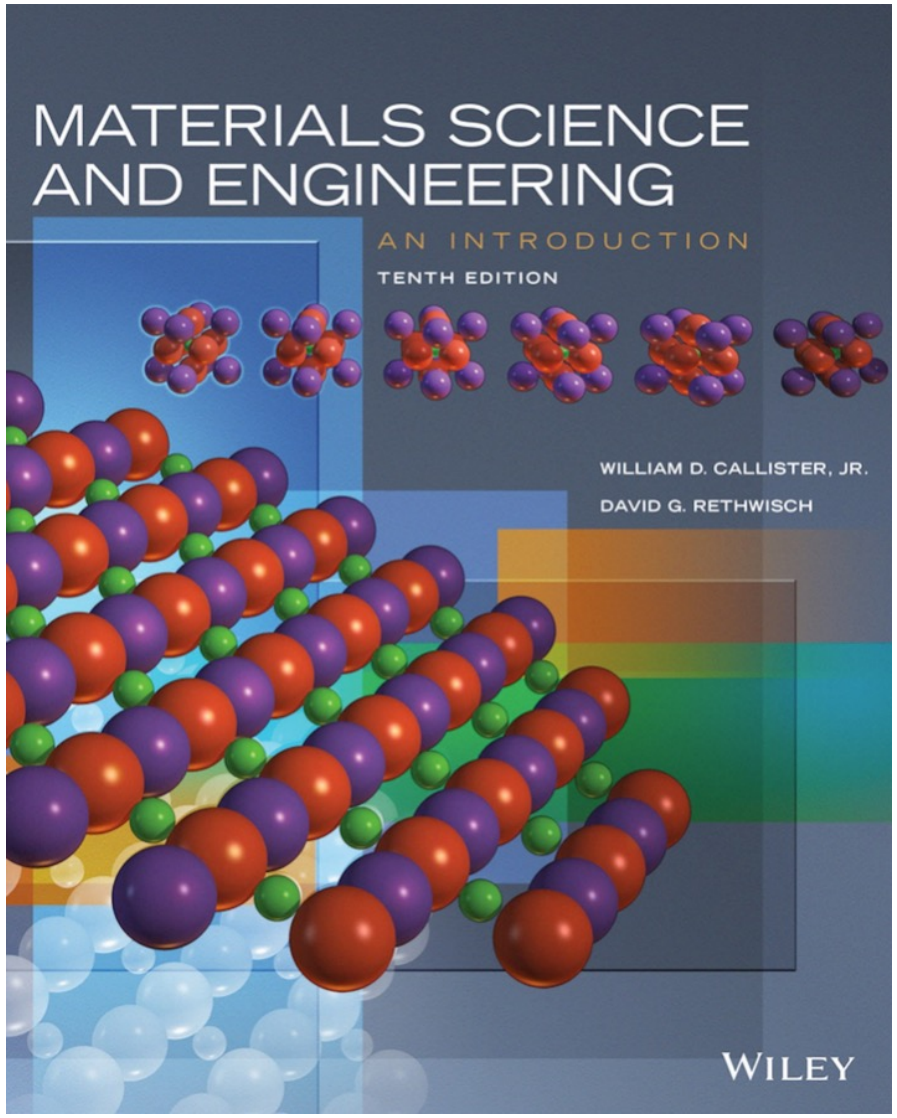
Lecture 5: Dislocation Slip, Strengthening Mechanisms, and Failure

Prof. Nathan Szymanski
nszymanski@seas.ucla.edu
Department of Materials Science & Engineering

Reading for this subject



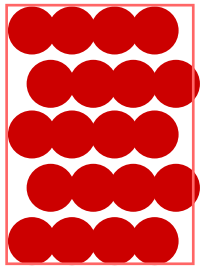
Chapter 7 Dislocations and Strengthening Mechanisms

This discussion will closely follow **Chapter 7** of Callister, **pages 181-205** of the 10th edition.

Review from last time: mechanical properties

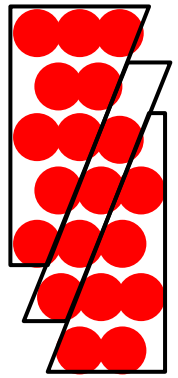
Materials **deform (strain)** in response to **applied force (stress)**

Elastic strain occurs at small deformation, and is completely reversible

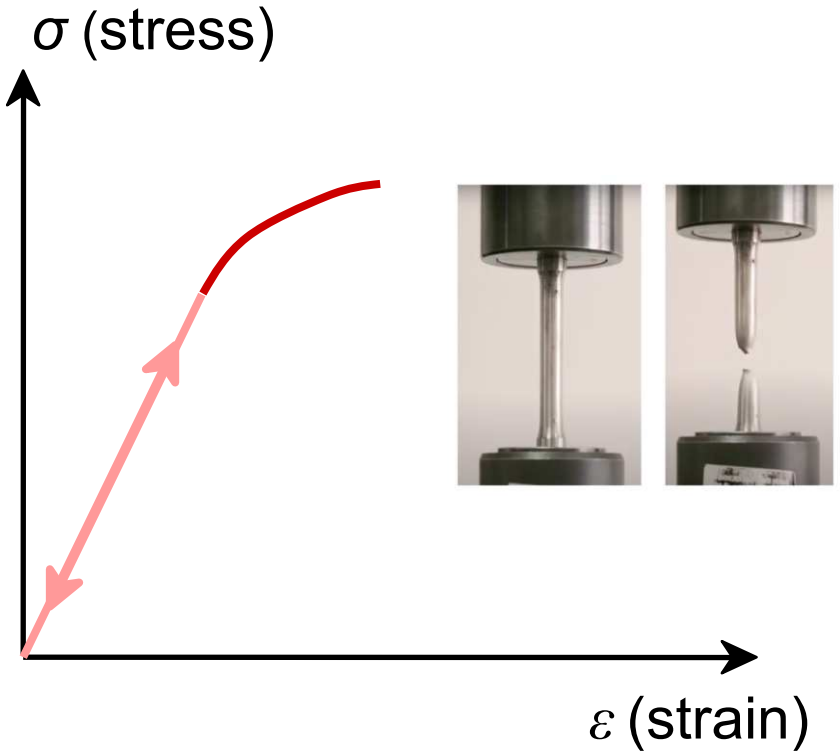


bonds stretch

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



Bonds are broken and reformed. Entire planes are shifted.



Review from last time: mechanical properties

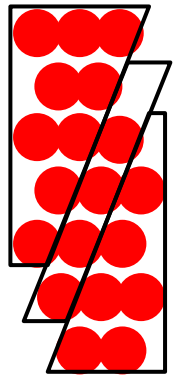
Materials **deform (strain)** in response to **applied force (stress)**

What is the atomic mechanism for plastic deformation?

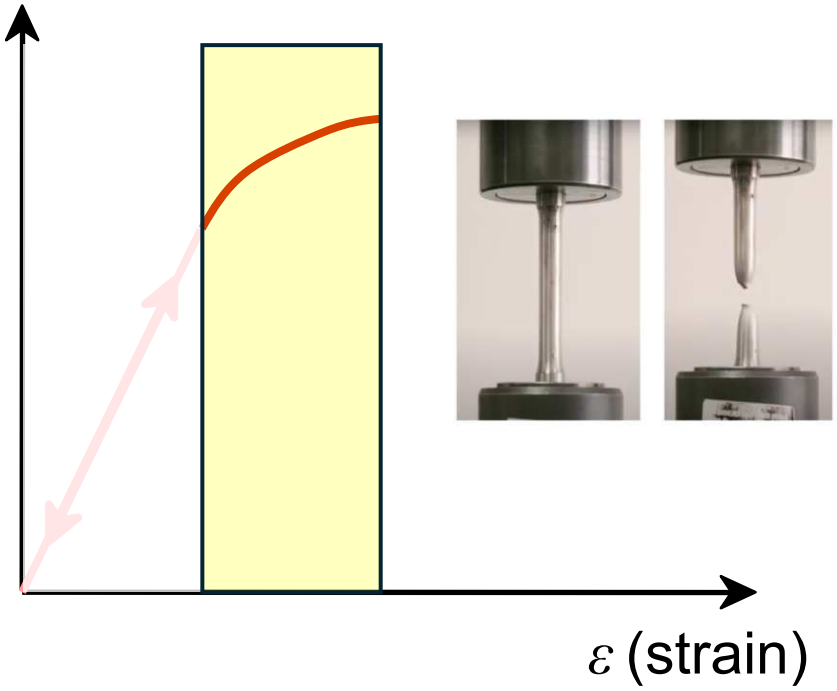
Elastic strain occurs at small deformation, and is completely reversible

bonds stretch

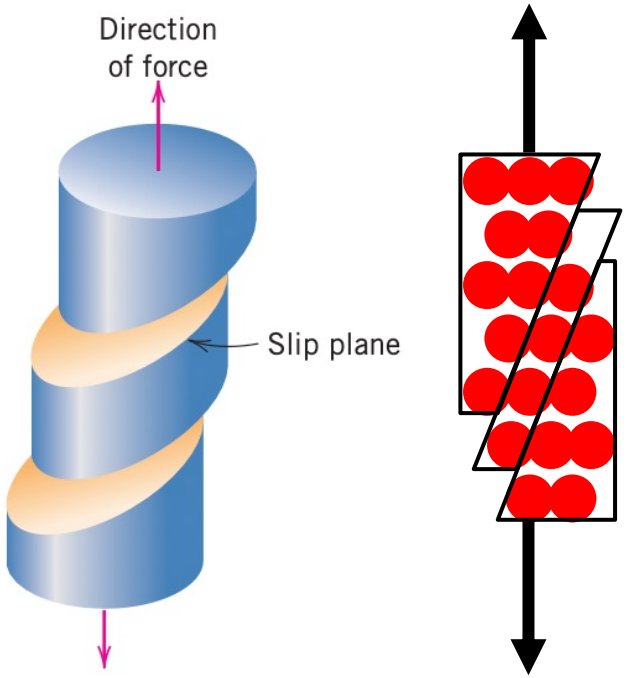
Plastic strain occurs at large deformation, and is *irreversible*



Bonds are broken and reformed. Entire planes are shifted.



