ENGG103 – Materials in Design

UNIVERSITY
OF WOLLONGONG
IN DUBAI

University of Wollongong in Dubai

ENGG103 – Materials in Design

Week 2: Lecture 2-Mechanical Properties of Materials

UNIVERSITY
OF WOLLONGONG
IN DUBAI

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Consultation hours:

Tuesday 12:30-15:30

Please email first for appointment.

LO1	Describe the structure, general properties and main applications of metals, polymers, ceramics and composites
LO2	Evaluate the main mechanical properties of materials from experimental data

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 does permanent deformation occur? What materials are most resistant to permanent deformation?
- Toughness and ductility: What are they and how do we measure them?

Mechanical Properties in Design

Mechanical properties determine a material's behaviour when subjected to mechanical stresses

- **Properties** include elastic modulus, ductility, hardness, strength, fatigue and fracture etc.

- **Dilemma**: mechanical properties that are desirable to the designer, such as high strength, usually make manufacturing more difficult

Young's modulus (E)

Young's modulus measures the resistance of a material to elastic (recoverable) deformation under load.

A ***stiff*** material has a **high Young's modulus** and changes its shape only slightly under elastic loads (e.g. diamond).

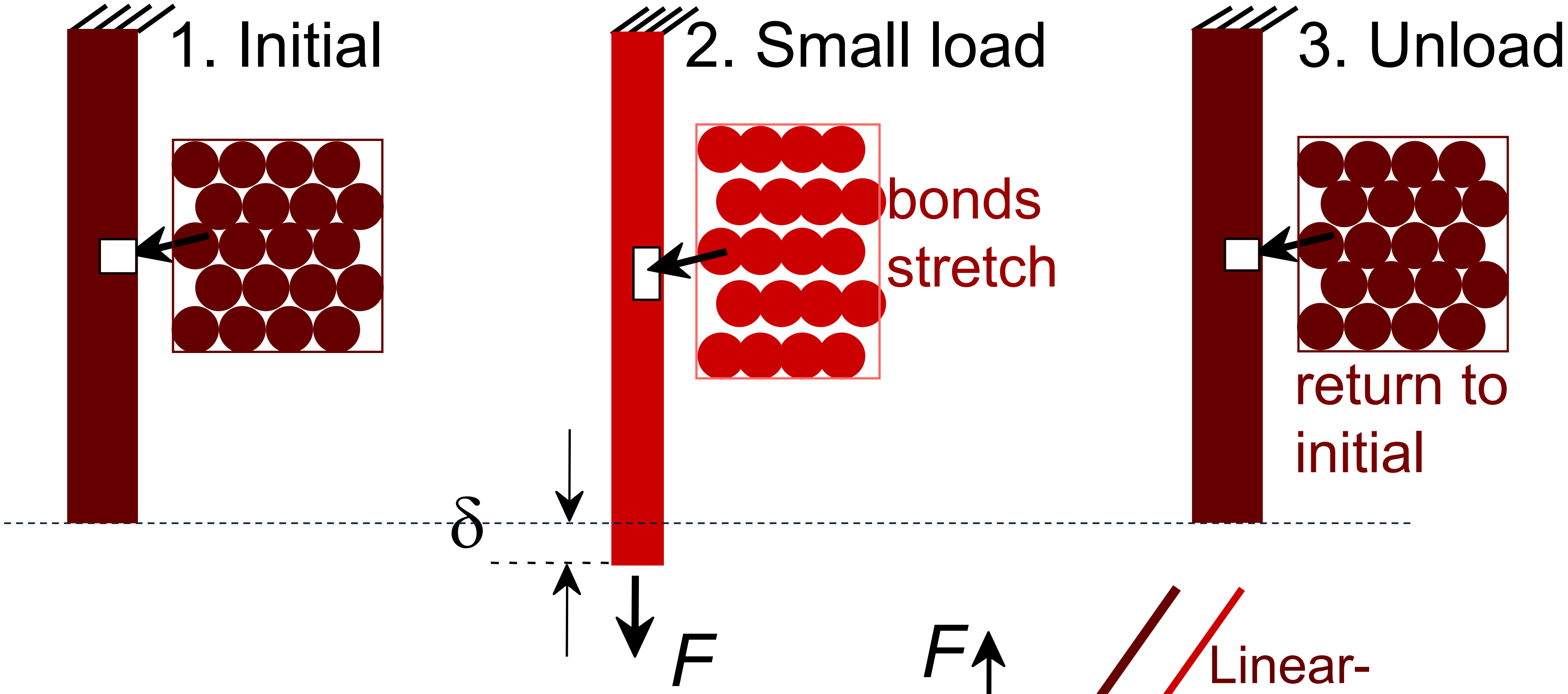
A ***flexible*** material has a **low Young's modulus** and changes its shape considerably (e.g. rubbers).

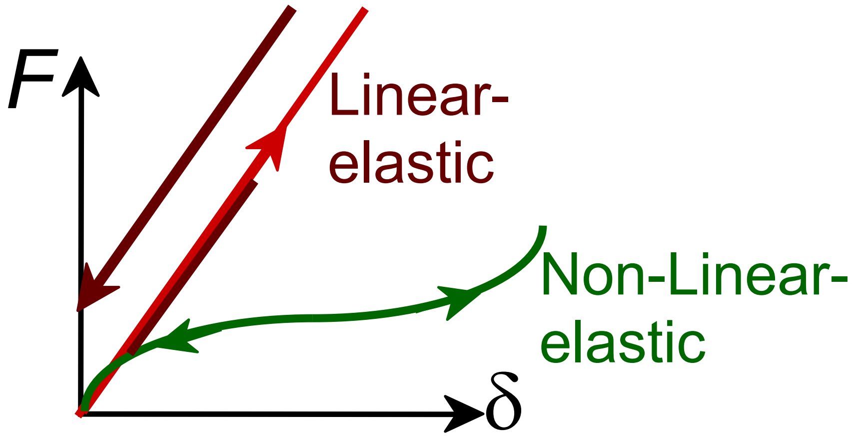
The stiffness of a component means how much it deflects under a given load.

Young’s Modulus is only meaningful in the range in which the stress is proportional to the strain.

It is the stiffness of the forces between the atoms that is being measured

Elastic Deformation

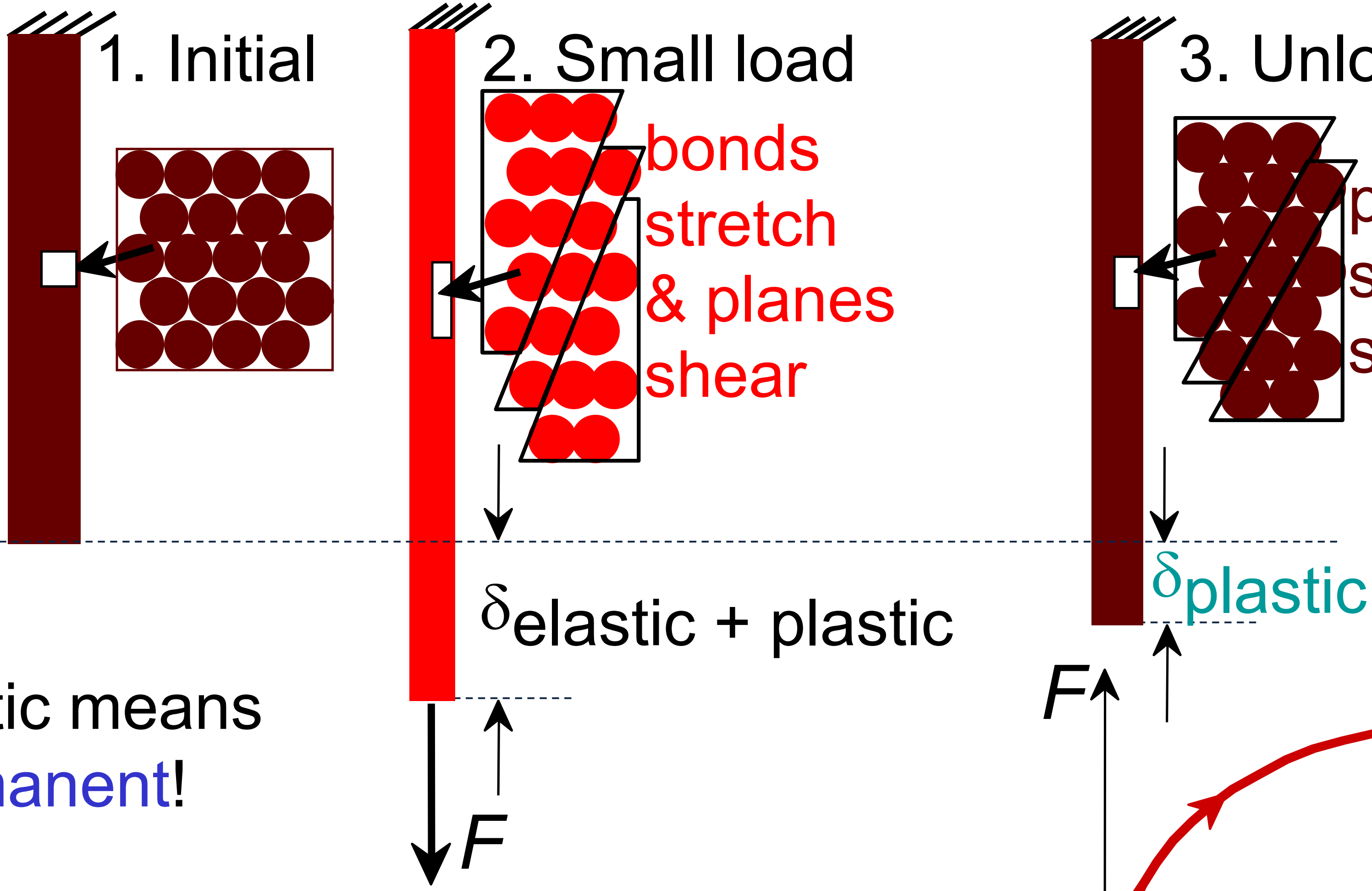




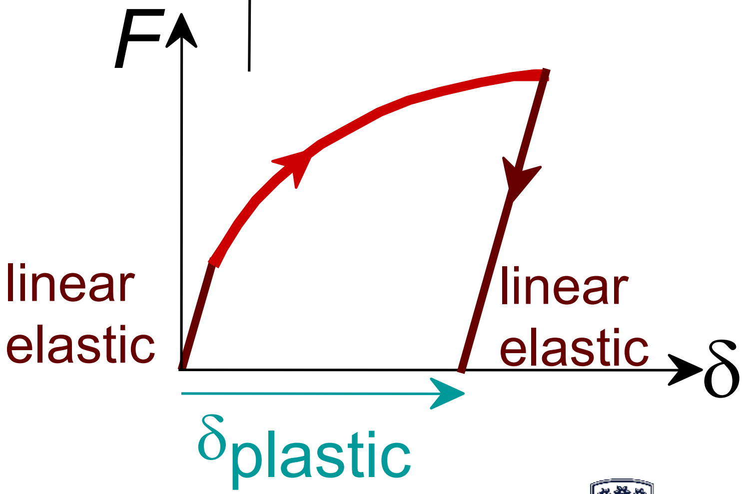
Elastic means reversible!

Elasticity: Ability of material to return to its original size, shape, and dimensions after being deformed

Plastic Deformation (Metals)



Plastic means permanent!



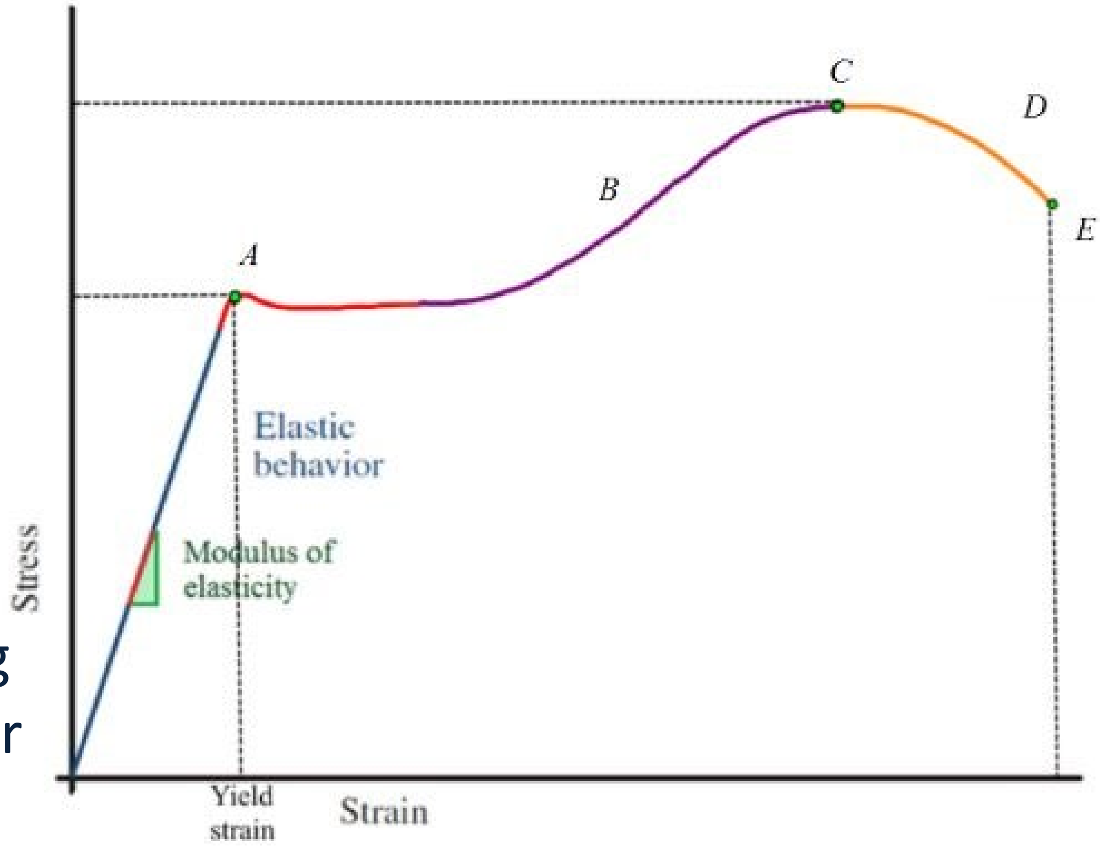
Plasticity: Property which enables a material to be deformed continuously and permanently without rupture

Plastic versus Elastic deformation

Stress-strain curve

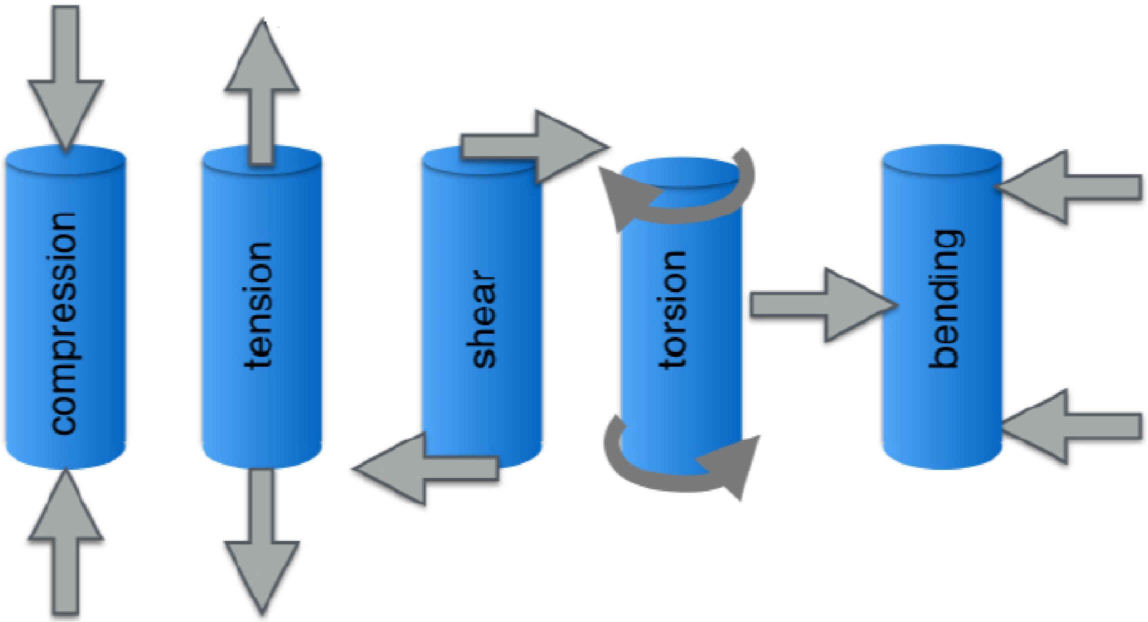
- **Elastic** deformations of a solid are entirely recoverable once the stress is removed
- **Plastic** deformation of a solid are permanent

- A yield strength or **yield point (A)** is the material property defined as the stress at which a material begins to deform plastically.
- **Ultimate tensile strength (C),** often shortened to **tensile strength** or **ultimate strength**, is the maximum **stress** that a material can withstand while being stretched or pulled before failing or breaking.



