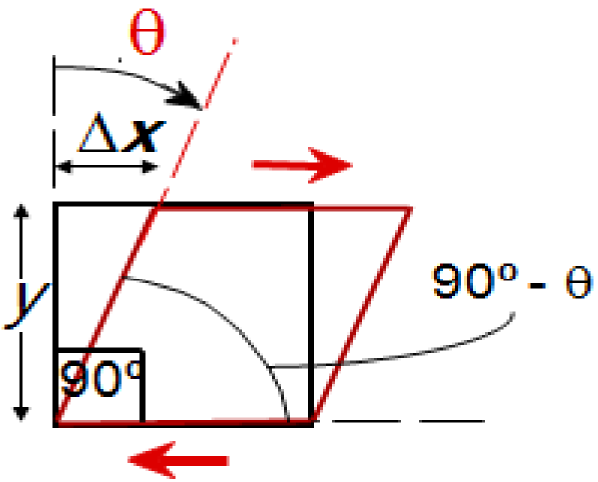
$$\varepsilon = \frac{\delta}{L_o}$$



- **Lateral strain:**

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

- **Shear strain:**

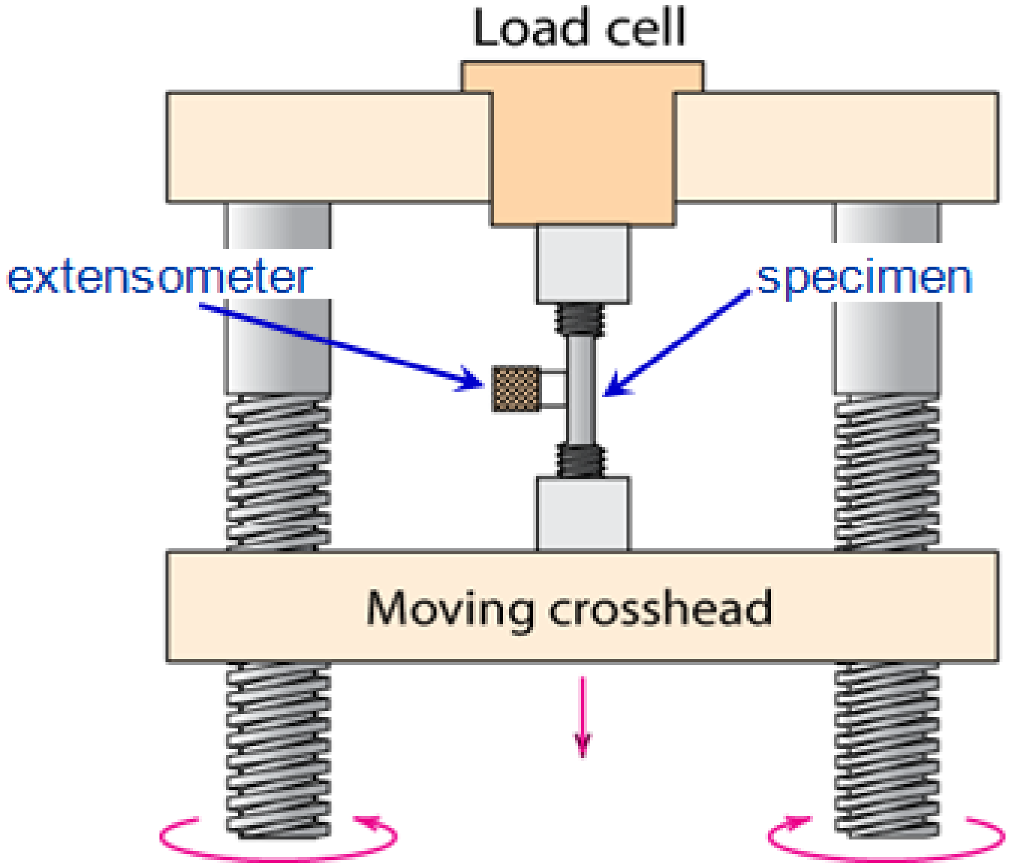


$$\gamma = \Delta x / y = \tan \theta$$

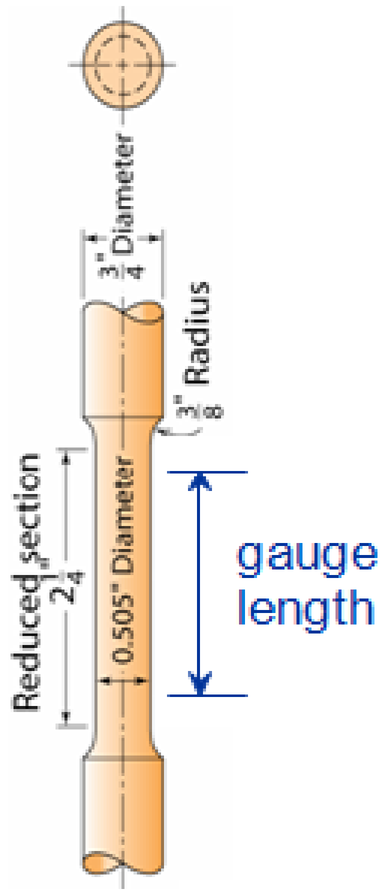
Strain is always dimensionless.

