Lecture 4:
Mechanical Properties of Metals

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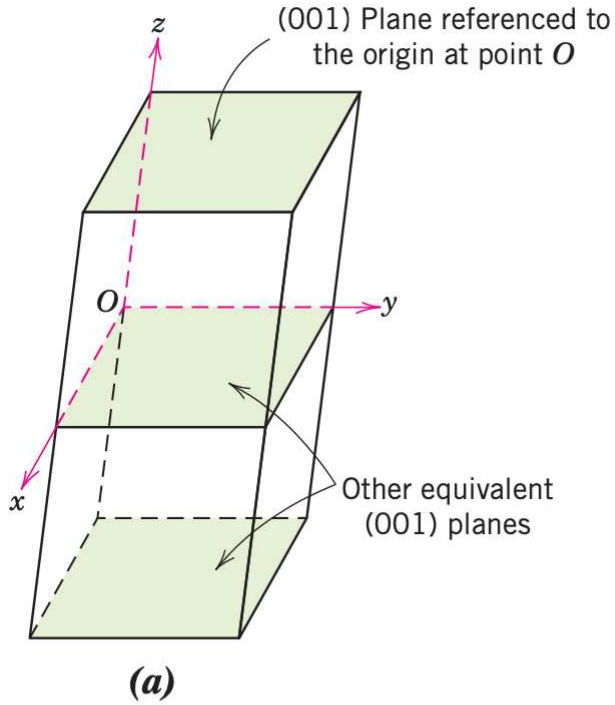
These planes repeat every unit cell



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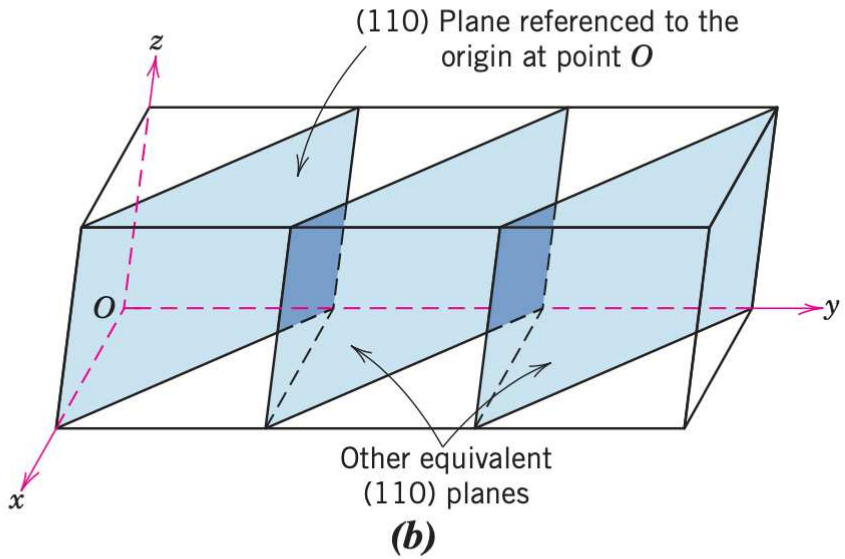

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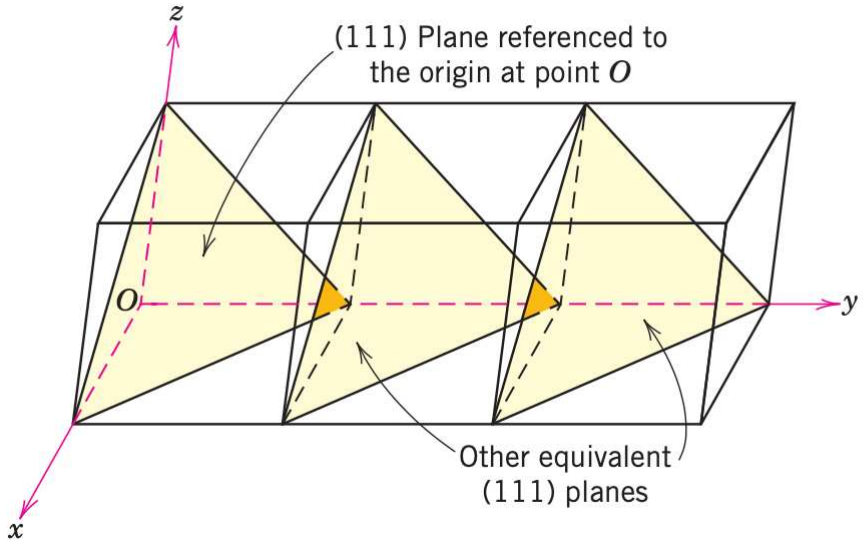
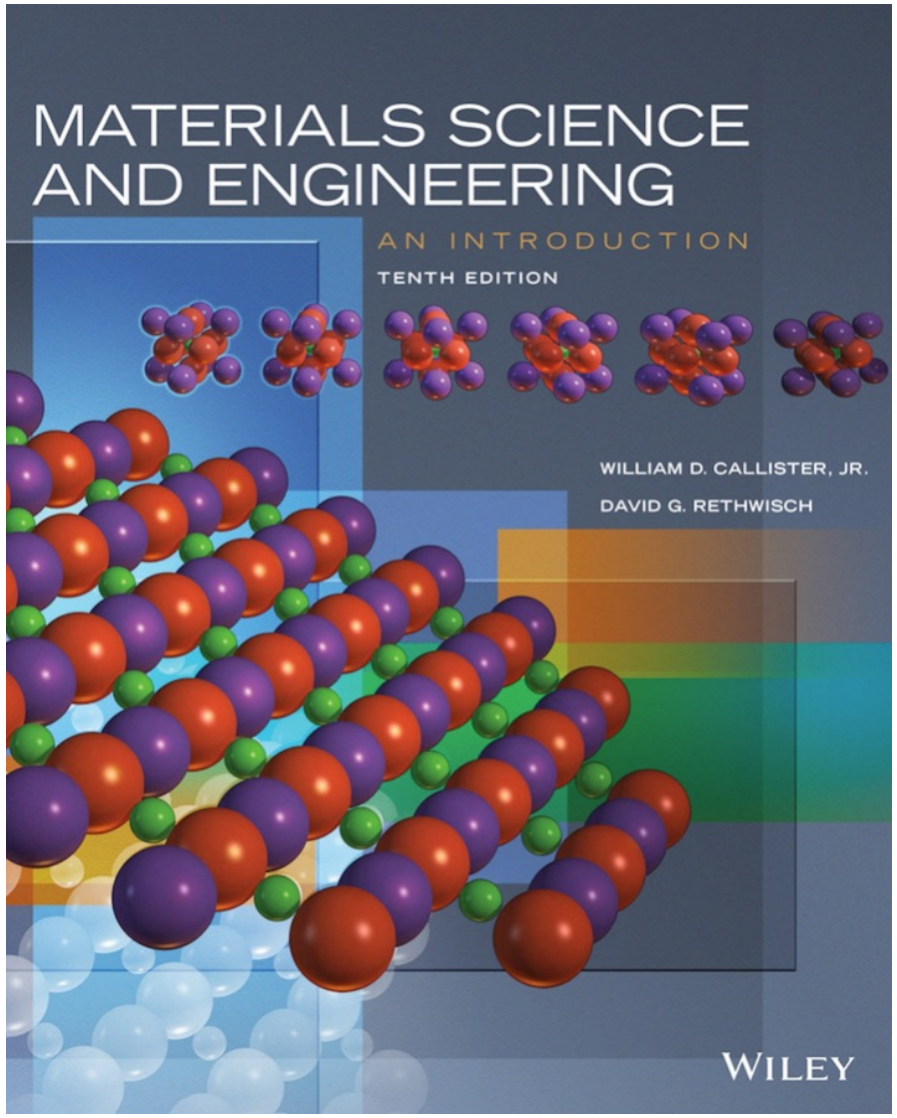


(c)

Reading for this subject



Chapter 6 Mechanical Properties of Metals

This discussion will closely follow **Chapter 6** of Callister, **pages 143-176** of the 10th edition.

Supplementary Texts:

- *Mechanical Behavior of Materials* by Courtney

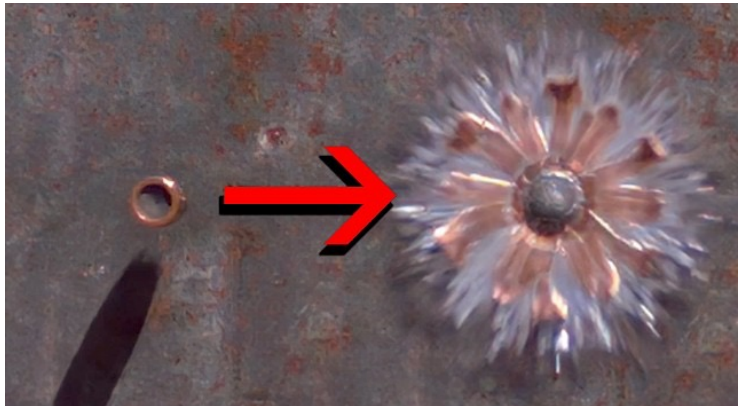
Metals are often used for their unique mechanical properties

Compression





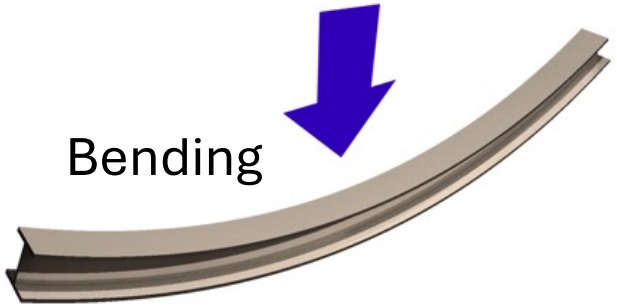
Impact



Tension



Bending

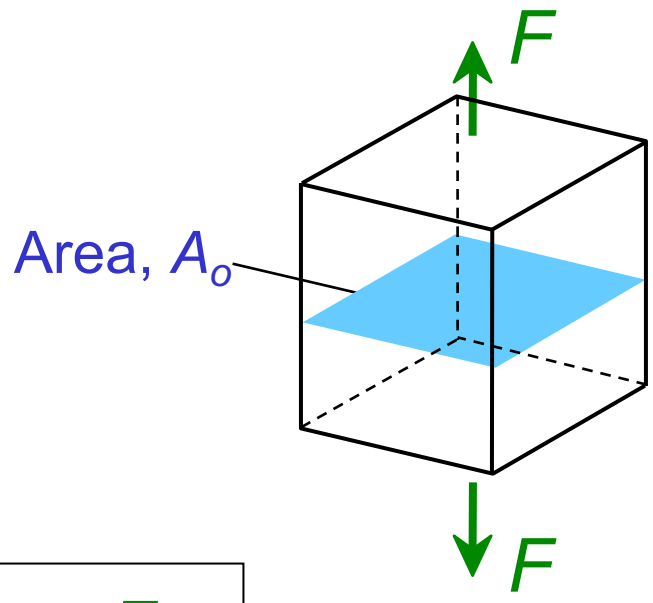


How do we quantify the resistance to deformation?

Deformations occur in response to *stress*

(force per unit area)

- Tensile stress, σ

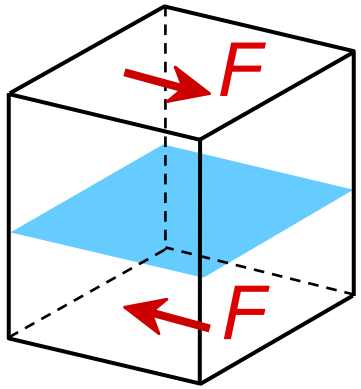


$$\sigma = \frac{F}{A_o}$$

original cross-sectional area *before* loading

- Shear stress, τ

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

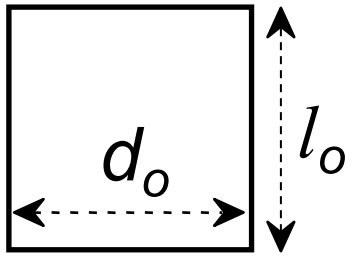


Units for stress: *pressure*

MPa = 10^6 Pa = 10^6 N/m^2

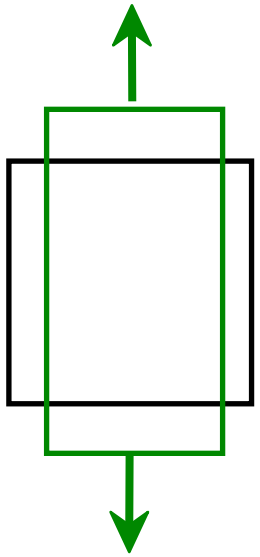
In US, we often use PSI (lbs. per sq. inch)

Deformations are quantified by ***strain***



Consider a specimen with dimensions d_o and l_0 before deformation

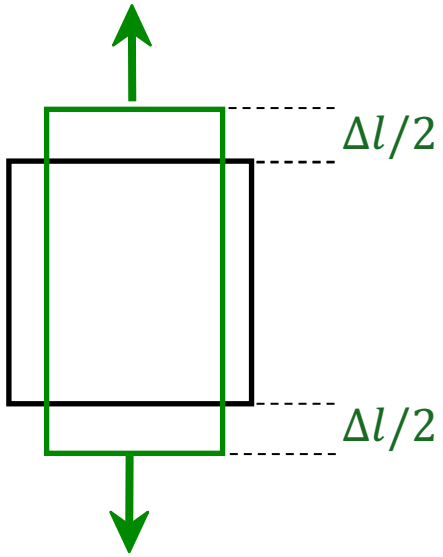
Deformations are quantified by ***strain***



Consider a specimen with dimensions d_o and l_0 before deformation

After deformation, we see two changes:

Deformations are quantified by *strain*

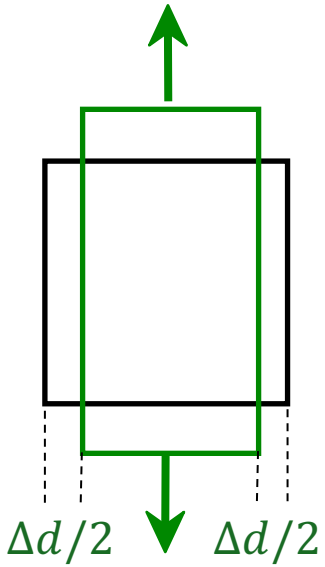


Consider a specimen with dimensions d_o and l_0 before deformation

After deformation, we see two changes:

- A **lengthening ($\Delta \boldsymbol{l}$)** along the direction of applied force

Deformations are quantified by *strain*



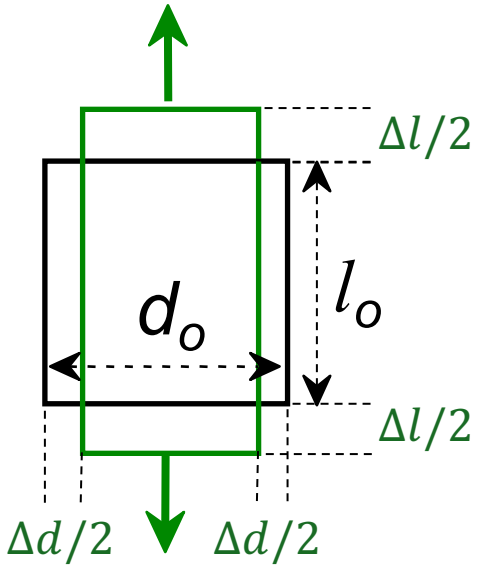
Consider a specimen with dimensions d_o and l_0 before deformation

After deformation, we see two changes:

- A **lengthening ($\Delta \boldsymbol{l}$)** along the direction of applied force
- A **shortening ($\Delta \boldsymbol{d}$)** in a direction *orthogonal* to the applied force

DEMO

Deformations are quantified by *strain*



Consider a specimen with dimensions d_o and l_0 before deformation

After deformation, we see two changes:

- A **lengthening (Δl)** along the direction of applied force
- A **shortening (Δd)** in a direction *orthogonal* to the applied force

Tensile strain:

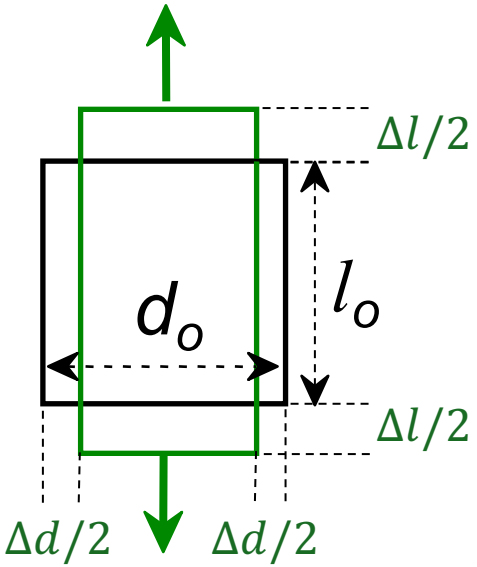
$$\epsilon_z = \frac{\Delta l}{l_0}$$

Lateral strain:

$$\epsilon_x = \frac{\Delta d}{d_0}$$

Note: these are **dimensionless** quantities. Think of them as fractions or percentages.

Deformations are quantified by *strain*



Poisson's ratio quantifies how much lateral strain occurs with a given amount of tensile strain:

$$\upsilon = -\frac{\epsilon_x}{\epsilon_z}$$

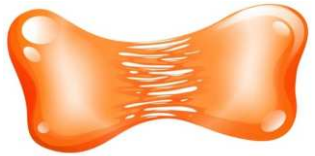
This is a **material-dependent property**

ceramics: $\nu \sim 0.25$

metals: $\nu \sim 0.33$

polymers: $\nu \sim 0.40$





Tensile strain:

$$\epsilon_z = \frac{\Delta l}{l_0}$$

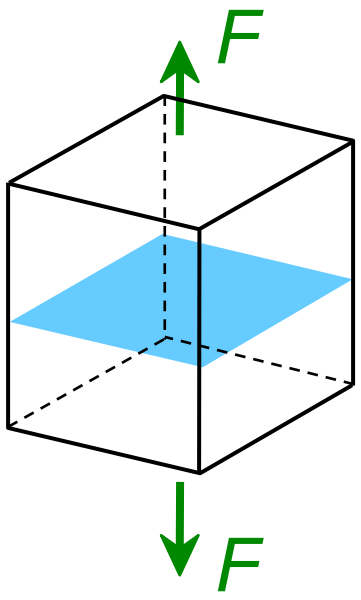
Lateral strain:

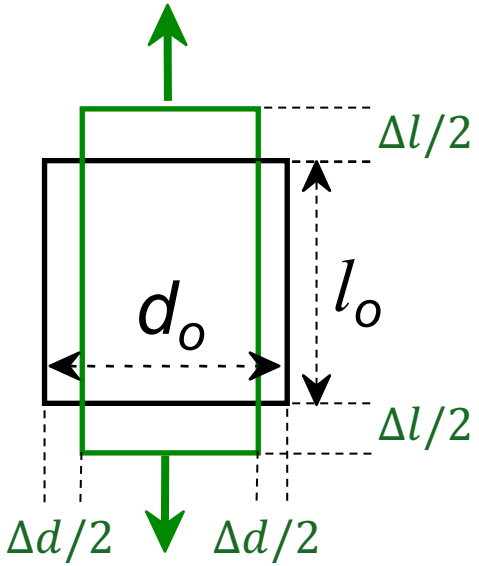
$$\epsilon_x = \frac{\Delta d}{d_0}$$

Note: these are **dimensionless** quantities. Think of them as fractions or percentages.