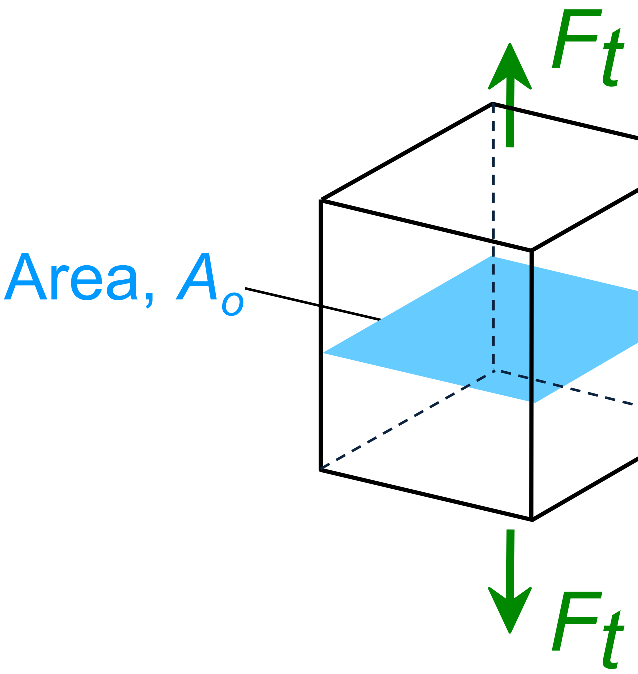
COMMON STRESS STATES

- All structures or parts are subject to loads during service. These external loads in turn result in opposing internal reaction forces (ENGG102).
- To ensure that a structure can withstand the applied external loads and resultant internal reaction forces, the design engineer must ensure that it has sufficient **strength** and **stiffness** to prevent failure, excessive deformation or displacement during service.



Engineering Stress

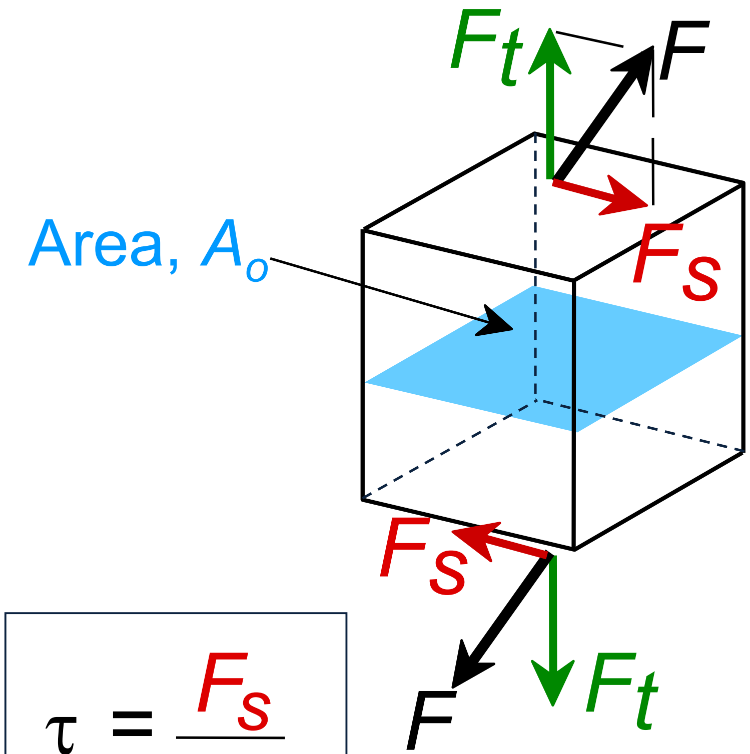
- Tensile stress, σ:



$$\sigma = \frac{F_t}{A_o} \quad \frac{\text{N}}{\text{m}^2}$$

original area before loading

- Shear stress, τ:

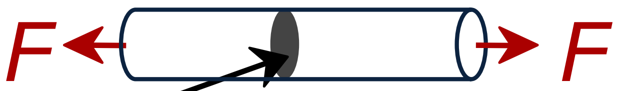


$$\tau = \frac{F_s}{A_o}$$

$\therefore$ Stress has units: N/m^2

Common States of Stress

- **Simple tension: cable**

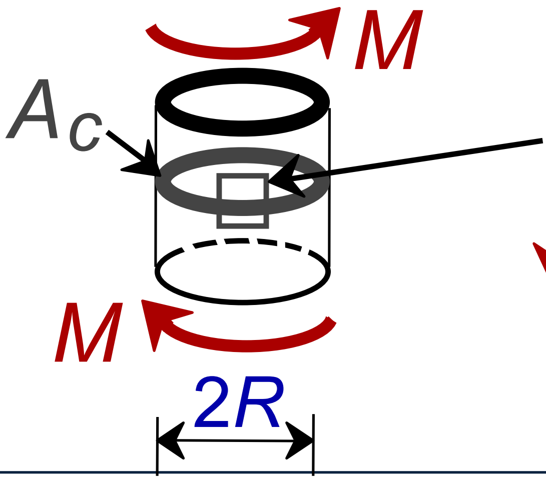


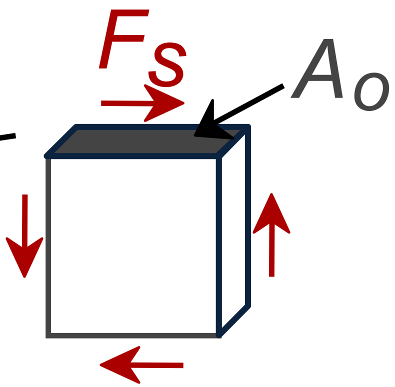
A_o = cross sectional area (when unloaded)

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

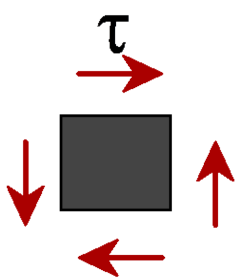
Ski lift (photo courtesy P.M. Anderson)

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



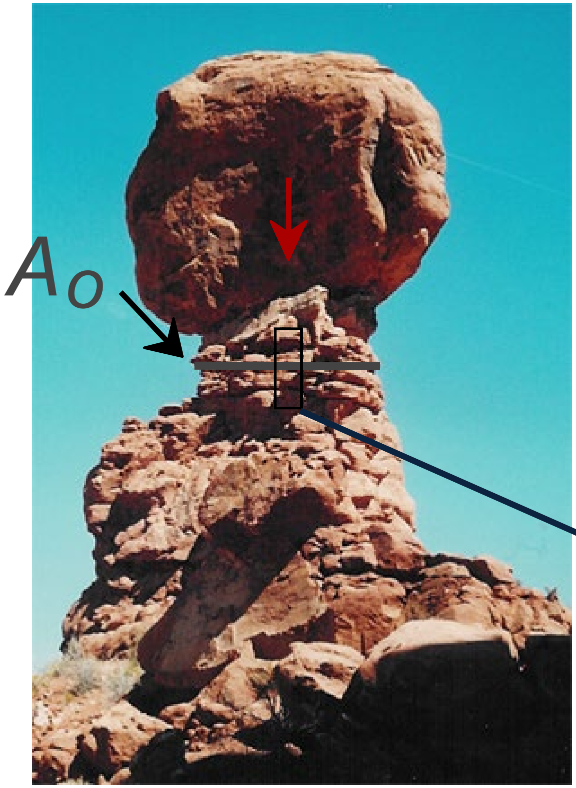


$$\tau = \frac{F_s}{A_o}$$



OTHER COMMON STRESS STATES (i)

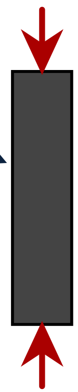
- **Simple compression**:



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

COMMON STRESS STATES

BENDING:

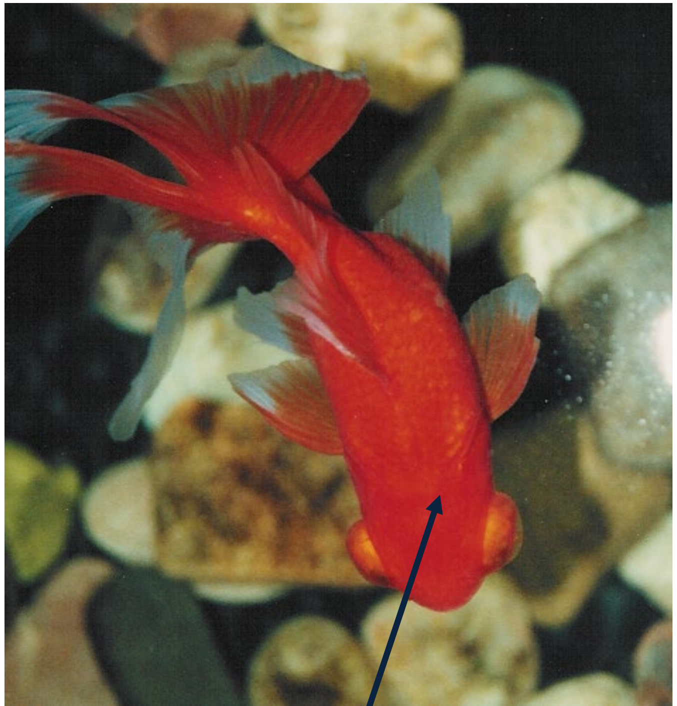
Girders loaded in bending

Bending generates both tensile and compressive forces in structural members.

OTHER COMMON STRESS STATES (ii)

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

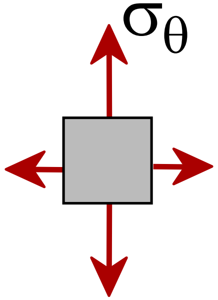
Pressurized tank
(photo courtesy
P.M. Anderson)



Fish under water

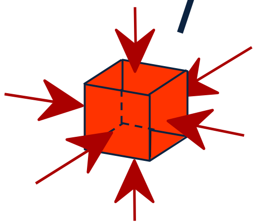
(photo courtesy
P.M. Anderson)

$\sigma_\theta > 0$



$\sigma_z > 0$

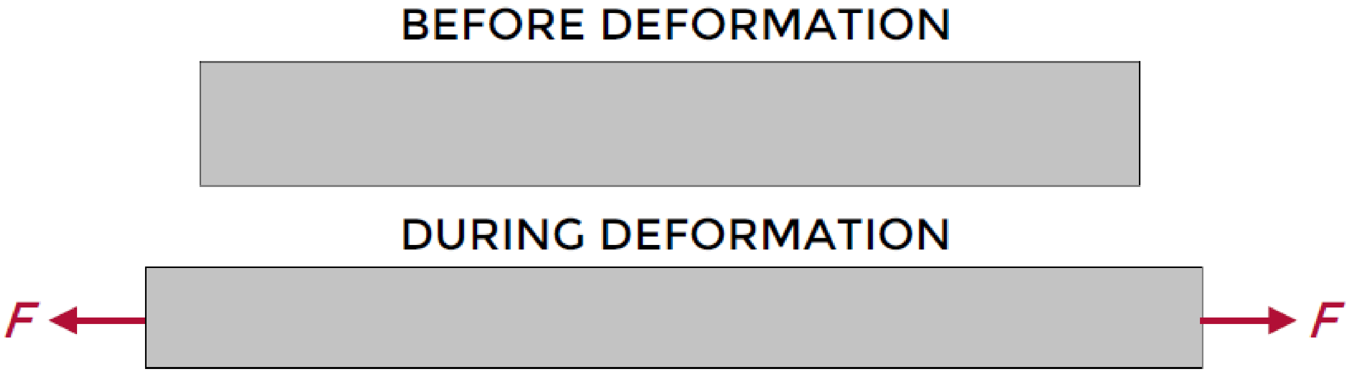
$\sigma_h < 0$



DEFORMATION IN METALS

When a metal is subjected to a tensile force, the metal stretches or deforms under the influence of the applied load.

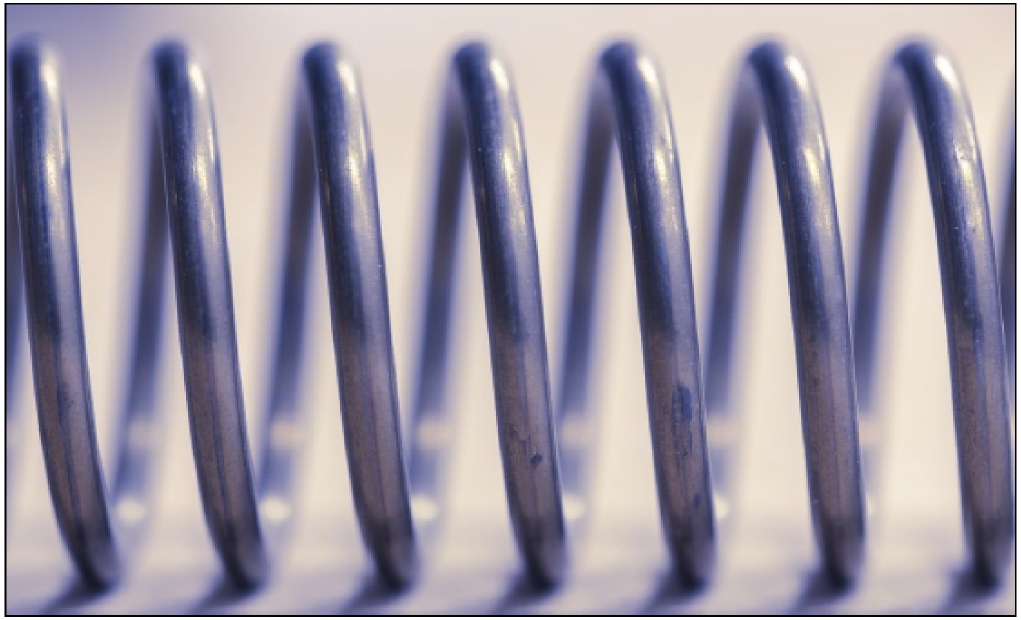
- Small amounts of deformation result in **elastic deformation**:
  - Deformation is fully recovered after the load is removed.
  - Object returns to its original dimensions.
- Larger amounts of deformation result in **plastic deformation**:
  - Deformation is permanent and not recovered after the load is removed.
  - Object dimensions are permanently altered.



DEFORMATION IN METALS

ELASTIC DEFORMATION:

- Bonds between atoms act like springs or rubber bands.
- On the atomic scale elastic deformation is related to **stretching bonds**.
- When the object is unloaded, it returns to its original dimensions.
- Elastic deformation is therefore **reversible**.



DEFORMATION IN METALS

PLASTIC DEFORMATION:

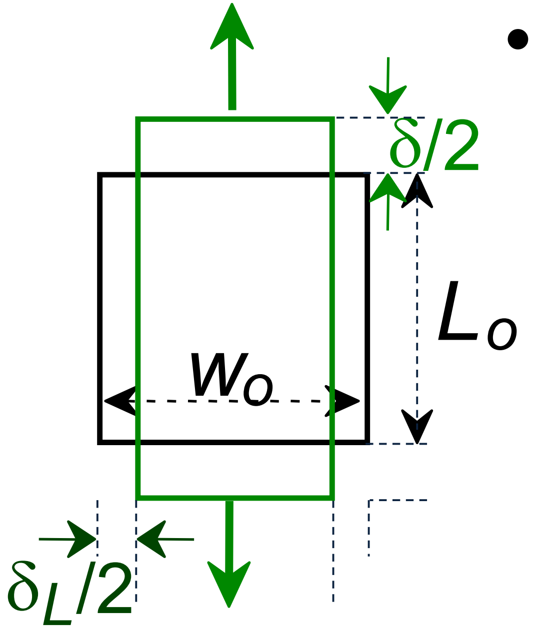
On the atomic scale plastic deformation is related to **breaking bonds** between atoms or molecules.

- Breaking and reforming of atomic bonds disrupt the atomic structure.
- This produces a net change in shape → plastic deformation.
- Many broken bonds gives macro scale **permanent deformation**.