Stress-Strain Testing

- **Typical tensile test machine**



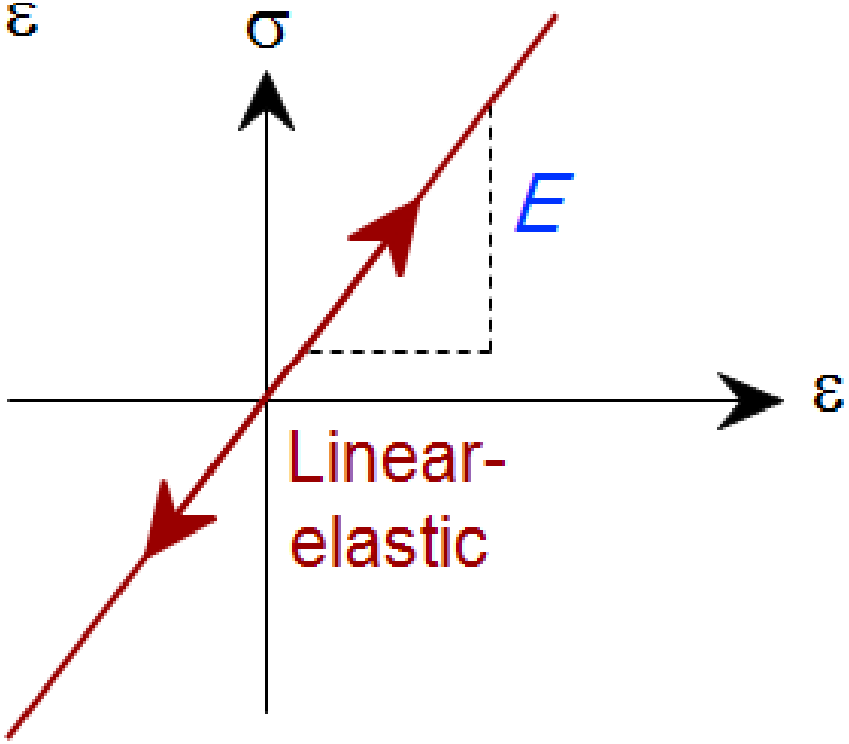
- **Typical tensile specimen**

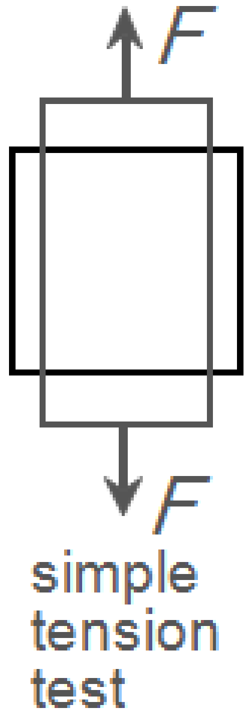


Linear Elastic Properties

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

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

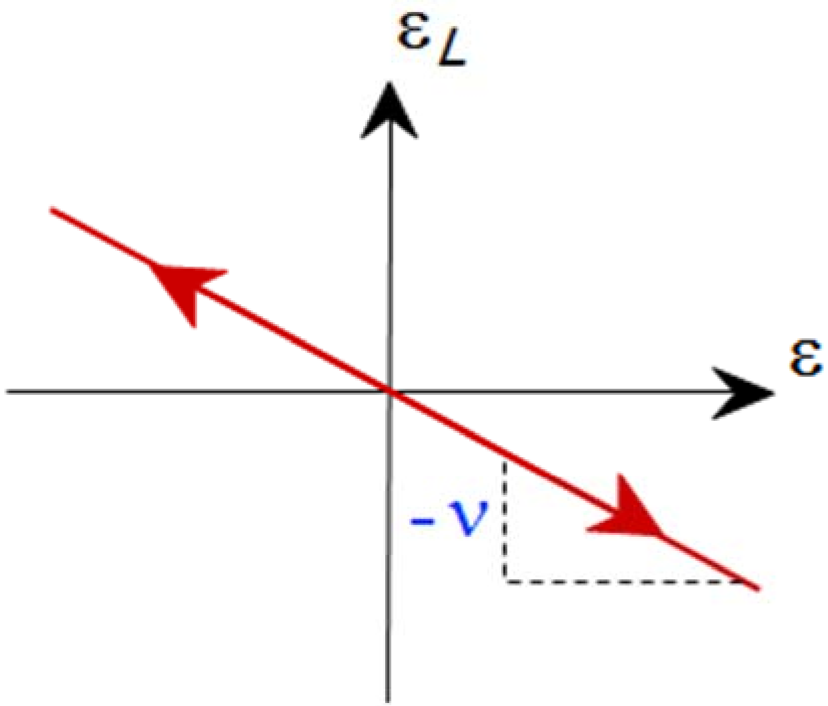




Poisson's ratio, υ

- **Poisson's ratio, ν:**

$$\nu = -\frac{\varepsilon_L}{\varepsilon}$$

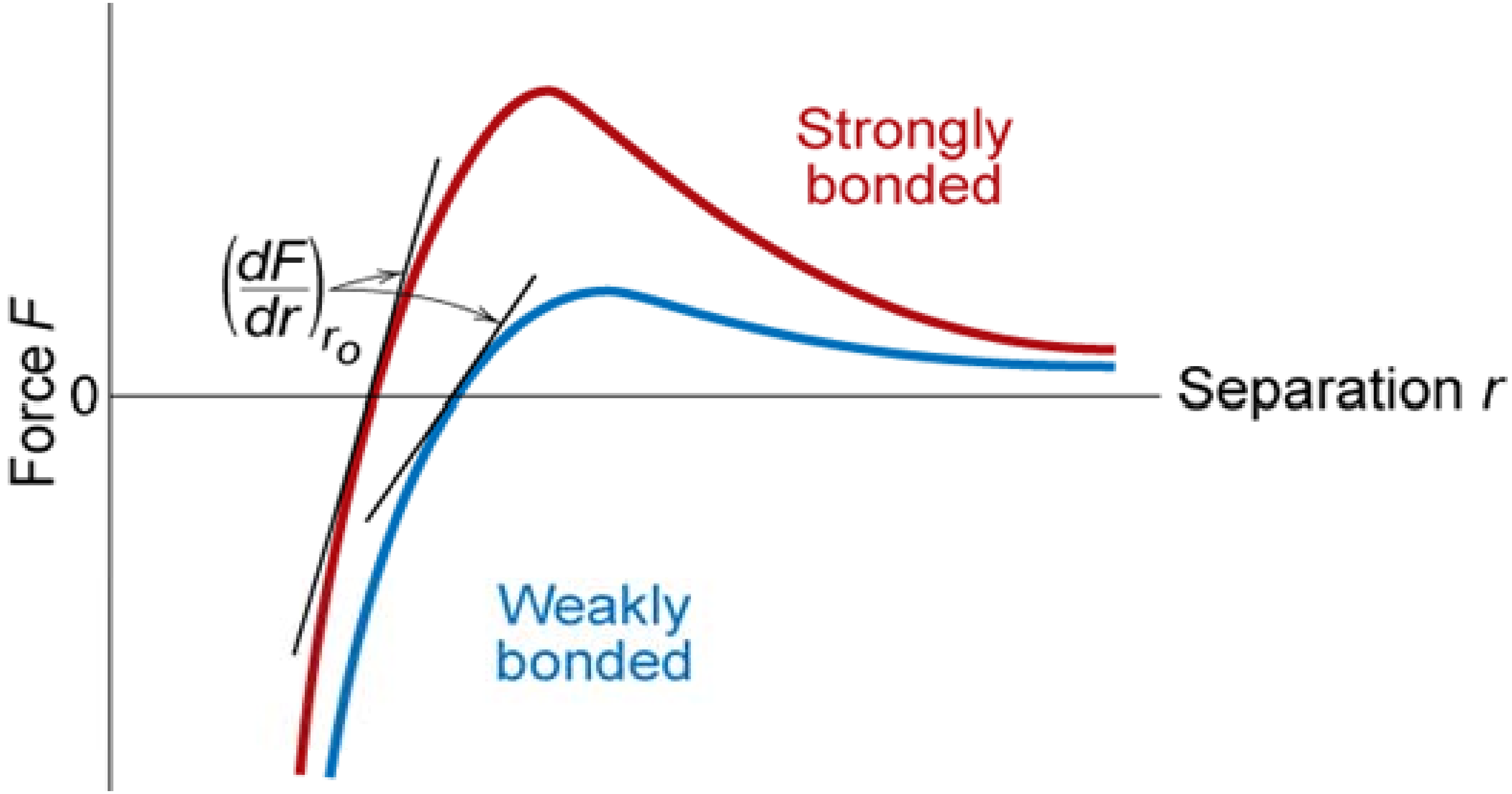


metals: ν ~ 0.33
ceramics: ν ~ 0.25
polymers: ν ~ 0.40

Units:
E: [GPa] or [psi]
ν: dimensionless

Mechanical Properties

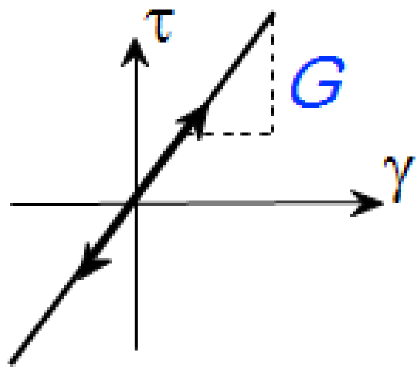
- Slope of stress strain plot (which is proportional to the elastic modulus) depends on bond strength of metal