How to probe stress-strain relationships?

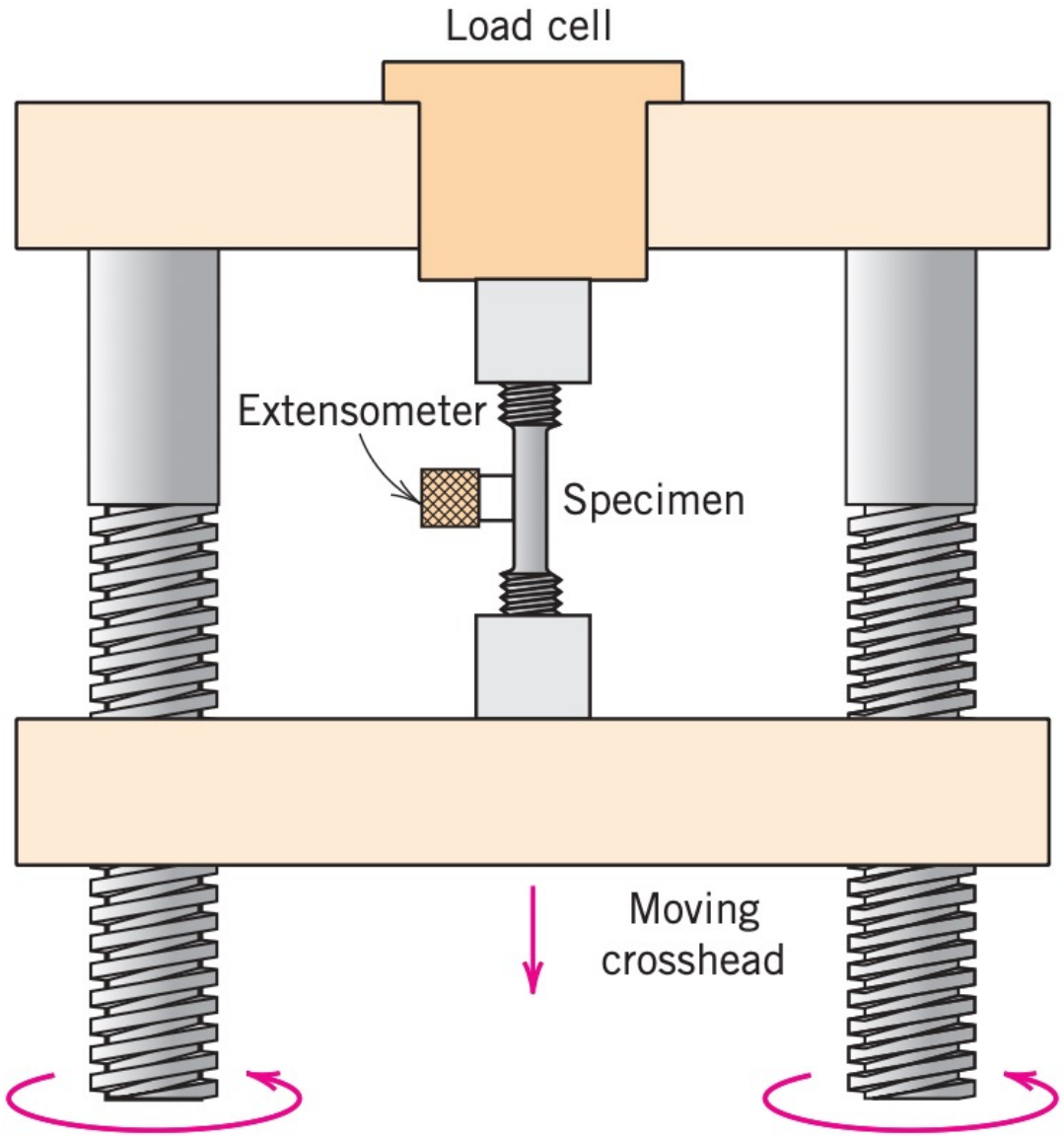
$$\sigma = \frac{F}{A_o}$$

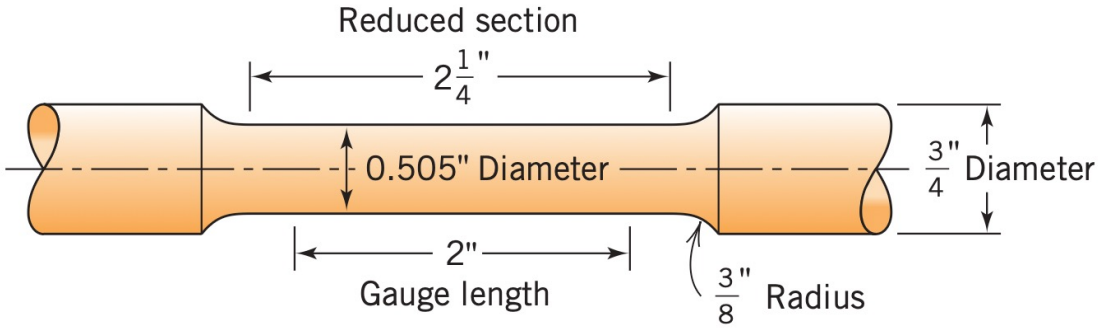




Clearly, there is some relationship between stress and strain. This is another **material-dependent property** that we can characterize.

Tensile testing: apply stress, monitor strain

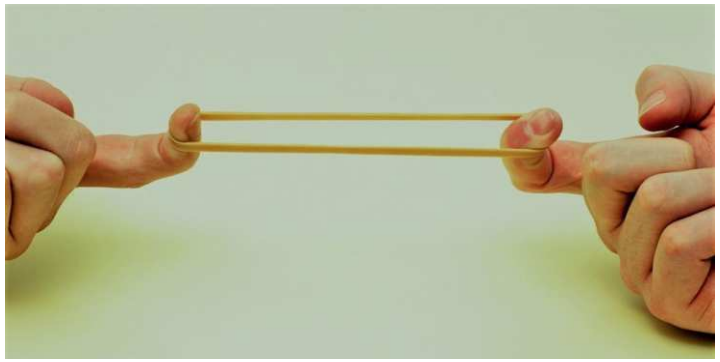








Tensile testing: apply stress, monitor strain



When the stresses and strains are small, the deformation is said to be ***elastic***

→ **Elastic deformation is completely reversible** ***(fully recovered)***

This case we'll get to later





Elastic deformation is characterized by a linear stress-strain relationship

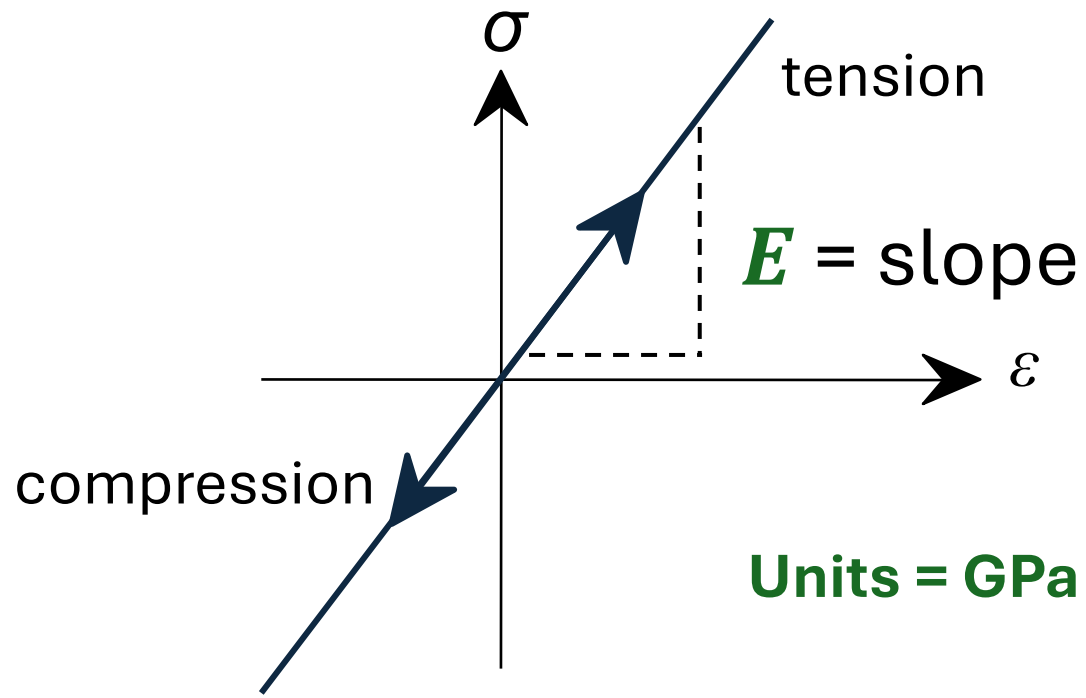
As long as the deformation is small enough, there will always be some **elastic behavior:**

$$\sigma = E\epsilon$$

Tensile stress

Elastic modulus

Tensile strain



Measures how "stiff" the material is:

- **High E → resistant to deformation**
- **Low E → easily deformed**

Units = GPa

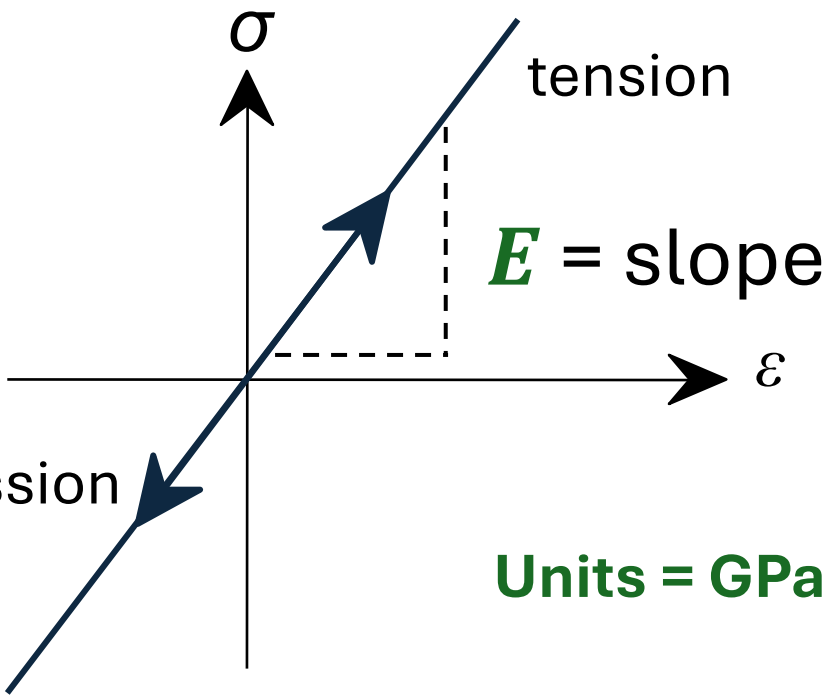
Quick pause…Any questions here?
It is important you understand this equation and plot!

$$\sigma = E\epsilon$$

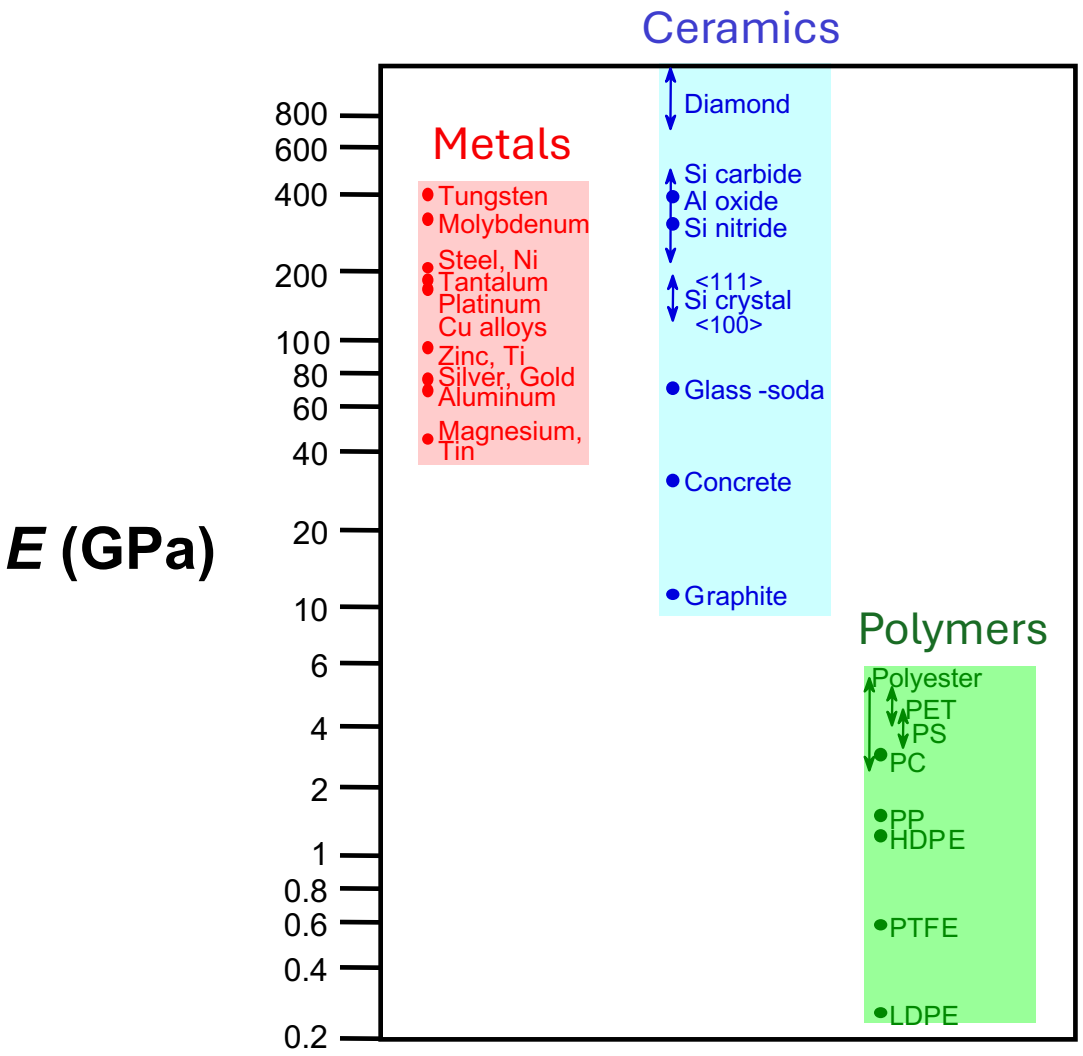
Tensile stress

Elastic modulus

Tensile strain



Elastic moduli of some common materials



Many of the **stiffest** materials (with very high elastic modulus) are **ceramics**. Think diamond.



Polymer are generally much less resistant to deformation. Think rubber.

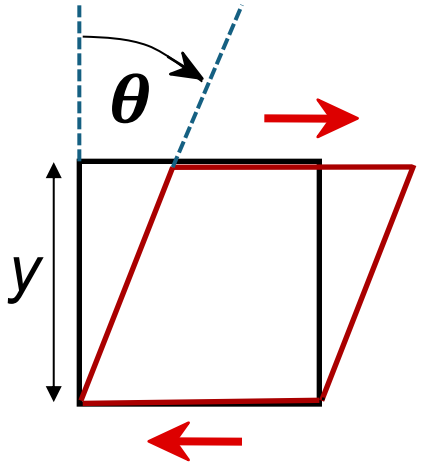


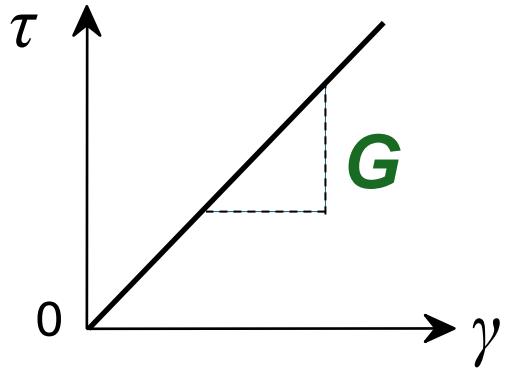
Metals lie in between. Something like steel is difficult to deform but aluminum and tin are more easily deformed.