Engineering Strain

- **Tensile strain:**

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



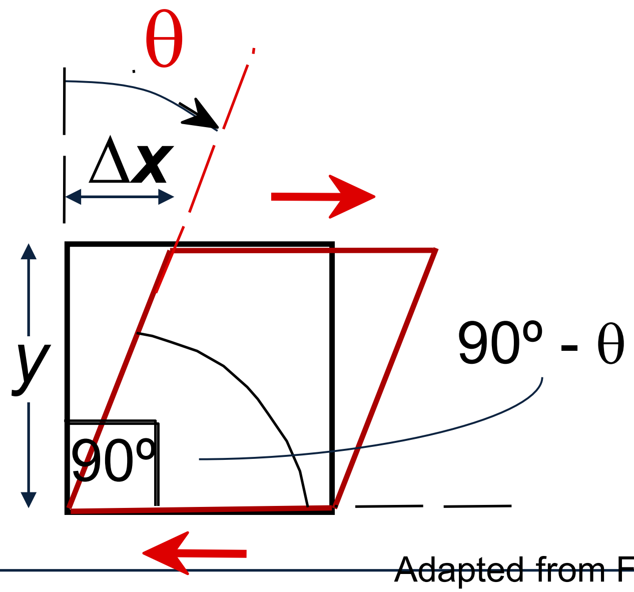
- **Lateral strain:**

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

$$\text{Strain} = \frac{\text{Displacement}}{\text{Length}}$$

$$\epsilon = \frac{\Delta l}{l}$$

- **Shear strain:**



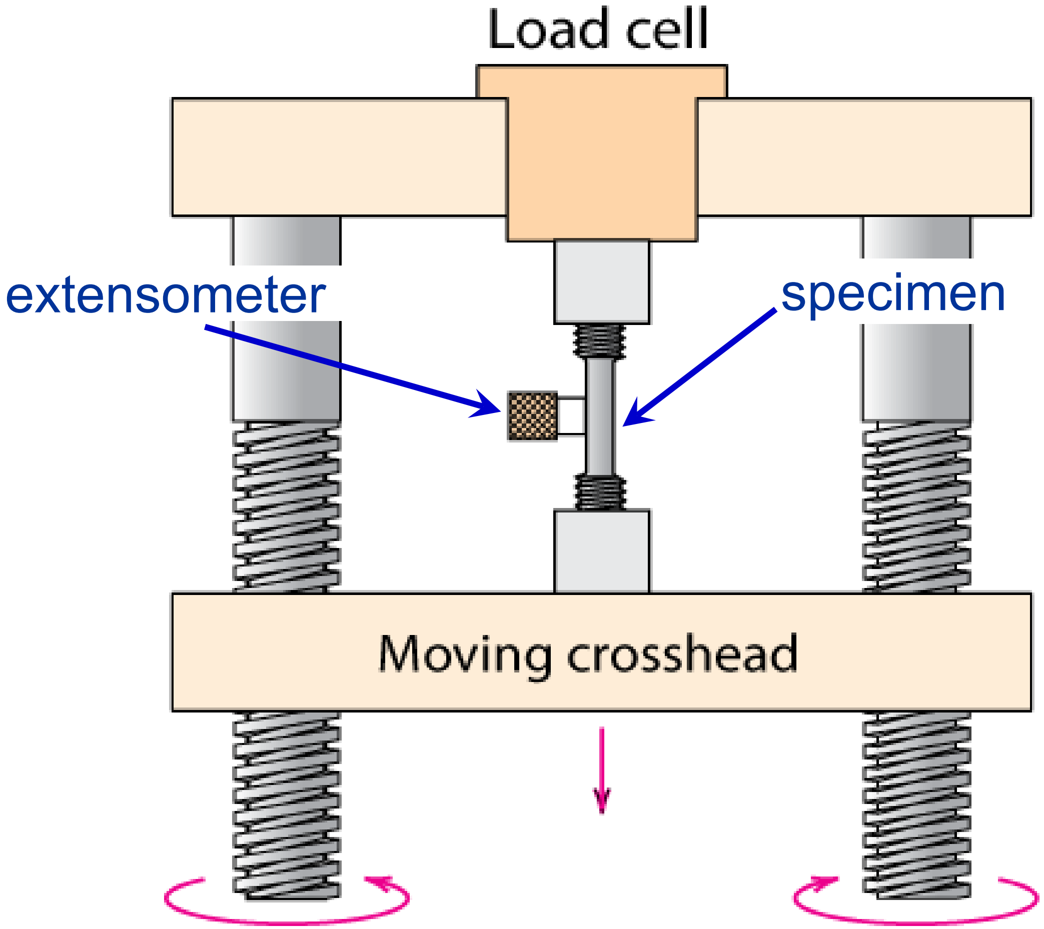
$$\gamma = \Delta x / y = \tan \theta$$

Strain is always dimensionless.

Adapted from Fig. 6.1(a) and (c), *Callister & Rethwisch 8e.*

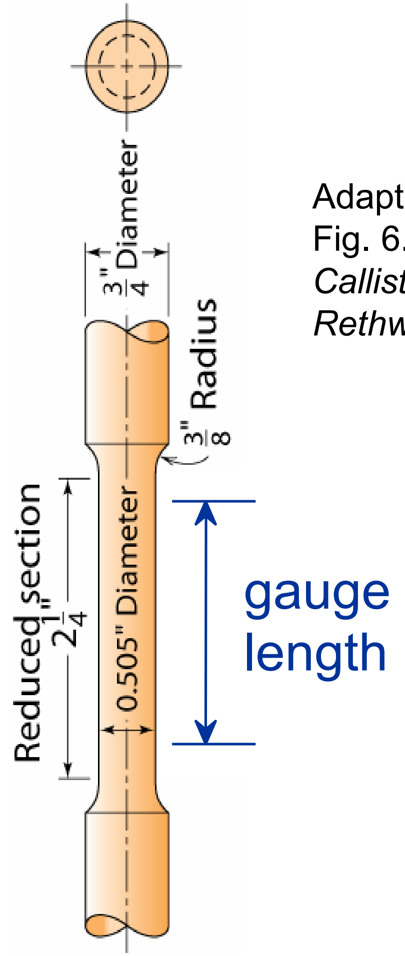
Stress-Strain Testing

- **Typical tensile test machine**



Adapted from Fig. 6.3, *Callister & Rethwisch 8e.* (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.)

- **Typical tensile specimen**



Adapted from Fig. 6.2, *Callister & Rethwisch 8e.*

Mechanical Properties – Young's Modulus

- Mechanical deformation puts energy into a material. The energy is stored elastically or dissipated plastically

Elastic Deformation is recovered immediately upon unloading

Plastic Deformation is **not** recovered upon unloading therefore is permanent

When a material deforms elastically, strain for a given stress is always the same and the two are related by **Hooke´s Law** (stress is directly proportional to strain):

$$\sigma = E . \varepsilon$$

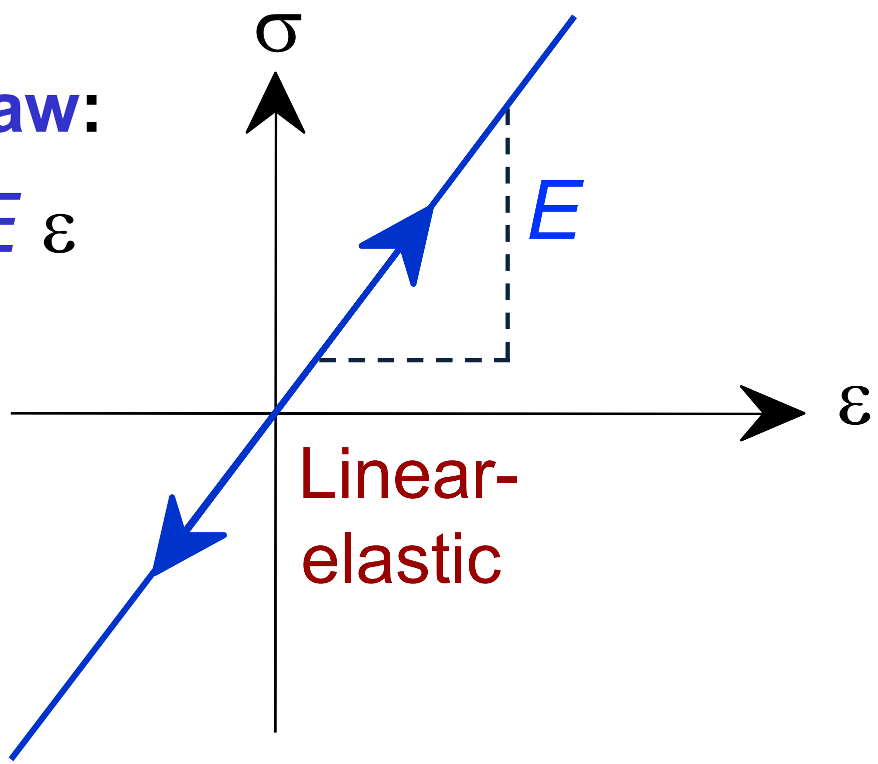
Stress = (Young's Modulus) . (Strain)

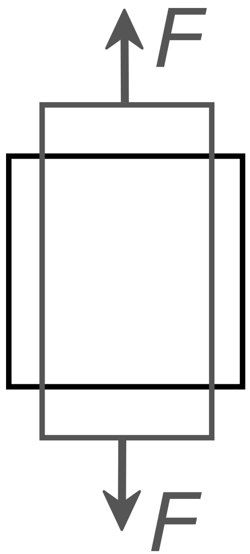
Linear Elastic Properties

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

- **Hooke's Law:**

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





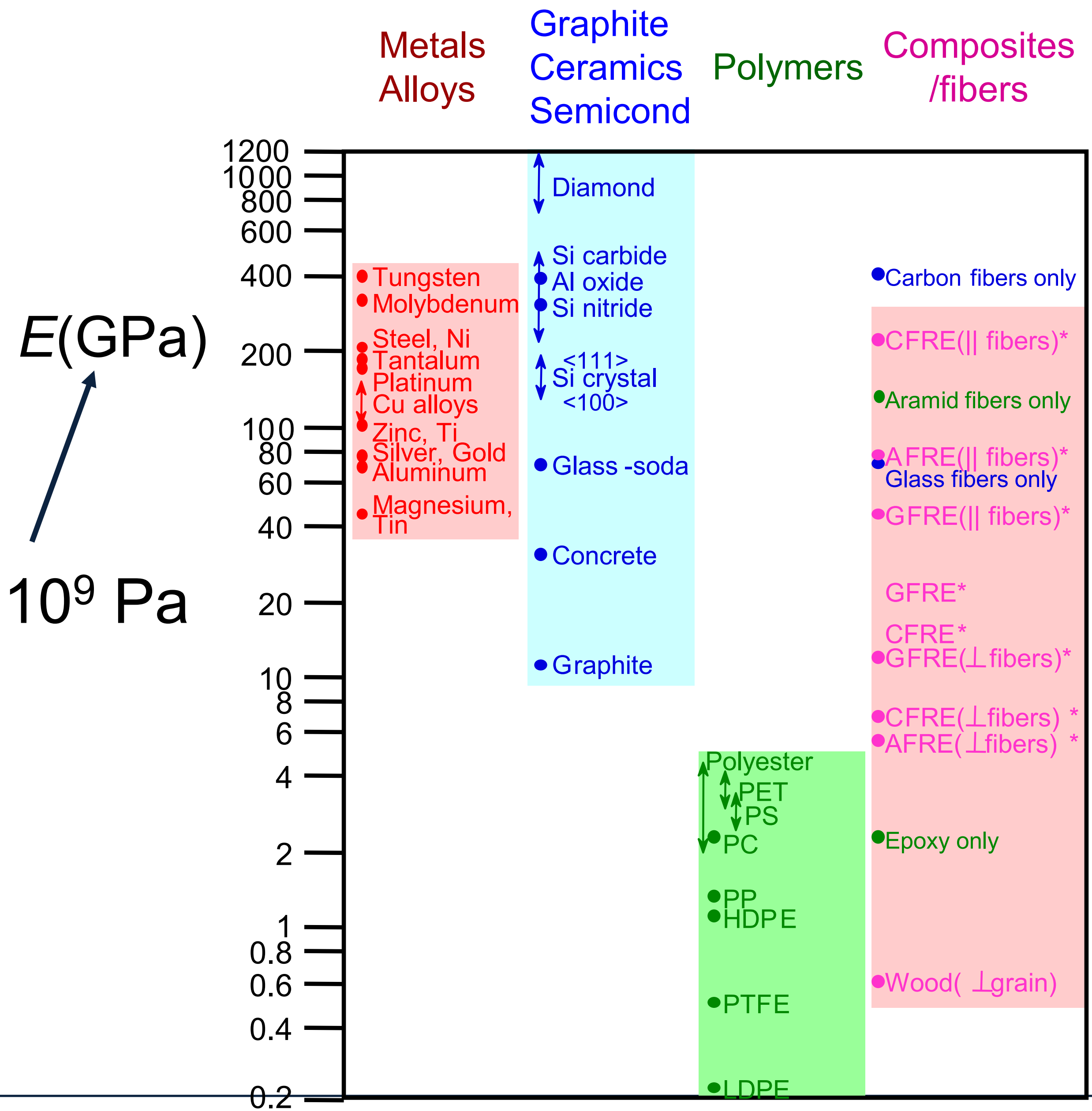
Mechanical Properties -The Elastic Modulus

Modulus of Elasticity (E) is a materials **resistance to being deformed elastically** when a stress is applied to it

Material	Youngs Modulus /GPa
Mild Steel	210
Copper	120
Bone	18
Plastic	2
Rubber	0.02

- Low modulus = floppy, stretch when pulled e.g. **Rubber band**
- High modulus = opposite, stiff e.g. **Mild Steel**

Young’s Moduli: Comparison



Based on data in Table B.2,
Callister & Rethwisch 8e.
Composite data based on reinforced epoxy with 60 vol% of aligned
carbon (CFRE),
aramid (AFRE), or
glass (GFRE)
fibers.

LINEAR ELASTIC PROPERTIES

EXAMPLE:

A steel cable has a length of 30 m and a diameter of 50 mm. What is the change in length when a tensile load of 100 kN is applied to the cable? Young's modulus of steel is 200 GPa. Assume elastic deformation.

$$\sigma = \frac{F}{A} = \frac{100 \times 10^3 \text{ N}}{\frac{\pi}{4}(50 \times 10^{-3} \text{ m})^2} = 51 \text{ x } 10^6 \text{ Pa} = \mathbf{51\ MPa}$$

Apply Hooke's law:

$$E = \frac{\sigma}{\varepsilon} \qquad \therefore \varepsilon = \frac{\sigma}{E} = \frac{51 \times 10^6 \text{ Pa}}{200 \times 10^9 \text{ Pa}} = \mathbf{2.55 \times 10^{-4}}$$

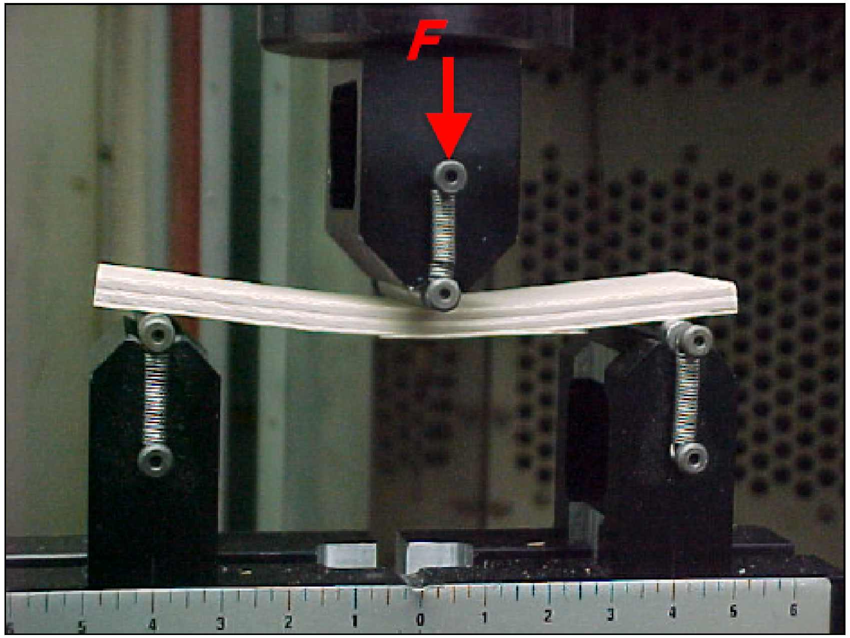
$$\varepsilon = \frac{\Delta l}{l}$$

$$\therefore \Delta l = l\varepsilon = (30 \text{ m})(2.55 \times 10^{-4}) = \mathbf{7.65\ mm}$$

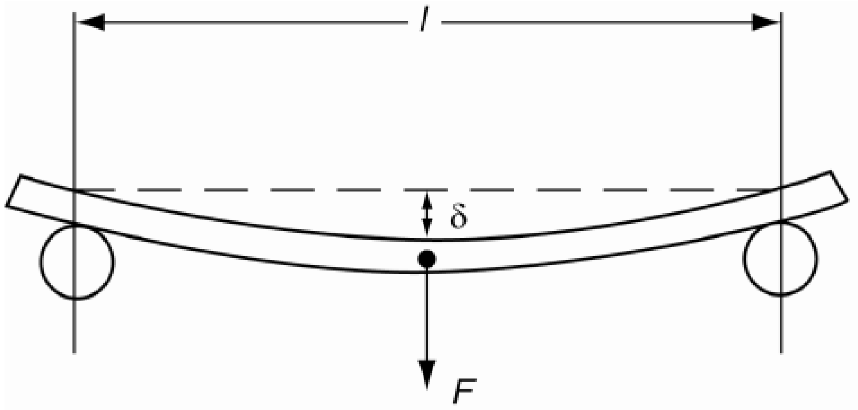
LINEAR ELASTIC PROPERTIES

YOUNG'S MODULUS (*E*):

A **Three Point Bend Test** is often used to measure the elastic modulus of brittle materials such as concrete or glass. These materials tend to break when placed in the grips of a tensile tester.