Plastic deformation involves bond rearrangement

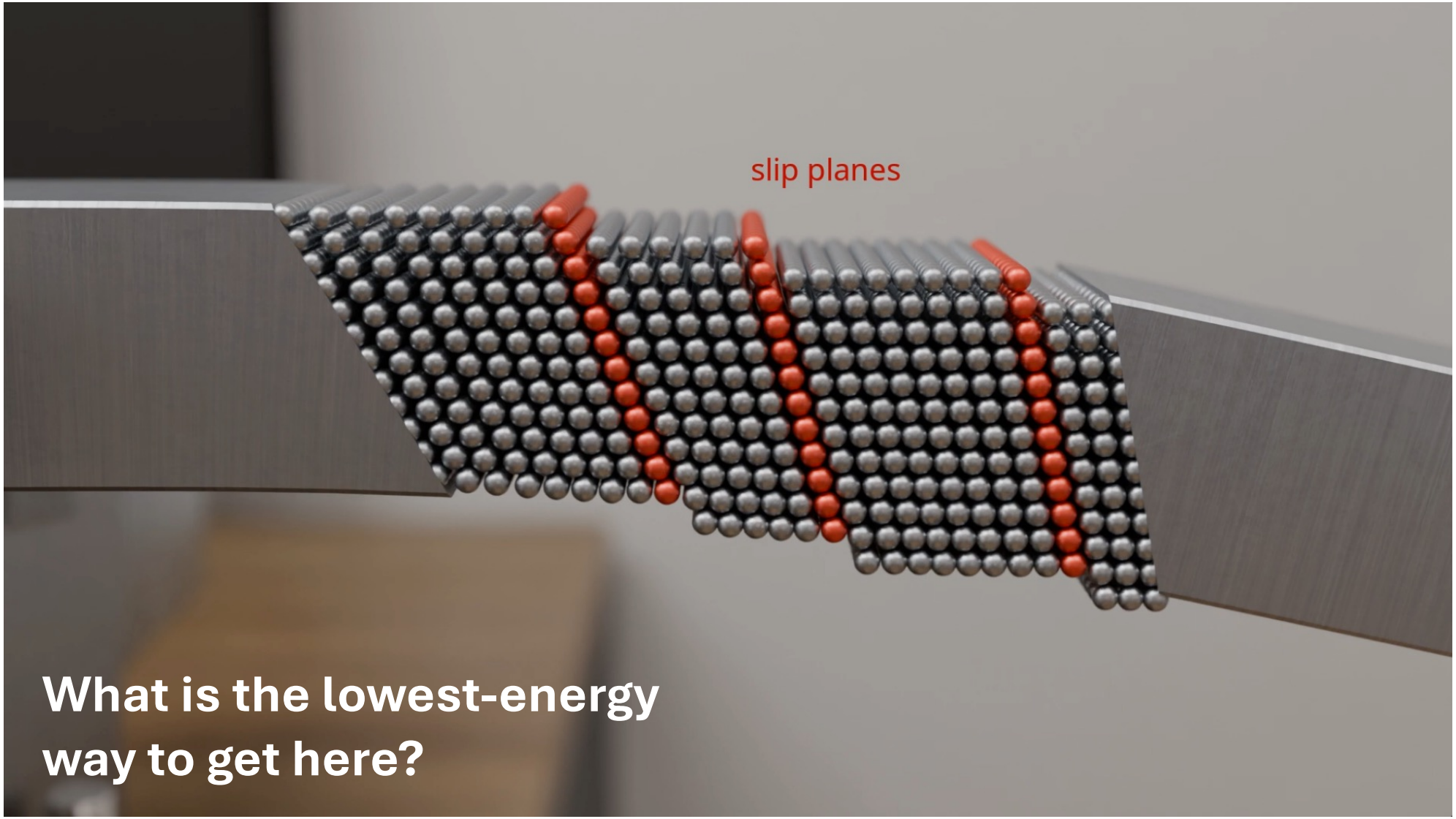


As I pull this material apart, some planes have to **“slip”** past one another to accommodate the strain

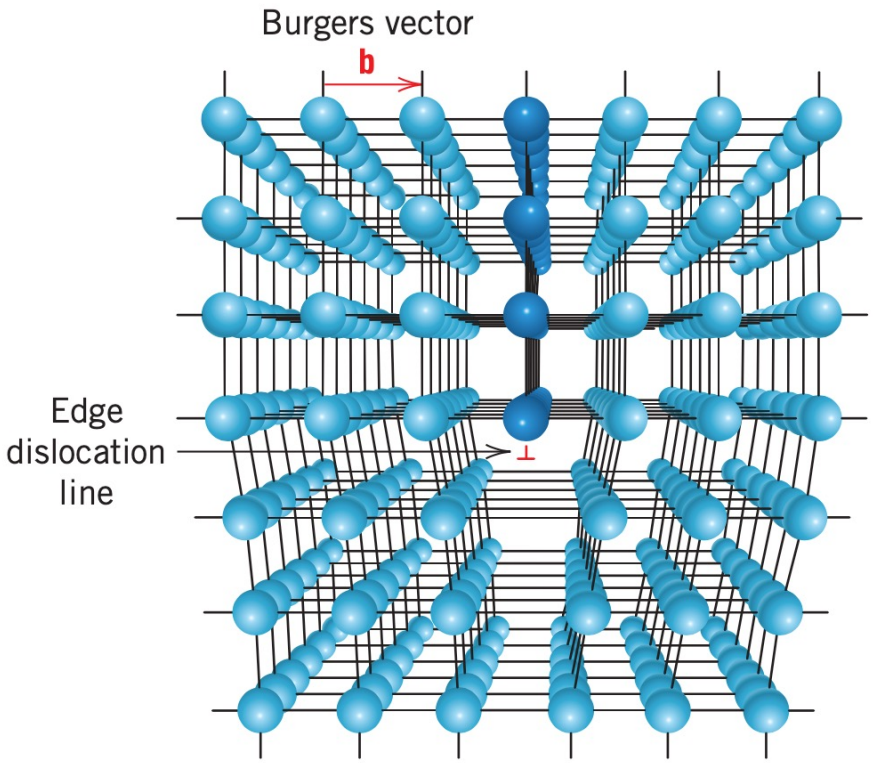
Plastic deformation involves bond rearrangement



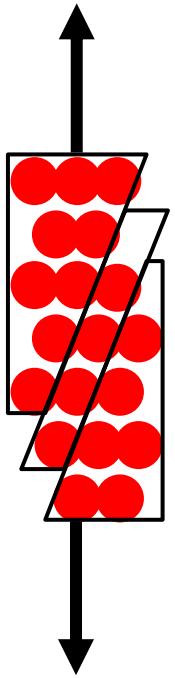
Plastic deformation involves bond rearrangement



Dislocation motion ↔ plastic deformation

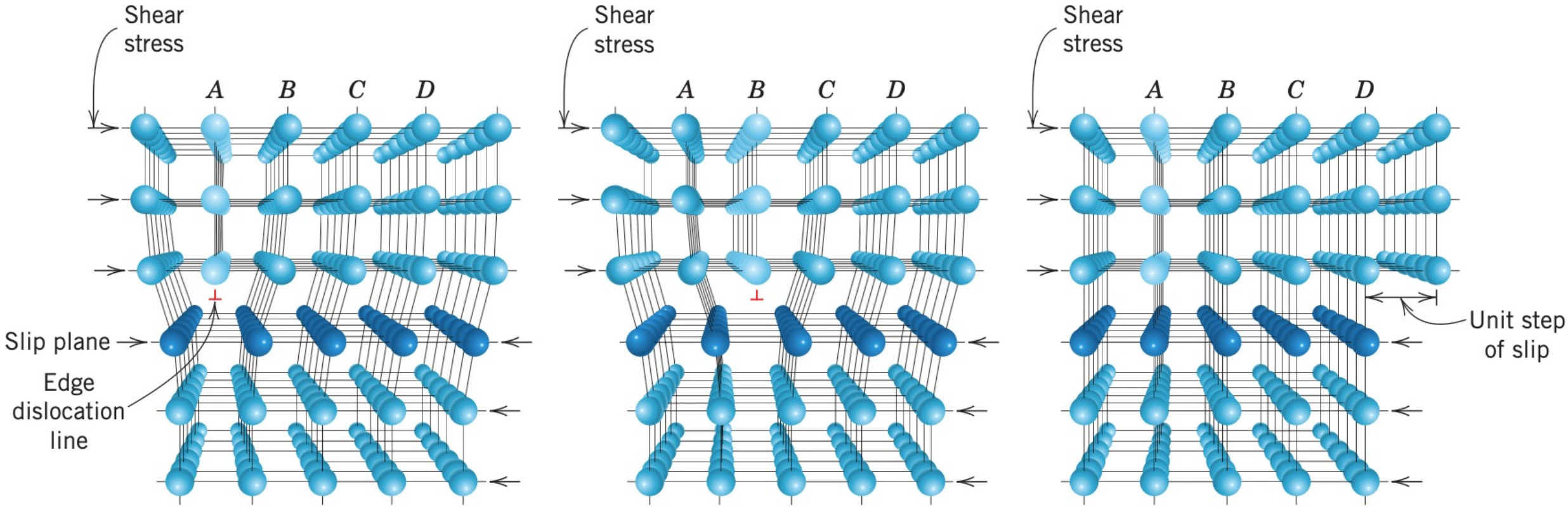


Recall: an edge dislocation contains an extra plane of atoms – **and this plane can move in response to stress**

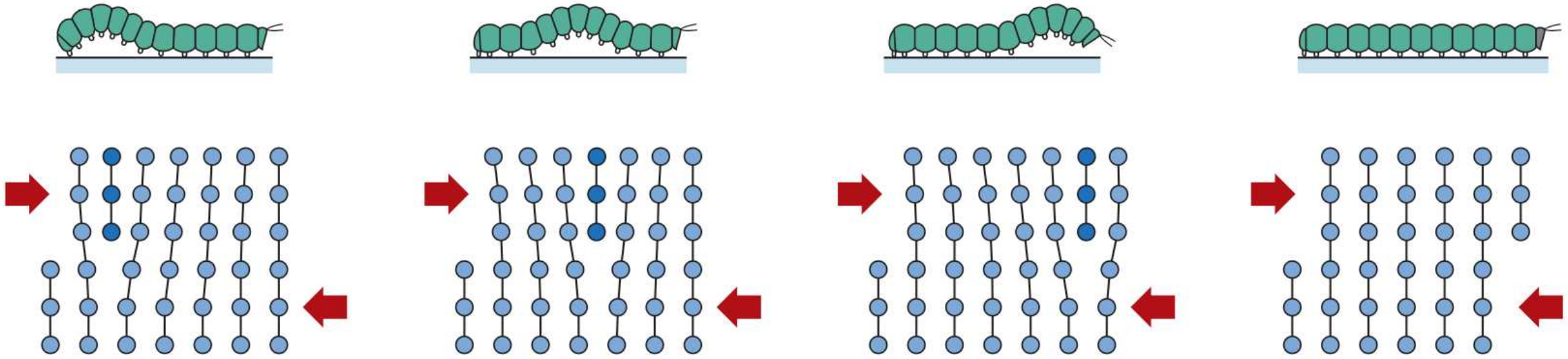


As I pull this material apart, some planes **slip** past one another by moving dislocations