Other elastic properties





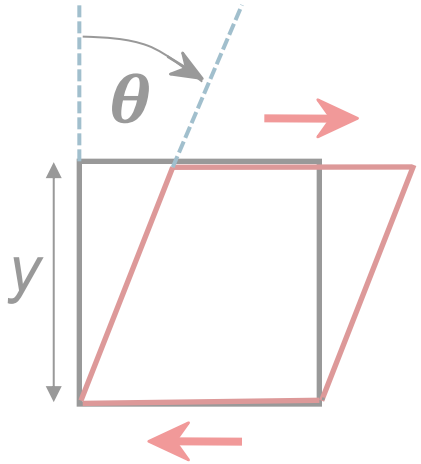
$$\tau = G\gamma$$

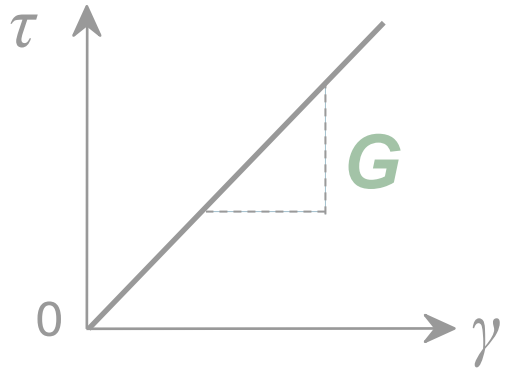
Shear stress

Shear modulus

Shear strain

Other elastic properties



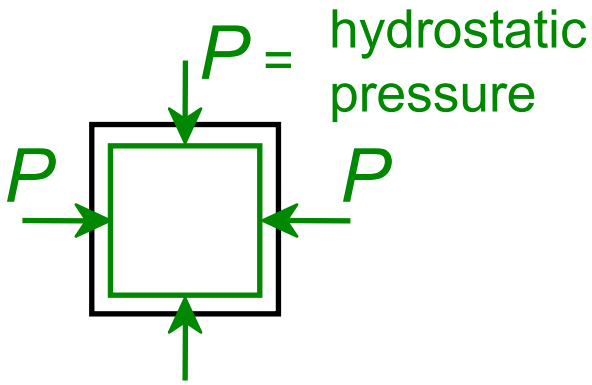


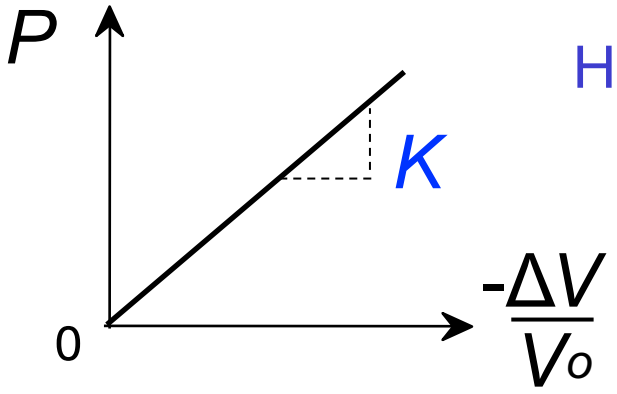
$$\tau = G\gamma$$

Shear stress

Shear modulus

Shear strain





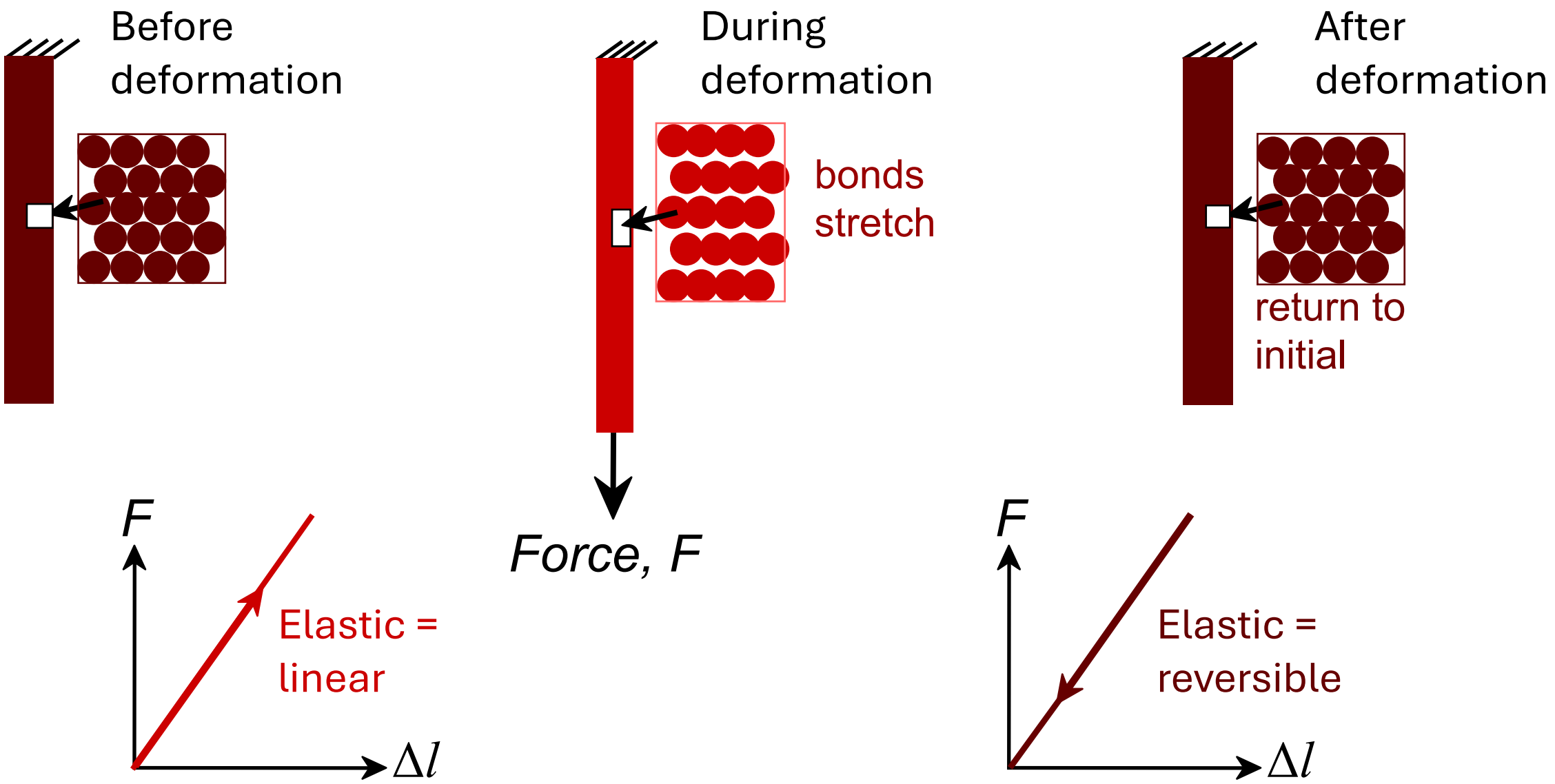
$$P = -K\Delta V/V_0$$

Hydrostatic pressure

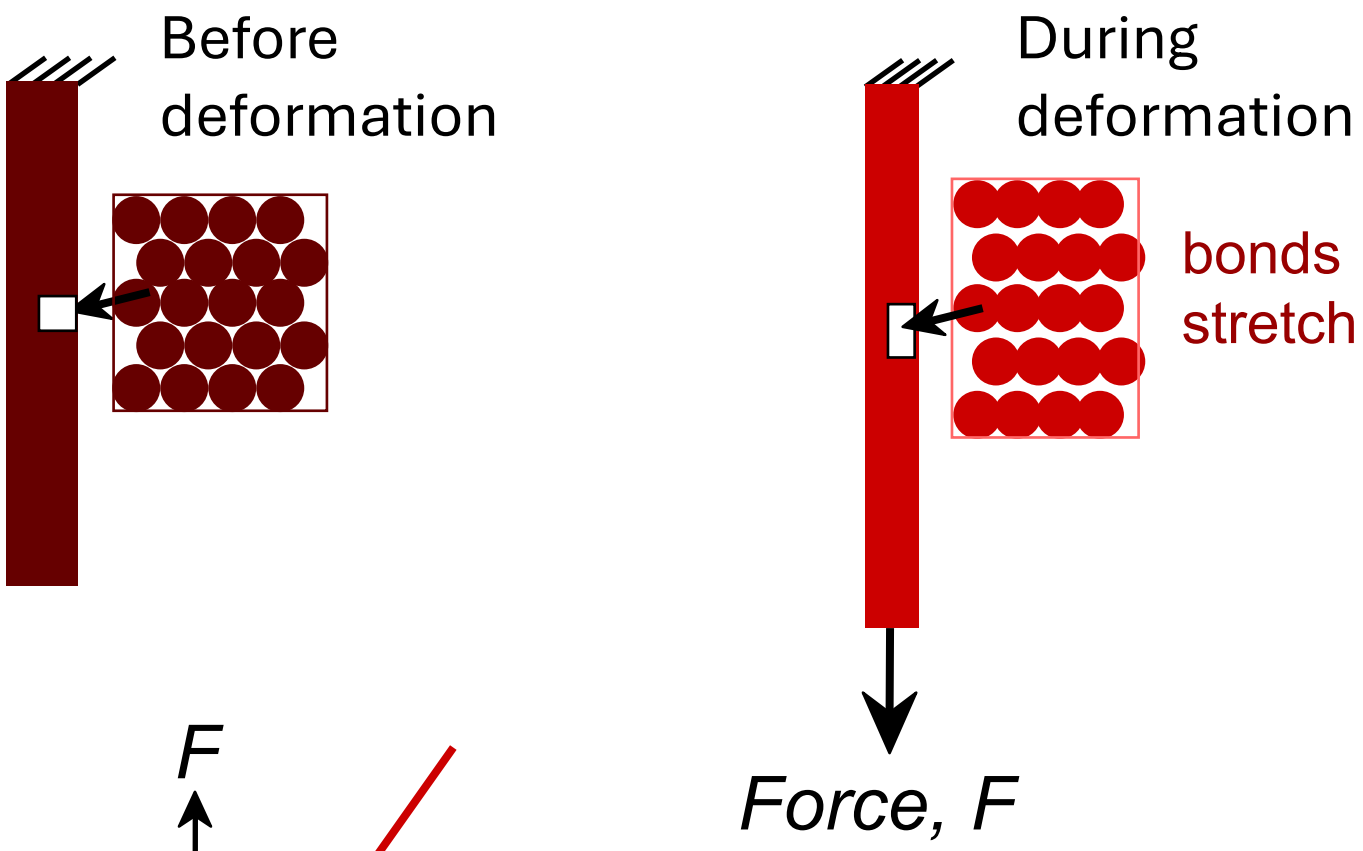
Bulk modulus

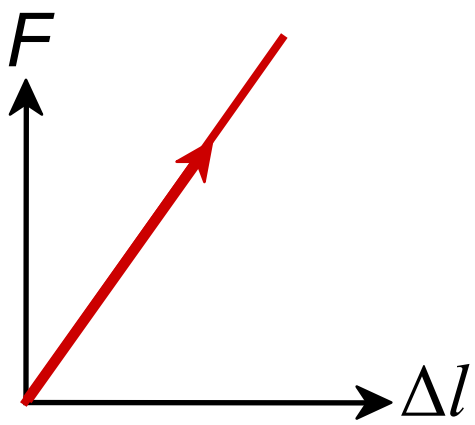
Volume change

Elastic/reversible deformation ↔ bond stretching



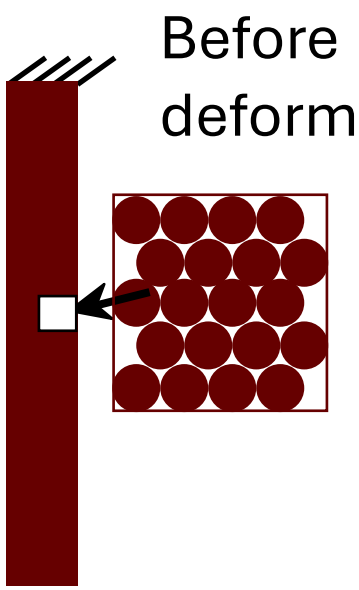
Elastic/reversible deformation ↔ bond stretching

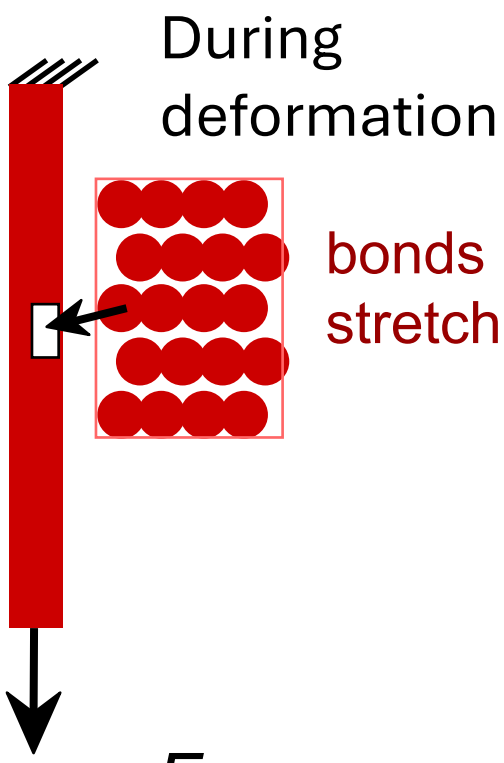


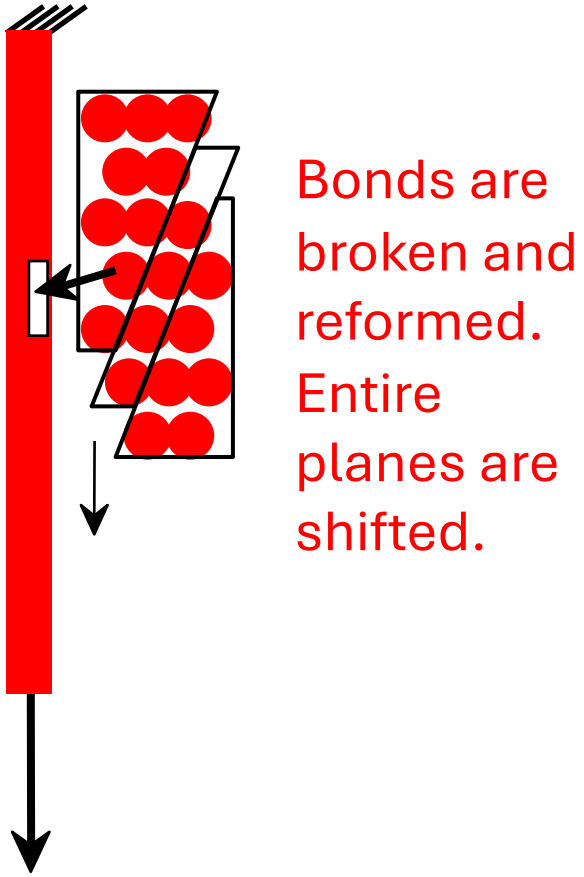


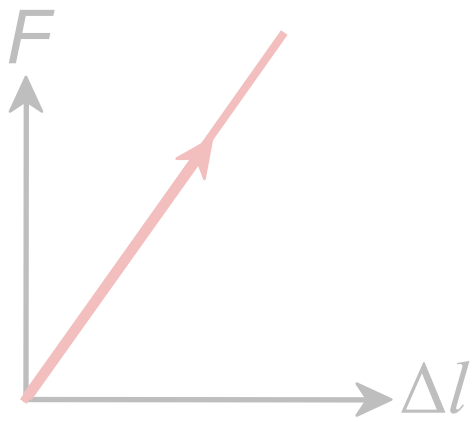
What if we were to keep going? Applying more force?

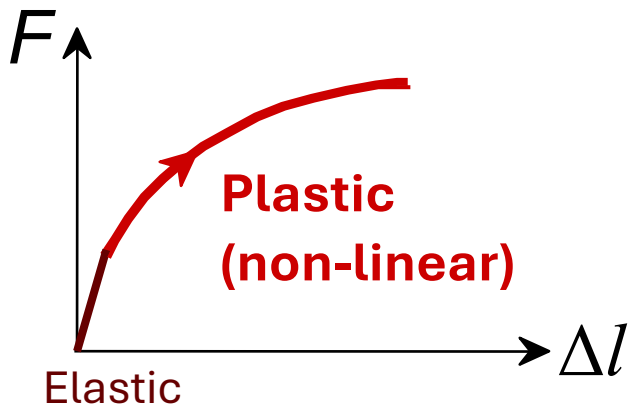
Plastic/irreversible deformation ↔ bond breaking



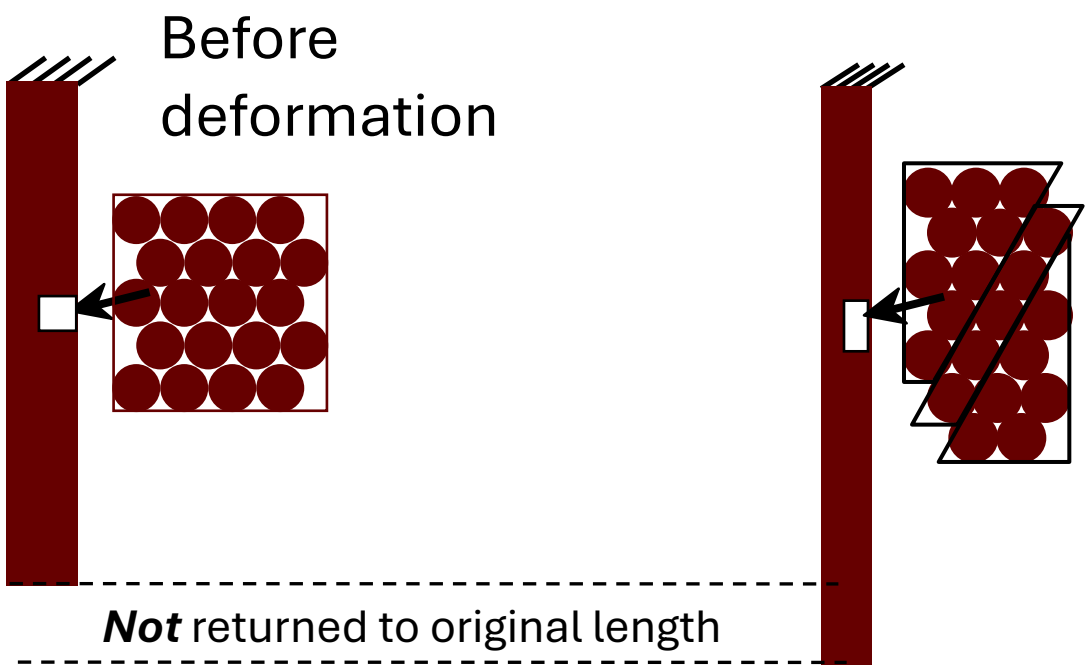




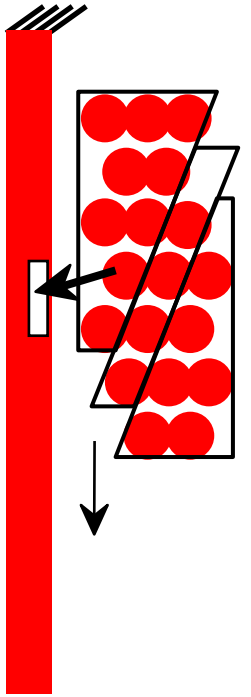




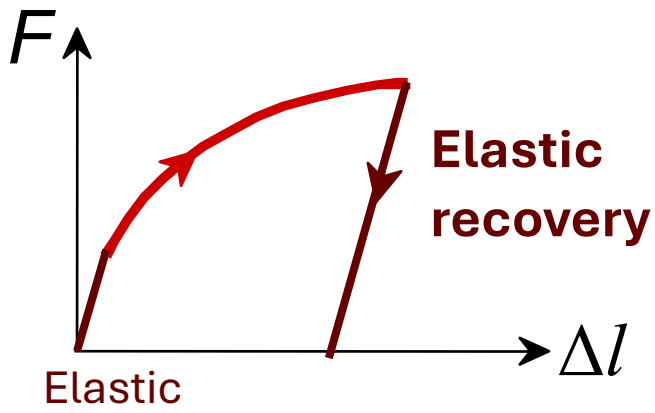
Plastic/irreversible deformation ↔ bond breaking



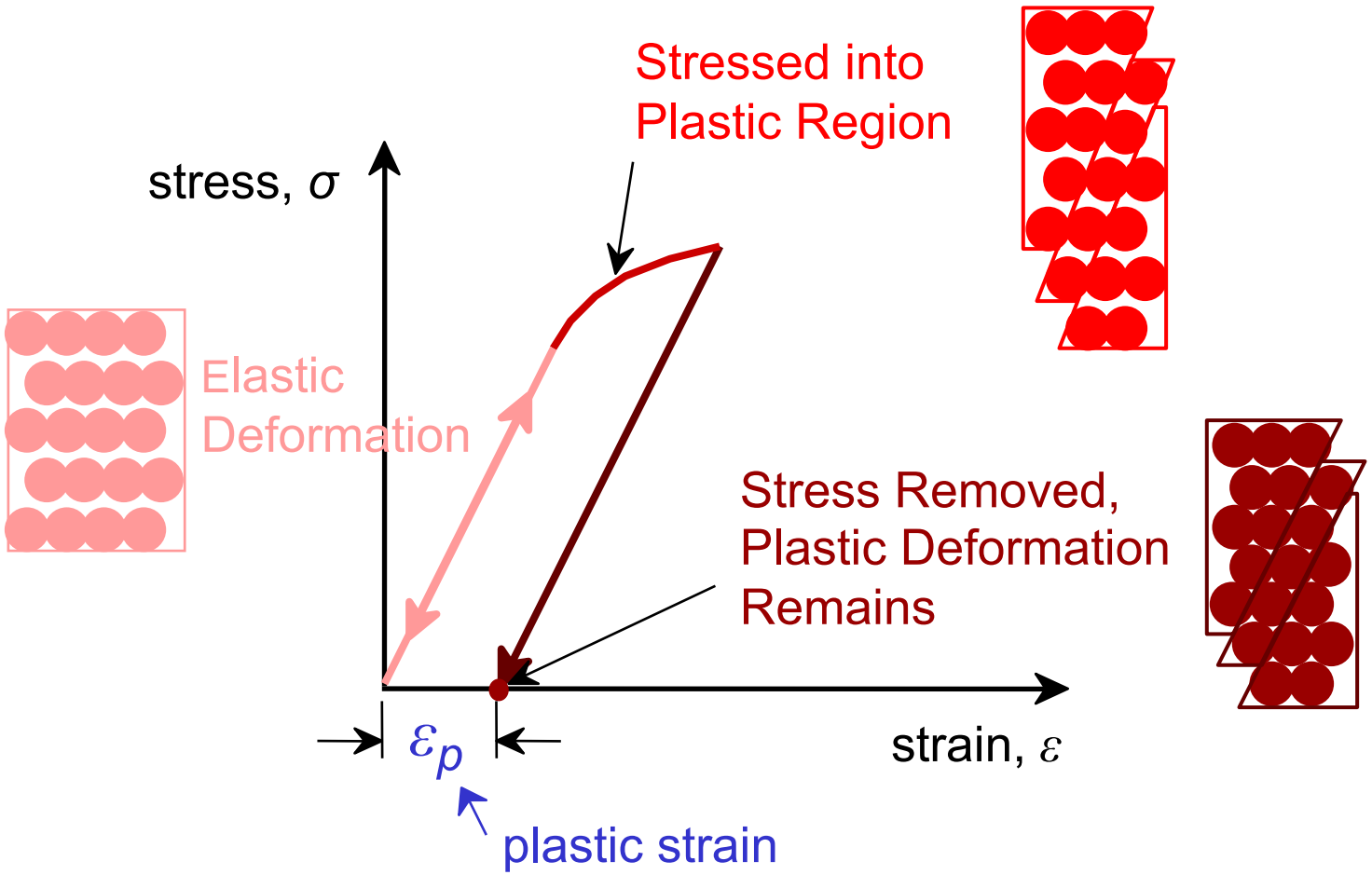
After unloading, some atoms **remain displaced.**



Bonds are broken and reformed. Entire planes are shifted.