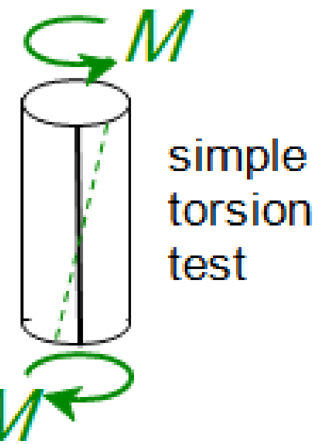


Other Elastic Properties

- **Elastic Shear modulus, *G*:**

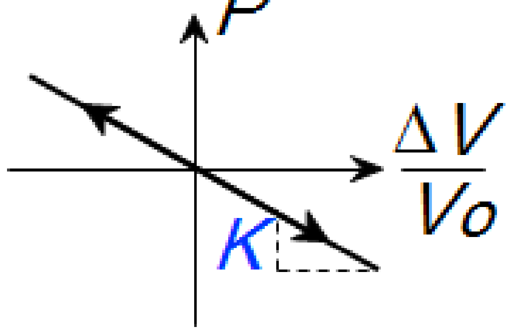
$$\tau = G\gamma$$

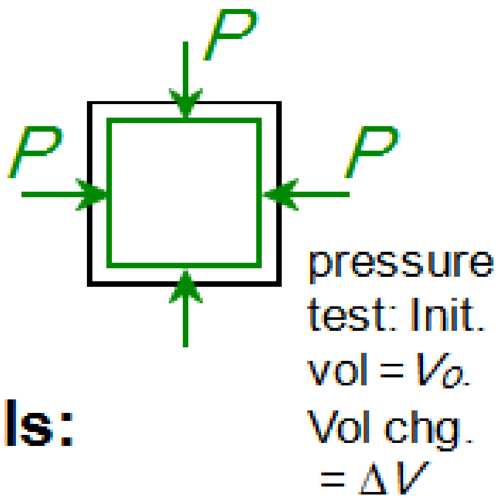




- **Elastic Bulk modulus, K:**

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

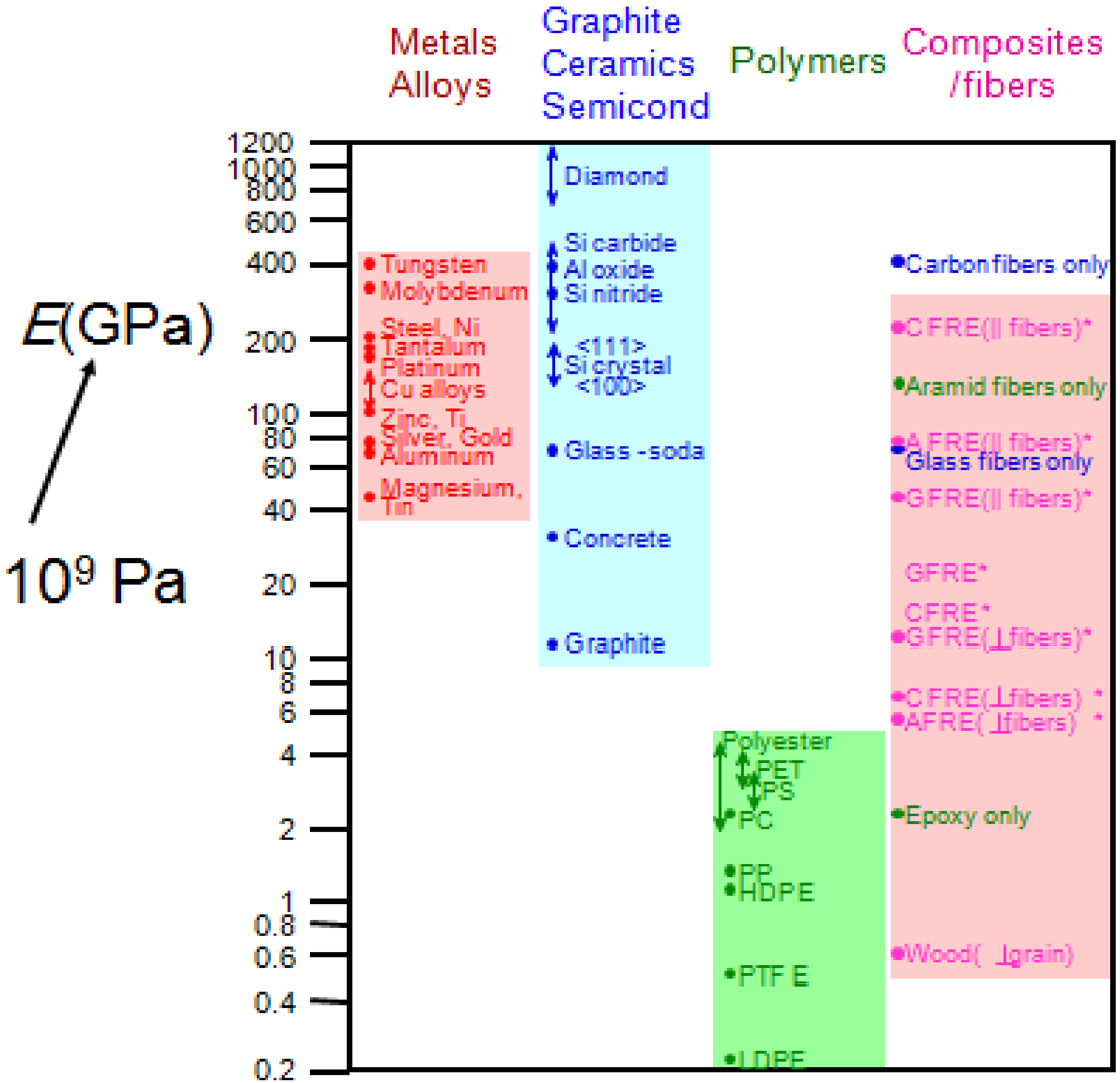




- **Special relations for isotropic materials:**

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

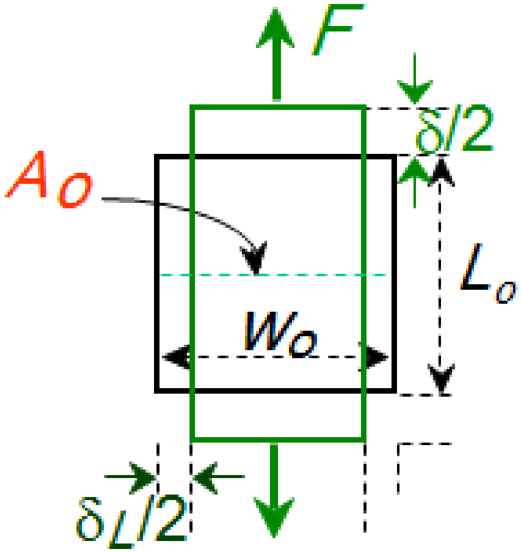
Young's Moduli: Comparison



Useful Linear Elastic Relationships

- **Simple tension:**

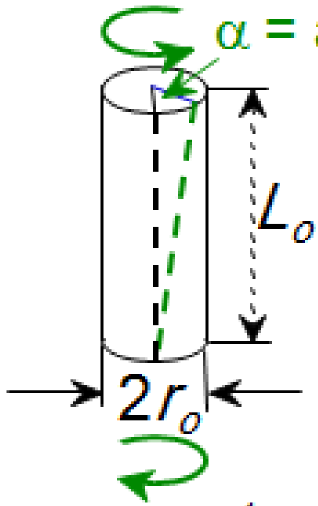
$$\delta = \frac{FL_o}{EA_o} \qquad \delta_L = -\nu \frac{Fw_o}{EA_o}$$