Three-point bend test



$$\delta = \frac{1}{48}\left(\frac{F l^3}{EI}\right)$$

where: δ is the amount of deflection during bending,
F is the applied force,
L is the length of the beam between the supports,
E is Young's modulus, and
I is the second moment of area.

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Stop and check videos on moodle

Lecture 2: Stop and Check videos

- **Stress and strain**
- **Young's Modulus**
- **Elastic and non elastic materials**

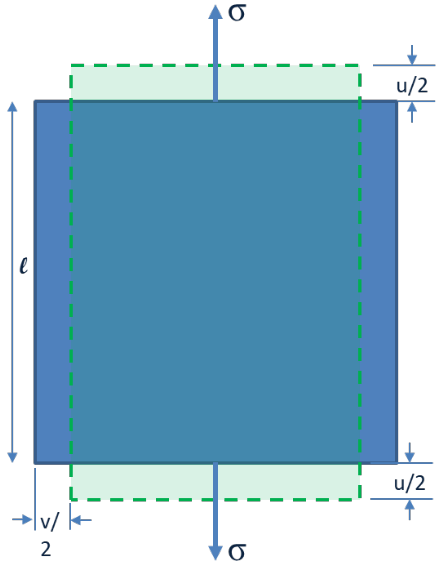
Poisson's ratio, ν

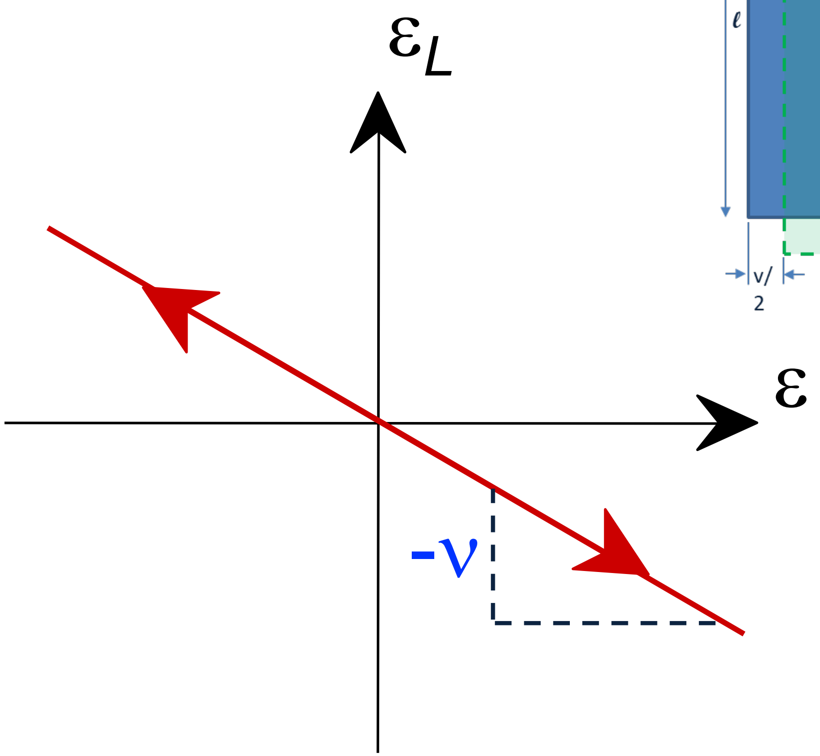
- **Poisson's ratio, ν:**

Lower case Greek letter 'nu' **ν**

$$\upsilon = -\frac{\text{lateral strain}}{\text{tensile strain}}$$

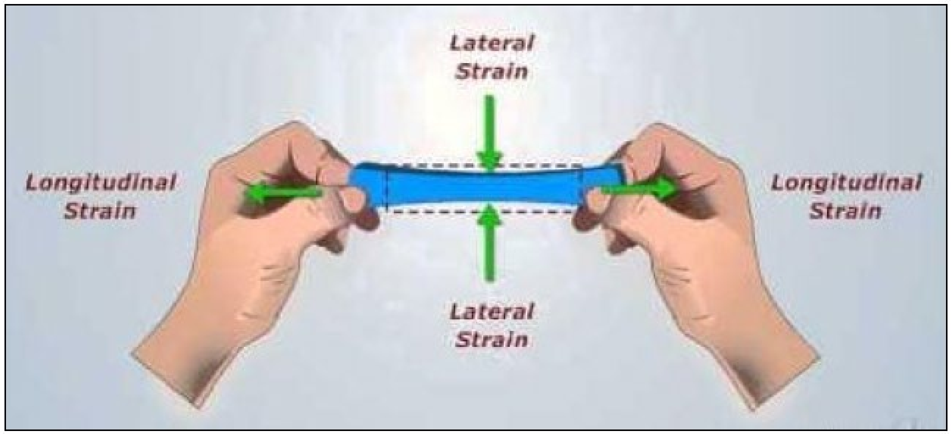
$$\nu = -\frac{\varepsilon_L}{\varepsilon}$$

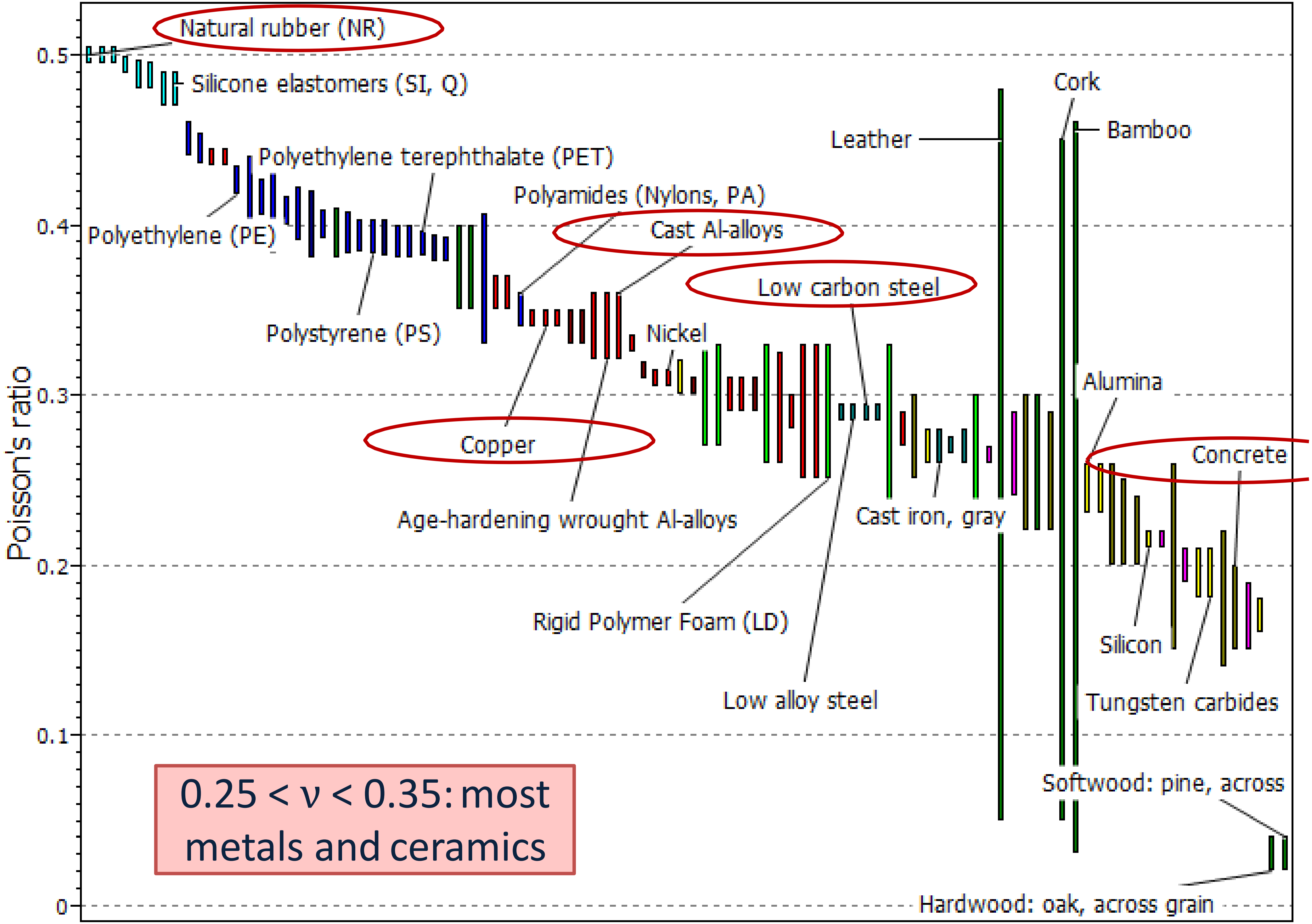




metals: ν ~ 0.33
ceramics: ν ~ 0.25
polymers: ν ~ 0.40

Units:
E: GPa
ν: dimensionless



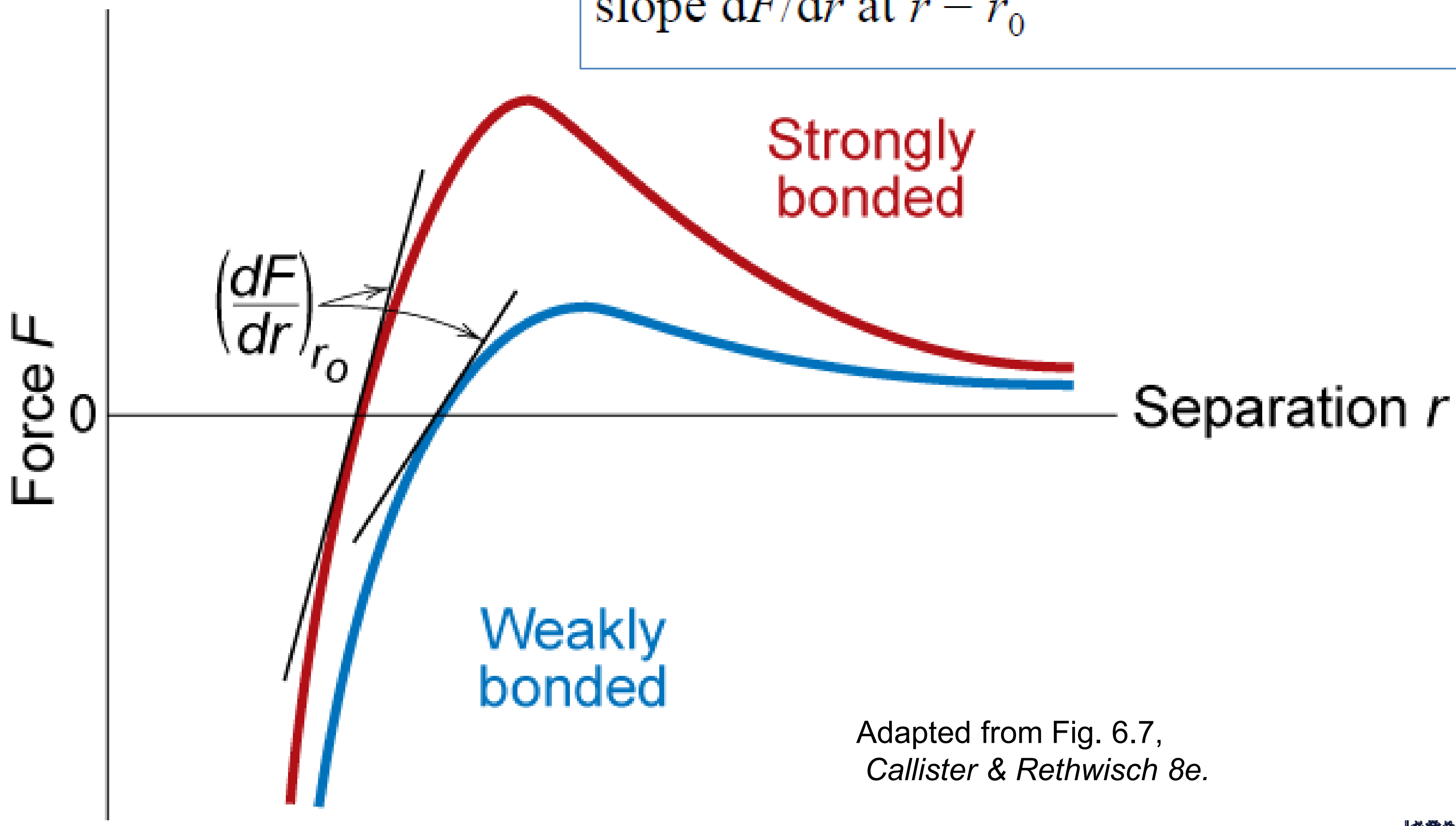


0.25 < ν < 0.35: most metals and ceramics

Mechanical Properties

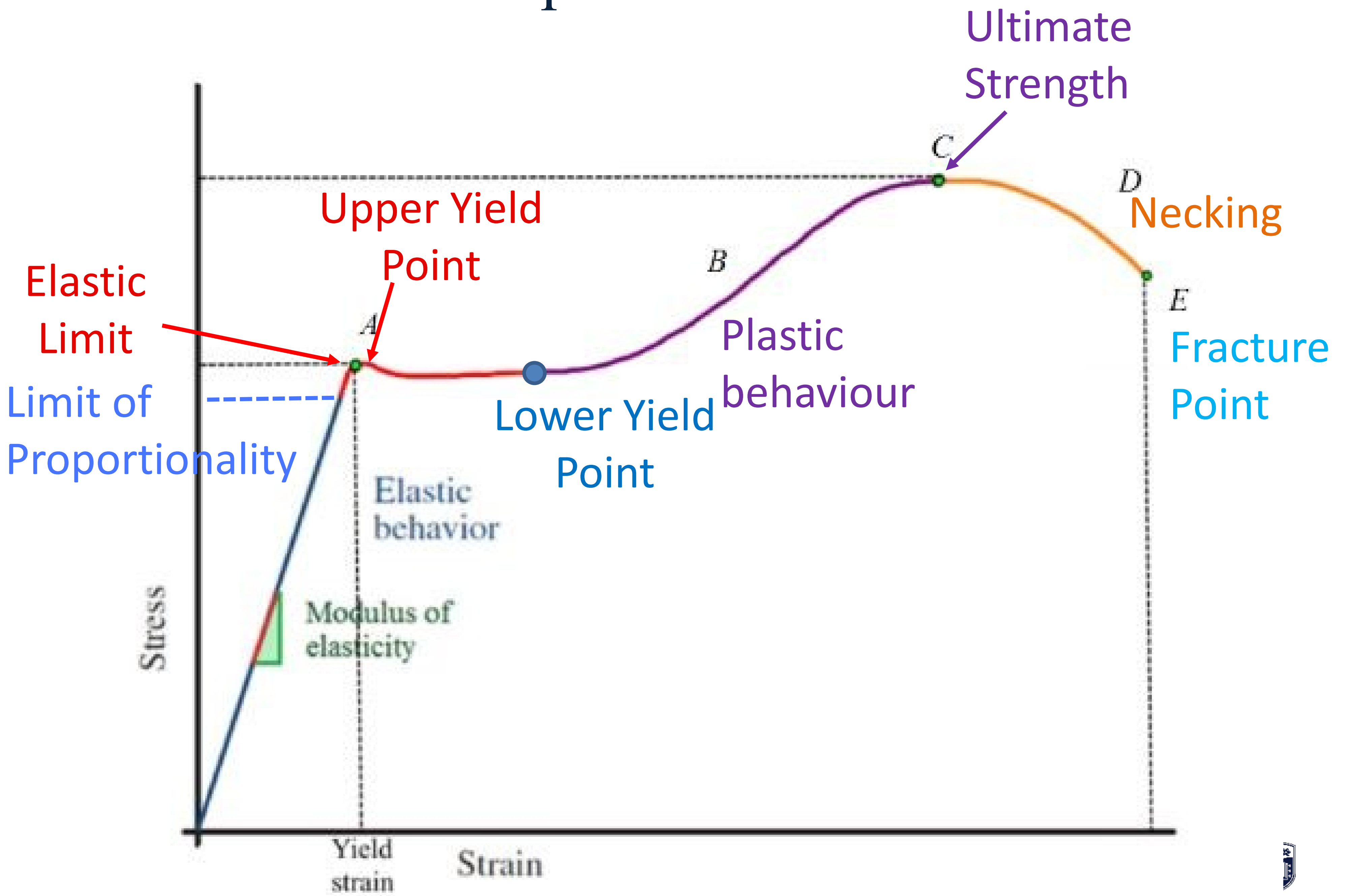
- Slope of stress strain plot (which is proportional to the elastic modulus) depends on bond strength of metal