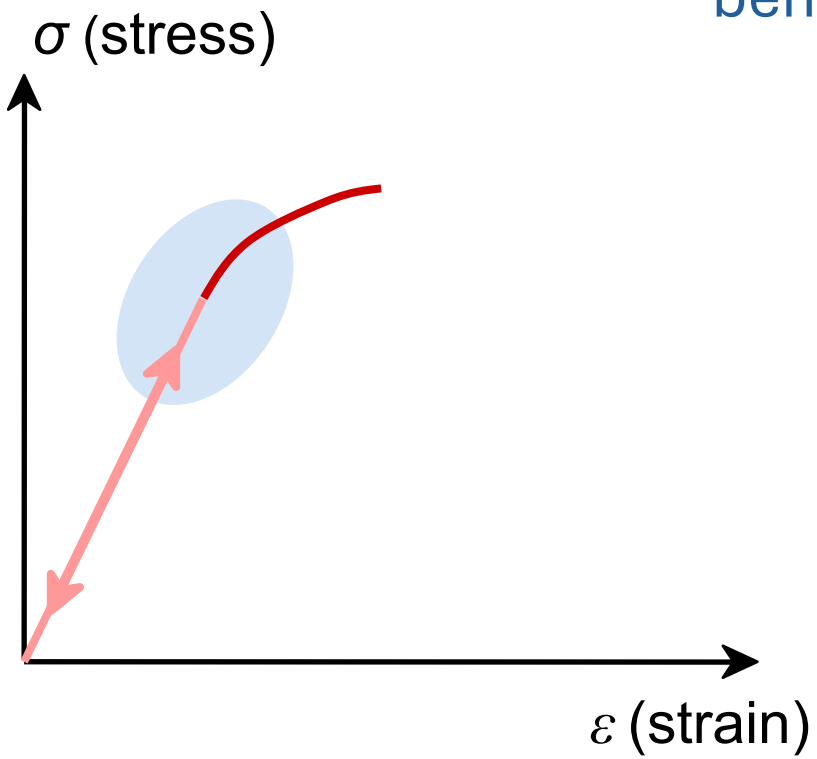
Elastic versus plastic deformation



Yield strength measures onset of plasticity

In practice, we would like to know how much stress a material can withstand before **"yielding"** (undergoing irreversible *plastic* deformation)

But the transition from elastic to plastic behavior is often subtle/continuous



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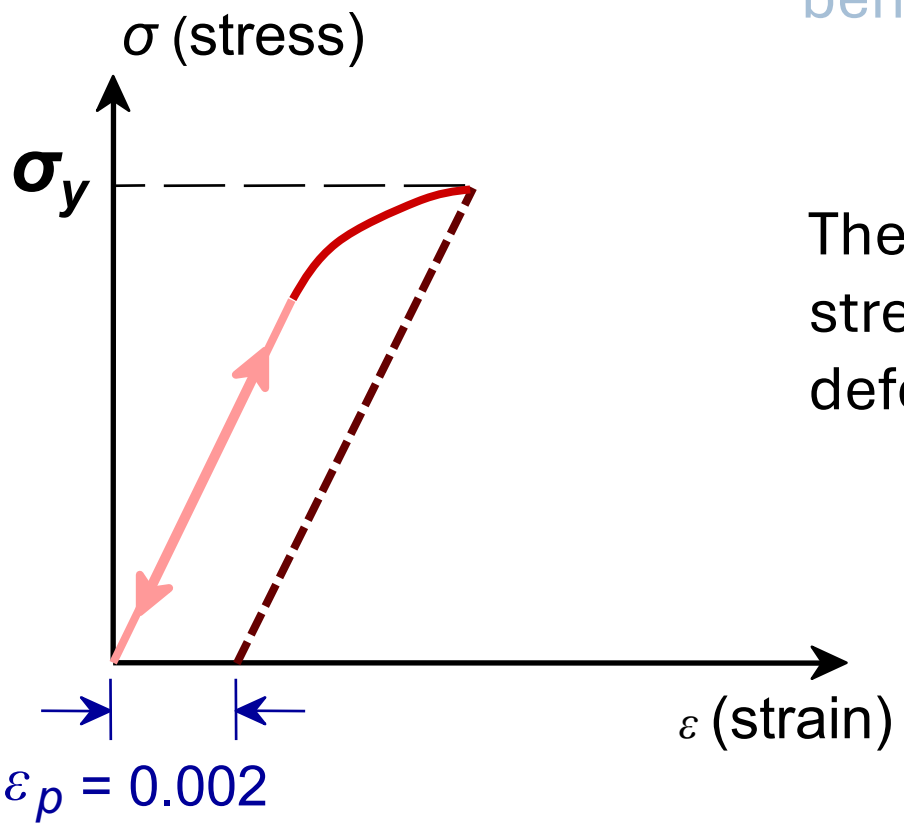
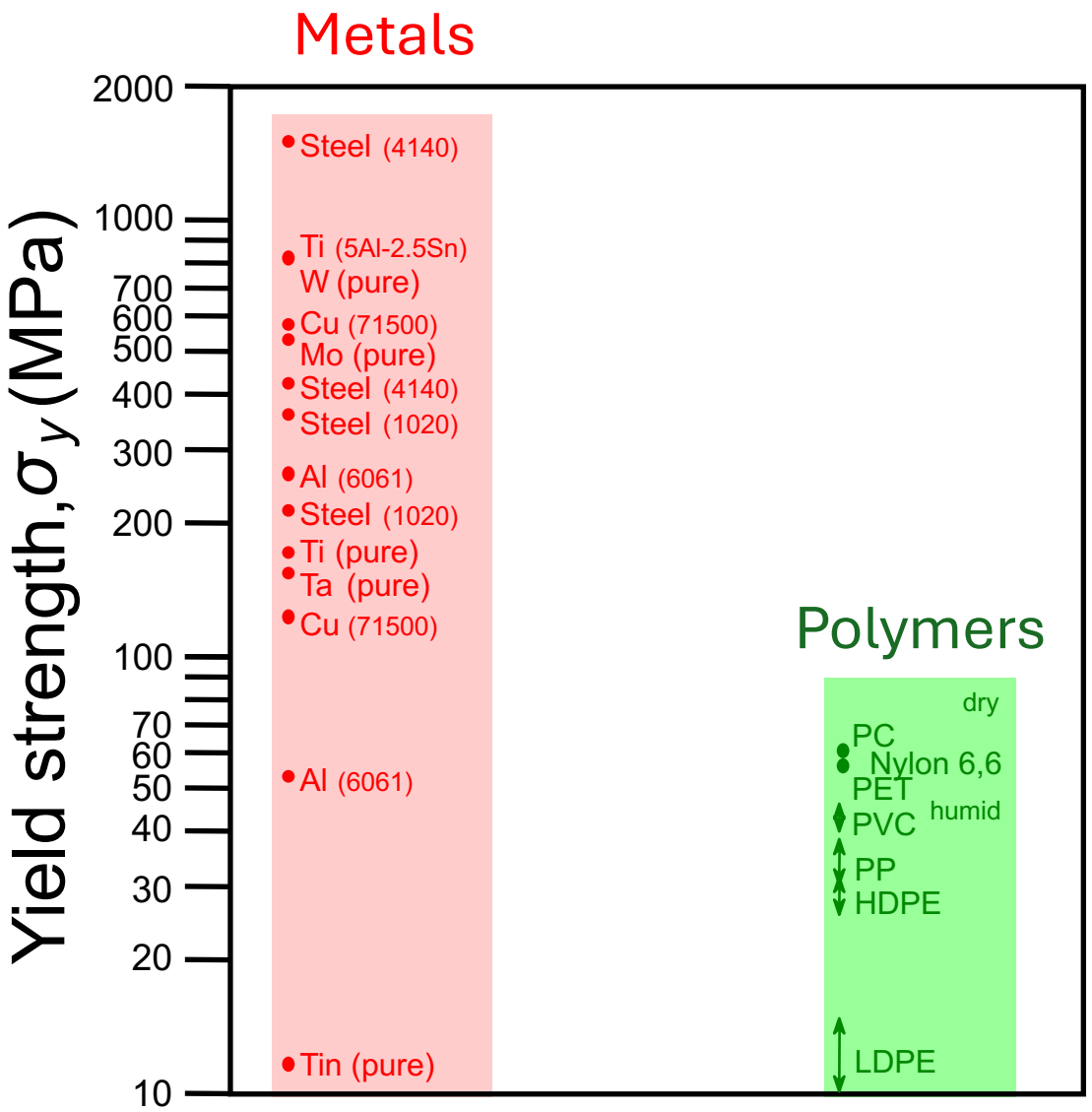


The **yield strength (σ_Y)** is measured by the stress at which *noticeable* (~0.2%) plastic deformation has occurred

High yield strength (often in units of MPa) means the material can withstand lots of force before irreversibly deforming

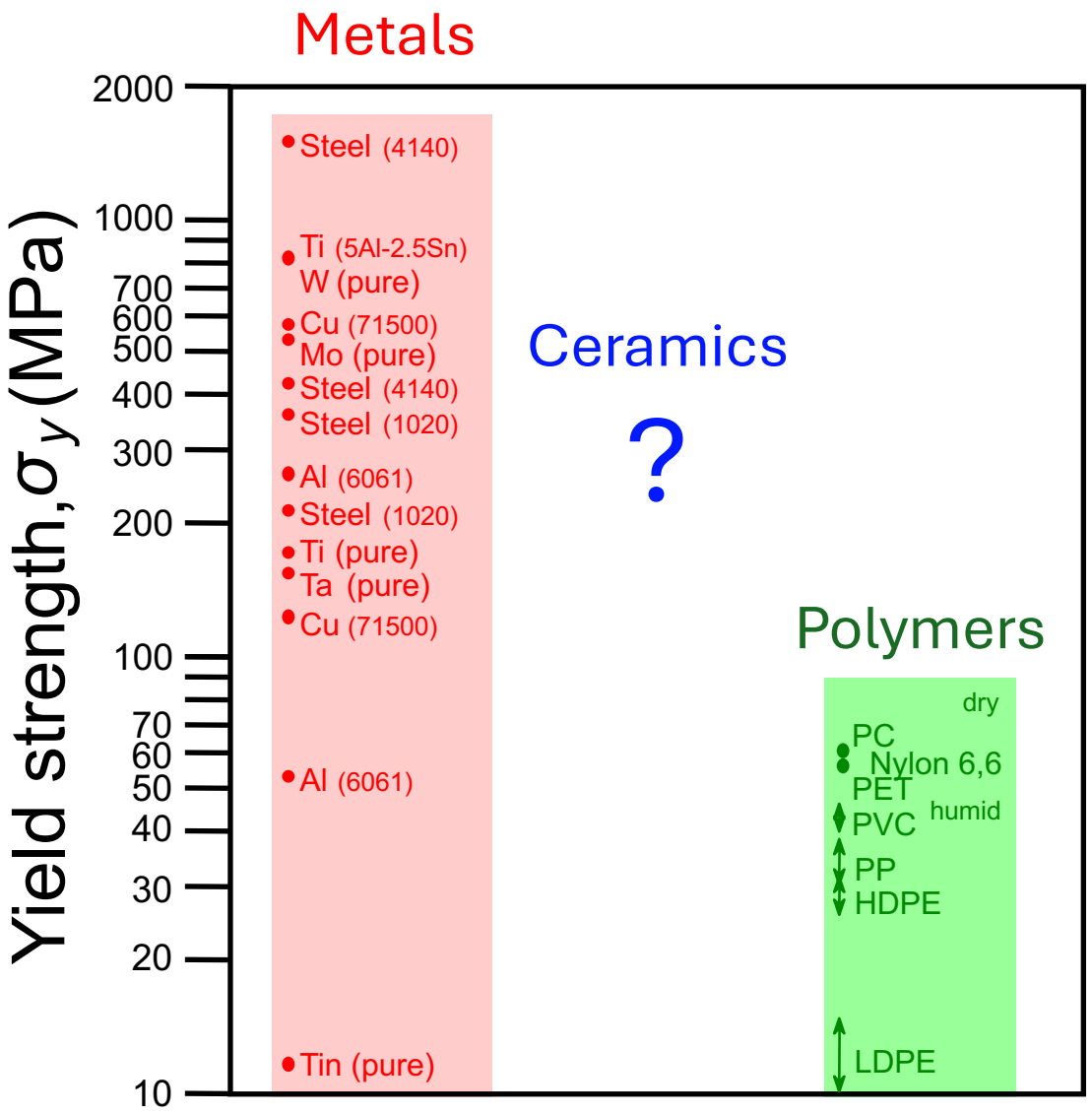
Comparison of yield strengths among materials



Metals can exhibit a very wide range of yield strengths, with steels often providing the highest values

Most polymers yield at much lower stresses than metals

Comparison of yield strengths among materials





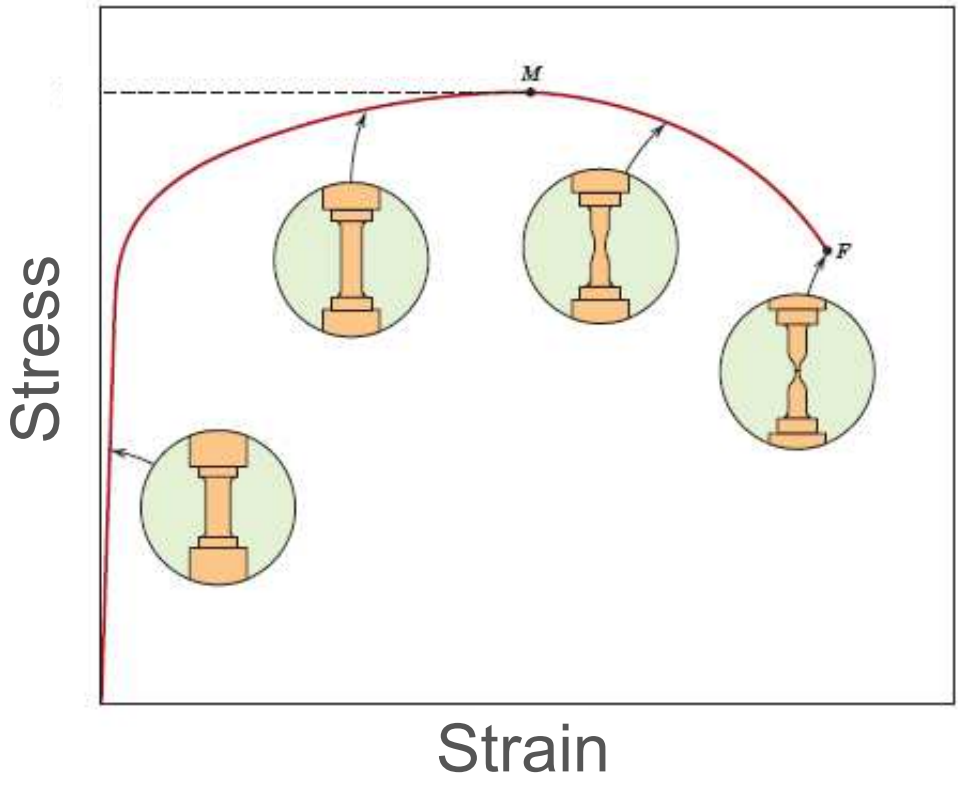
vs.



Yield strength is difficult to measure for **ceramics** because they **fracture** before undergoing plastic deformation

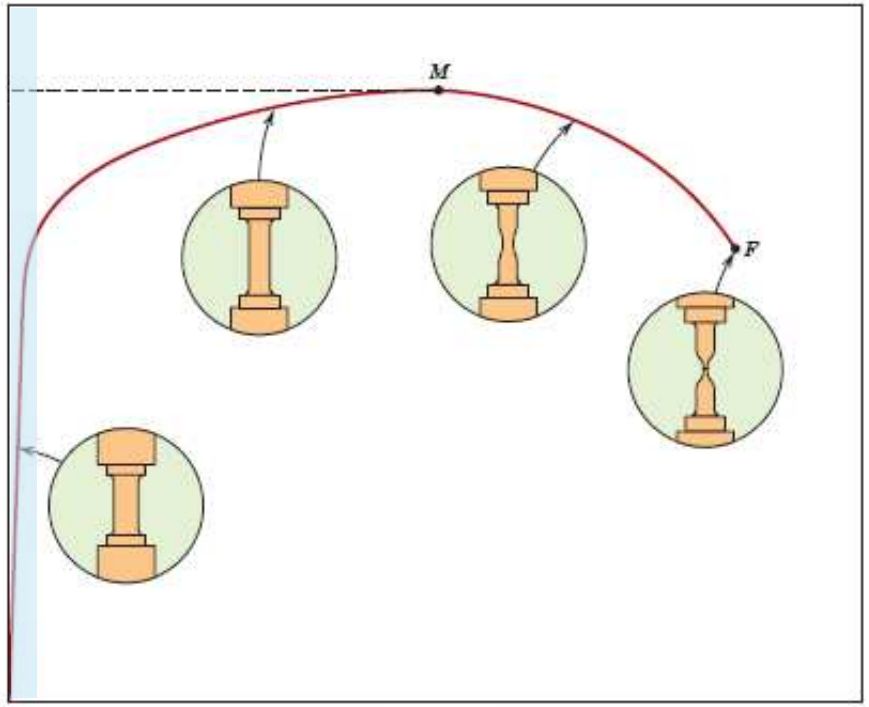
Quick pause. Any questions?