- **Simple torsion:**

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

M = moment
α = angle of twist

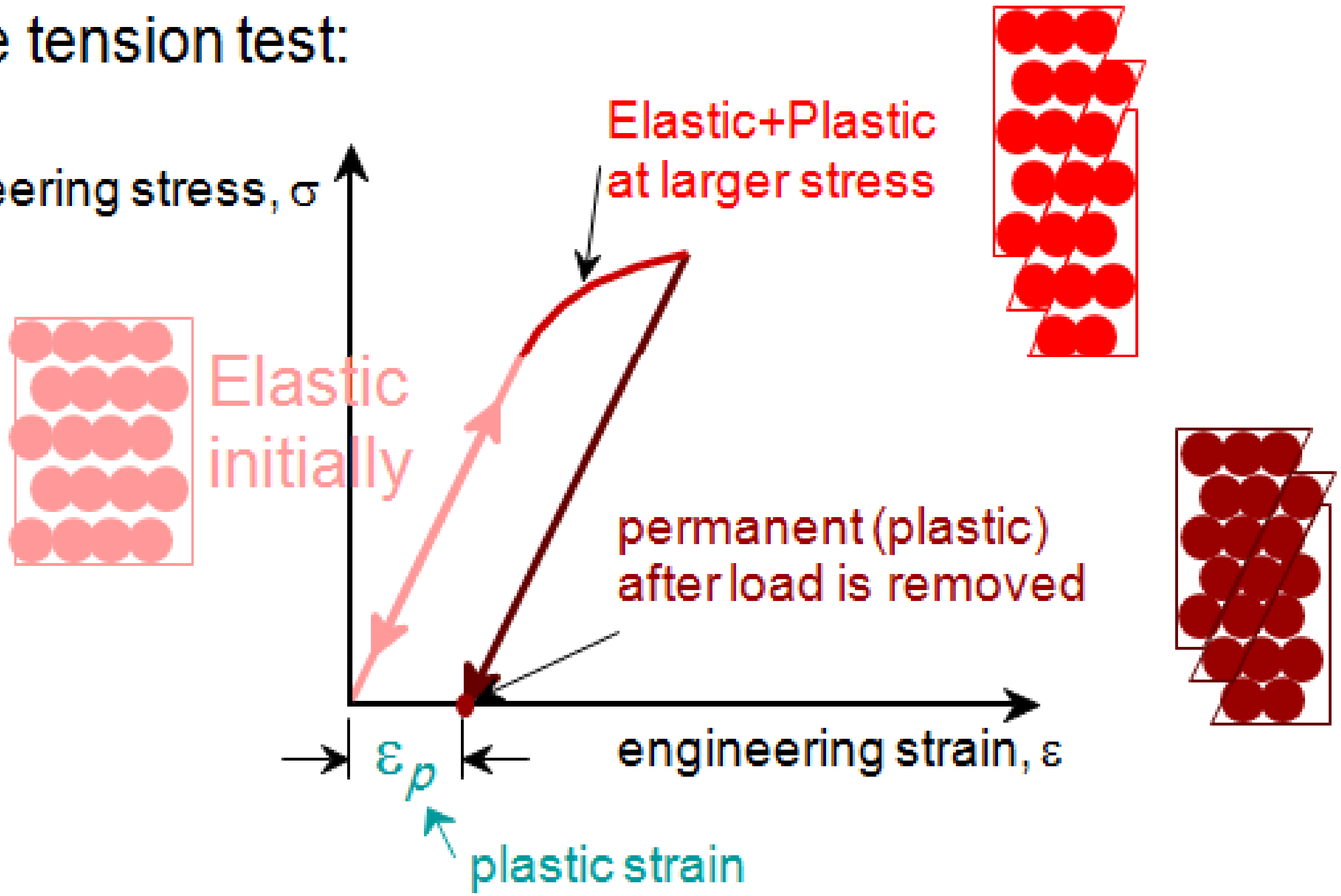


- Material, geometric, and loading parameters all contribute to deflection.
- Larger elastic moduli minimize elastic deflection.

Plastic (Permanent) Deformation

(at lower temperatures, i.e. $T < T_{melt}/3$)

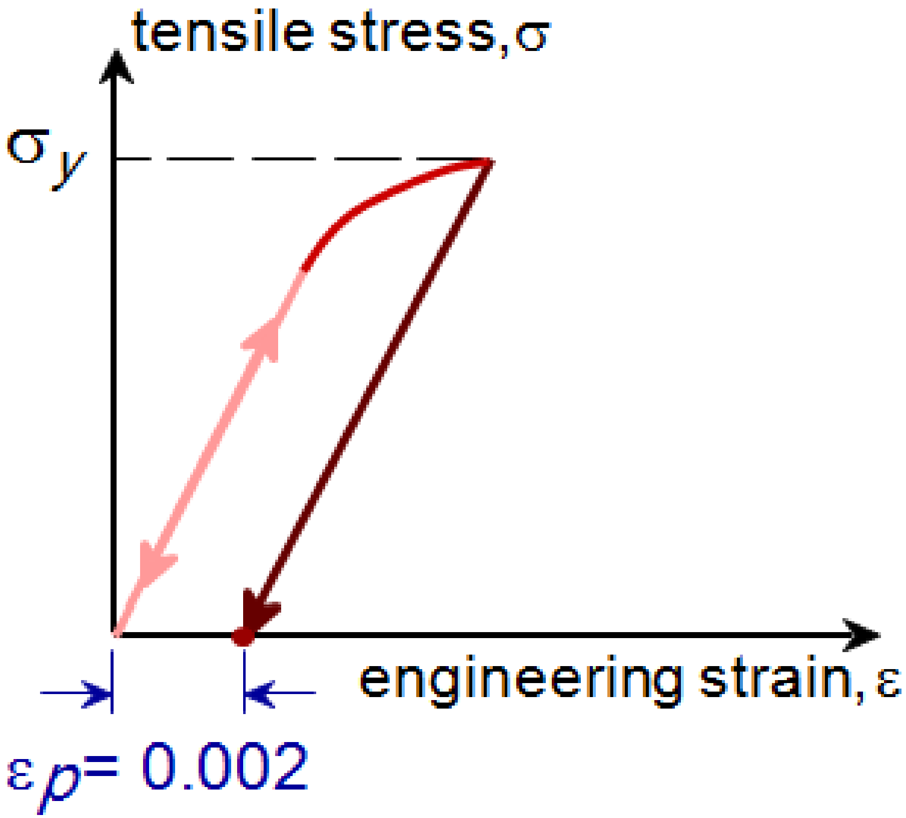
- Simple tension test:



Yield Strength, σ_y

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

when $\varepsilon_p = 0.002$



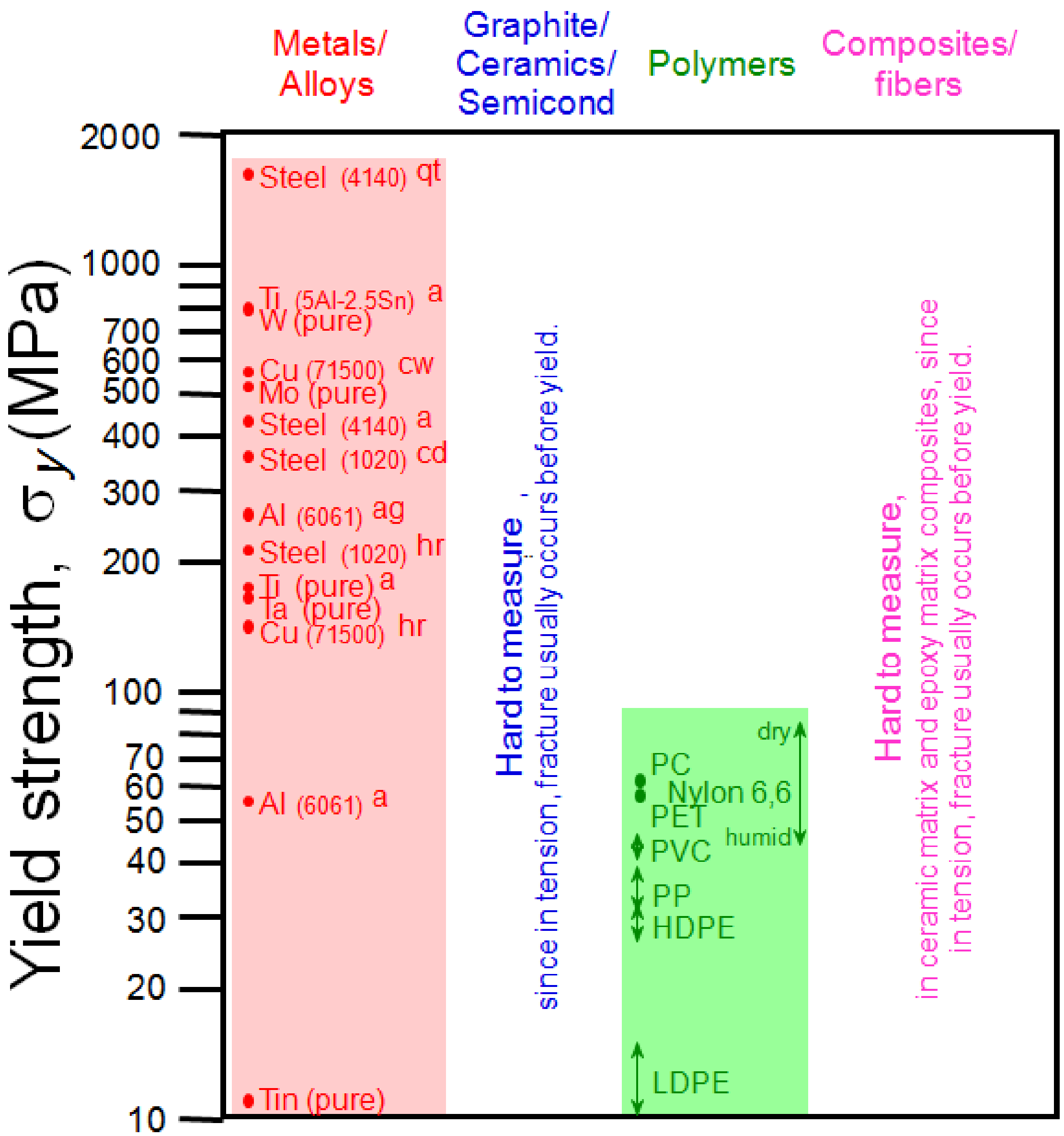
σ_y = yield strength

Note: for 2 inch sample

$\varepsilon = 0.002 = \Delta z / z$

$\therefore \ \Delta z = 0.004$ in

Yield Strength : Comparison



Based on data in Table B4, *Callister 7e*.