Young's modulus (E) is proportional to the slope dF/dr at $r = r_0$



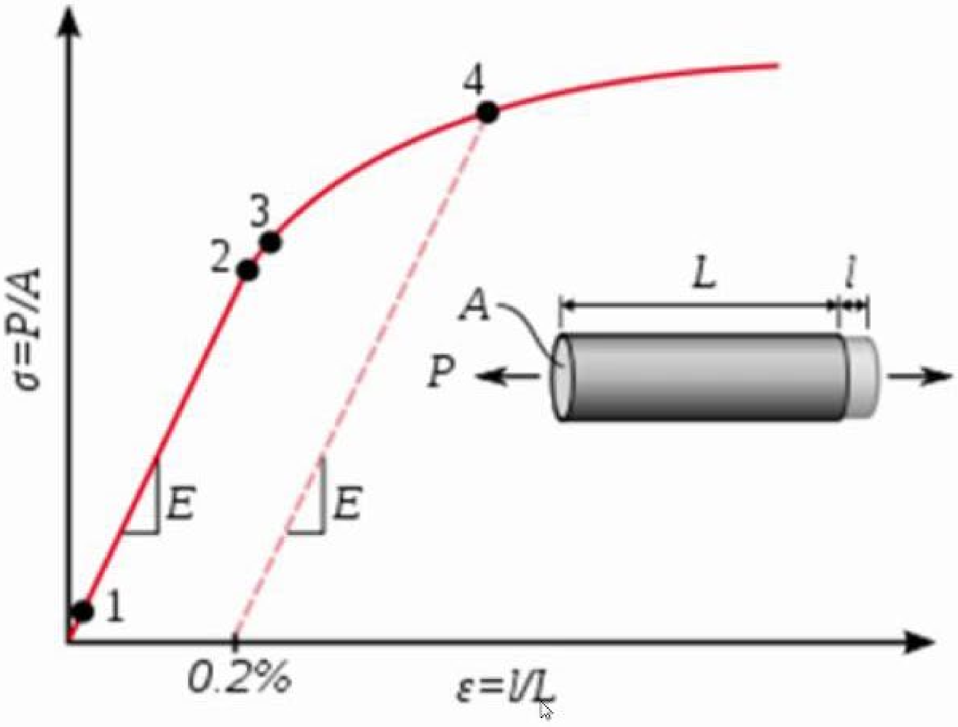
Adapted from Fig. 6.7, *Callister & Rethwisch 8e.*

Mechanical Properties – Stress-Strain curve



Mechanical Properties – Stress-Strain curve

Values



1 - 2) Elastic Region
Modulus

2) Proportional Limit

3) Yield Strength

4) Yield Strength at
0.2% Offset

Mechanical Properties – Young’s Modulus

- Young’s modulus is a measure of the material’s resistance to deformation.

- Young’s modulus quantifies how much stress is required to generate a given strain.

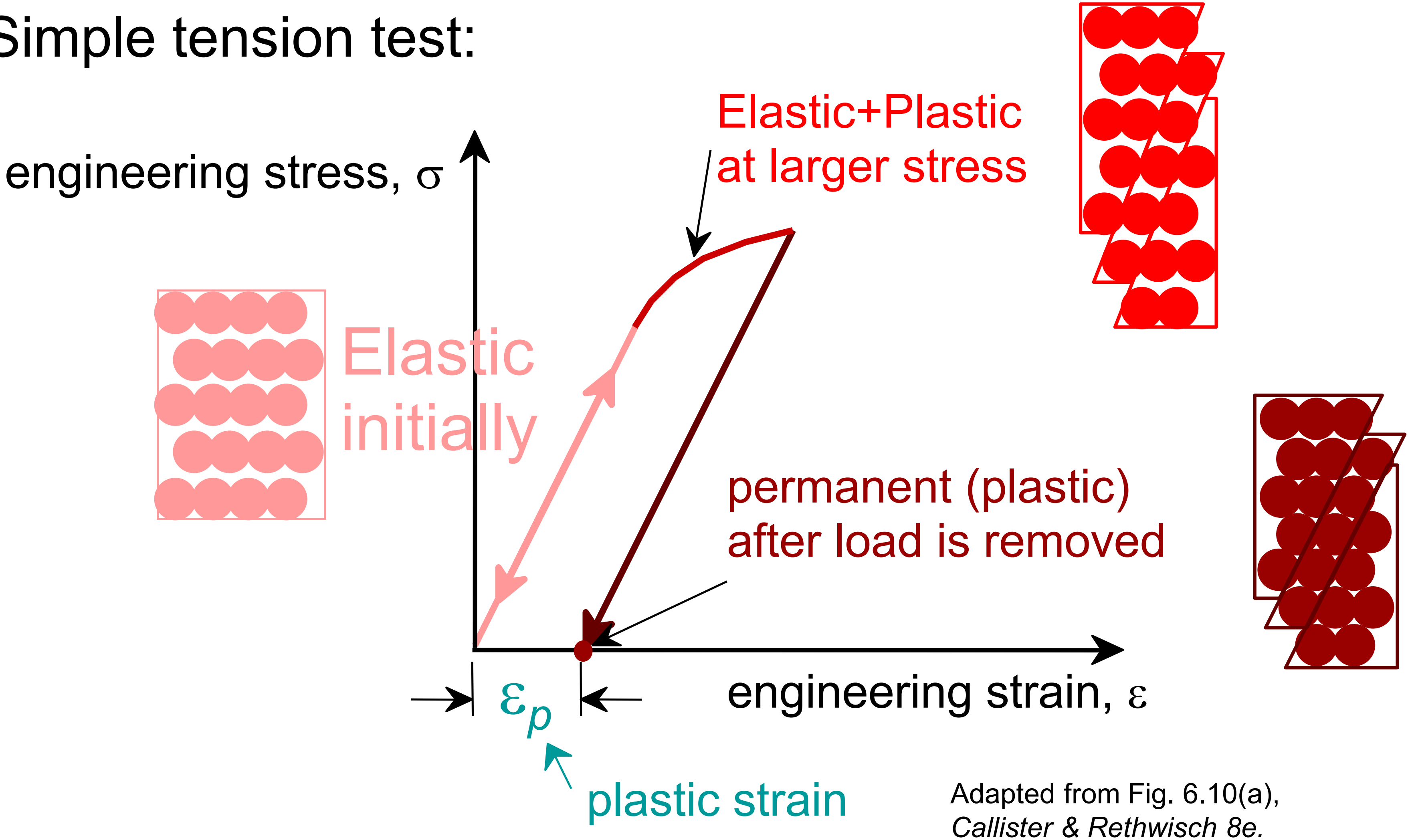
- It does not depend upon the size or shape of the object, but only the material the object is composed of.

- Copper has a modulus of 120 x 10^9 Pa. (120GPa)
- Steel has a modulus of 210 x 10^9 Pa. (210 GPa)

- Thus, steel is more resistant to deformation then is copper.

Plastic (Permanent) Deformation

- Simple tension test:



Adapted from Fig. 6.10(a), *Callister & Rethwisch 8e.*

SUMMARY

- Materials are subjected to a variety of loading conditions in service. It is of vital importance that these materials have sufficient **strength** and **stiffness** to resist the forces imposed without failing or undergoing excessive deformation.
- Depending on the magnitude of the applied stress, metals can undergo **elastic** (reversible) deformation or **plastic** (permanent) deformation.
- **Hooke's law** describes the relationship between stress and strain during elastic deformation.
- **Young's modulus** is a measure of a material's stiffness (resistance to deflection and deformation).
- Young's modulus is determined by the **atomic bond strength** in the material.