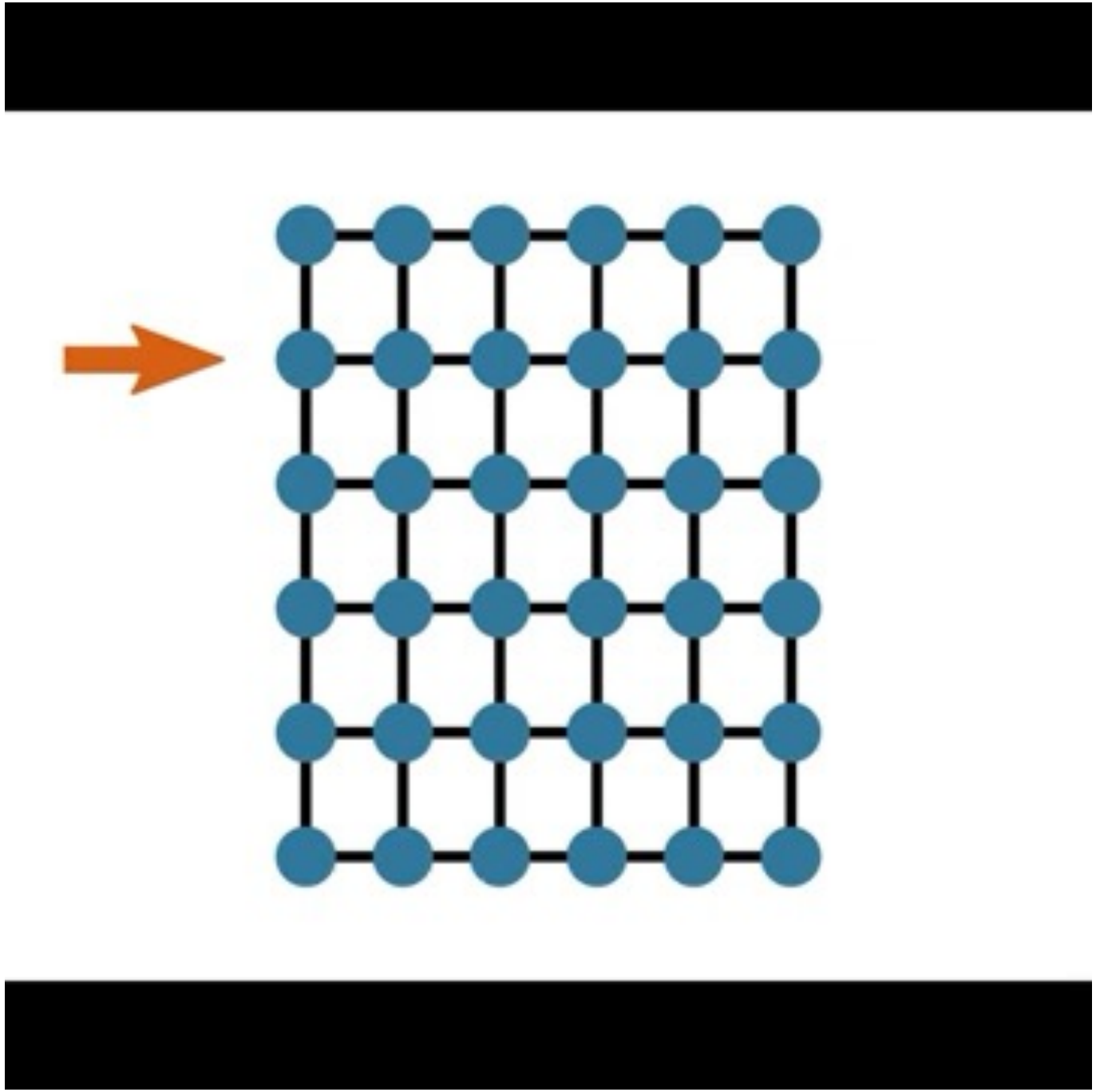
Dislocation motion allows slip to occur while breaking (relatively) few bonds at each step



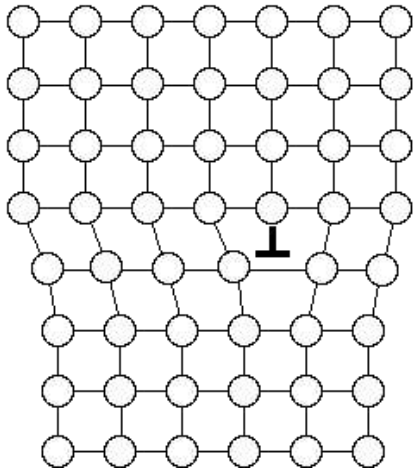
Dislocation motion allows slip to occur while breaking (relatively) few bonds at each step

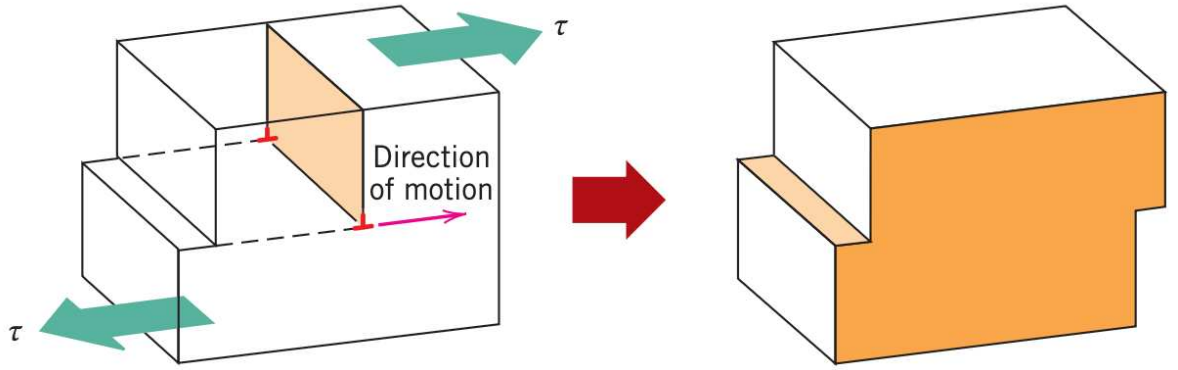


Notice the extra half plane moves to the right at each step,
breaking and reforming bonds around it

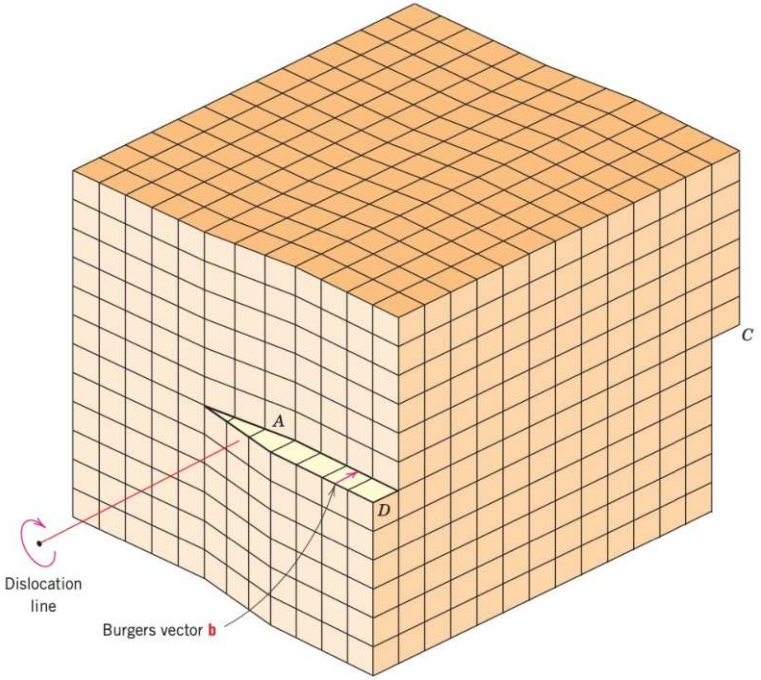


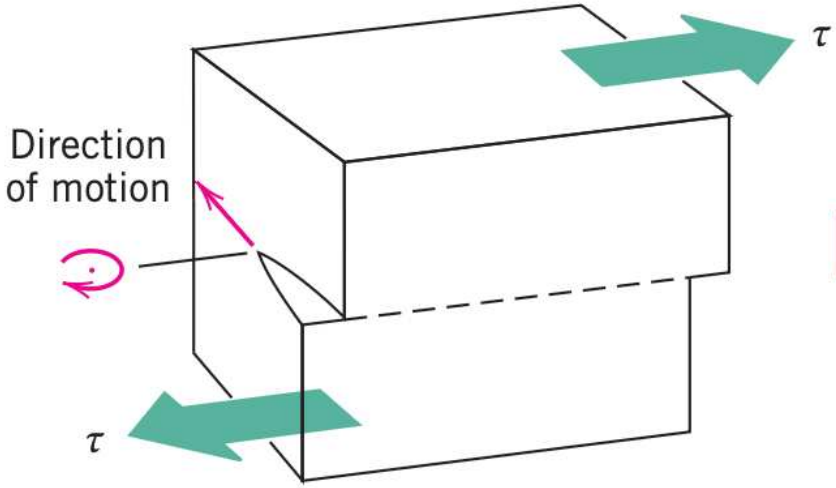
Slip direction depends on the dislocation type





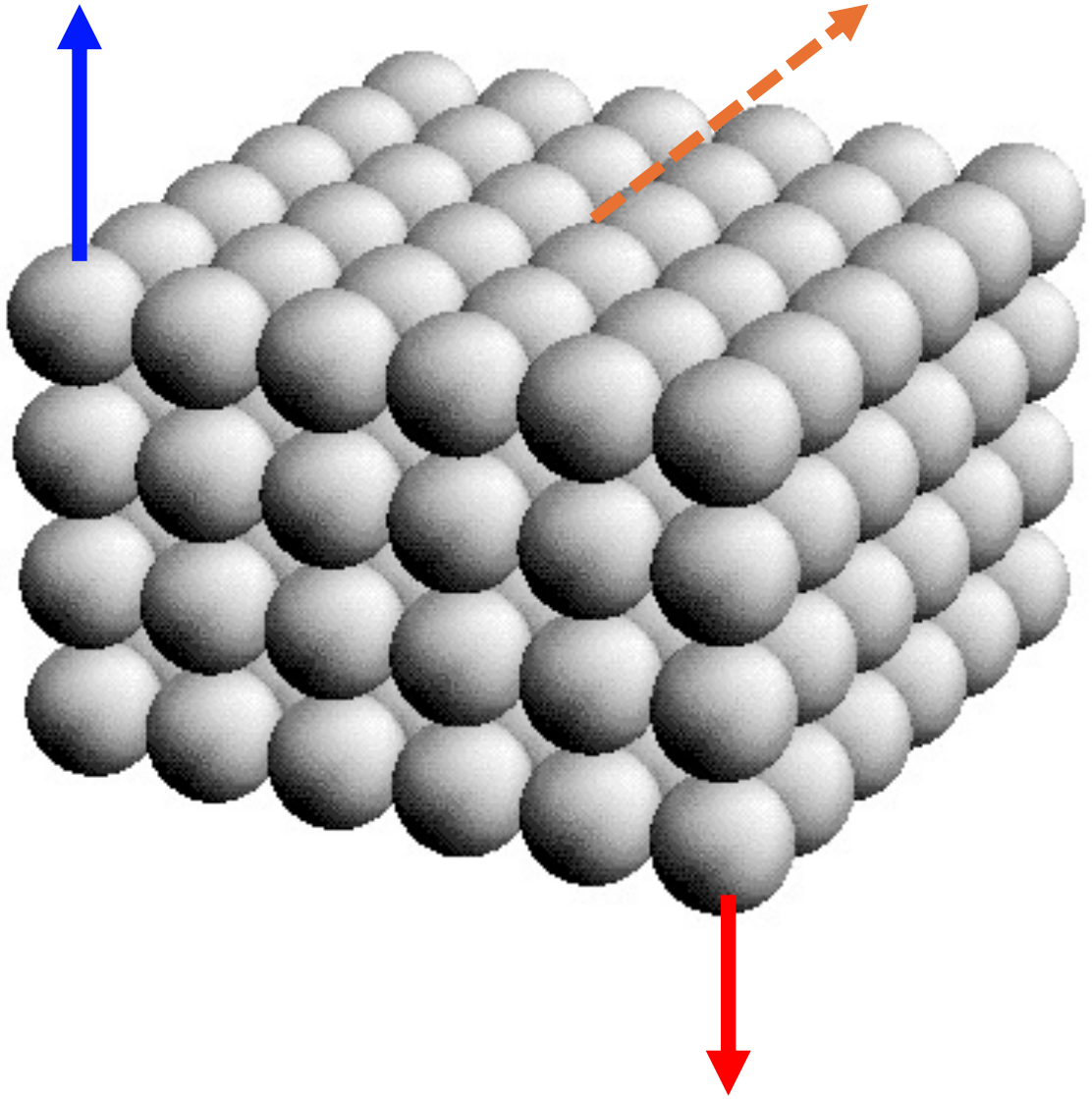
Edge dislocations move along the direction of applies shear stress