a = annealed

hr = hot rolled

ag = aged

cd = cold drawn

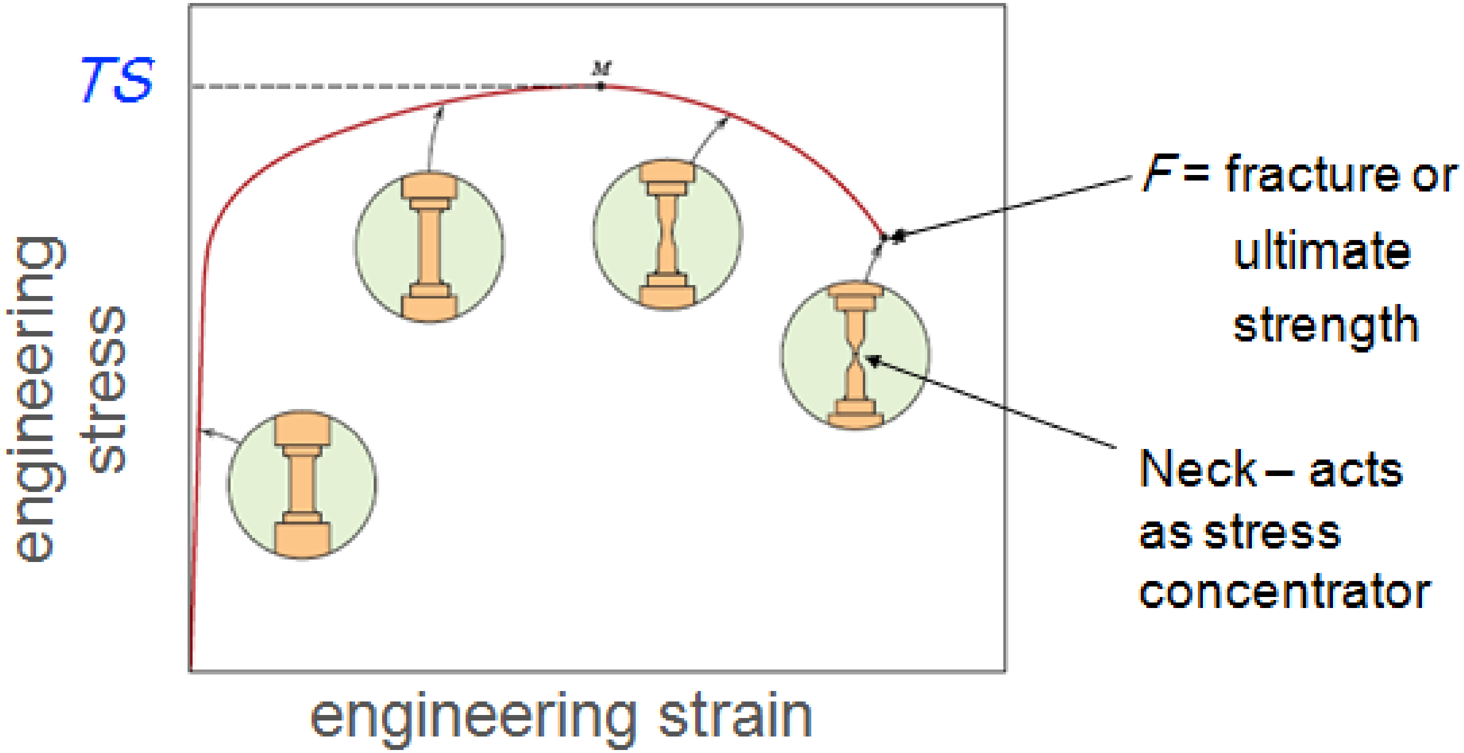
cw = cold worked

qt = quenched & tempered

Dr. Mubarak

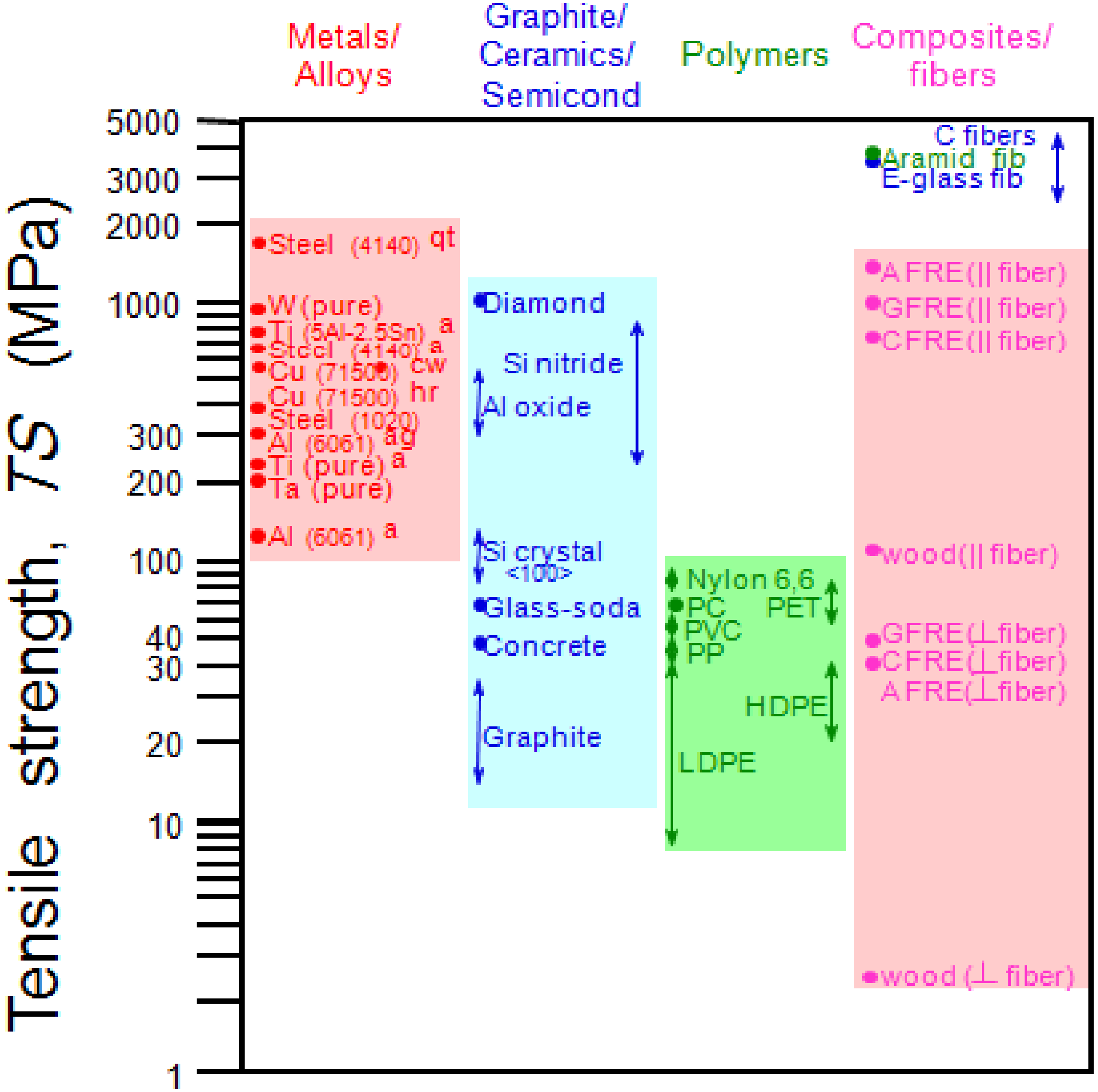
Tensile Strength, TS

• Maximum stress on engineering stress-strain curve.