Stop and check videos on moodle

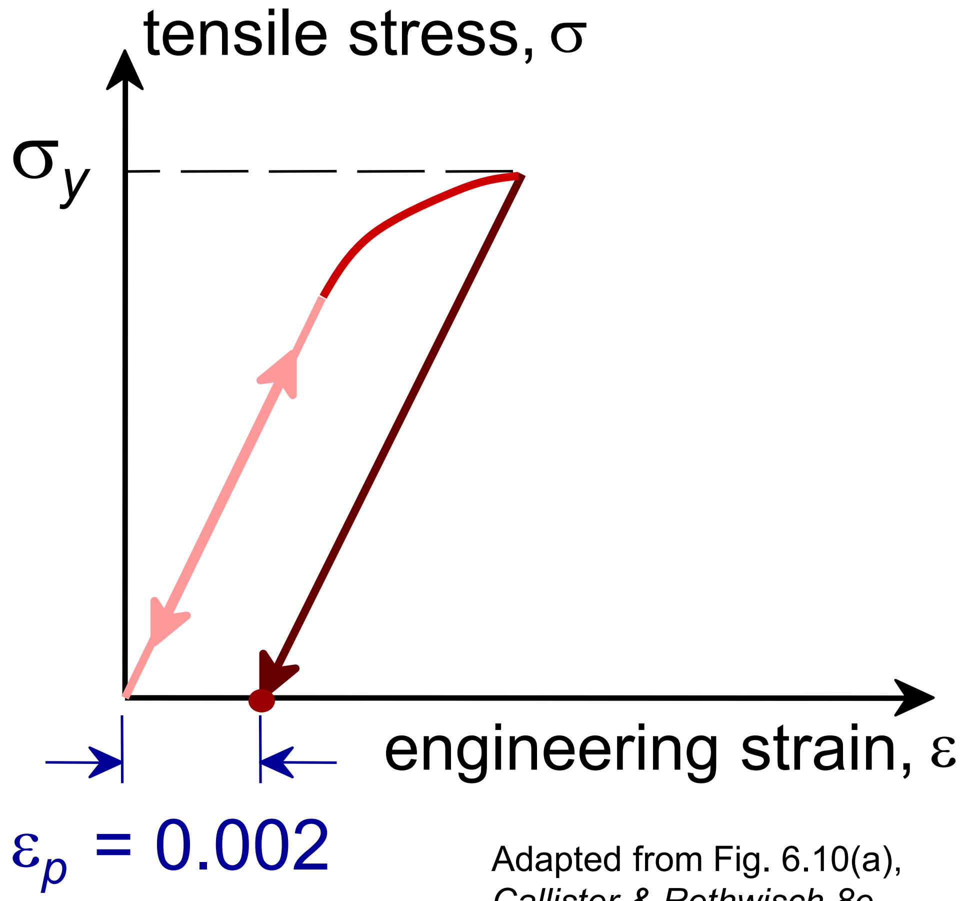
Lecture 2: Stop and Check videos

- **Understanding Poisson's ratio**

Yield Strength, σ_y

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

when $\varepsilon_p = 0.002$



Adapted from Fig. 6.10(a), *Callister & Rethwisch 8e.*

σ_y = yield strength

Note: for 50mm sample

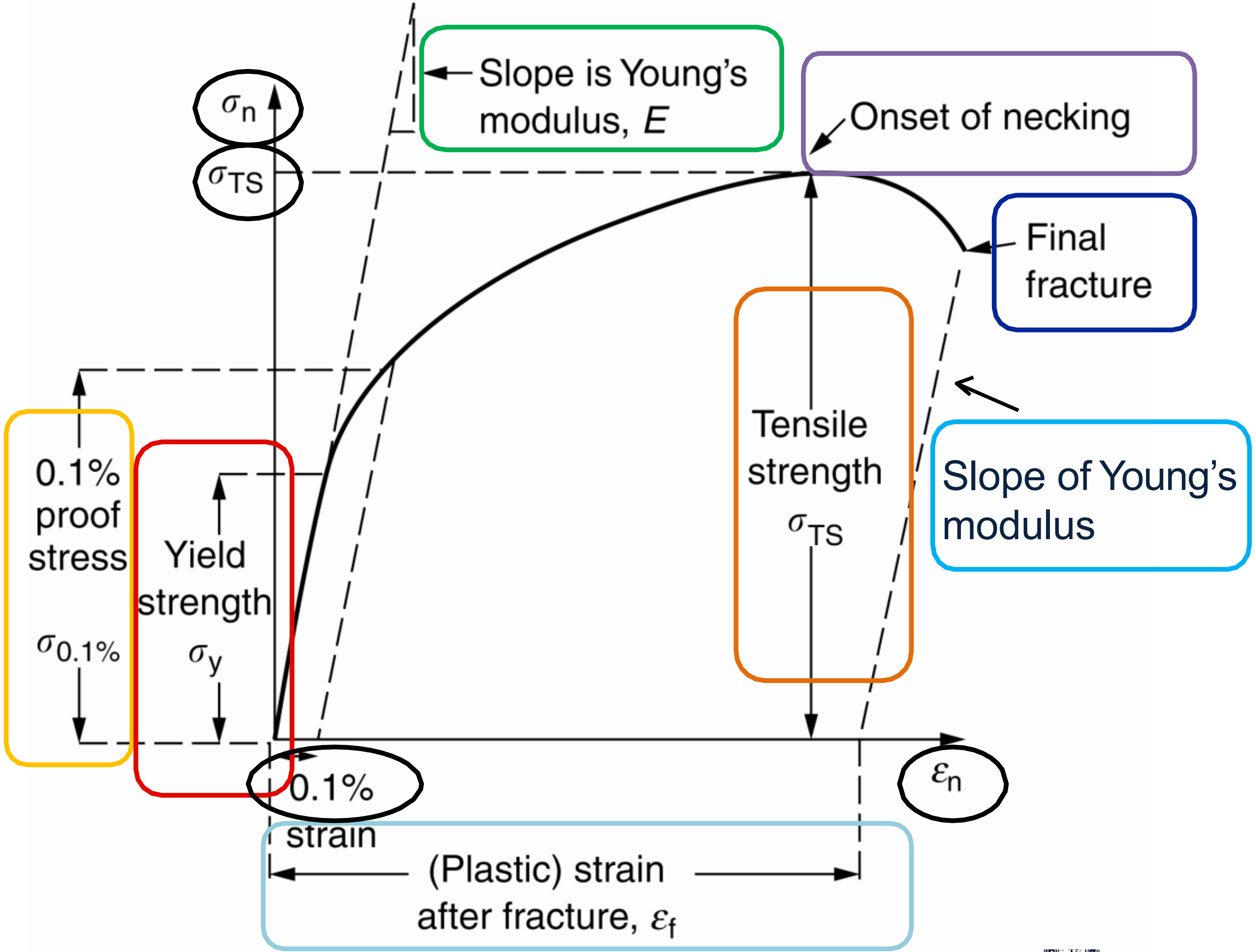
$$\varepsilon = 0.002 = \Delta z/z$$

$$\therefore\ \Delta z = 0.1 \text{ mm}$$

Tensile Test Data

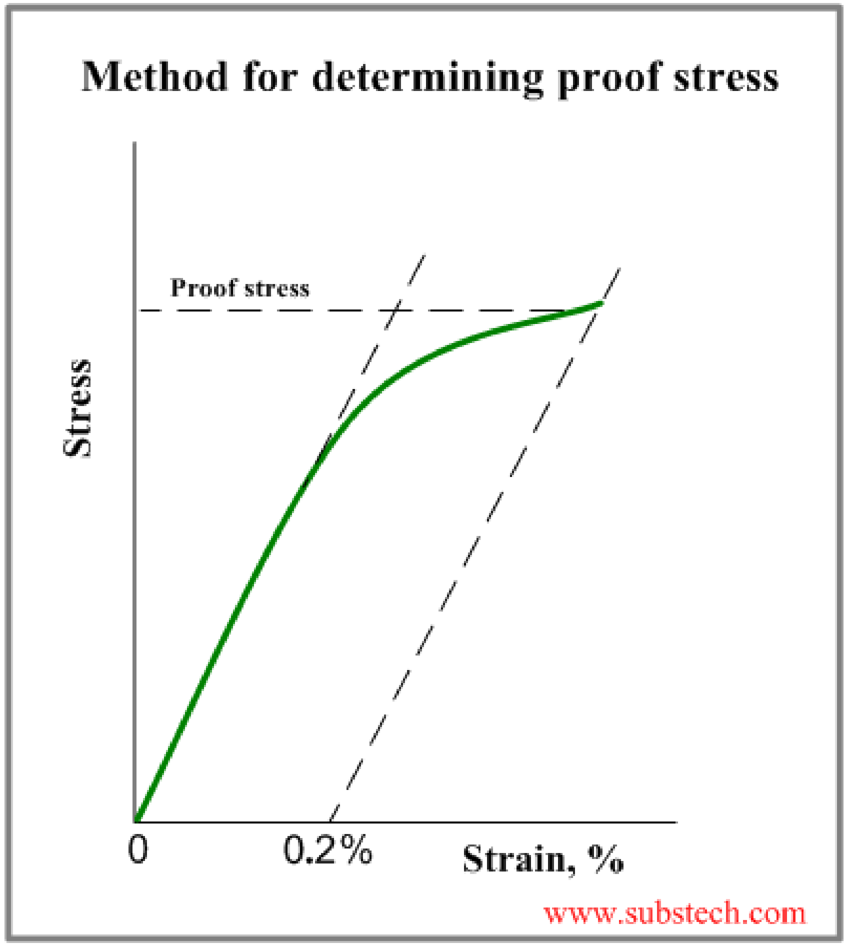
Revisiting the important information derived from a tensile test

- 0.1% or 0.2% proof stress is often quoted for Yield of a material; it is useful for characterizing yield of a material that yields gradually and does not show a distinct yield point



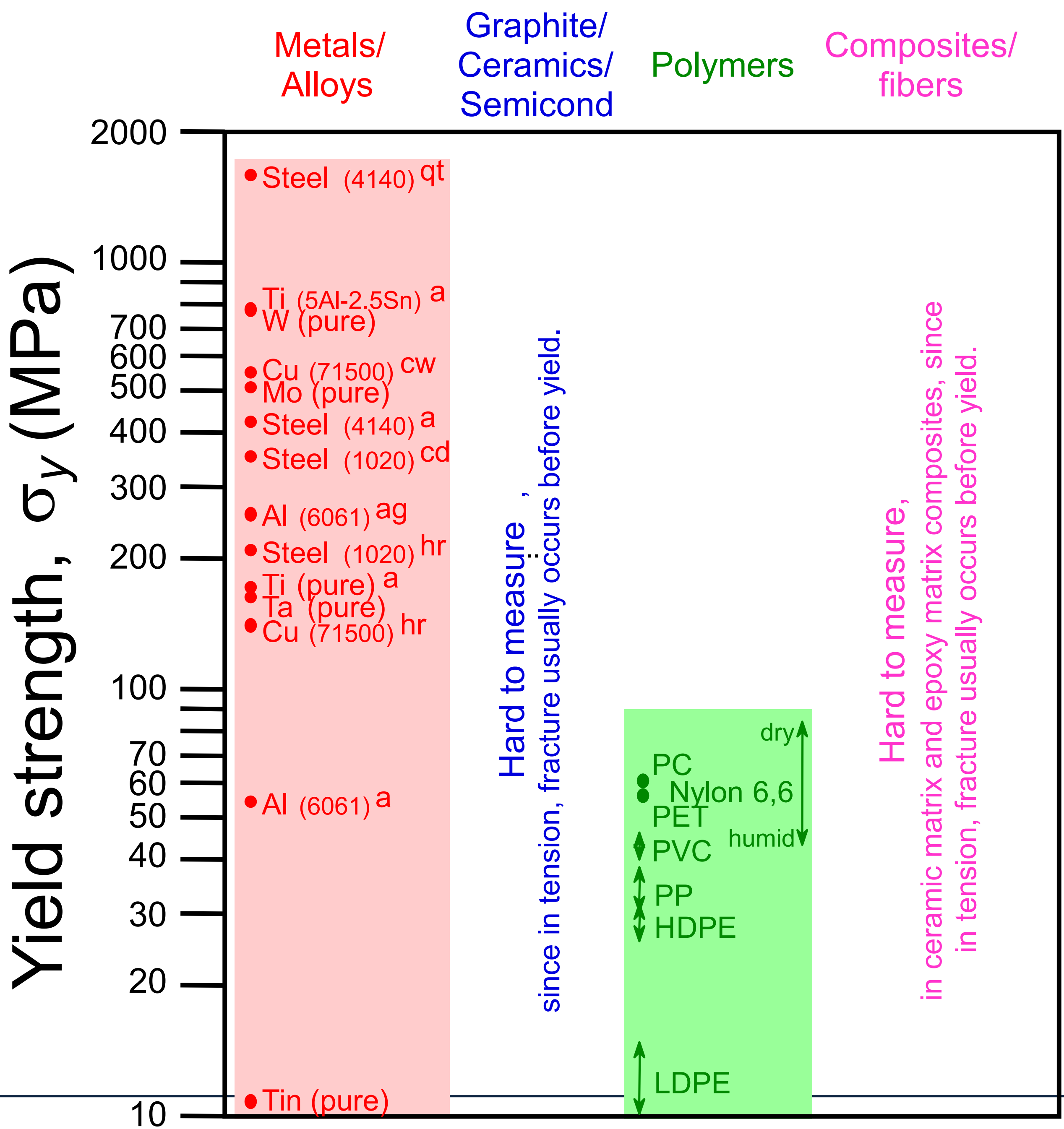
Calculate Yield strength at a 0.2% offset

- The tensile test can reveal several important engineering properties of materials. These properties are strength (yield point, yield strength, and tensile strength) and ductility (elongation and reduction in area).



- Stress-strain curve, at 0.2% strain (0.002) a straight line is drawn parallel to elastic curve which follows hooks law, will cut the strain curve.
- That point is considered as proof stress.
- Practically considered as yield point for some materials where original yield point is difficult to get.

Yield Strength : Comparison



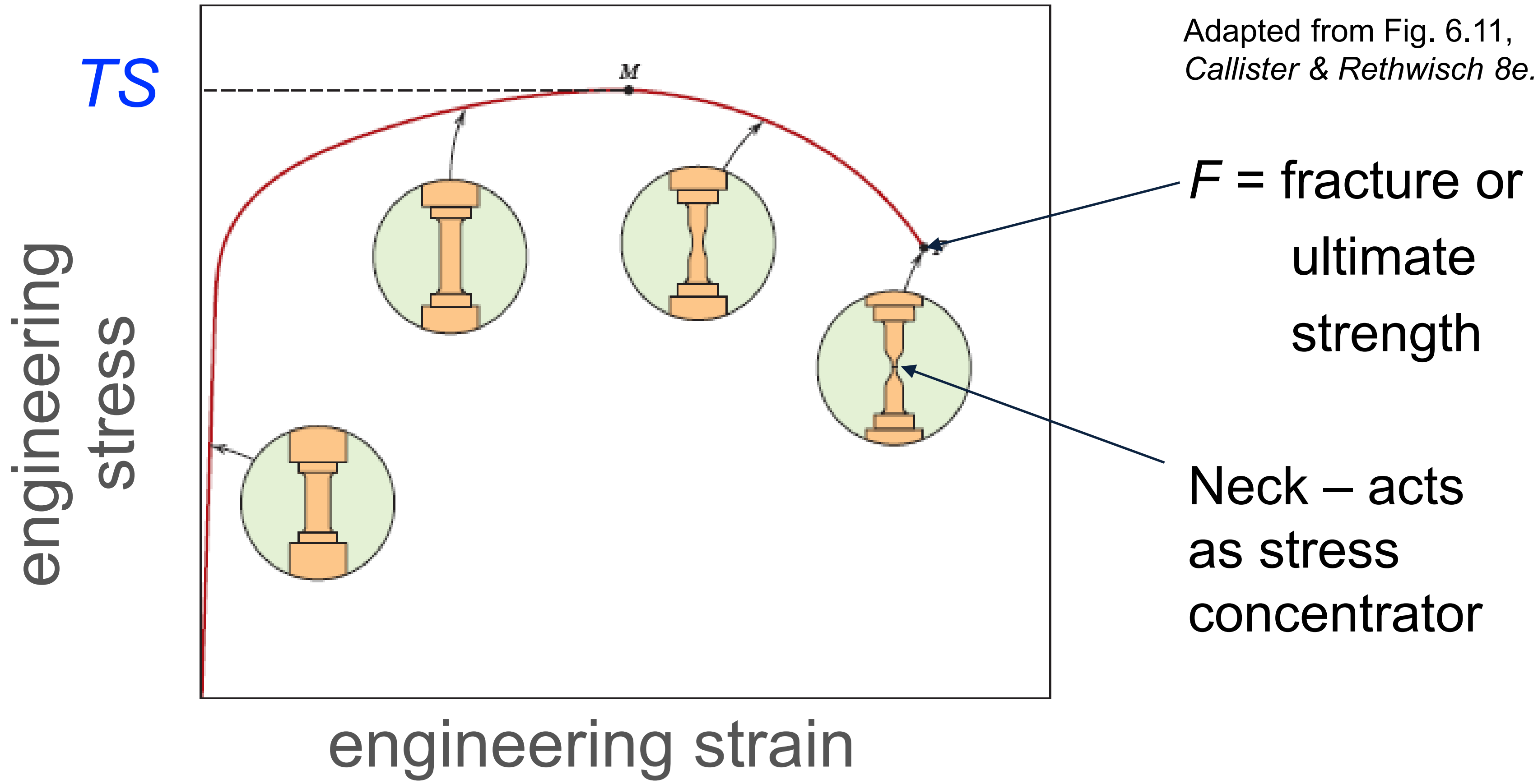
Room temperature values

Based on data in Table B.4, *Callister & Rethwisch 8e.*

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

Tensile Strength, TS

- Maximum stress on engineering stress-strain curve.



Adapted from Fig. 6.11, *Callister & Rethwisch 8e.*

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

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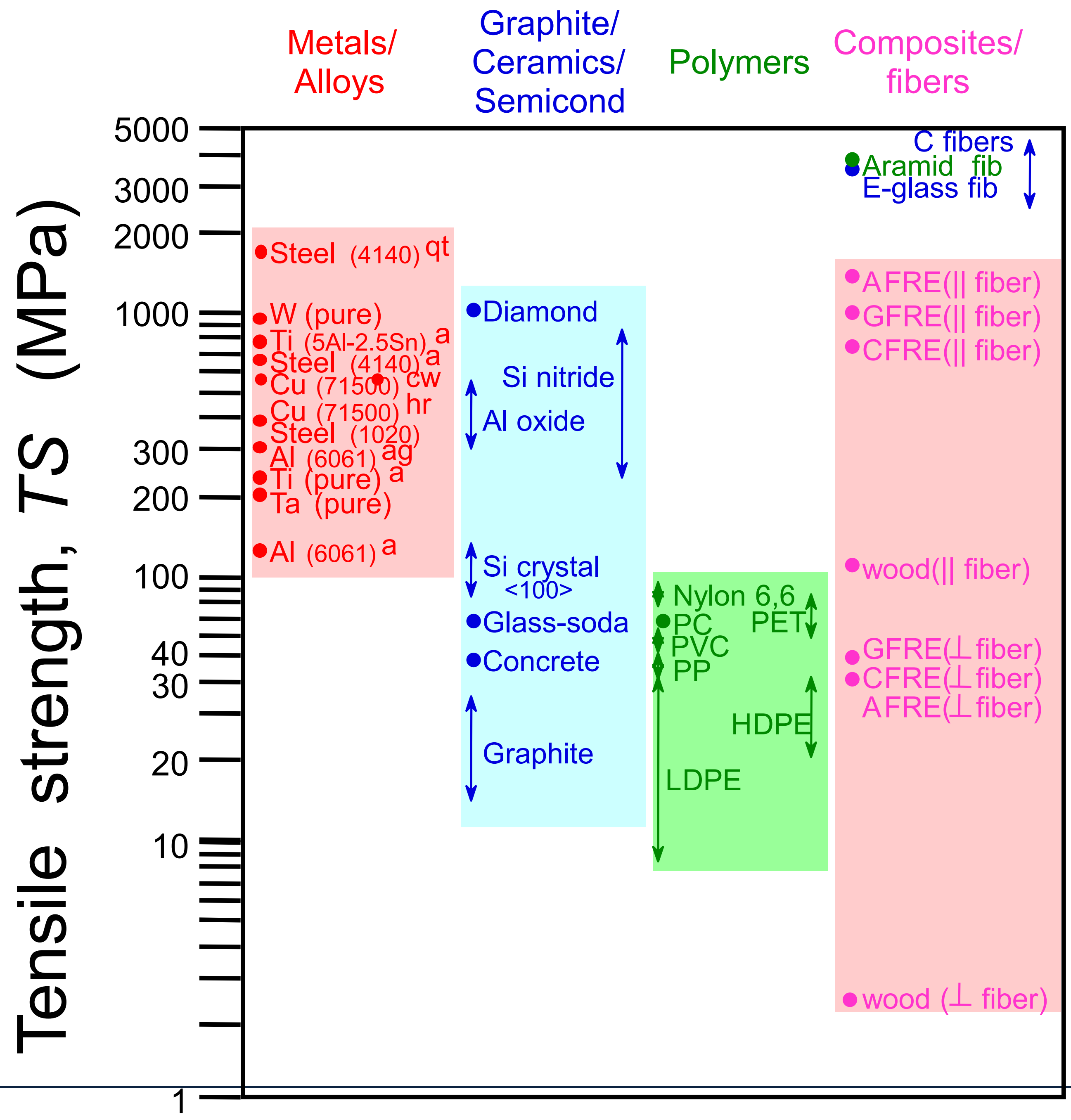
Tensile Strength: Comparison



Room temperature values

Based on data in Table B.4, *Callister & Rethwisch 8e.*

a = annealed
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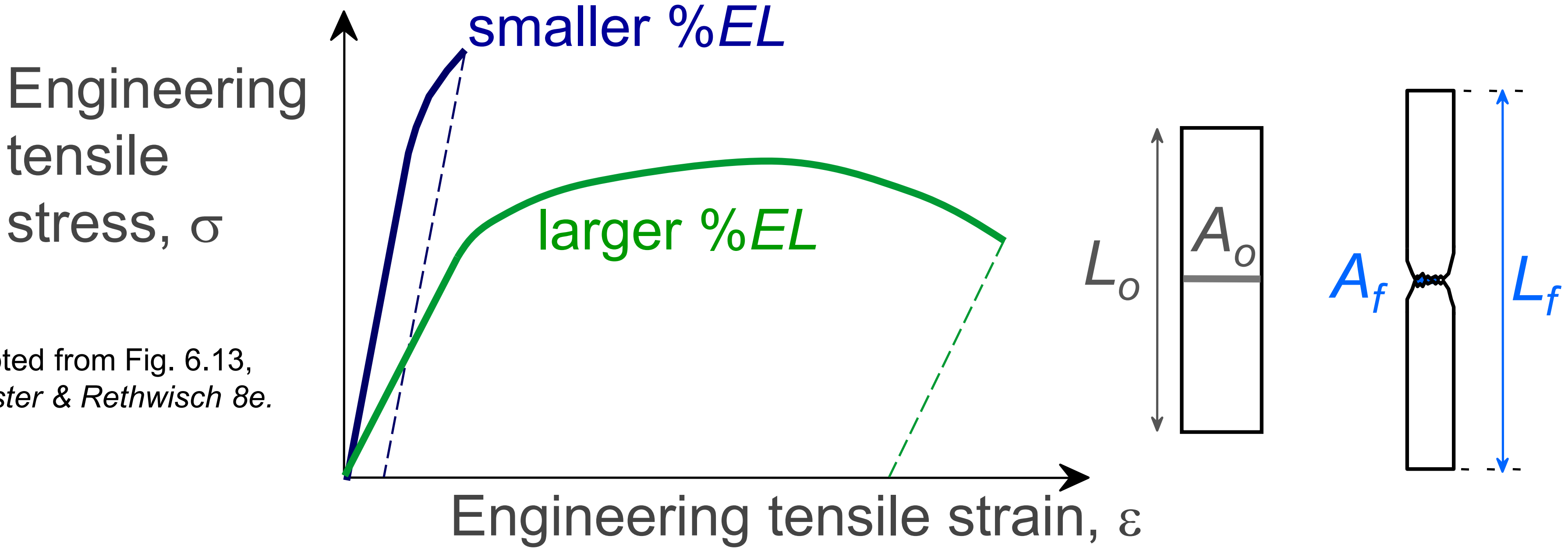
qt = quenched & tempered

AFRE, GFRE, & CFRE = aramid, glass, & carbon fiber-reinforced epoxy composites, with 60 vol% fibers.