Screw dislocations move *orthogonal to* the direction of applies shear stress

Visualizing screw dislocation motion

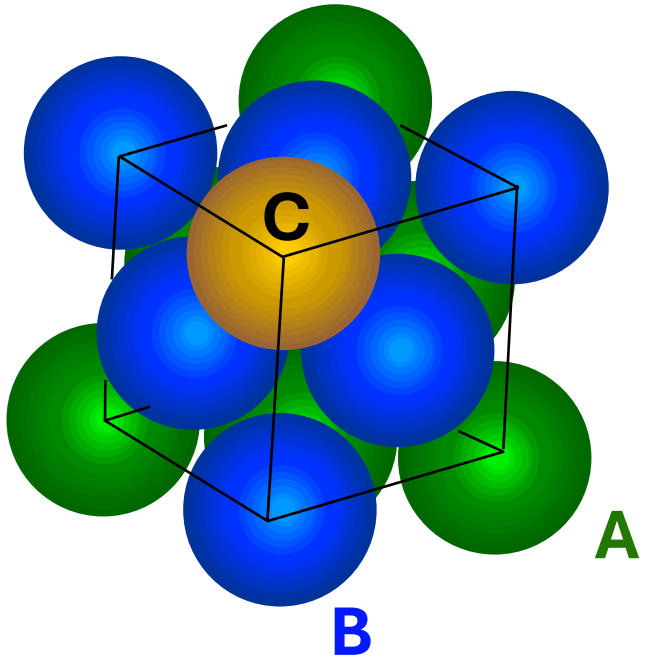


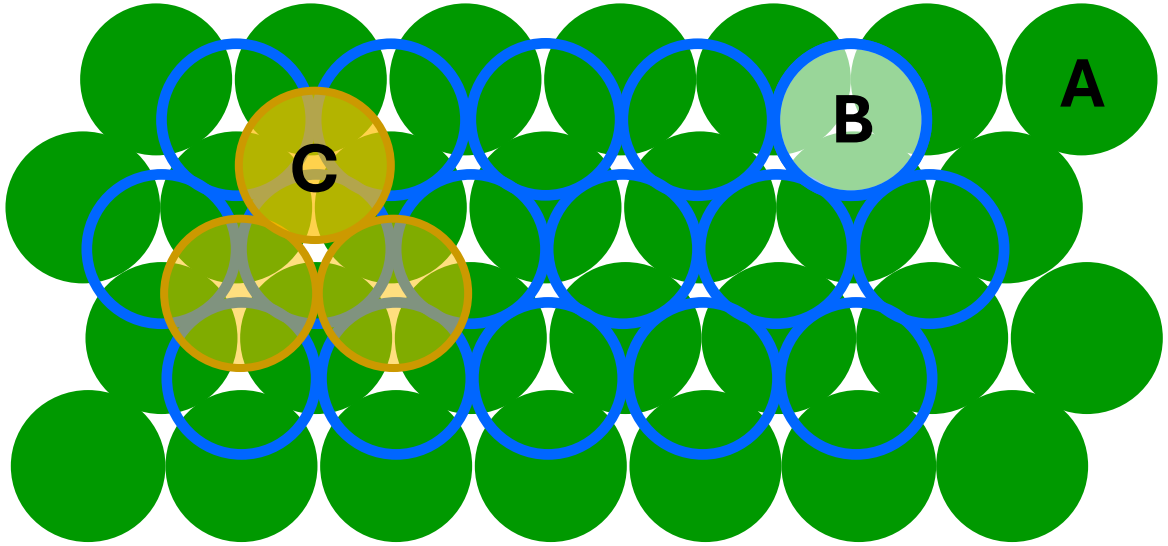
Notice the crack grows in a direction that is orthogonal to the applied stresses

Is this slip direction always possible?

Slip systems: planes and directions

For a given structure (*e.g.*, FCC) there are certain crystallographic planes – known as **slip planes** – over which dislocations move most easily





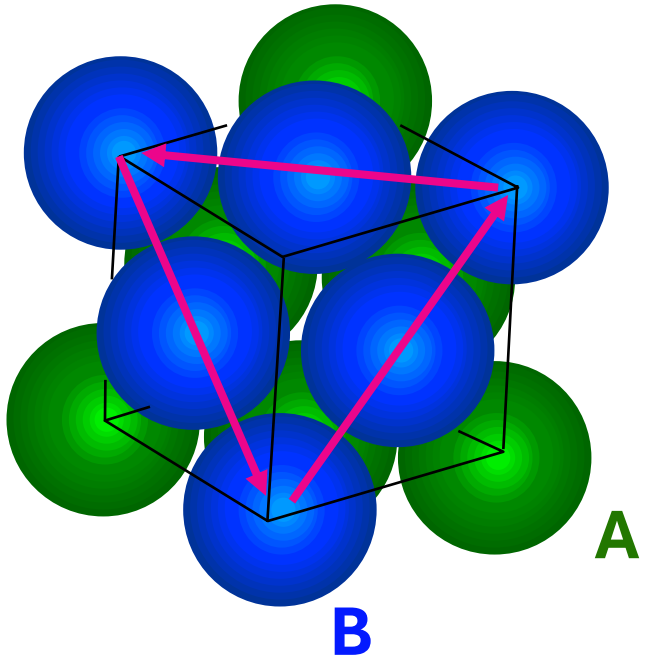
These are usually the **planes with the densest atomic packing** – *e.g.*, {111} in FCC

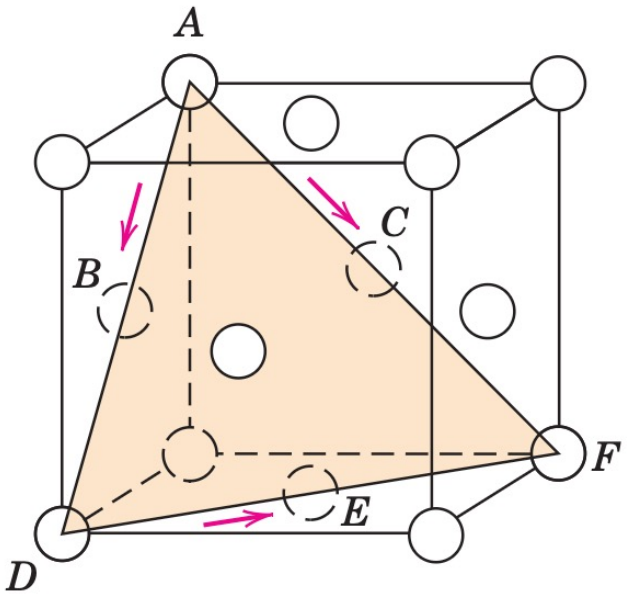
Imagine the **blue** **and** **green** **layers "gliding"** over one another

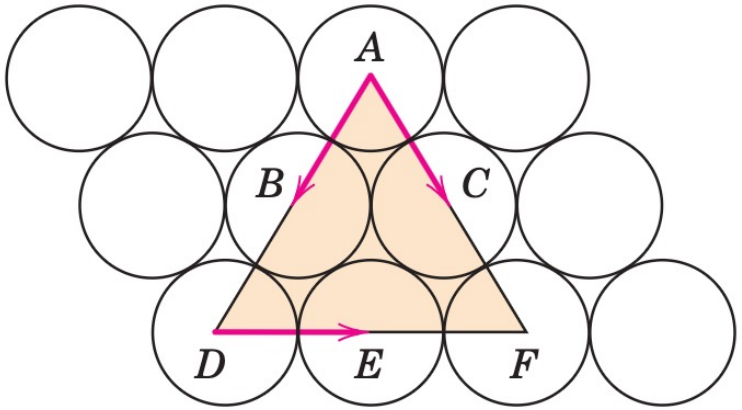
DEMO

Slip systems: planes and directions

Similarly, there will be certain directions – **slip directions** –
along which these planes will glide most easily



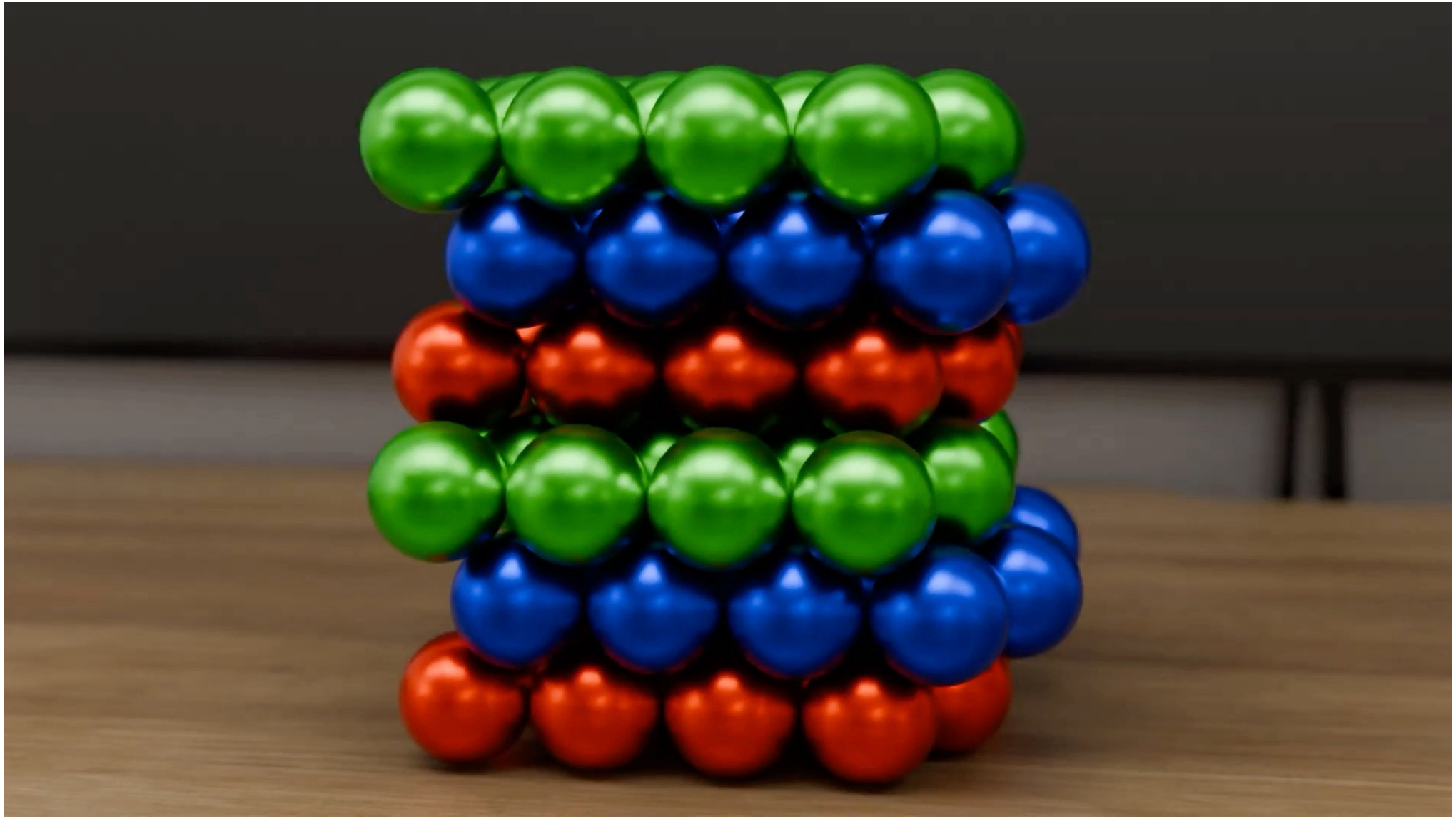




These are usually the **closest-packed directions** – *e.g.*, <111> in FCC

Moving the slip plane along this close-packed direction, where most atoms touch,
requires the **least amount of bond breaking**