• Metals: occurs when noticeable necking starts.
• Polymers: occurs when polymer backbone chains are aligned and about to break.

Tensile Strength : Comparison



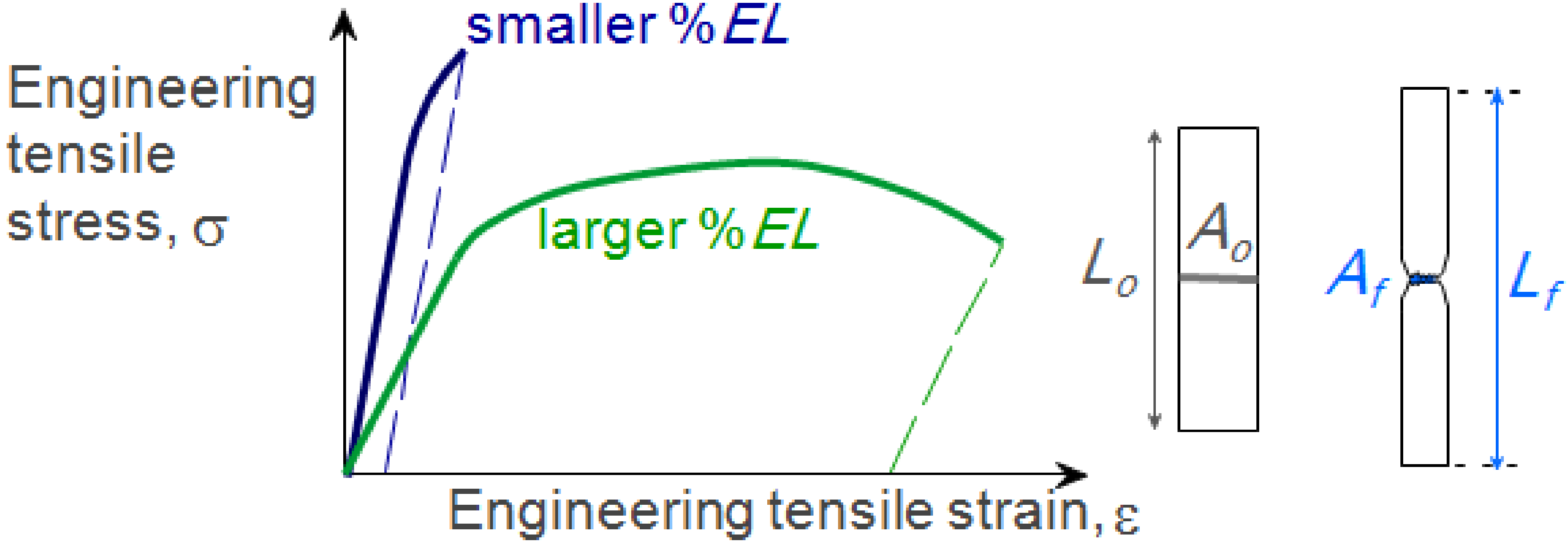
Room Temp. values

a = annealed
hr = hot rolled
ag = aged
cd = cold drawn
cw = cold worked
qt = quenched & tempered
AFRE, GFRE, & CFRE = aramid, glass, & carbon fiber-reinforced epoxy composites, with 60 vol% fibers.

Ductility

- Plastic tensile strain at failure:

$$\%EL = \frac{L_f - L_o}{L_o} \times 100$$

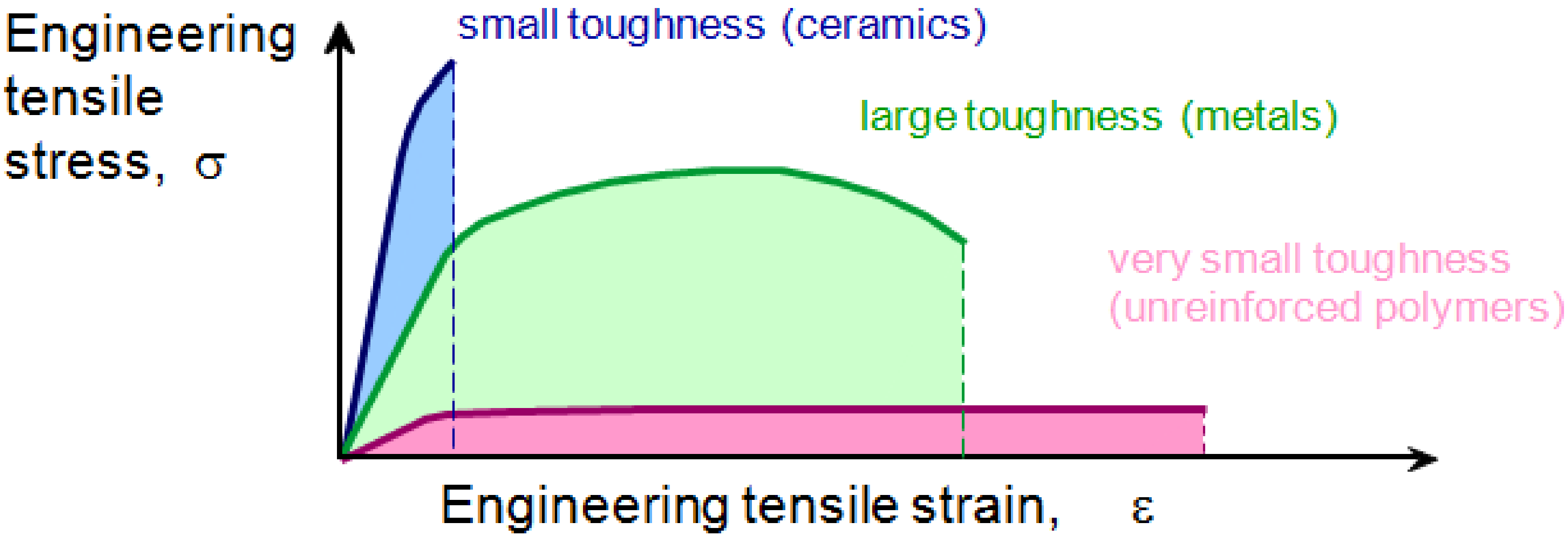


- Another ductility measure:

$$\%RA = \frac{A_o - A_f}{A_o} \times 100$$

Toughness

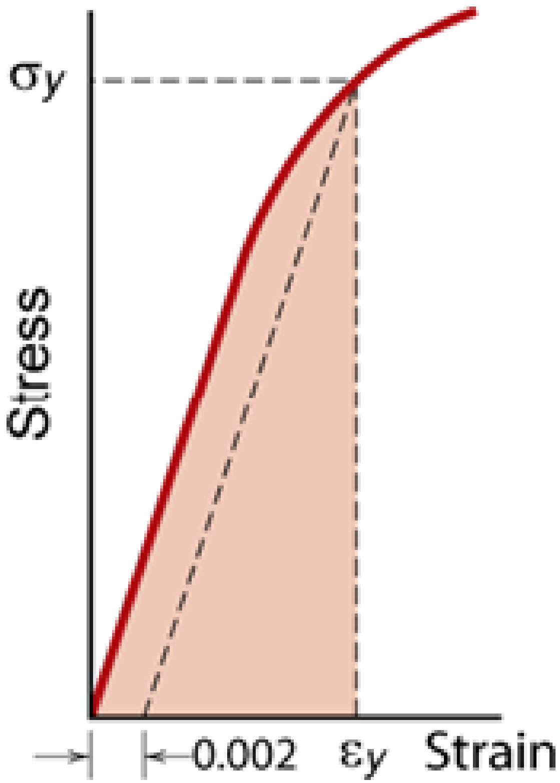
- Energy to break a unit volume of material
- Approximate by the area under the stress-strain curve.