Ductility

- Plastic tensile strain at failure:

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



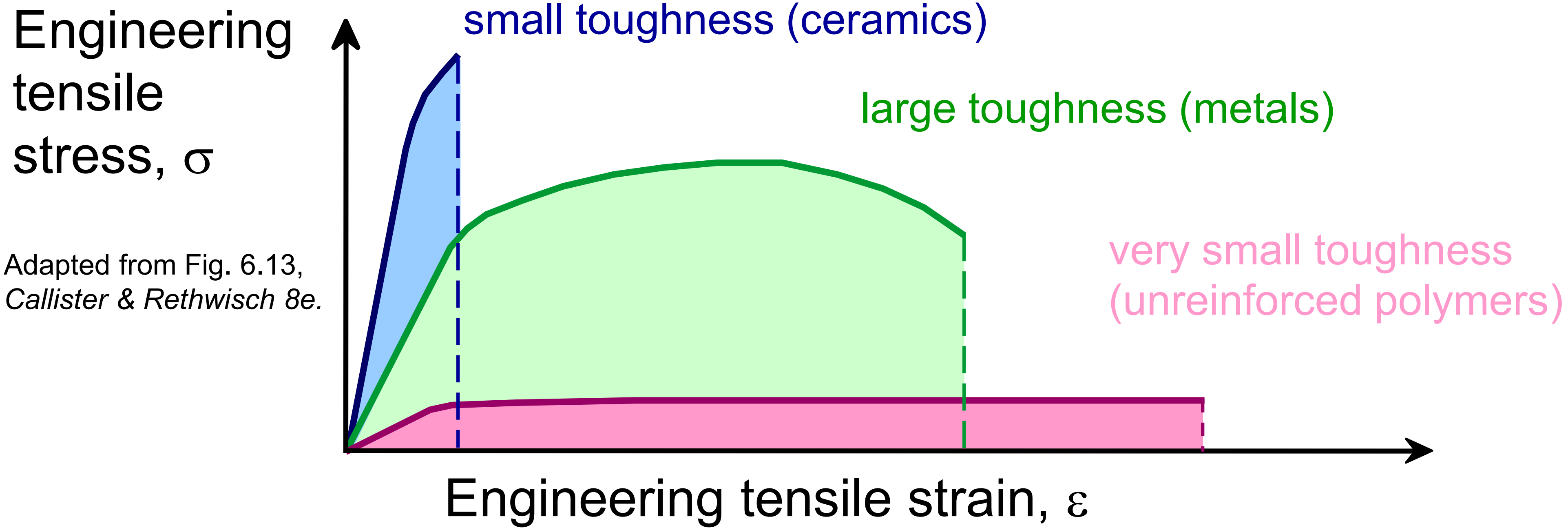
Adapted from Fig. 6.13, *Callister & Rethwisch 8e.*

- Another ductility measure:

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

Toughness

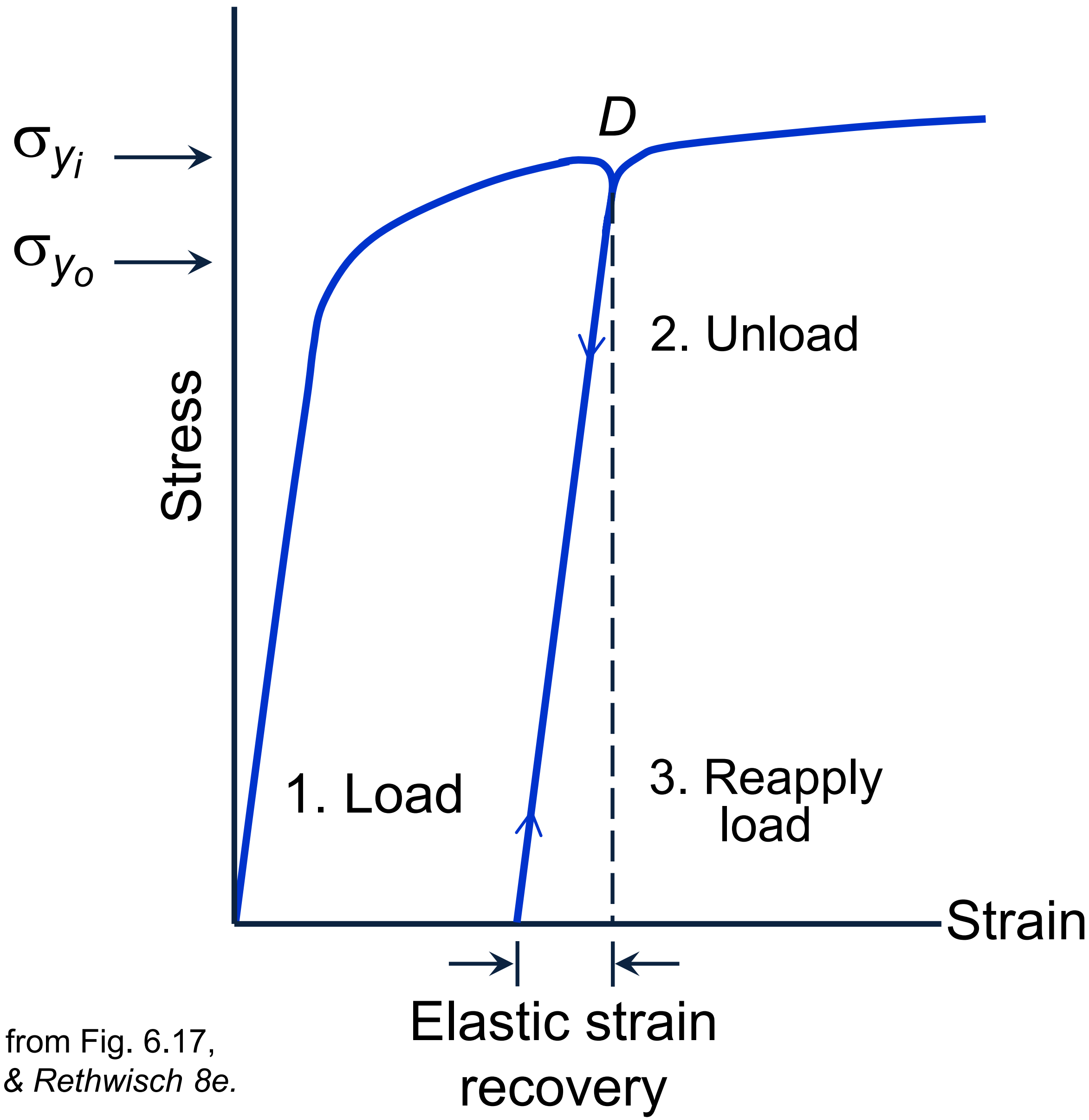
- Energy to break a unit volume of material
- Approximate by the area under the stress-strain curve.



Adapted from Fig. 6.13, *Callister & Rethwisch 8e.*

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

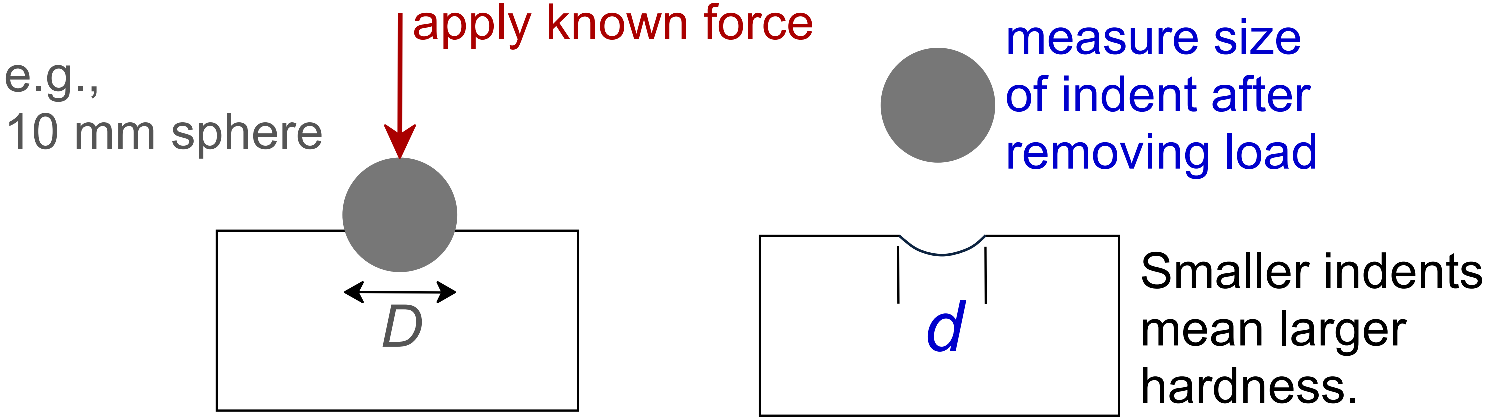
Elastic Strain Recovery

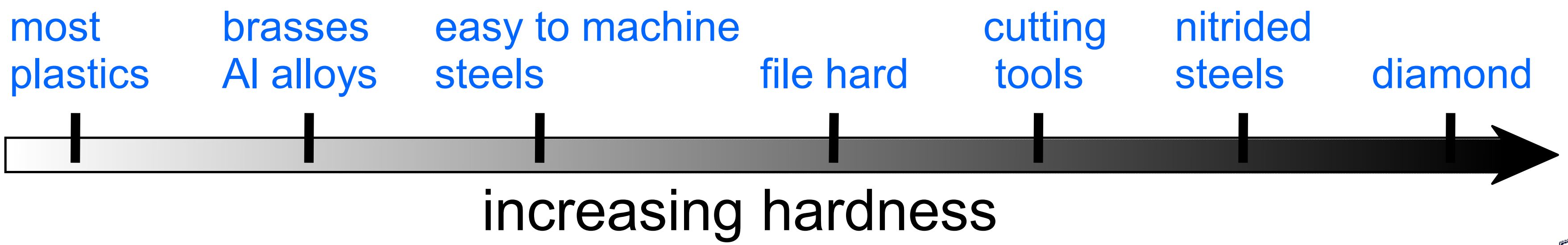


Adapted from Fig. 6.17,
Callister & Rethwisch 8e.

Hardness

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

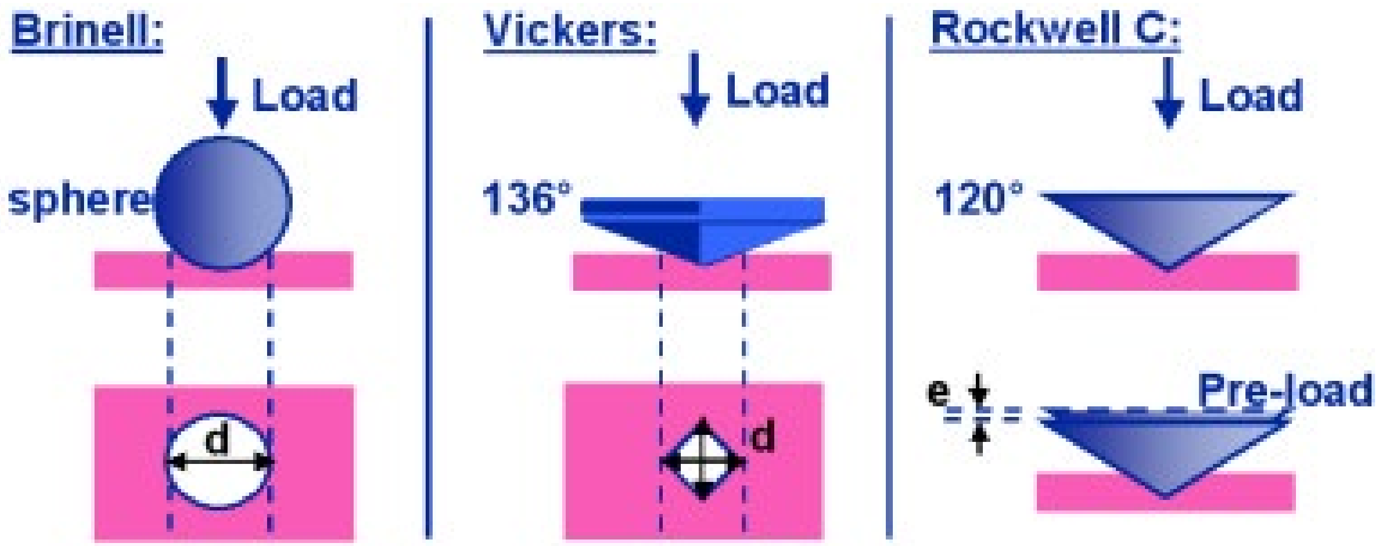




The hardness test

- The hardness test measures a material's resistance to plastic deformation
- It is widely used as a non-destructive test to estimate mechanical properties
- Different test scales were created to assist engineers in selecting the appropriate metals and hardness for their specific application.