Slip systems: planes and directions



Slip systems vary with crystal structure

Metals	*Slip Plane*	*Slip Direction*
	Face-Centered Cubic	
Cu, Al, Ni, Ag, Au	{111}	⟨110⟩

Slip system = plane + direction

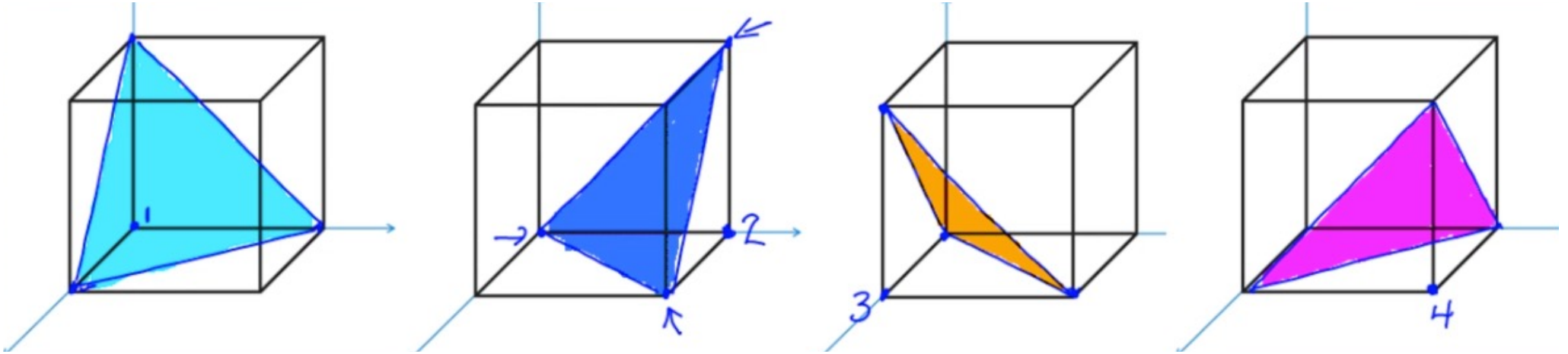
$\{111\}\langle 110\rangle$ **for FCC**

Close-packed plane

Close-packed direction

Slip systems vary with crystal structure

Metals	*Slip Plane*	*Slip Direction*	*Number of Slip Systems*
	Face-Centered Cubic		
Cu, Al, Ni, Ag, Au	{111}	⟨110⟩	12

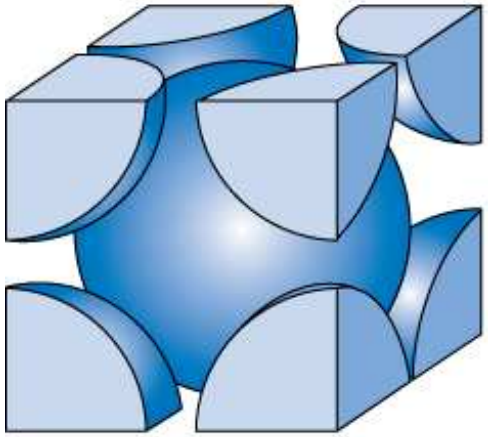


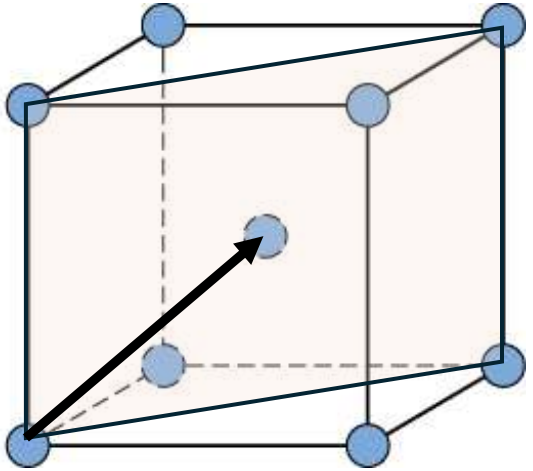
There are many (×12) planes with perfectly close packed planes over which slip can occur relatively easily → **FCC metals are usually ductile!**



Slip systems vary with crystal structure

Metals	*Slip Plane*	*Slip Direction*	*Number of Slip Systems*
	Face-Centered Cubic		
Cu, Al, Ni, Ag, Au	{111}	⟨110⟩	12





What about BCC?

- **{110}** is the densest plane, but is *not* close-packed like FCC
- **<111>** is the close-packed direction, but again, it is *not* perfectly close packed

Slip systems vary with crystal structure

Metals	*Slip Plane*	*Slip Direction*	*Number of Slip Systems*
	Face-Centered Cubic		
Cu, Al, Ni, Ag, Au	{111}	⟨110⟩	12
	Body-Centered Cubic		
α-Fe, W, Mo	{110}	⟨111⟩	12

There are a similar number of slip systems but since they are not close packed, **BCC metals tend to be more brittle than FCC.**



Tungsten

- **{110}** is the densest plane, but is *not* close-packed like FCC
- **<111>** is the close-packed direction, but again, it is *not* perfectly close packed

Slip systems vary with crystal structure

Metals	*Slip Plane*	*Slip Direction*	*Number of Slip Systems*
	Face-Centered Cubic		
Cu, Al, Ni, Ag, Au	{111}	⟨110⟩	12
	Body-Centered Cubic		
α-Fe, W, Mo	{110}	⟨111⟩	12
α-Fe,W	{211}	⟨111⟩	12
α-Fe, K	{321}	⟨111⟩	24

At high enough temperatures, other slip systems can become active, but none of them are as efficient as the {111} systems in FCC.

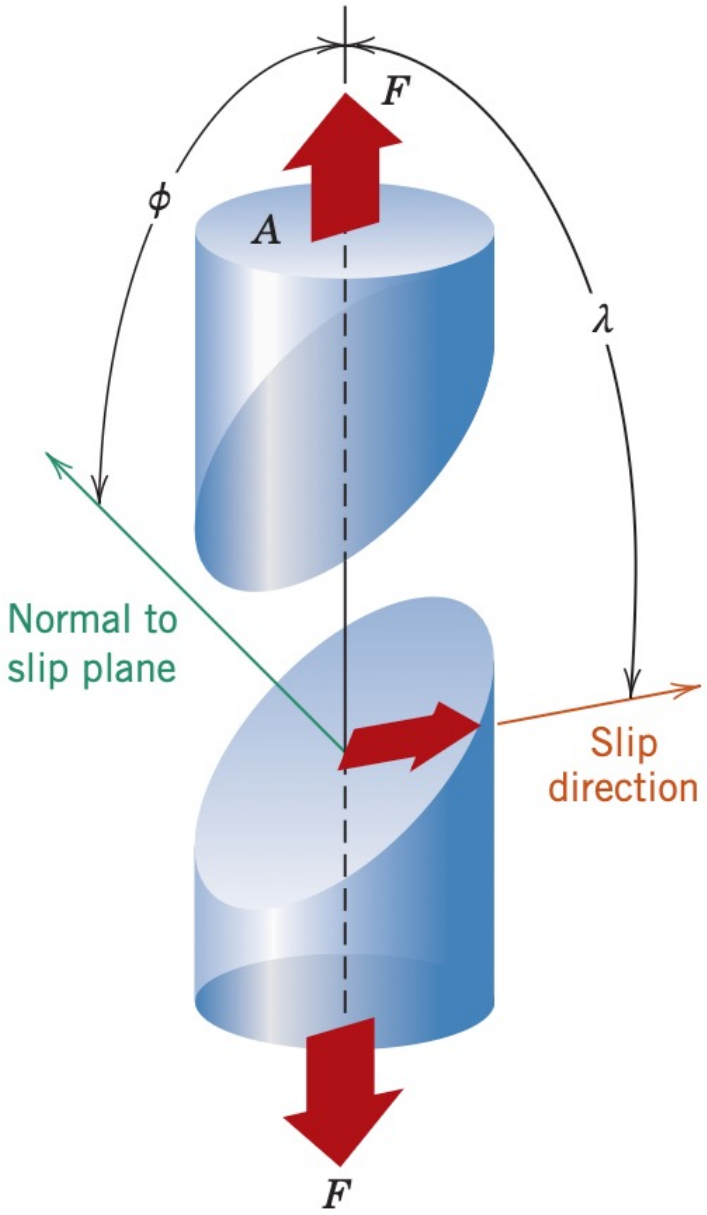
High temperature can improve ductility in BCC metals but they are still usually more brittle than FCC metals.

Slip systems vary with crystal structure

Metals	*Slip Plane*	*Slip Direction*	*Number of Slip Systems*
	Face-Centered Cubic		
Cu, Al, Ni, Ag, Au	{111}	⟨110⟩	12
	Body-Centered Cubic		
α-Fe, W, Mo	{110}	⟨111⟩	12
α-Fe,W	{211}	⟨111⟩	12
α-Fe, K	{321}	⟨111⟩	24
	Hexagonal Close-Packed		
Cd, Zn, Mg, Ti, Be	{0001}	$\langle 11\bar{2}0 \rangle$	3

For **HCP**: the slip planes are close packed but there are ***fewer*** of them → **more brittle**

Over which system will slip occur?