Brittle fracture: elastic energy
Ductile fracture: elastic + plastic energy

Resilience, U_r

- Ability of a material to store energy
  - Energy stored best in elastic region

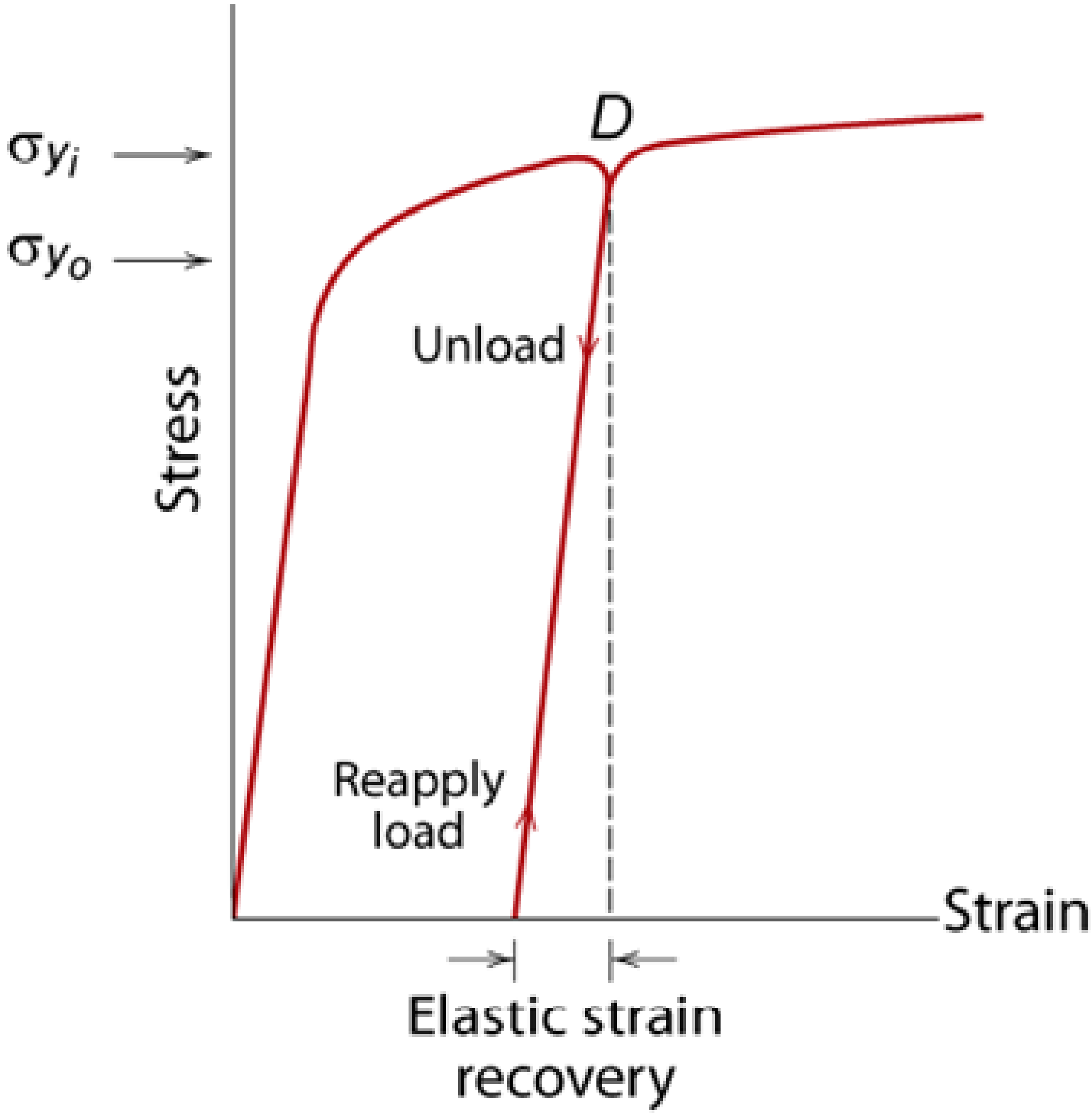


$$U_r = \int_0^{\varepsilon_y} \sigma d\varepsilon$$

If we assume a linear stress-strain curve this simplifies to

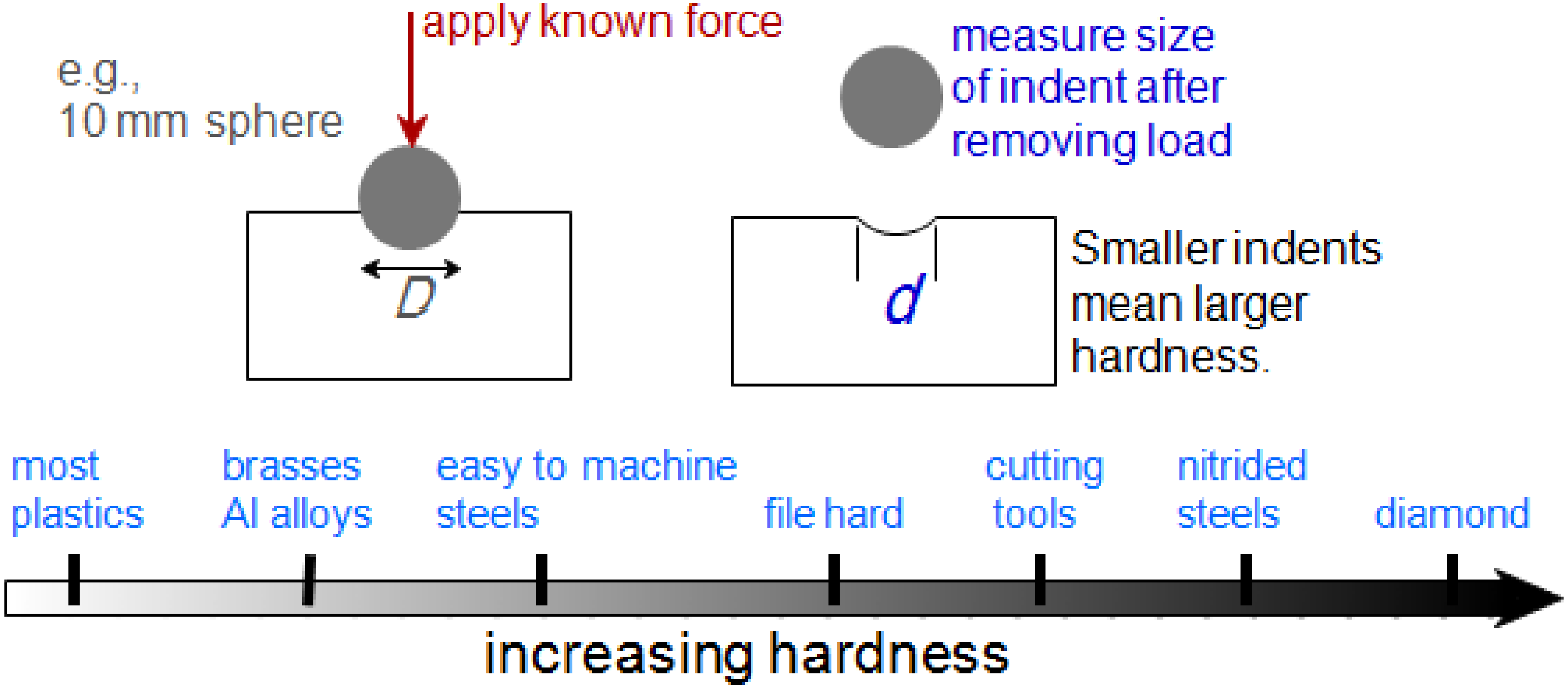
$$U_r \cong \frac{1}{2}\sigma_y \varepsilon_y$$

Elastic Strain Recovery



Hardness

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

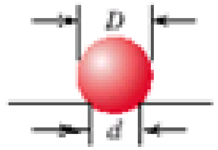
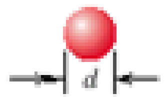
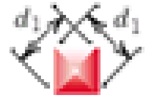
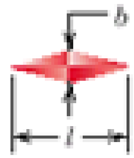
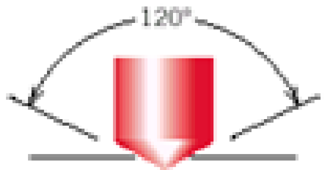
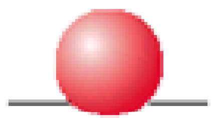
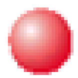
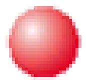