Elasticity → Plasticity → Fracture





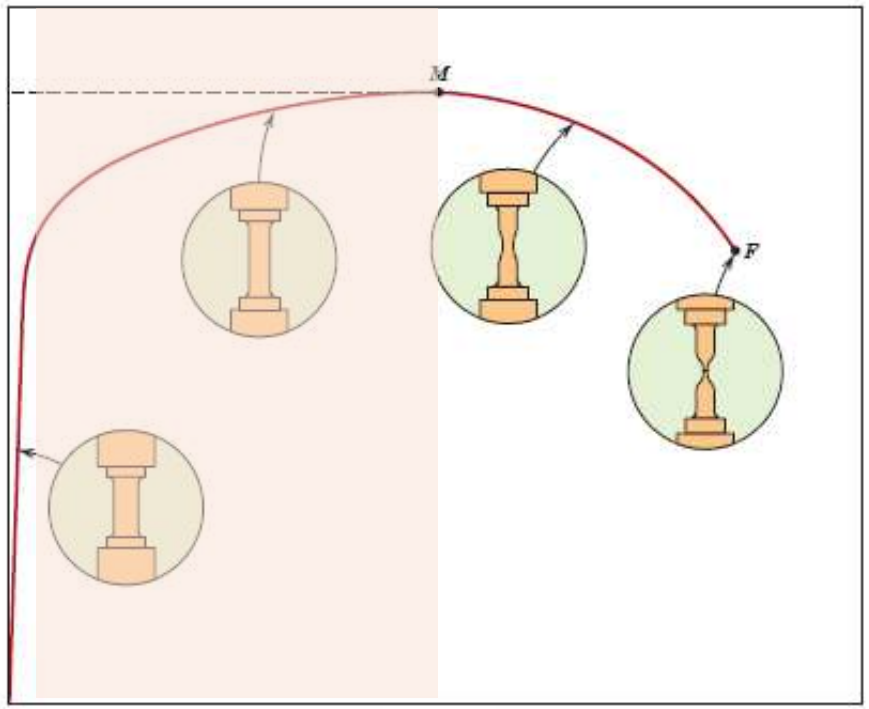
Elasticity → Plasticity → Fracture



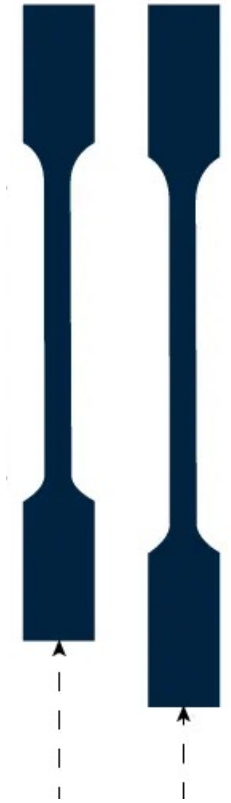
Elasticity at very small strain



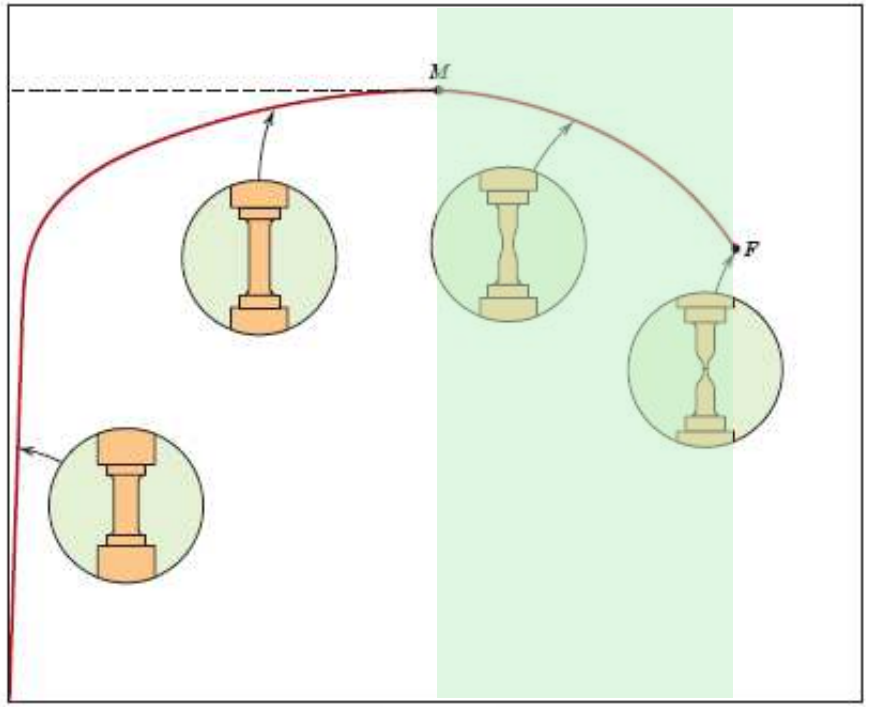
Elasticity → Plasticity → Fracture

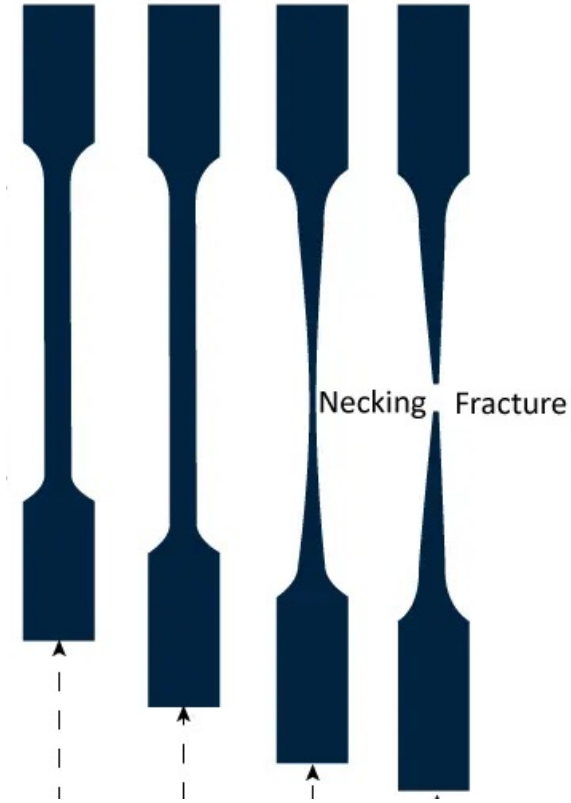


Plasticity occurs over much wider range (for metals)



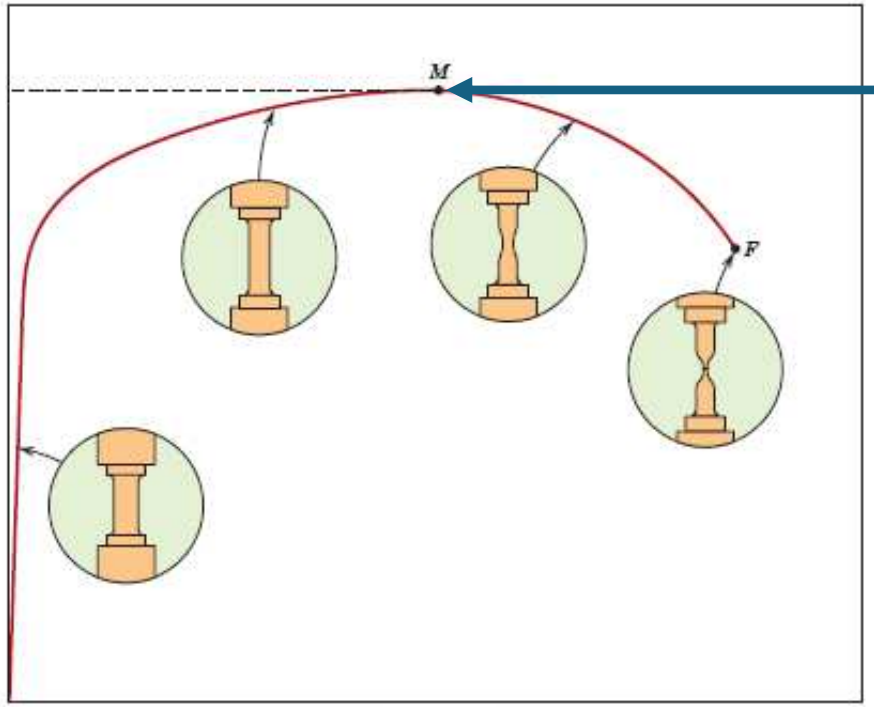
Elasticity → Plasticity → Fracture





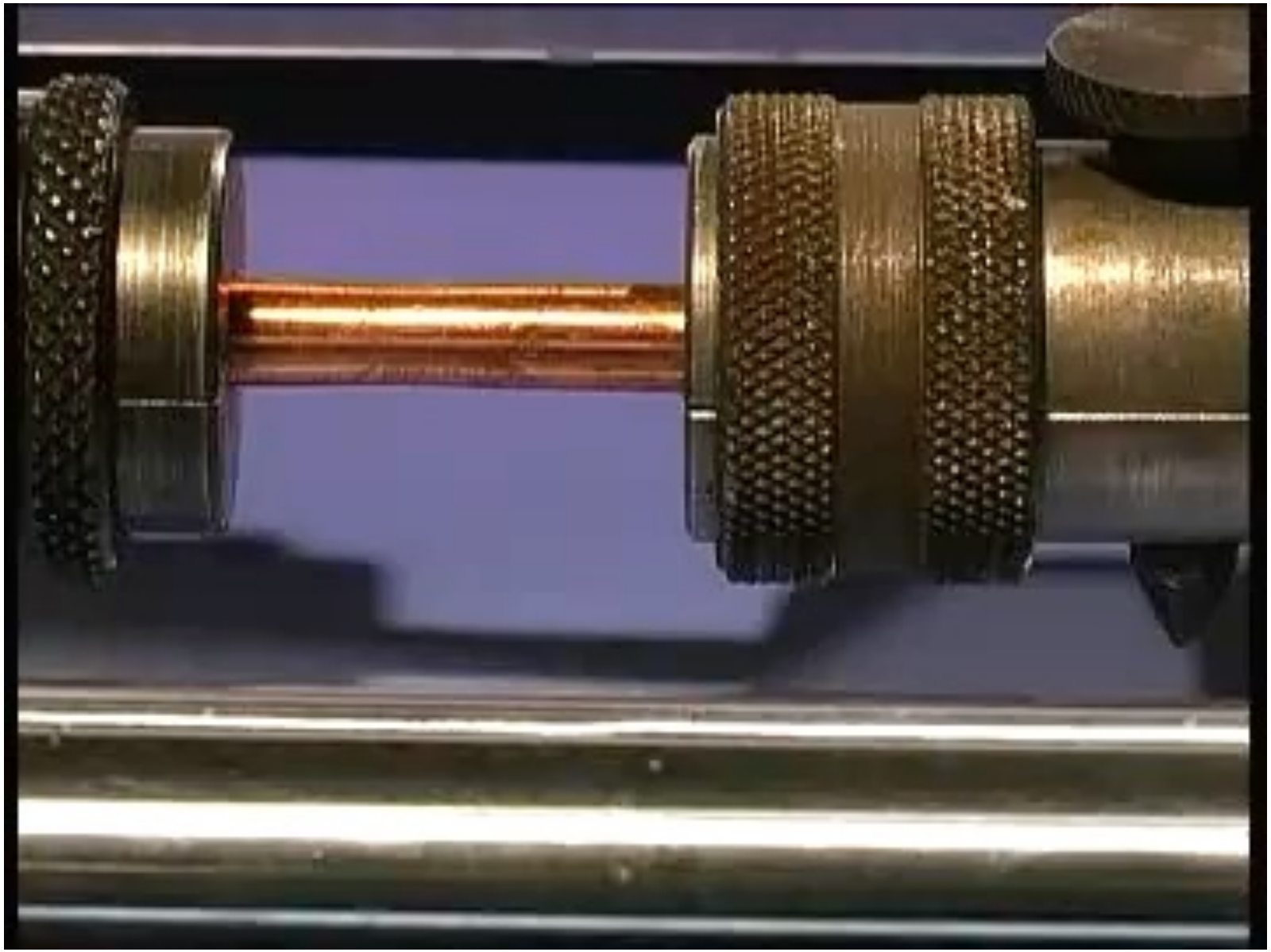
“Necking” concentrates stress in smaller area until fracture occurs

Elasticity → Plasticity → Fracture



The **tensile strength** measures the onset of necking. It is the maximum on the stress-strain curve.

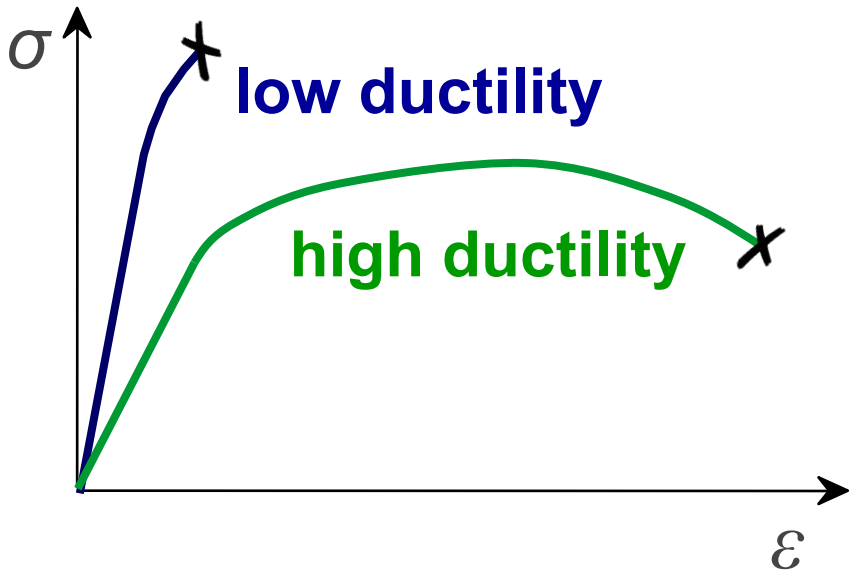
Do not approach this stress level if you want to avoid failure!



https://www.youtube.com/watch?v=M7OyH0wNTrY

Another important property: Ductility

The **ductility** measures the **amount of plastic deformation at failure**



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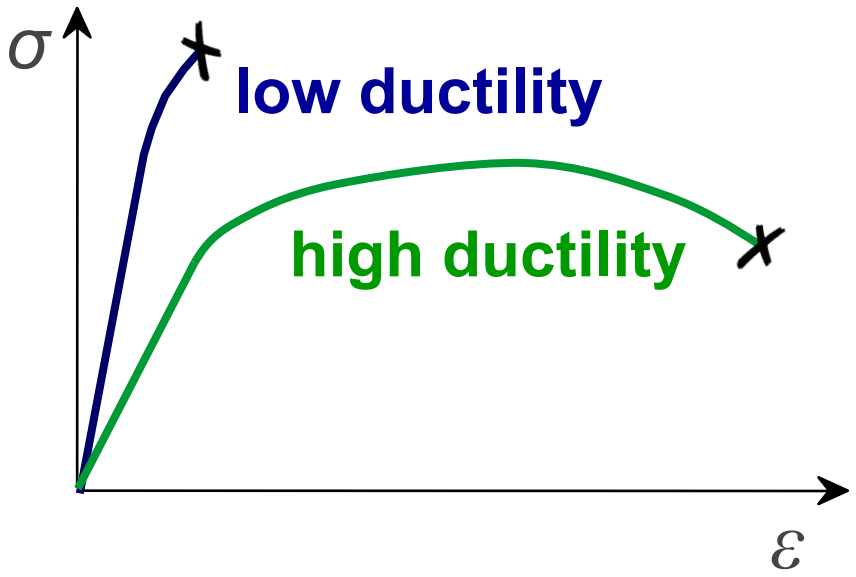

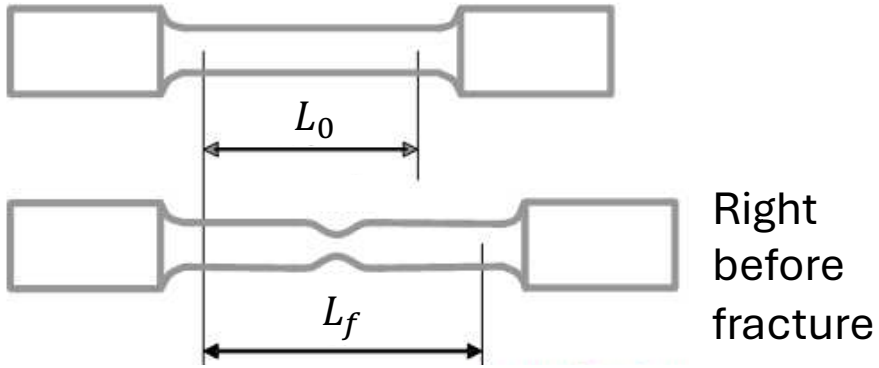

Right before fracture

We can measure this either as:

- **The % elongation at failure:**

$$\%\mathrm{EL} = \left(\frac{l_f - l_0}{l_0}\right) \times 100$$

Another important property: Ductility

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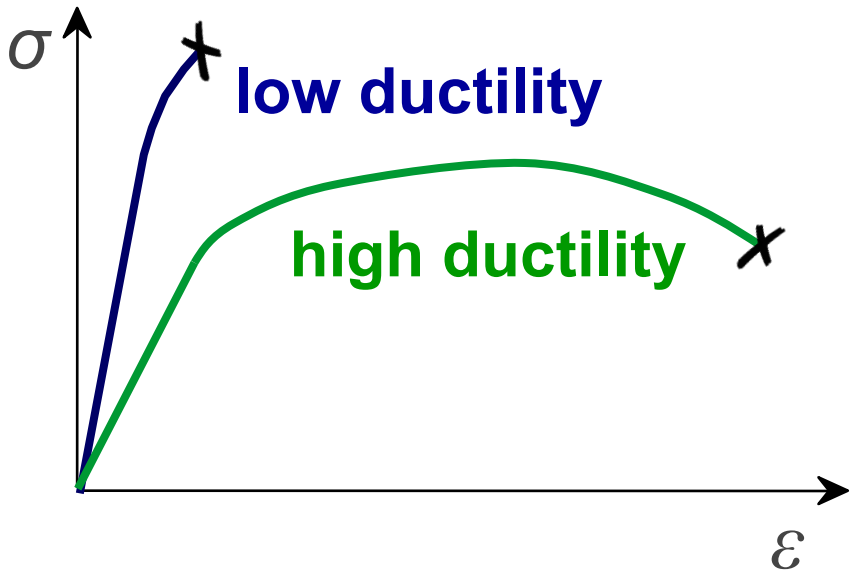
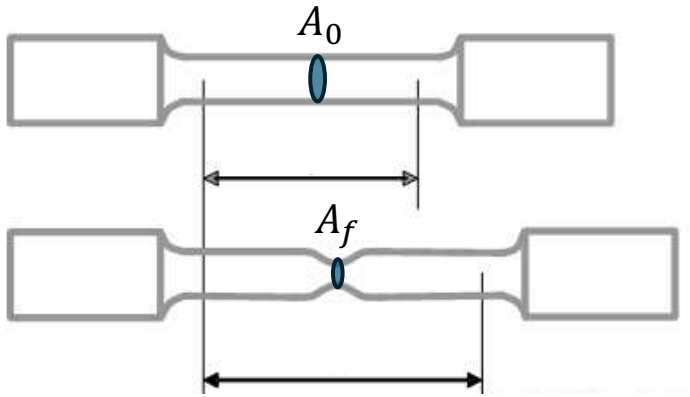




Right before fracture

We can measure this either as:

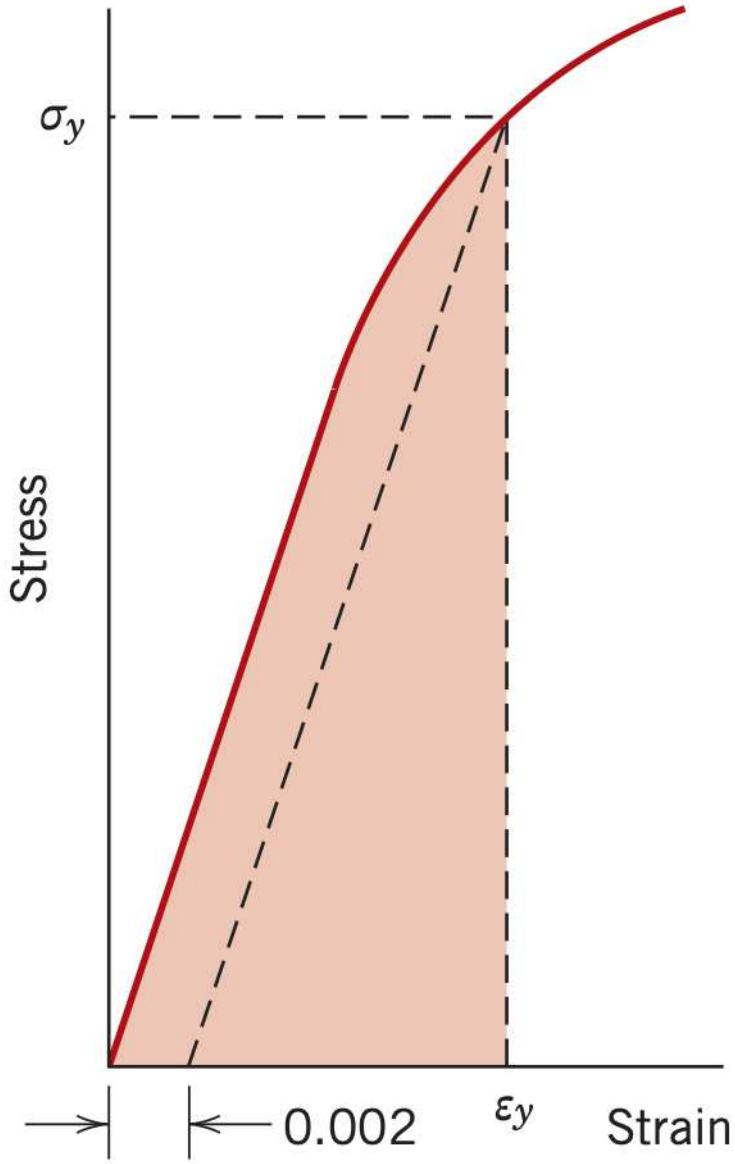
- The % elongation at failure:

$$\%\mathrm{EL} = \left(\frac{l_f - l_0}{l_0}\right) \times 100$$

- **The % reduction in area:**

$$\%\mathrm{RA} = \left(\frac{A_0 - A_f}{A_0}\right) \times 100$$

Related to ductility: Resilience



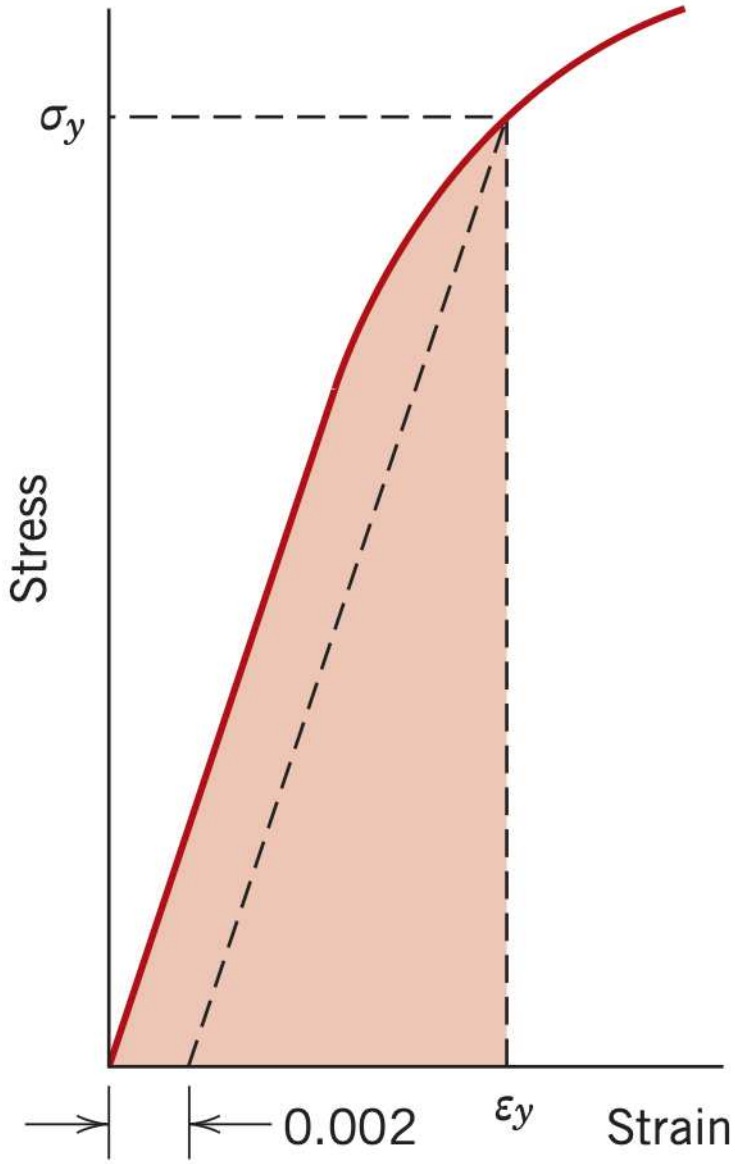
Recall from your Physics course: the work done by a force ($\vec{F}$) over some path ($d\vec{r}$) is given by:

$$W = \int \vec{F} \cdot d\vec{r}$$

We can think of stress (σ) and strain (ϵ) as another version of force and displacement. The **energy absorbed** by the material is:

$$U = \int \sigma d\epsilon$$

Related to ductility: Resilience

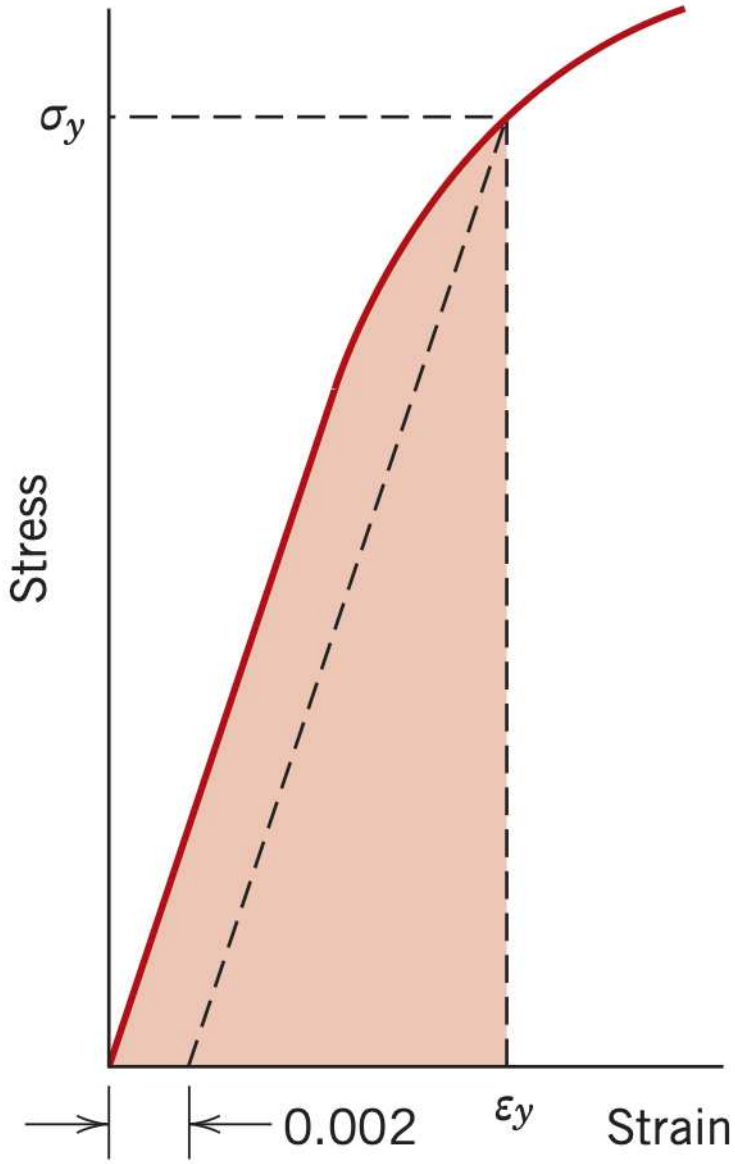


If we focus on the **elastic regime**, we can assume $\boldsymbol{\sigma(\epsilon)}$ **is linear** up to the yield strength (σ_Y) and therefore this integral becomes:

$$\boldsymbol{U = \frac{1}{2}\sigma_Y \epsilon_Y}$$

$$U = \int \sigma d\epsilon$$

Related to ductility: Resilience



If we focus on the **elastic regime**, we can assume $\boldsymbol{\sigma(\epsilon)}$ **is linear** up to the yield strength (σ_Y) and therefore this integral becomes:

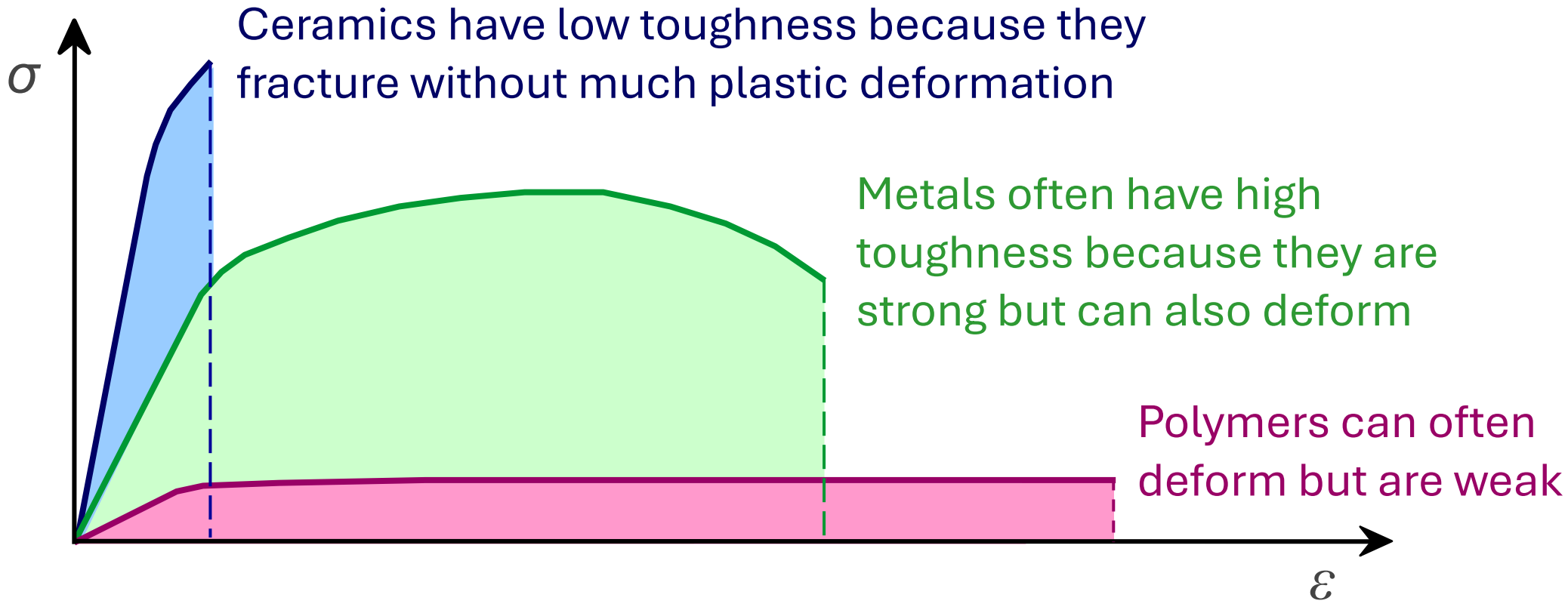
$$\boldsymbol{U = \frac{1}{2}\sigma_Y \epsilon_Y}$$

This is known as the **resilience.** It measures **how much energy a material can absorb through elastic deformation.**

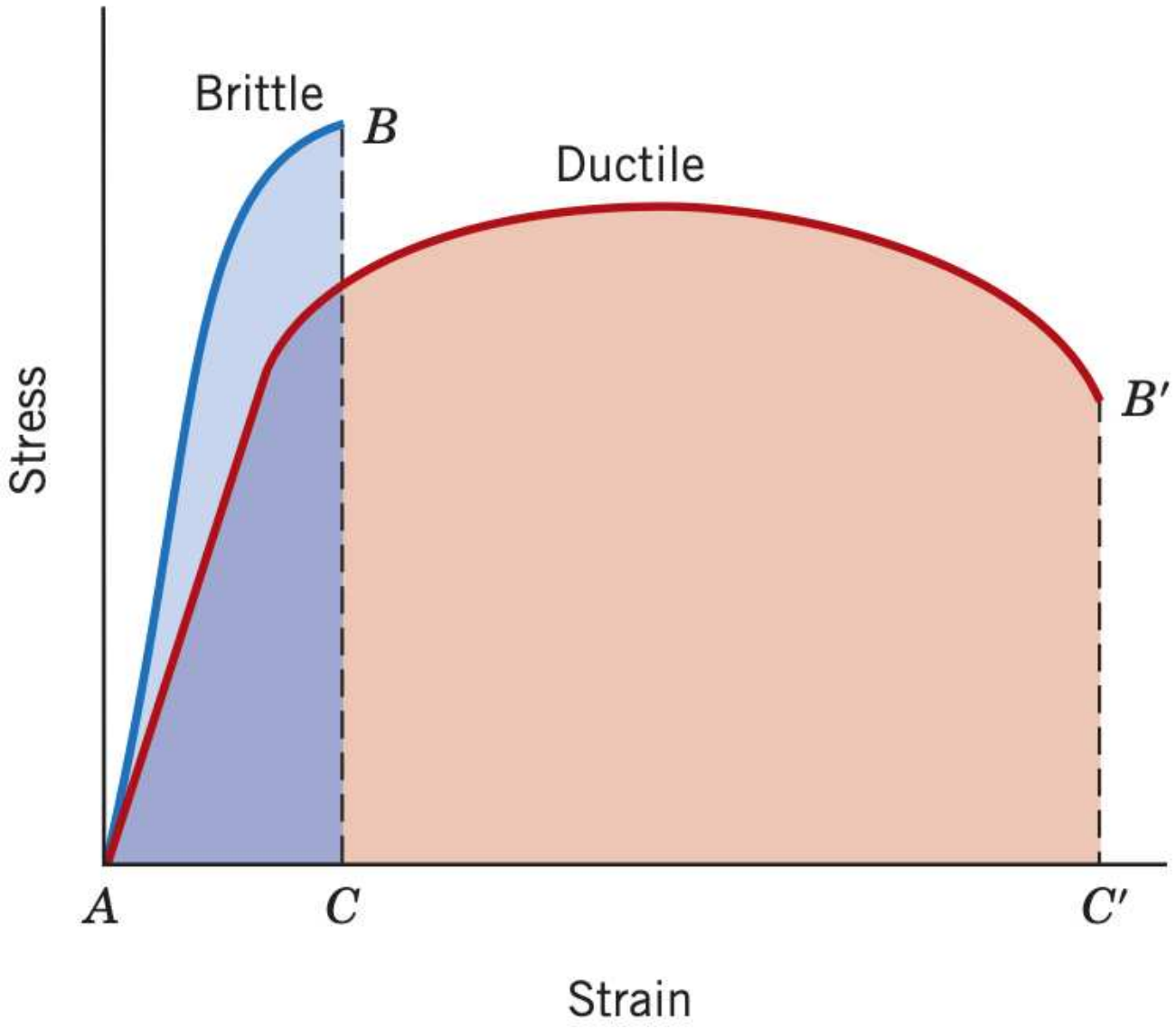
One more property: Toughness

Resilience = energy absorbed under ***elastic deformation only***

Toughness = energy absorbed under ***total deformation until fracture***



One more property: Toughness



Ductile materials are usually tougher than brittle* ones because they can absorb a lot of energy through plastic deformation

***Brittle = *not* ductile, fractures easily and without much/any plastic deformation**

These properties depend not only on material, but also temperature!

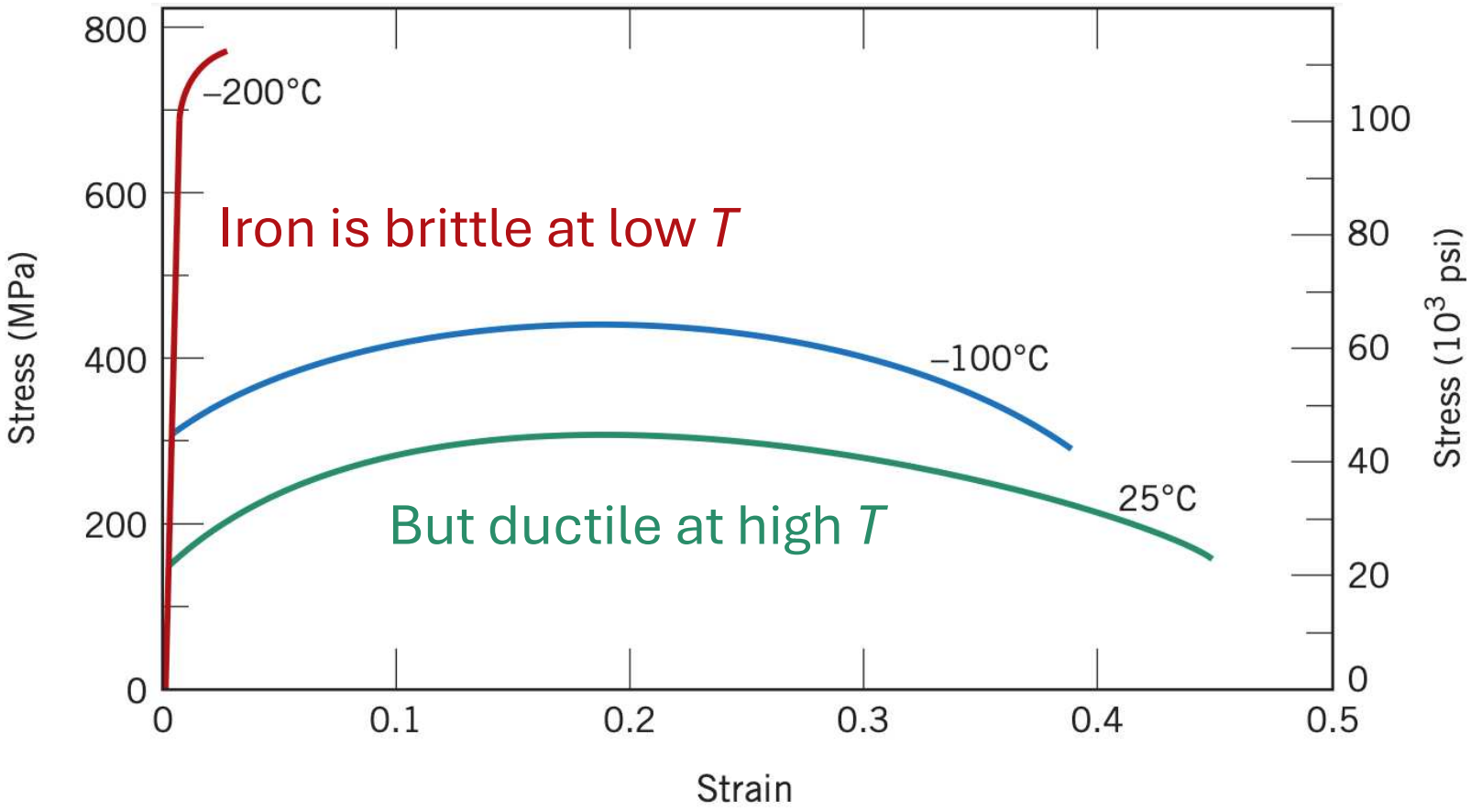


Figure 6.14 Engineering stress–strain behavior for iron at three temperatures.