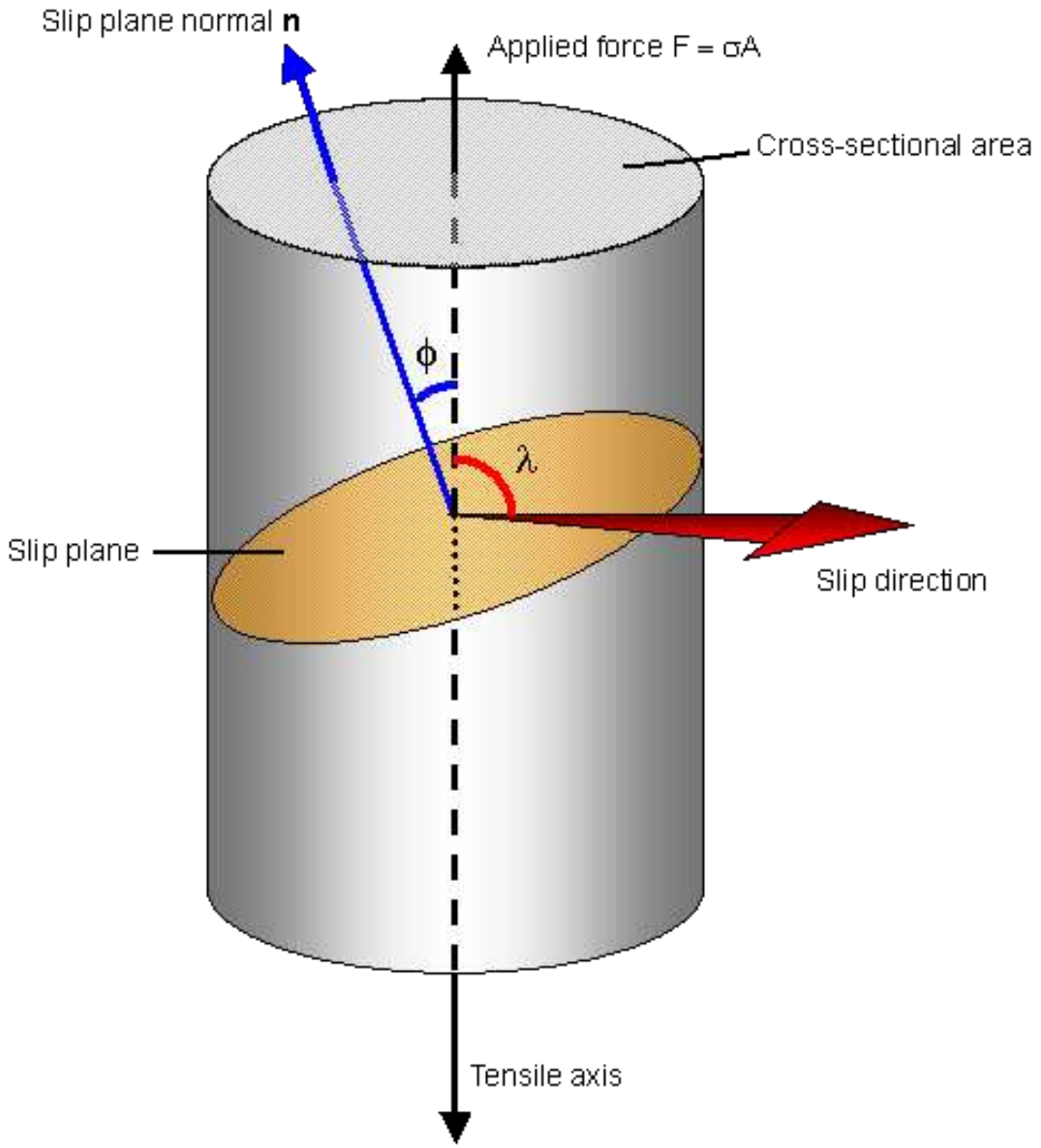
- We know that slip can *only* occur along certain planes & directions. But the stress you apply may not be in that direction.
- Given some applied stress, we can **resolve the component of that stress along the slip direction**

$$\tau_R = \sigma \cos\phi \cos\lambda$$

Angle between applied stress and **normal to the slip plane**

Angle between applied stress and **slip direction**

Over which system will slip occur?



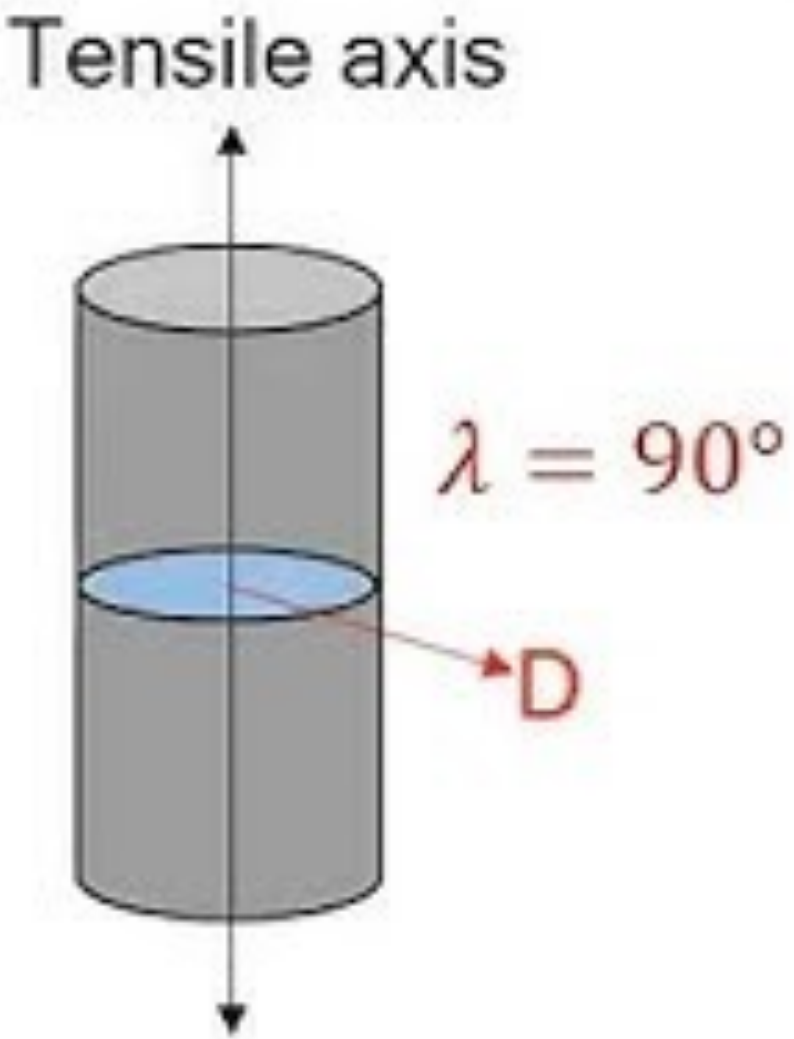
Here is another visual

$$\tau_R = \sigma \cos\phi \cos\lambda$$

Angle between applied stress and **normal to the slip plane**

Angle between applied stress and **slip direction**

Over which system will slip occur?



Extreme case #1: slip direction is **orthogonal** to applied stress

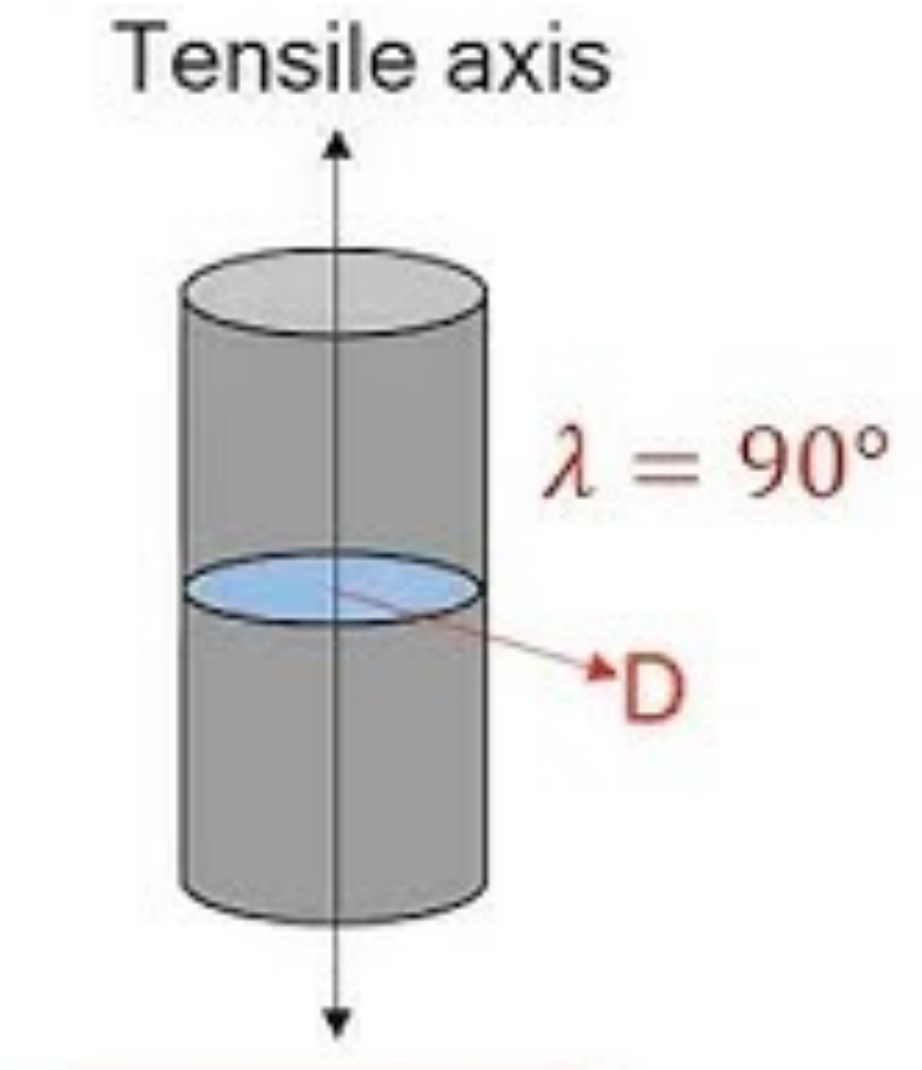
$$\tau_R = \sigma \cos\phi \cos\lambda$$