  1. Rockwell
  2. Brinell
  3. Vickers



Stop and check videos on moodle

Lecture 2: Stop and Check videos

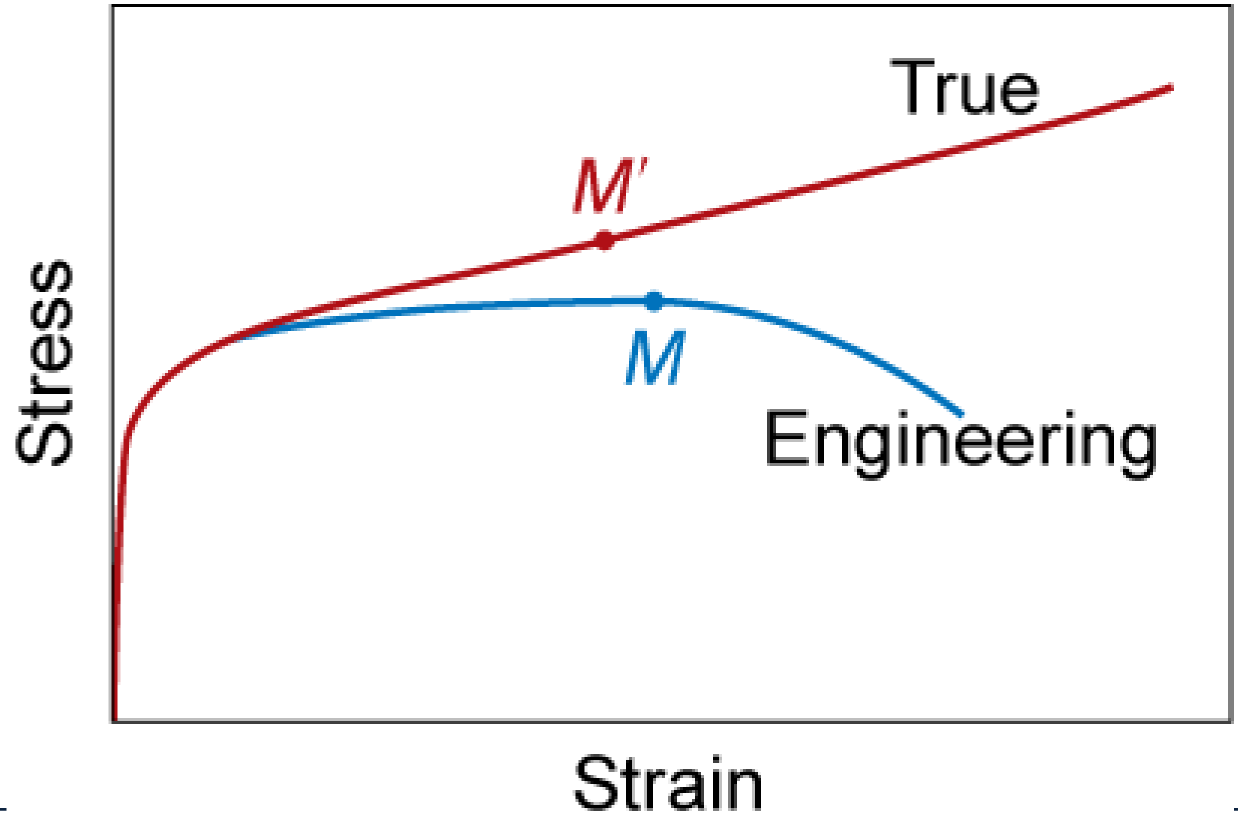
- **Understanding material strength, ductility, toughness**

True Stress & Strain

Note: C.S.A. changes when sample stretched

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

$$\boxed{\begin{aligned}\sigma_T &= \sigma(1+\varepsilon)\\ \varepsilon_T &= \ln(1+\varepsilon)\end{aligned}}$$



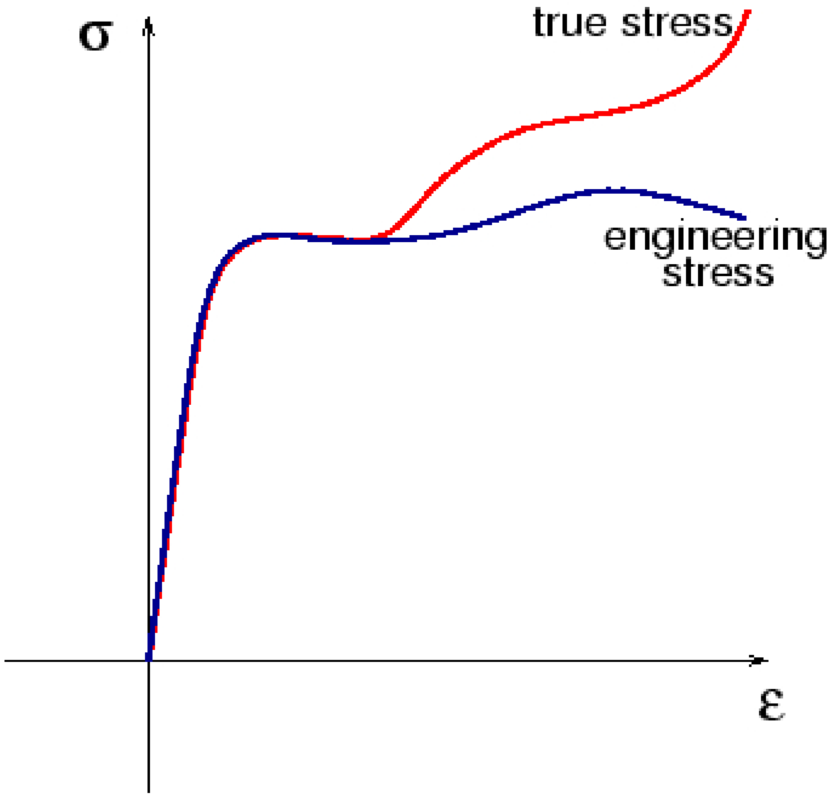
Adapted from Fig. 6.16, *Callister & Rethwisch 8e.*

Small strain increments

If we define **True Stress** as $\sigma = \frac{F}{A_0}$

and **True Strain** as $\varepsilon = ln\left(\frac{l_i}{l_o}\right)$

True stress and true strain are used for accurate definition of plastic behaviour of **ductile** materials by considering the actual (instantaneous) dimensions.



The approximate linear relationship between **true stress** and **true strain** can mathematically be expressed by the so-called **Power Law**

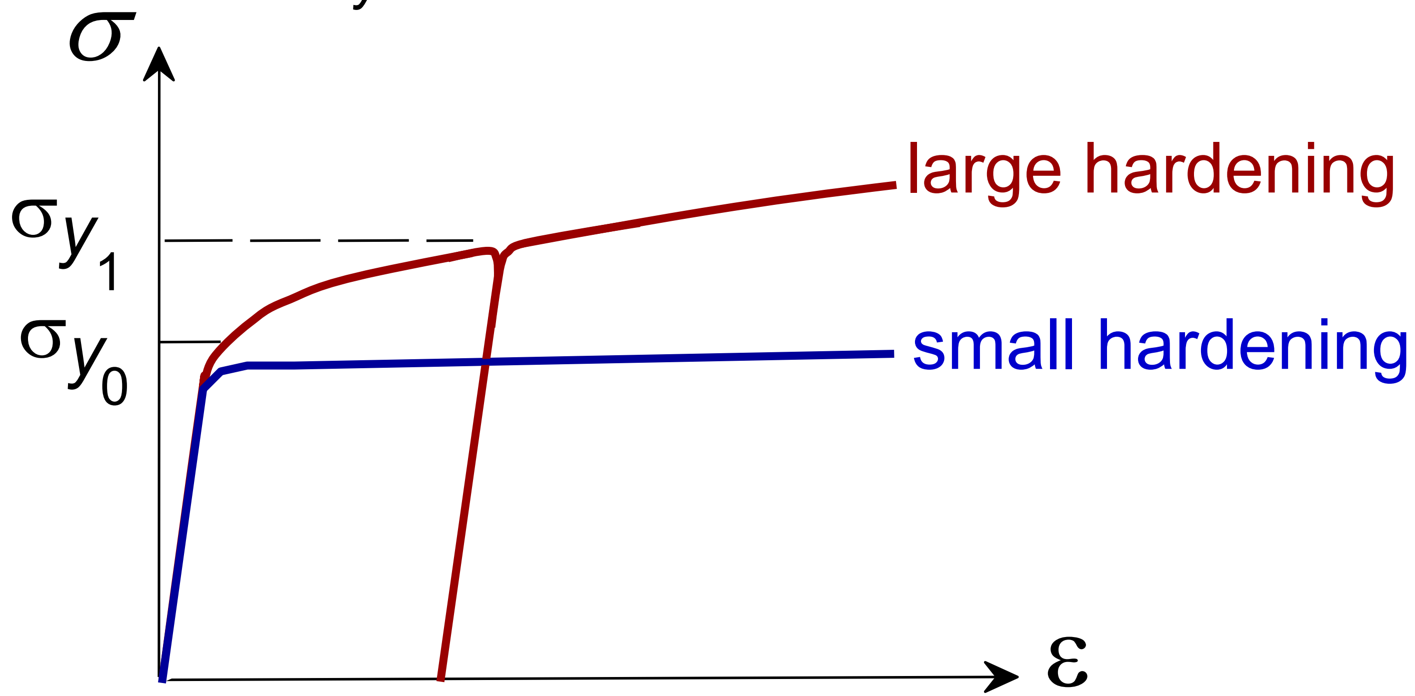
$$\boldsymbol{\sigma = K\varepsilon^n}$$

K = Strength coefficient (MPa)

n = strain hardening exponent

Hardening

- An increase in σ_y due to plastic deformation.



- Curve fit to the stress-strain response:

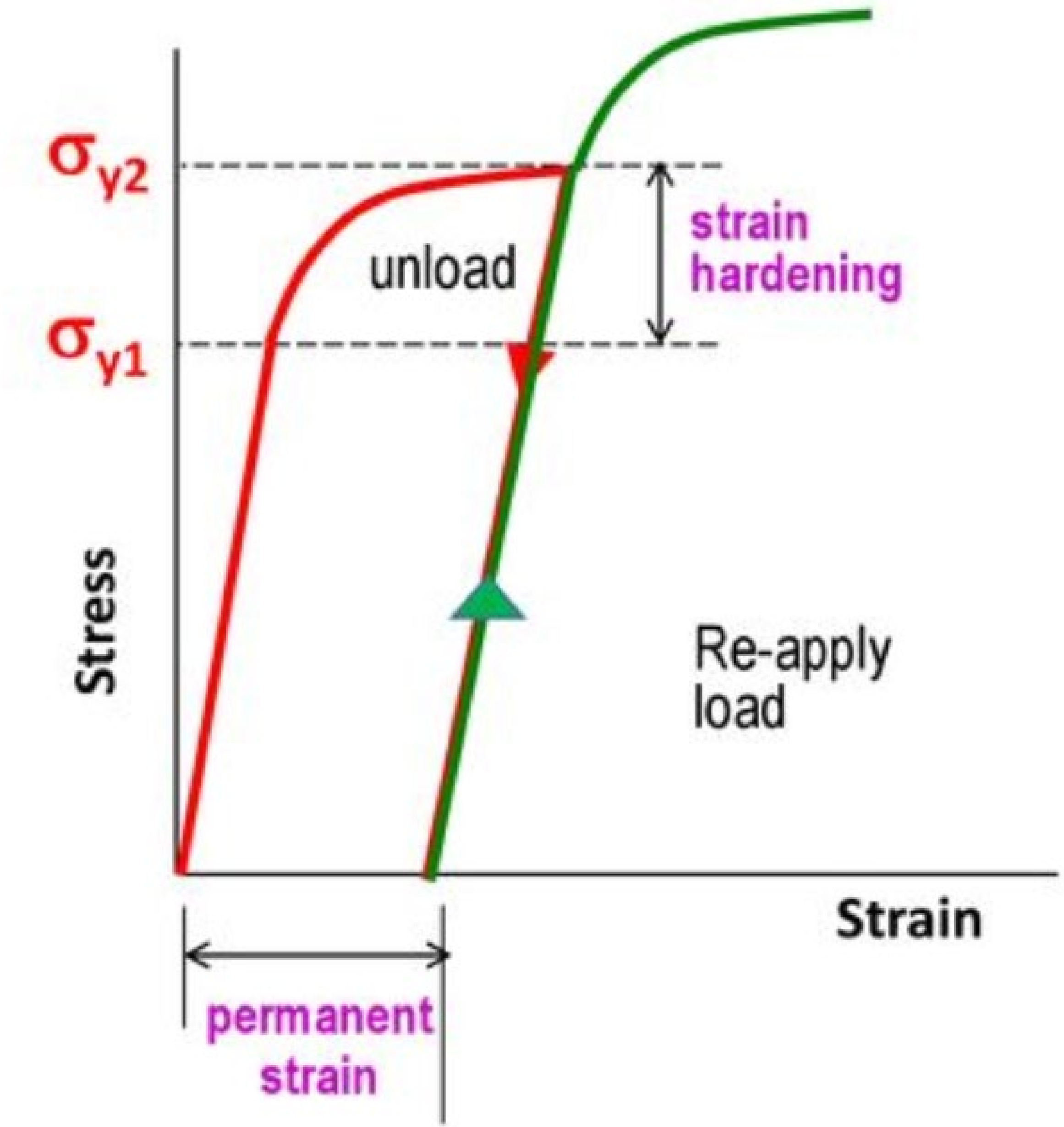
$$\sigma_T = K(\varepsilon_T)^n$$

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

"true" stress (F/A)

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

Strain or Work hardening



- If a material is deformed plastically and the stress is then released, the material ends up with a net, **permanent strain**.

- If the stress is reapplied, the material again responds elastically at the beginning up to a new yield point that is higher than the original yield point. this is due to **strain or work hardening** of material.

It is strengthening of a metal by plastic deformation.

- This **strengthening occurs** because of **dislocation movements** and **dislocation generation** within the crystal structure of the material

Design or Safety Factors

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

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

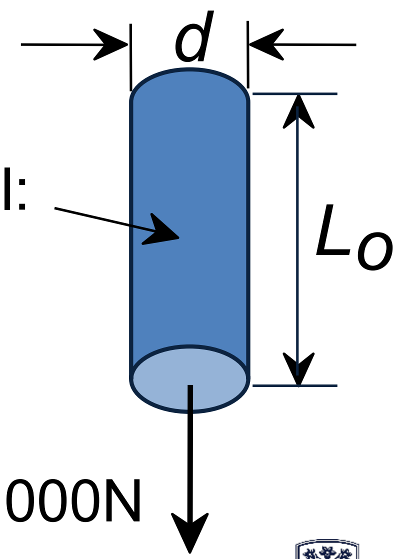
Often N is between 1.2 and 4

- 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.

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

$$\frac{220{,}000N}{\pi\left(d^2/4\right)} = \frac{\sigma_y}{5}$$

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



$F = 220{,}000$N

$d = 0.067$ m $= 6.7$ cm

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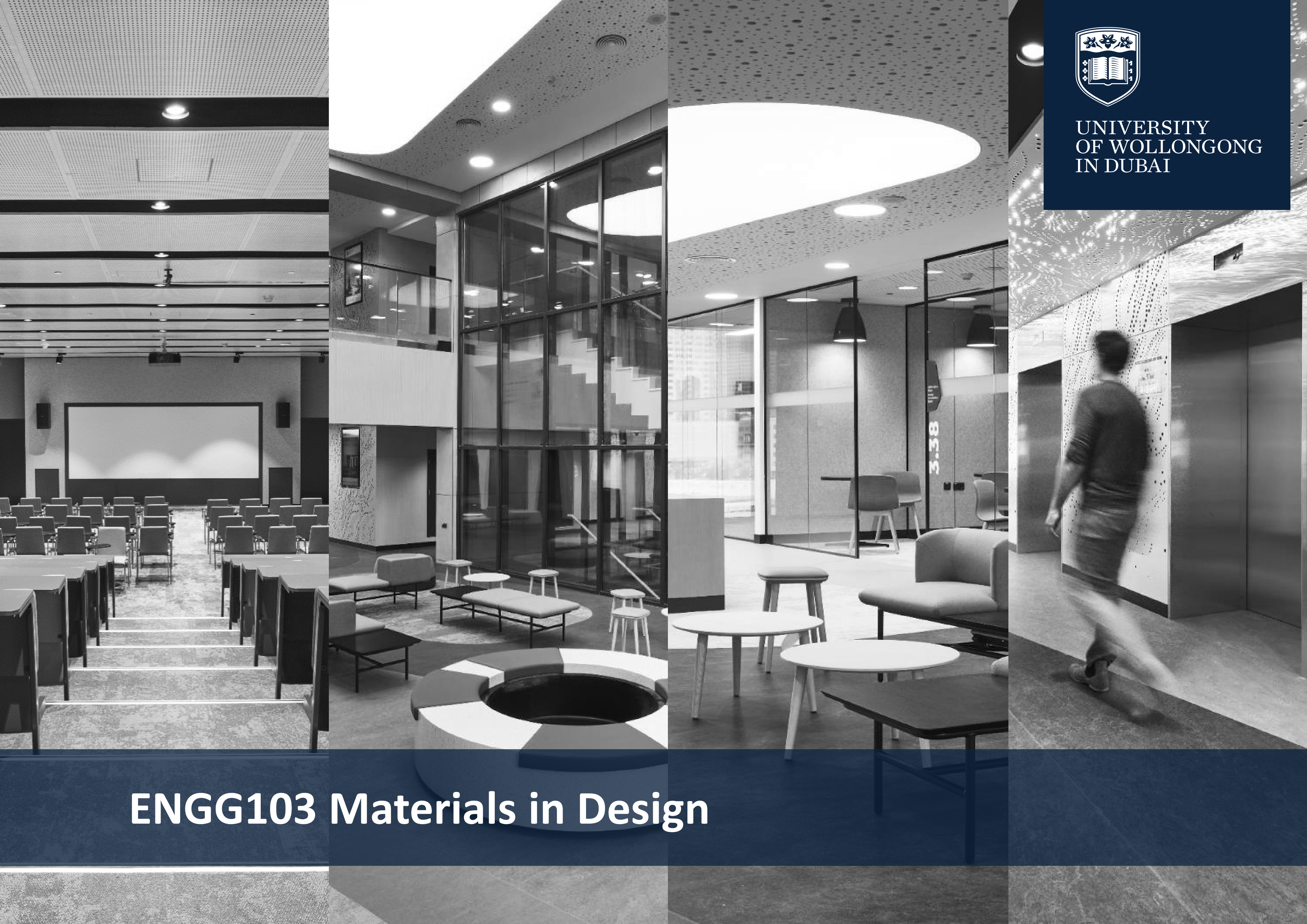
Lecture 2: Stop and Check videos

- **Understanding true stress and true strain**

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.



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