We'll come back to this later…





Stress-strain curves? Ductility? Resilience? Toughness?

A bit of semantics on “true” stress and strain

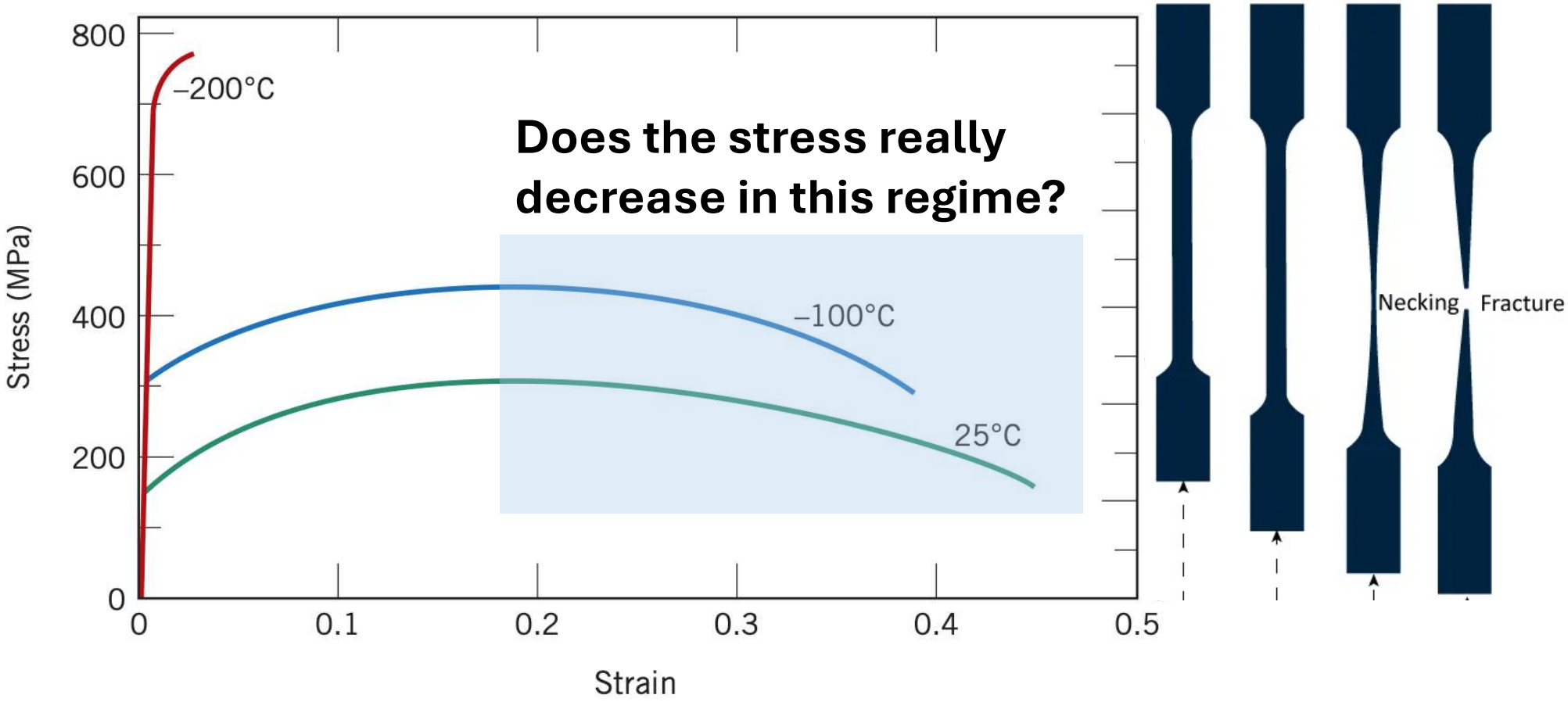
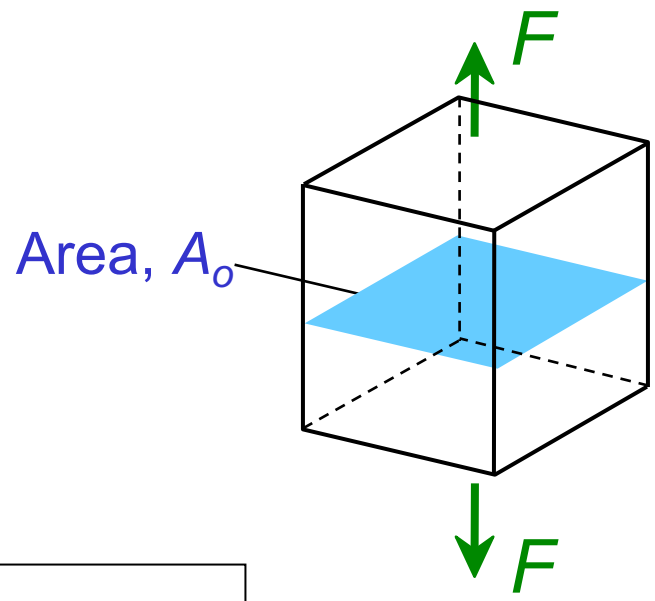


Figure 6.14 Engineering stress–strain behavior for iron at three temperatures.

A bit of semantics on “true” stress and strain

- Tensile stress, σ

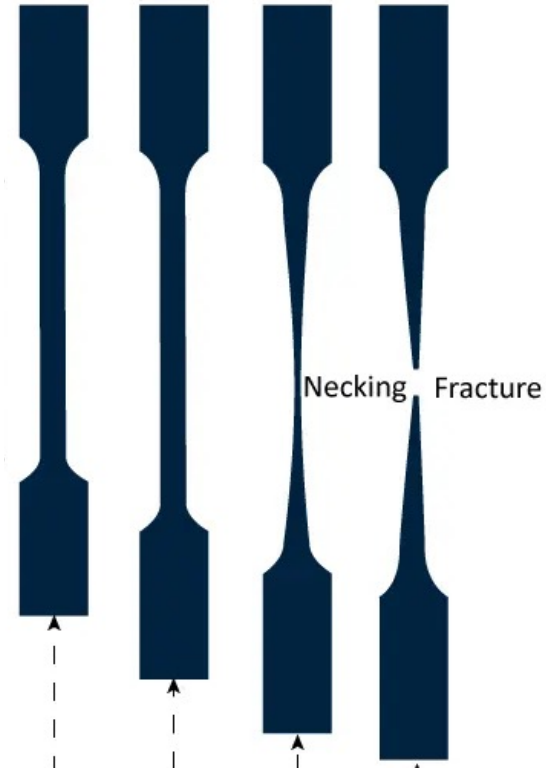


$$\sigma = \frac{F}{A_o}$$

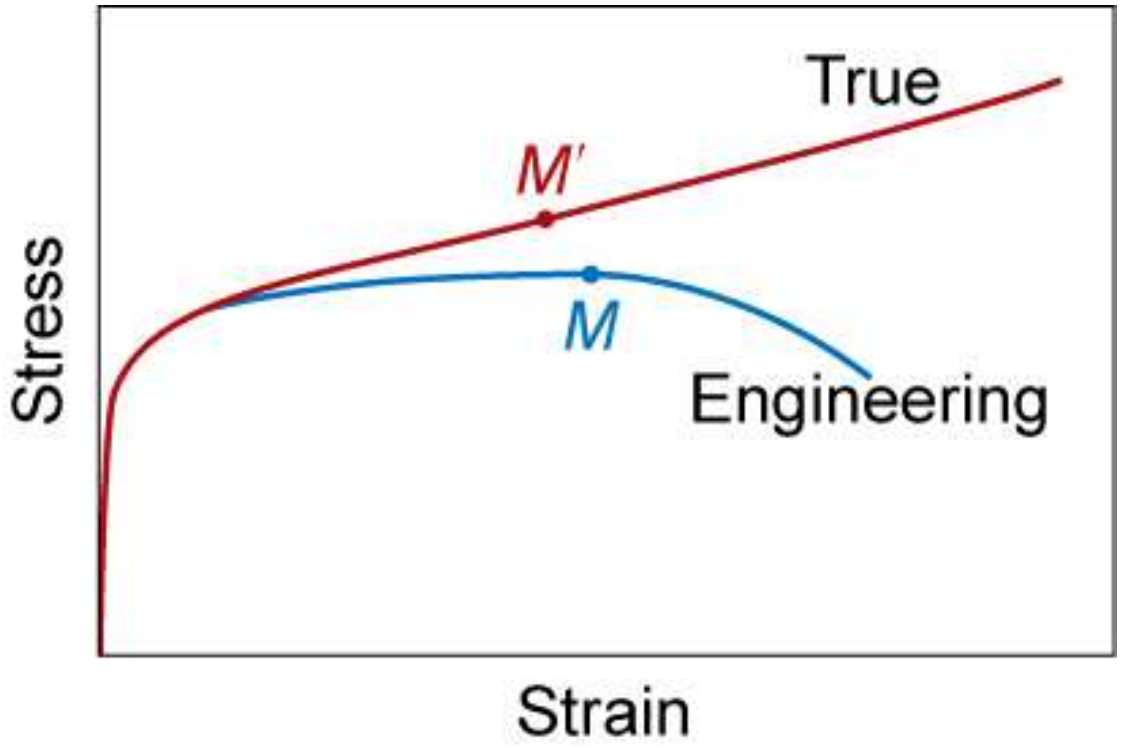
original cross-sectional area *before* loading

What we’ve been using is really the **“engineering stress”** – which is calculated using the **original cross-sectional area**

But as the material deforms, the ***true* area is reduced**, which leads to a stress concentration



A bit of semantics on “true” stress and strain



In other words, the material itself always gets stronger, but it “feels” weaker because the cross-sectional area is decreasing

The **true stress** accounts for this change in area:

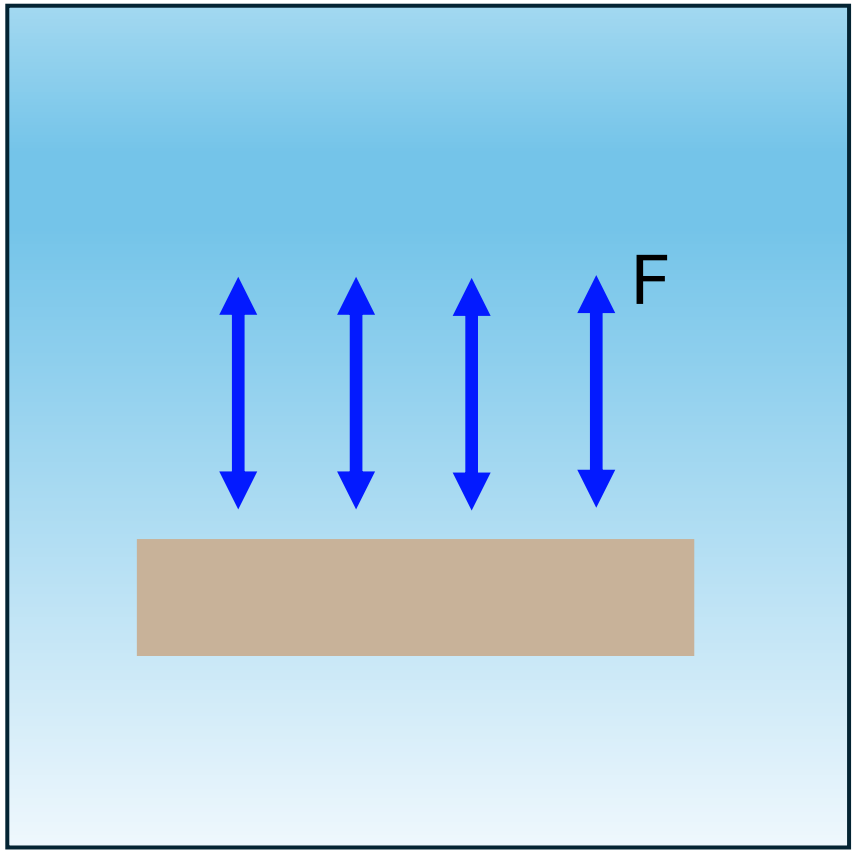
$$\sigma_T = F/\boldsymbol{A_i}$$

Instantaneous area

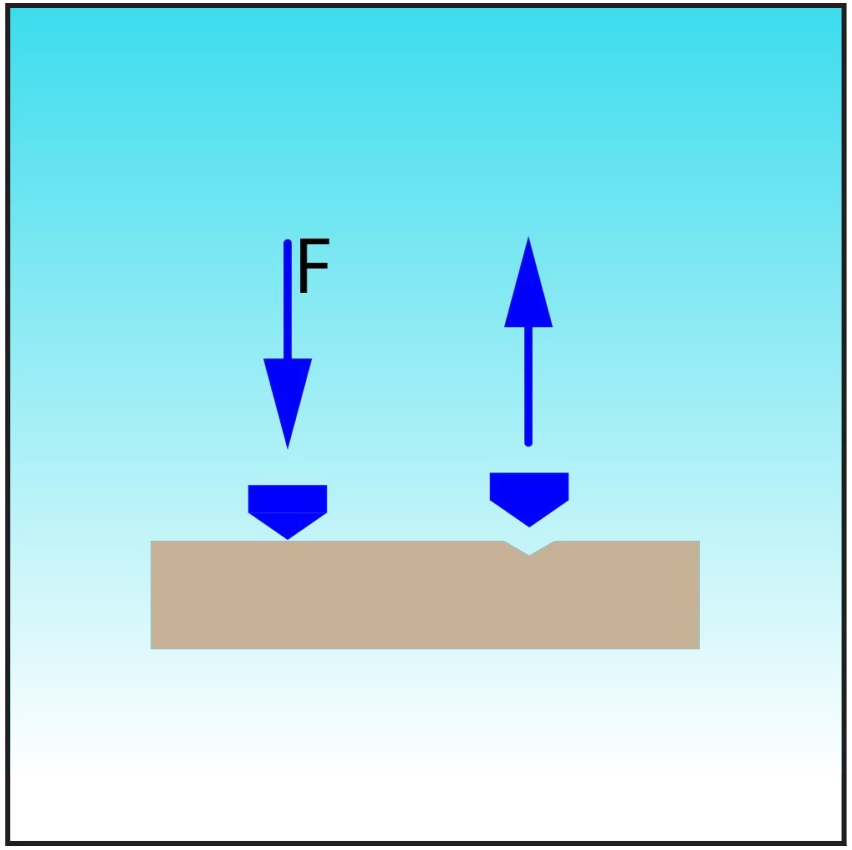
Unlike the engineering stress, which decreases at large strain, the true stress *always* increases

See Callister for conversion equations

Uniform versus localized deformation



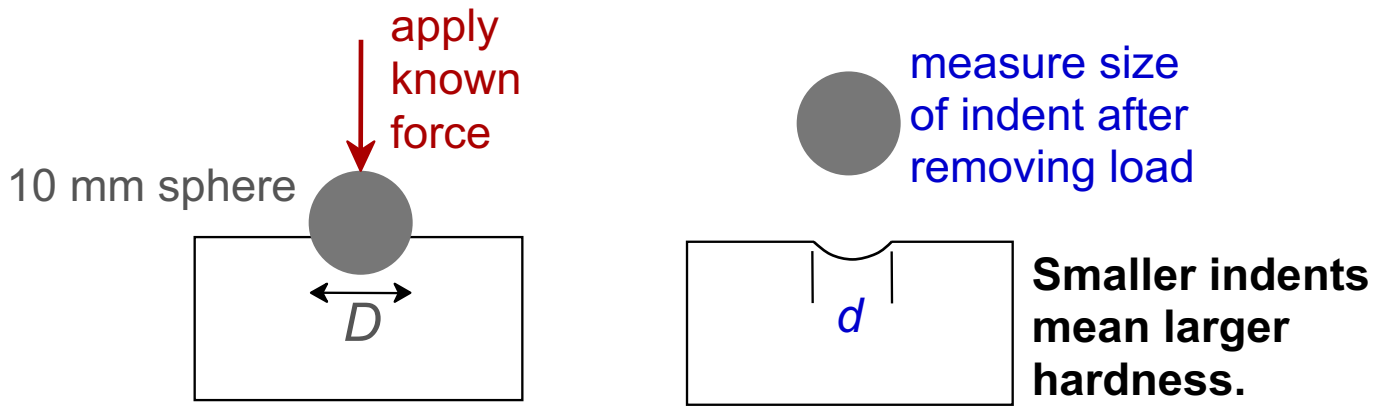
Uniform force applied to specimen

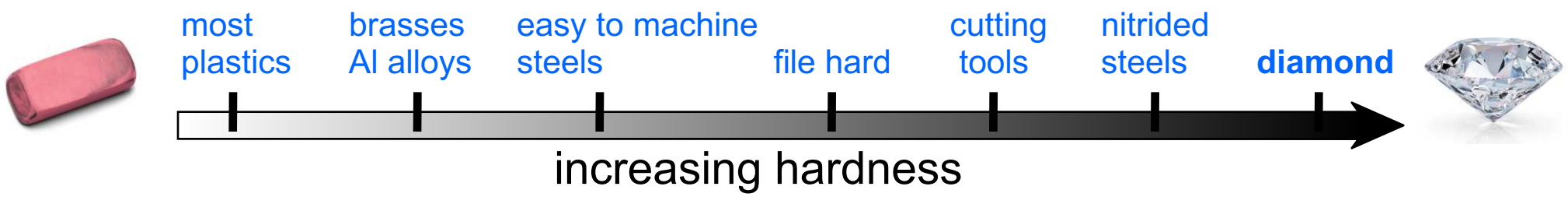


Localized force applied to specimen

Hardness = resistance to localized deformation

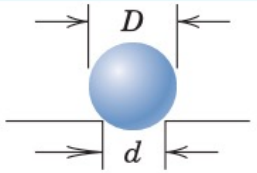
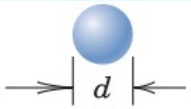
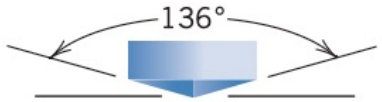
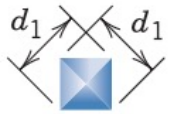
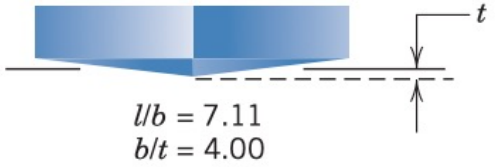
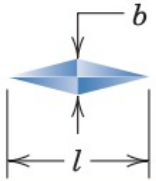
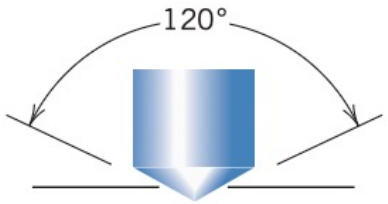
This property is somewhat loosely defined, and there are **multiple ways to measure it**.