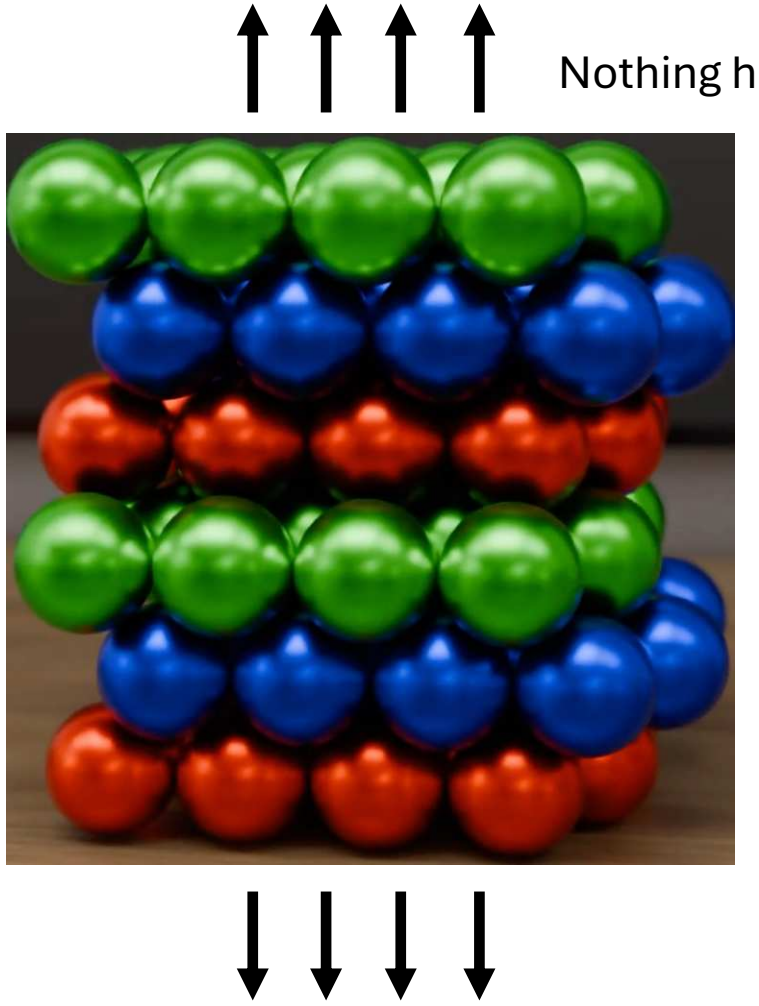
$$\lambda = 90° \rightarrow \cos\lambda = 0$$

$$\boldsymbol{\tau_R = 0 \rightarrow}\ \textbf{no slip will occur}$$

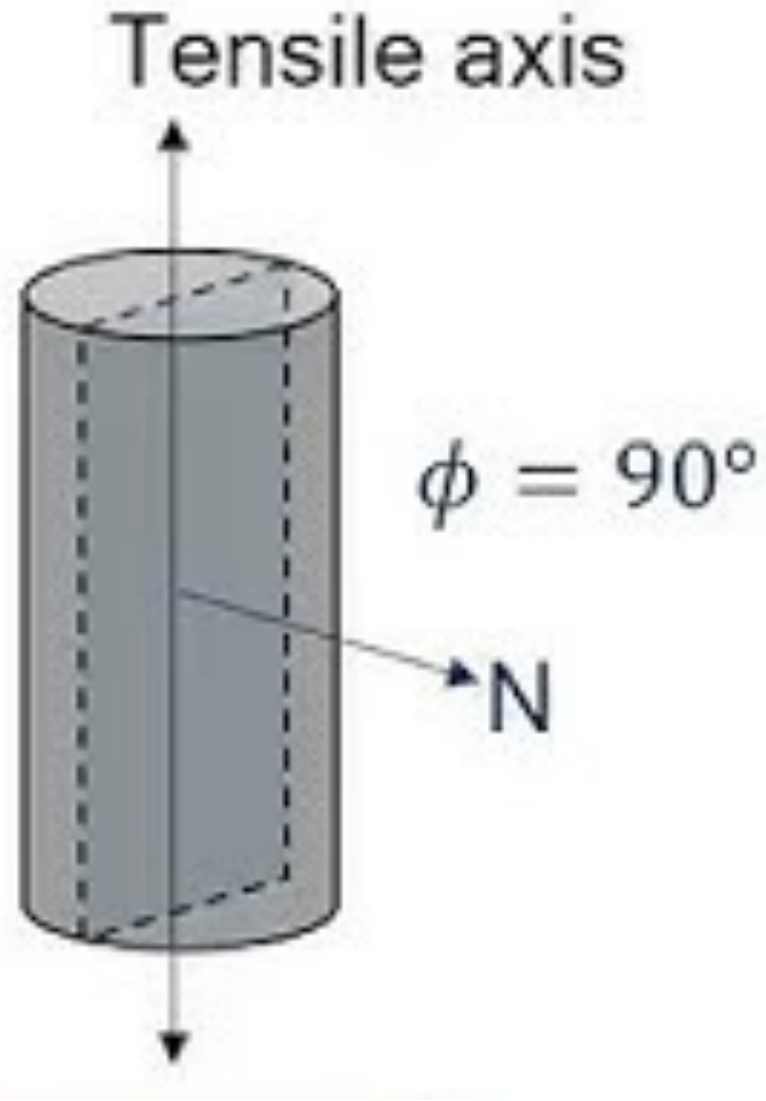
DEMO

Over which system will slip occur?





Over which system will slip occur?



Extreme case #2: slip *plane* normal is **orthogonal** to applied stress

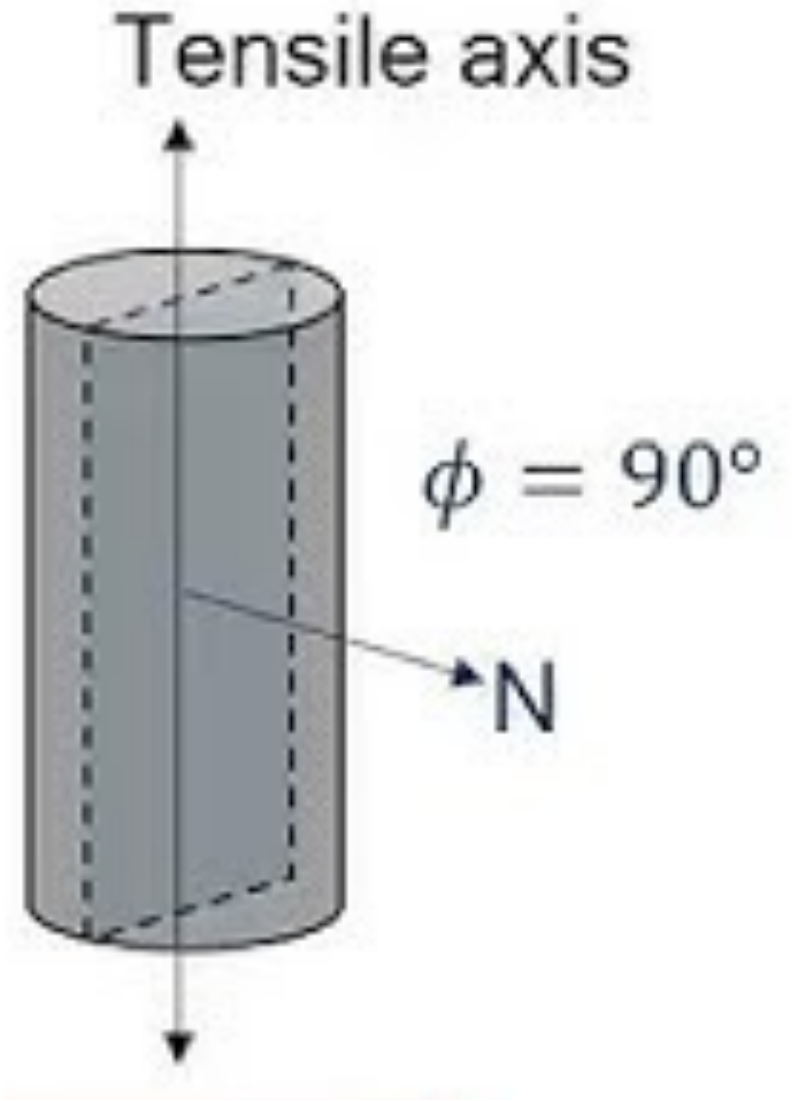
$$\tau_R = \sigma \cos\phi \cos\lambda$$

$$\phi = 90° \rightarrow \cos\phi = 0$$

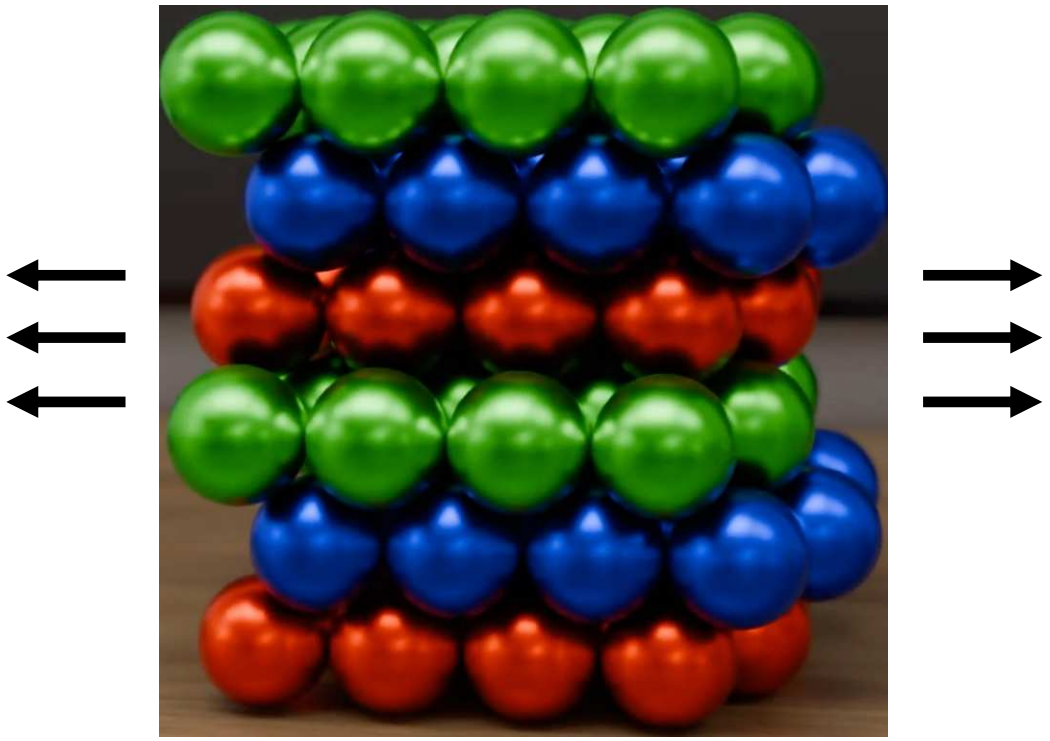
$$\boldsymbol{\tau_R = 0 \rightarrow}\ \textbf{no slip will occur}$$

DEMO

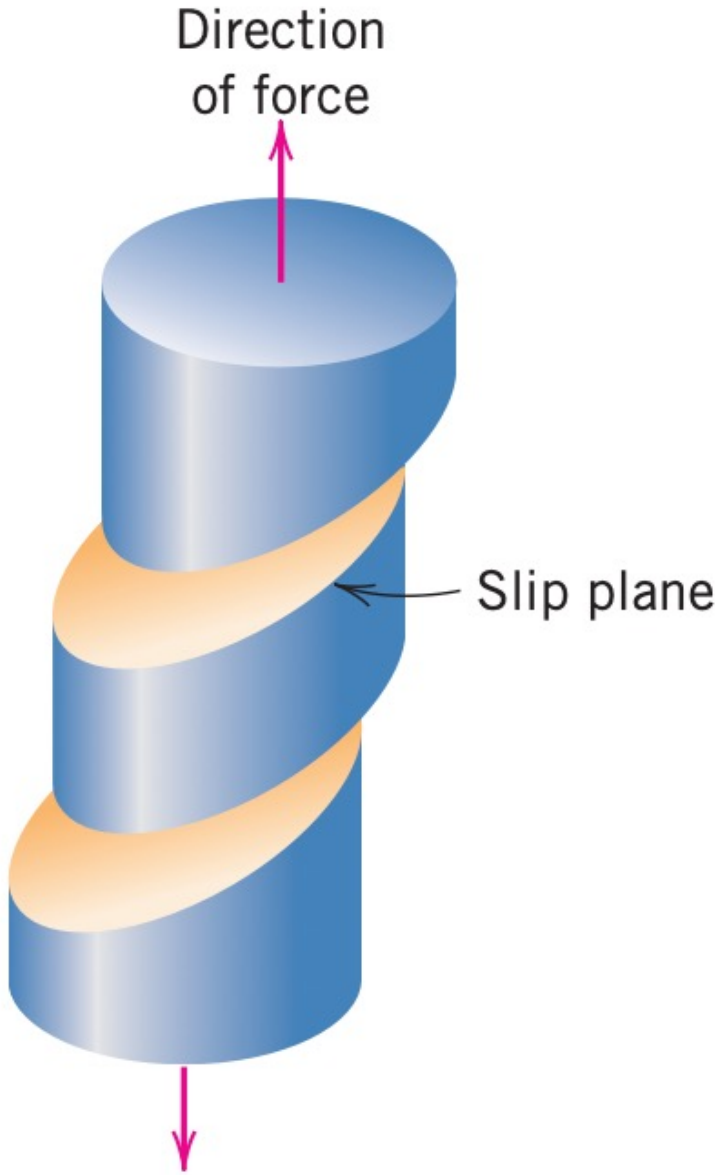
Over which system will slip occur?