Hardness: Measurement

- Rockwell
  - No major sample damage
  - Each scale runs to 130 but only useful in range 20-100.
  - Minor load 10 kg
  - Major load 60 (A), 100 (B) & 150 (C) kg
    - A = diamond, B = 1/16 in. ball, C = diamond

- HB = Brinell Hardness
  - *TS* (psia) = 500 x HB
  - *TS* (MPa) = 3.45 x HB

Hardness: Measurement

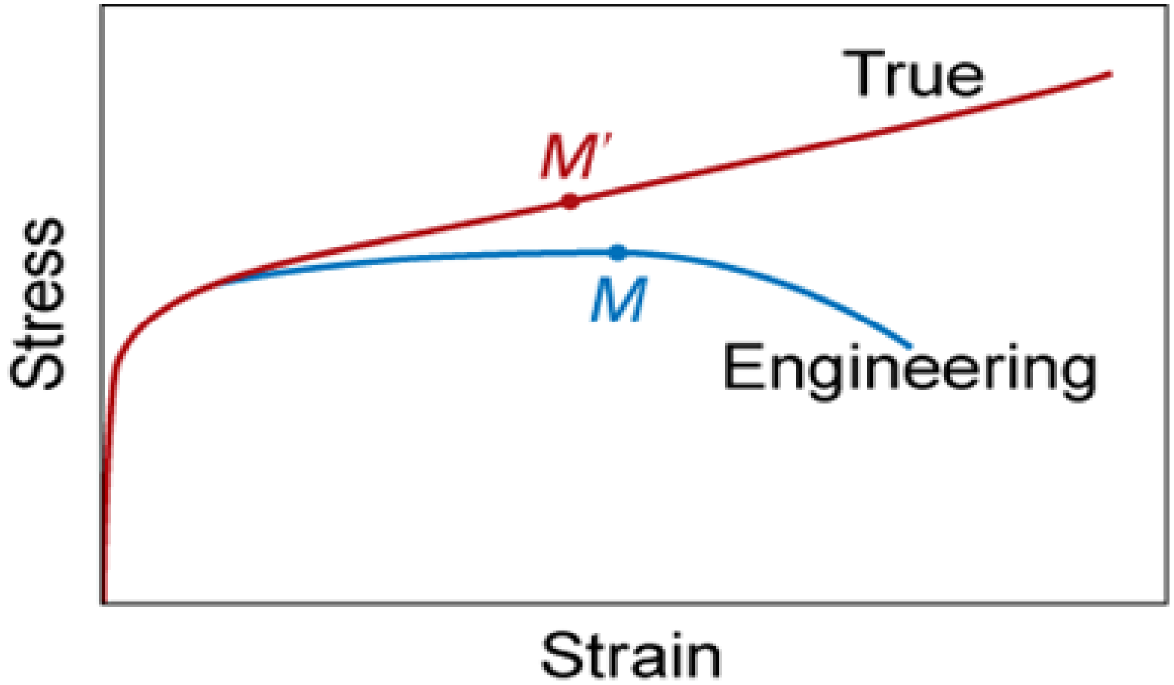
Test	Indenter	Shape of Indentation: Side View	Shape of Indentation: Top View	Load	Formula for Hardness Number[a]
Brinell	10-mm sphere of steel or tungsten carbide			P	$HB = \frac{2P}{\pi D[D - \sqrt{D^2 - d^2}]}$
Vickers microhardness	Diamond pyramid			P	$HV = 1.854P/d_1^2$
Knoop microhardness	Diamond pyramid			P	$HK = 14.2P/l^2$
Rockwell and Superficial Rockwell	Diamond cone; $\frac{1}{16}, \frac{1}{8}, \frac{1}{4}, \frac{1}{2}$ in. diameter steel spheres	 	 	60 kg, 100 kg, 150 kg } Rockwell 15 kg, 30 kg, 45 kg } Superficial Rockwell	

True Stress & Strain

Note: S.A. changes when sample stretched

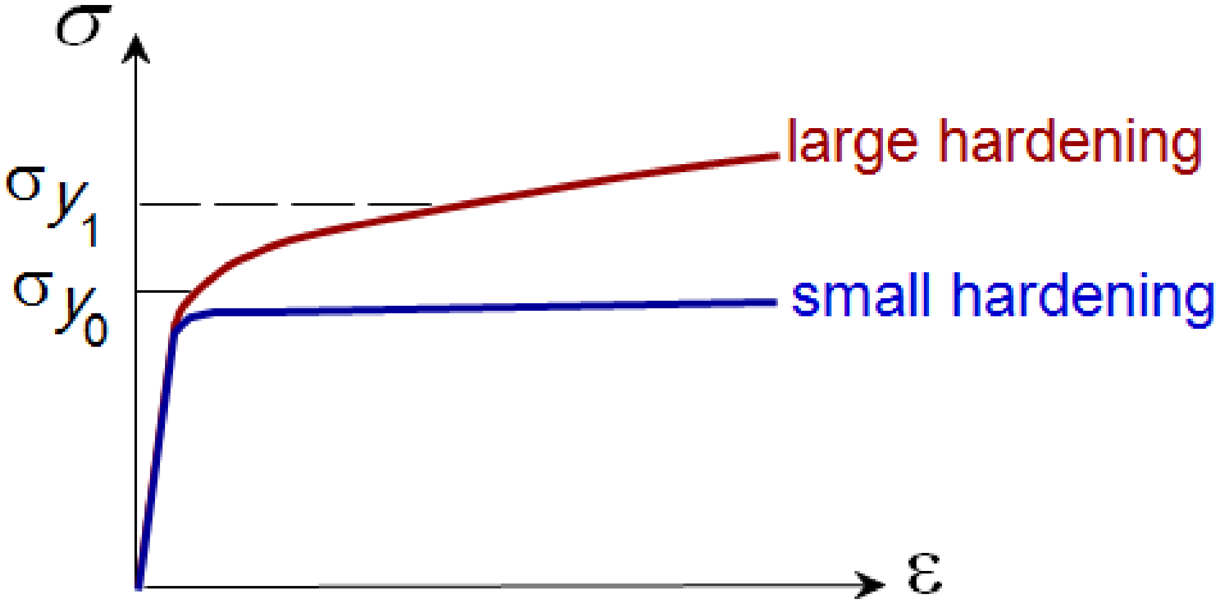
- True stress $\sigma_T = F/A_i$
- True Strain $\varepsilon_T = \ln(\ell_i/\ell_o)$

$$\sigma_T = \sigma(1+\varepsilon)$$
$$\varepsilon_T = \ln(1+\varepsilon)$$



Hardening

- An increase in σ_y due to plastic deformation.



- Curve fit to the stress-strain response:

$$\sigma_T = K(\varepsilon_T)^n$$

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

"true" stress (F/A)

"true" strain: $\ln(L/L_o)$

Variability in Material Properties

- Elastic modulus is material property
- Critical properties depend largely on sample flaws (defects, etc.). Large sample to sample variability.
- Statistics
  - Mean

$$\bar{x} = \frac{\overset{n}{\Sigma} x_n}{n}$$

  - Standard Deviation

$$s = \left[\frac{\overset{n}{\Sigma} (x_i - \bar{x})^2}{n-1} \right]^{\frac{1}{2}}$$

where n is the number of data points

Design or Safety Factors

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

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

Often *N* is between 1.2 and 4

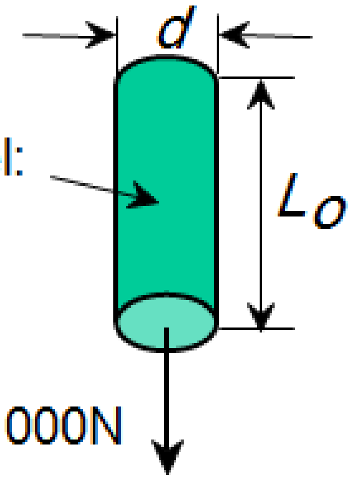
- Example: Calculate a diameter, *d*, to ensure that yield does not occur in the 1045 carbon steel rod below. Use a factor of safety of 5.

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

$$\frac{220{,}000N}{\pi\left(d^2/4\right)}$$

5

1045 plain carbon steel:
σ_y = 310 MPa
TS = 565 MPa



F = 220,000N

***d* = 0.067 m = 6.7 cm**