Higher hardness means: 1) better resistance to localized compressive loads, and 2) **better wear resistance** – unlikely to be scratched by other materials

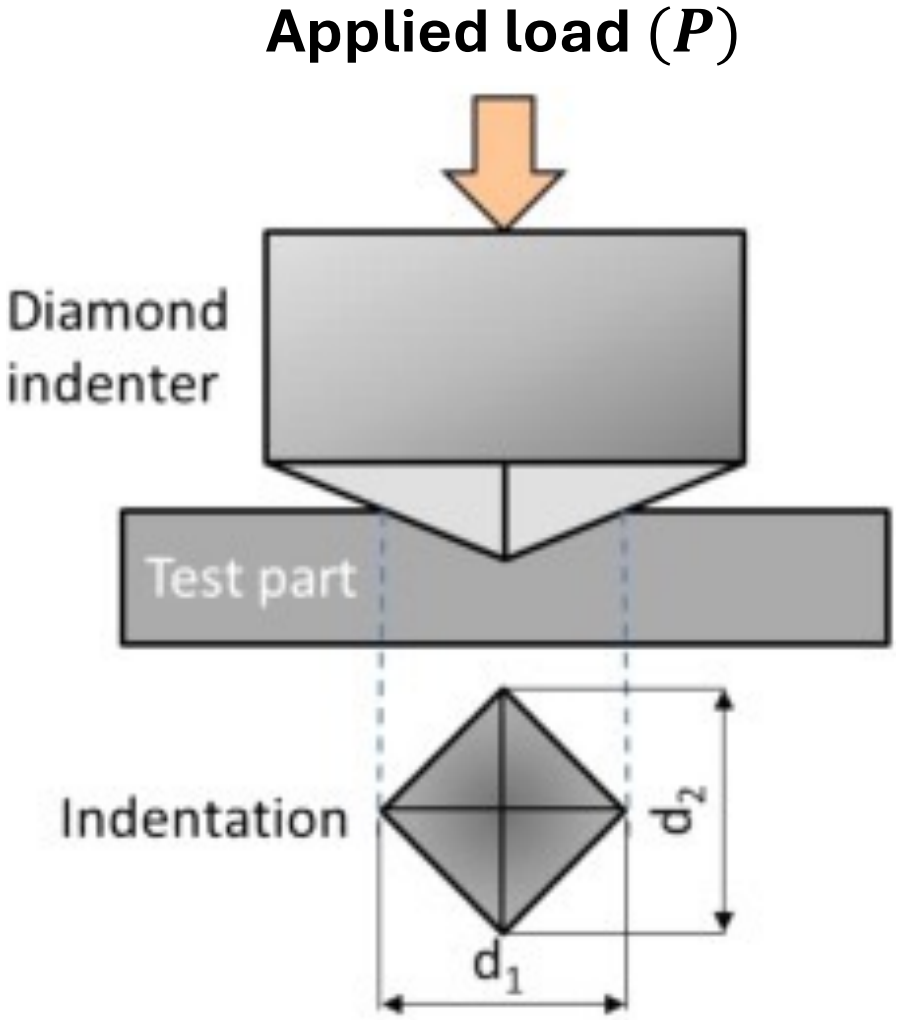
Hardness = resistance to localized deformation

Test	Indenter	Shape of Indentation: Side View	Shape of Indentation: Top View
Brinell	10-mm sphere of steel or tungsten carbide		
Vickers microhardness	Diamond pyramid		
Knoop microhardness	Diamond pyramid		
Rockwell and superficial Rockwell	Diamond cone: $\frac{1}{16}$-, $\frac{1}{8}$-, $\frac{1}{4}$-, $\frac{1}{2}$-in. diameter steel spheres		 

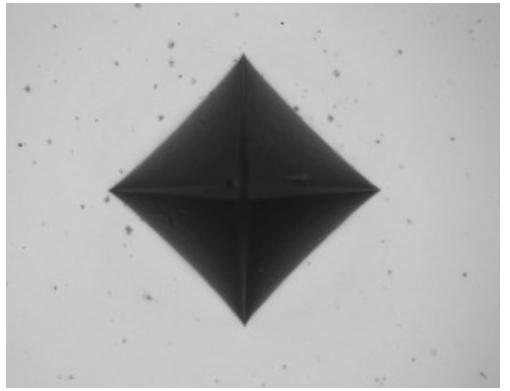
There are different tests people use to measure hardness. Each has a **uniquely shaped object that makes the indent.**

See Table 6.5 in Callister for details

A common method: Vickers hardness



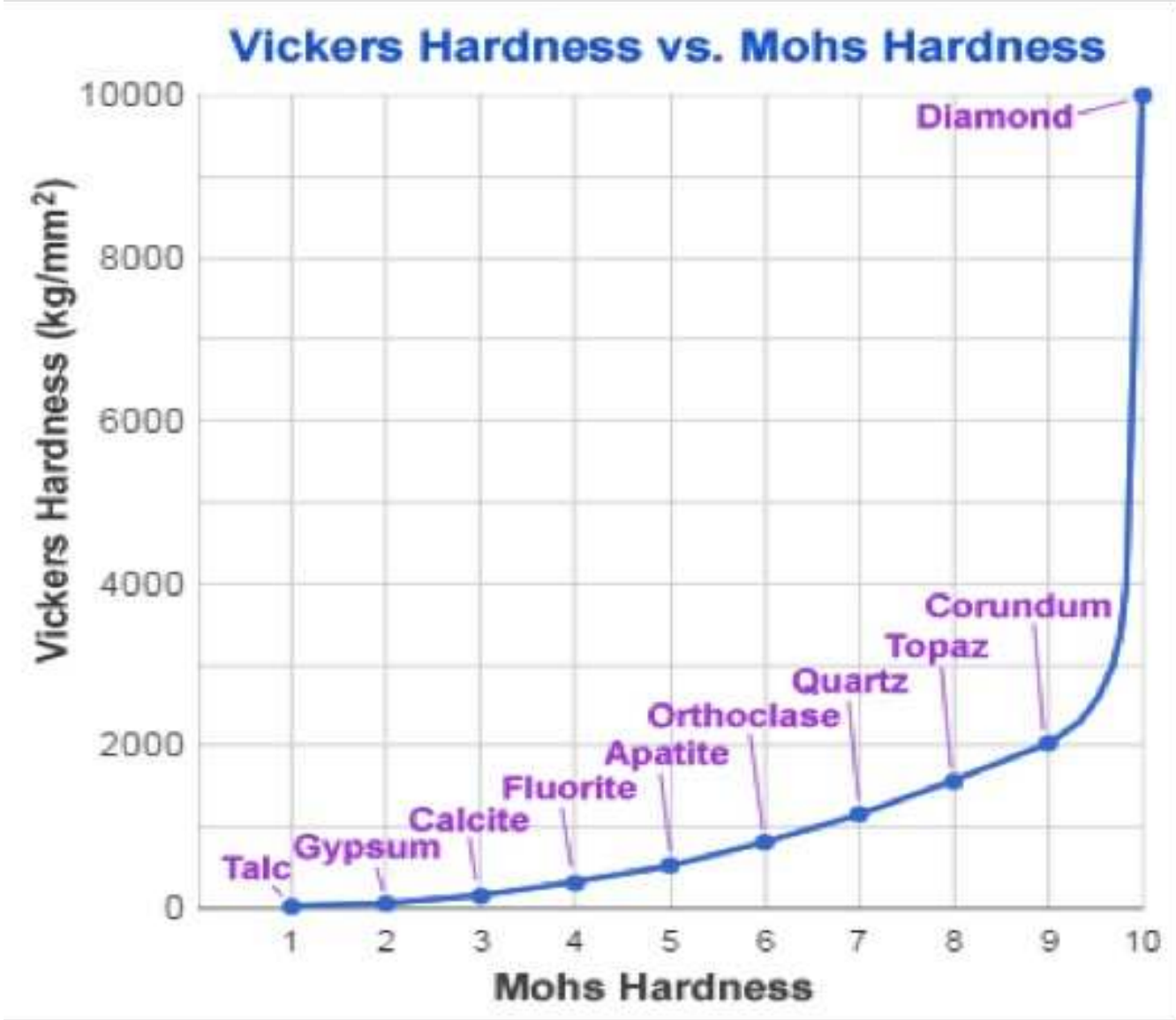




$$\mathrm{HV} = 1.854P/d_1^2$$

Larger indent = lower hardness

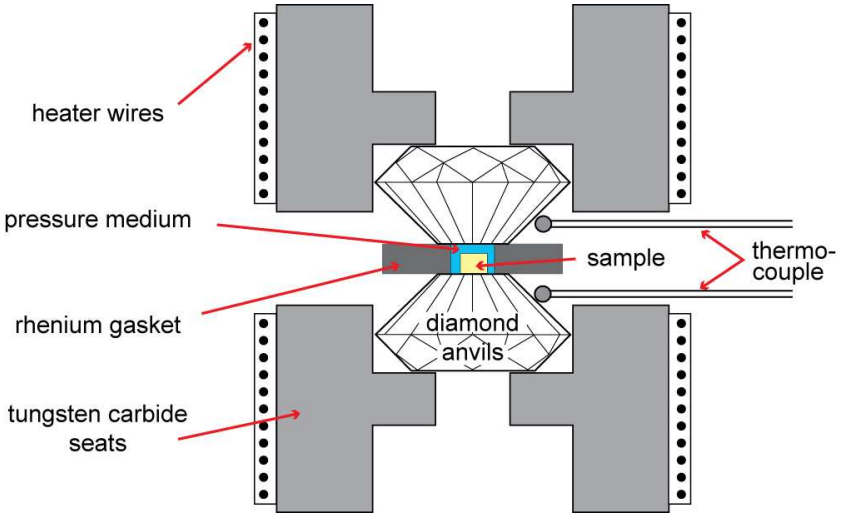
A common method: Vickers hardness



Diamond is *very* hard!







Speaking of applications…A design example

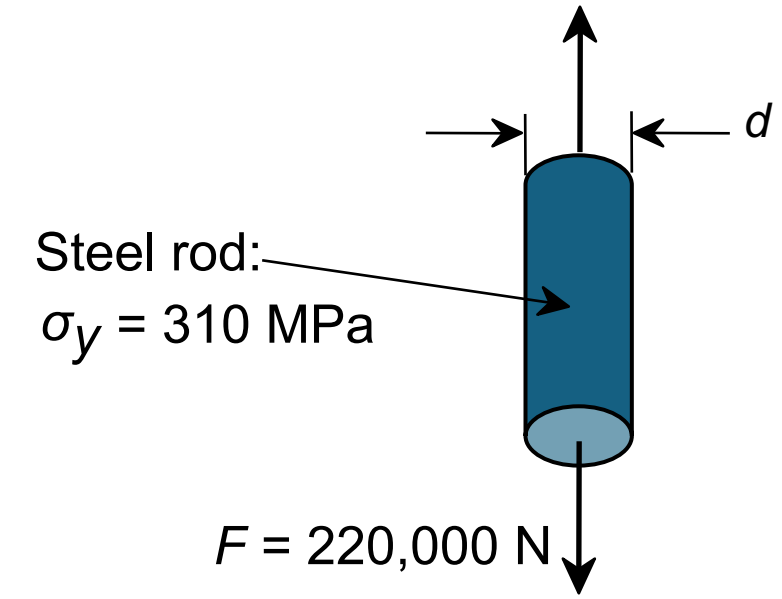
A **cylindrical rod**, constructed from a steel that has a **yield strength of 310 MPa**, is to **withstand a load of 220,000 N without yielding**. Find the **smallest diameter** at which the steel bar will be able to meet this requirement. **?**

$$\sigma = F/A$$

$$310\times10^{6}\ \text{Pa} = 220{,}000\ \text{N}/(\pi r^{2})$$

$$\boldsymbol{r = 0.015\ \text{m} = 1.5\ \text{cm}}$$

$$\boldsymbol{d = 3\ \text{cm}}$$



Is this really what you would use?
Probably not….Better to be safe!

Design and safety factors

- Because of design uncertainties (*e.g.*, material variations/imperfections) allowances must be made to protect against unanticipated failure
- For structural applications, to protect against possibility of failure, we often use a **working stress (σ_w) with a chosen factor of safety (N)**

$$\sigma_w = \frac{\sigma_y}{N}$$

yield strength

Depending on application, N is between 1.2 and 4

Back to our example

A **cylindrical rod**, constructed from a steel that has a **yield strength of 310 MPa**, is to **withstand a load of 220,000 N without yielding**. Find the **minimal *safe* diameter ?** at which the steel bar will be able to meet this requirement.

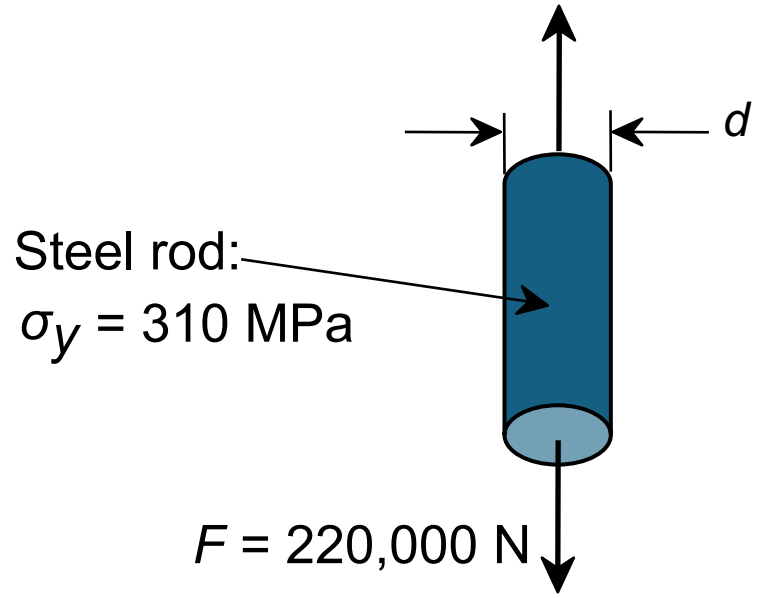
Let the factor of safety = 4

$$(310\times10^6\ \text{Pa})/4 = 220{,}000\ \text{N}/(\pi r^2)$$

$$\boldsymbol{r = 0.03\ \text{m} = 3\ \text{cm}}$$

$$\boldsymbol{d = 6\ \text{cm}}$$

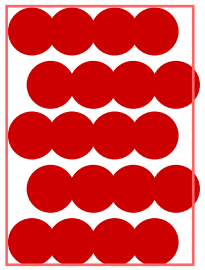
So, to be safe, we'll use a diameter twice as large as previously calculated



Summary

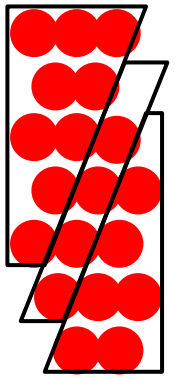
Materials **deform (strain)** in response to **applied force (stress)**

Elastic strain occurs at small deformation, and is completely reversible

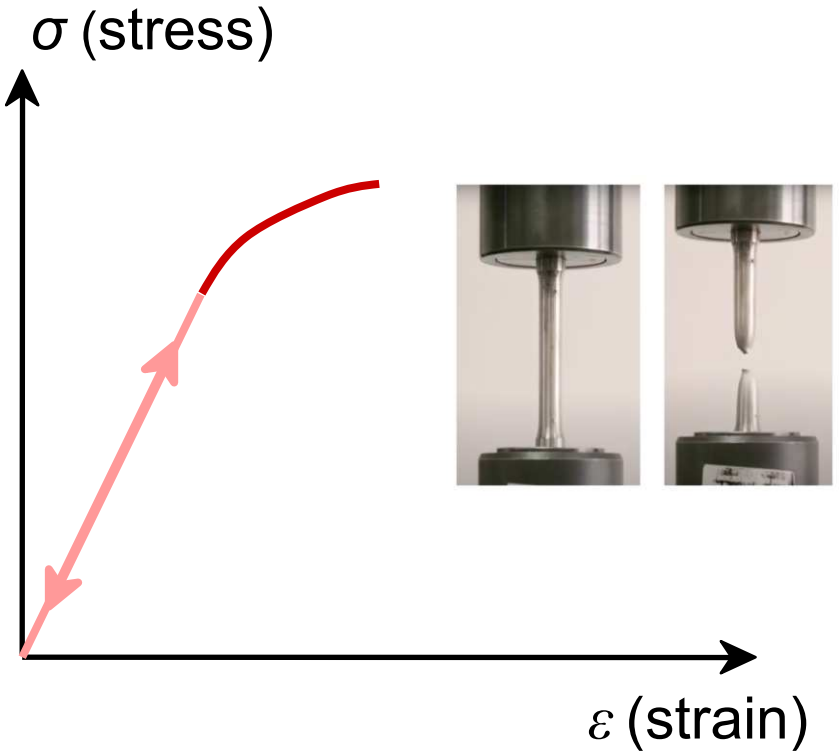


bonds stretch

Plastic strain occurs at large deformation, and is *irreversible*

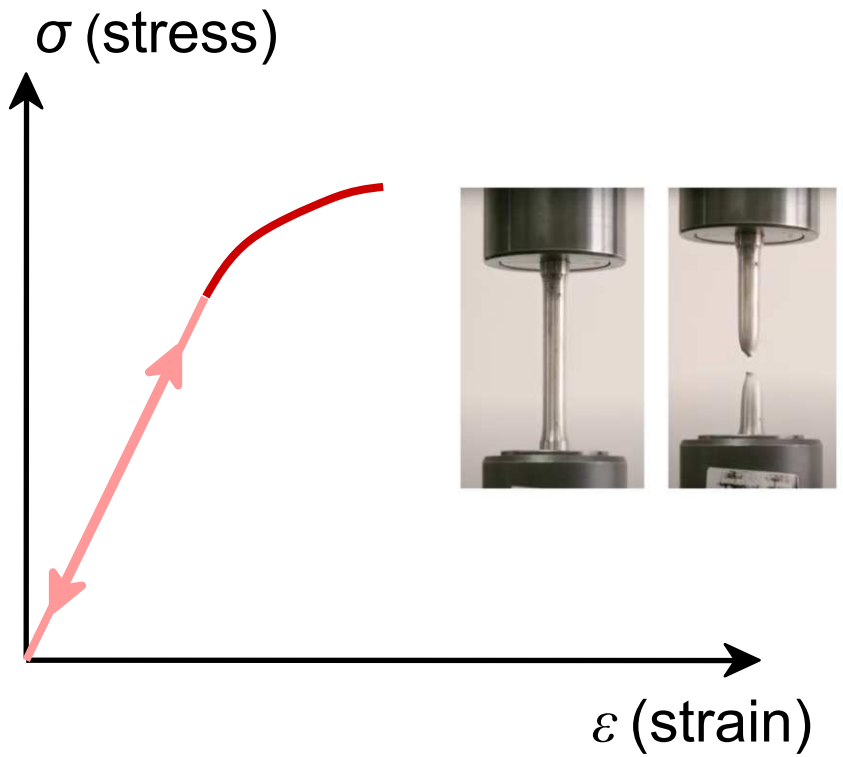


Bonds are broken and reformed. Entire planes are shifted.



Summary

1) Stiffness (elastic modulus) = resistance to *elastic* deformation
2) Yield strength = resistance to *plastic* deformation
3) Ductility = amount of *plastic* deformation at failure
4) Resilience = energy absorbed through *elastic* deformation
5) Toughness = energy absorbed through *plastic* deformation



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2) Yield strength = resistance to *plastic* deformation
3) Ductility = amount of *plastic* deformation at failure
4) Resilience = energy absorbed through *elastic* deformation
5) Toughness = energy absorbed through *plastic* deformation
6) **Hardness = resistance to local compressive forces**