Nothing happens…



Over which system will slip occur?



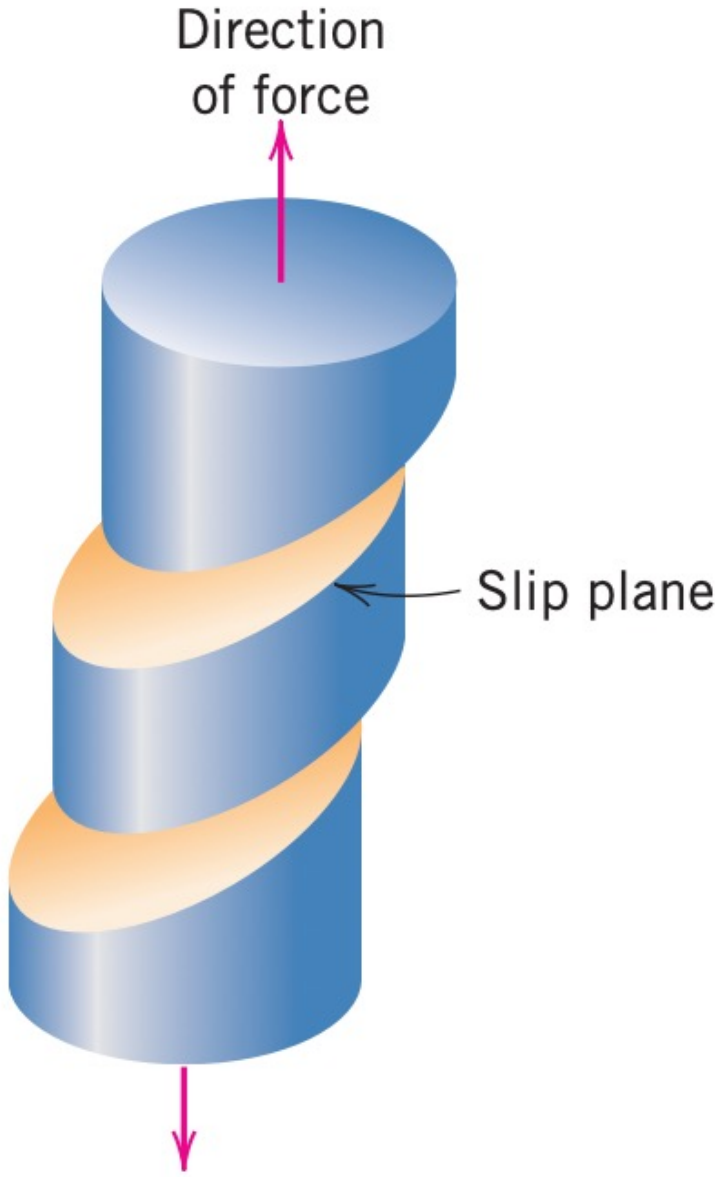
In general: there exists *some* slip plane and direction that is non-orthogonal to the stress
→ deformation can occur

$$\tau_R = \sigma \cos\phi \cos\lambda$$

Where $\phi, \lambda \neq 90°$

$\rightarrow \boldsymbol{\tau_R \neq 0}$

Over which system will slip occur?



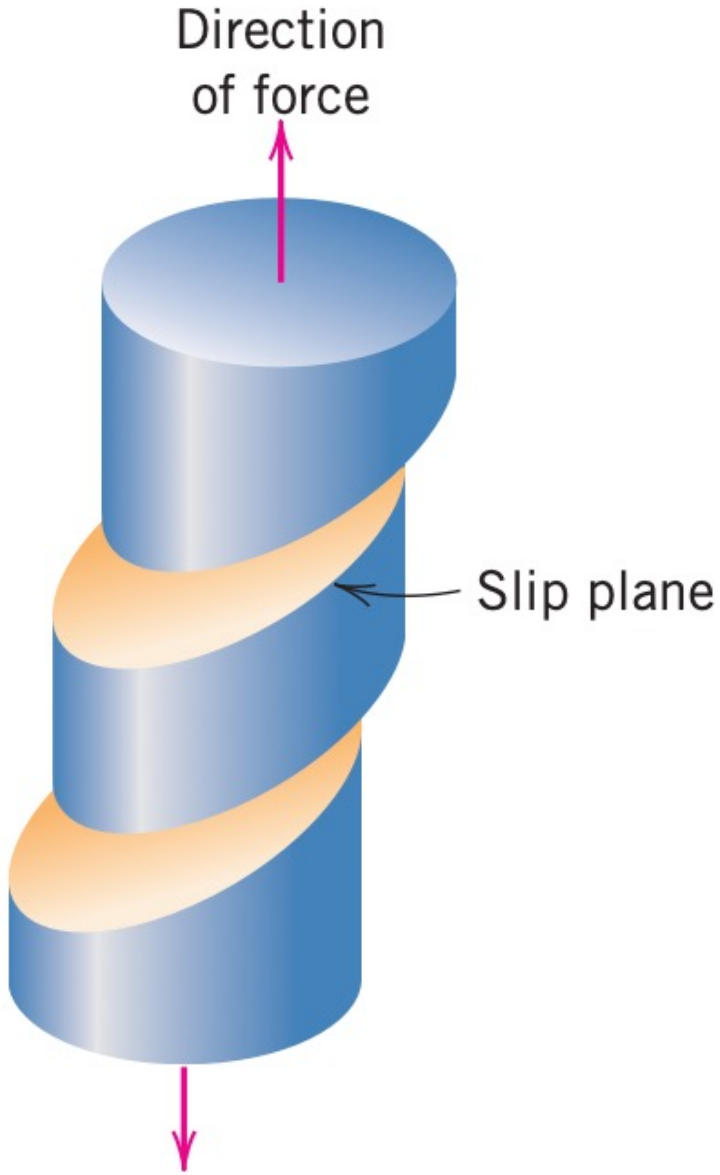
This can be true for *multiple* slip planes/directions. The one that matters most is the one with the largest resolved stress:

$$\tau_R = \sigma \cos\phi \cos\lambda$$

$$\tau_R(\max) = \sigma(\cos\phi \cos\lambda)_{\max}$$

These are most **favorably oriented for slip**; usually around 45° as shown to the left

How do we know if slip will occur?



τ_R tells us how much stress exists along the preferred slip direction – **is it enough to actually cause slip?**

Answer: there is some threshold, the **critical resolved shear stress (τ_{CRSS}),** above which slip occurs

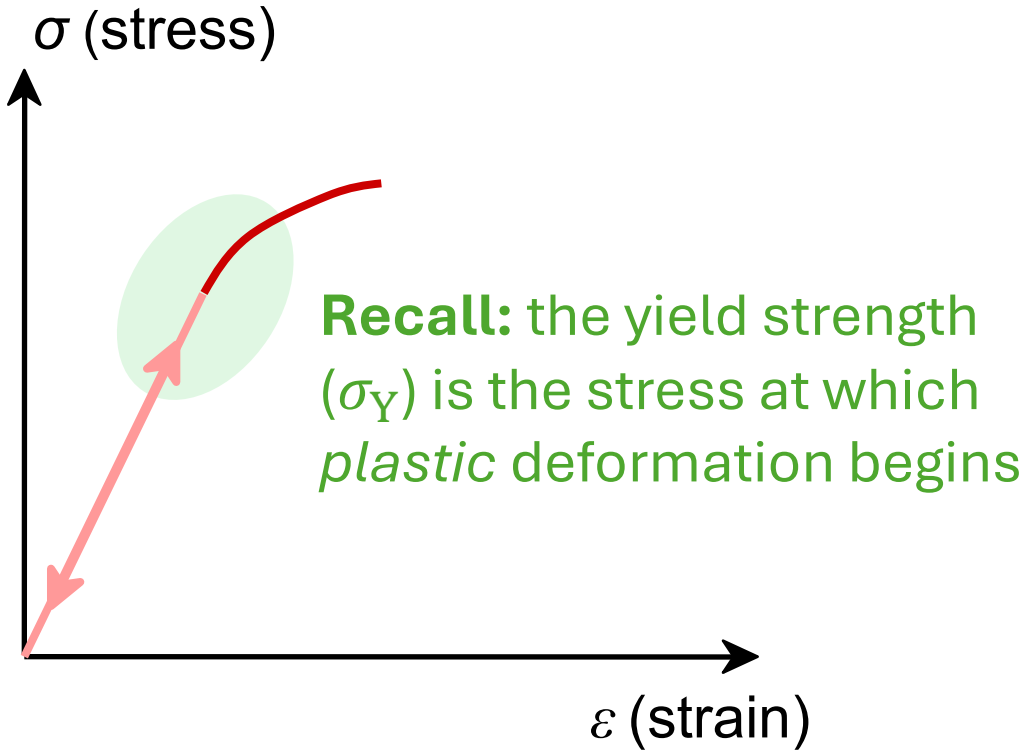
Slip occurs when $\tau_R(\max) \geq \tau_{CRSS}$

Yield strength ↔ critical resolved shear stress

The critical resolved shear stress is closely related to the yield strength of a material:

$$\sigma_y = \frac{\tau_{crss}}{(\cos\phi \cos\lambda)_{max}}$$

If a high stress is needed to cause slip, the material will have a high yield strength



Recall: the yield strength (σ_Y) is the stress at which *plastic* deformation begins

Slip occurs when $\tau_R(\max) \geq \tau_{CRSS}$

Example calculations involving the CRSS

A crystal of some metal has a **critical resolved shear stress (τ_{CRSS}) of 20.7 MPa** and is exposed to a **tensile stress of 45 MPa.**

Q: Will yielding occur when $\phi = 60°$ and $\lambda = 35°$?

First, let's compute the **resolved stress (τ_R)** along the slip direction:

$$\tau_R = \sigma \cos\phi \cos\lambda = (45\ MPa) \cos 60° \cos 35° \approx 18.4\ \text{MPa}$$

$$\underset{\tau_R}{18.4\ \text{Mpa}} < \underset{\tau_{CRSS}}{20.7\ \text{MPa}}$$

No yielding will occur!
(despite the large tensile stress)

Pause...Questions?

Yield strength ↔ critical resolved shear stress

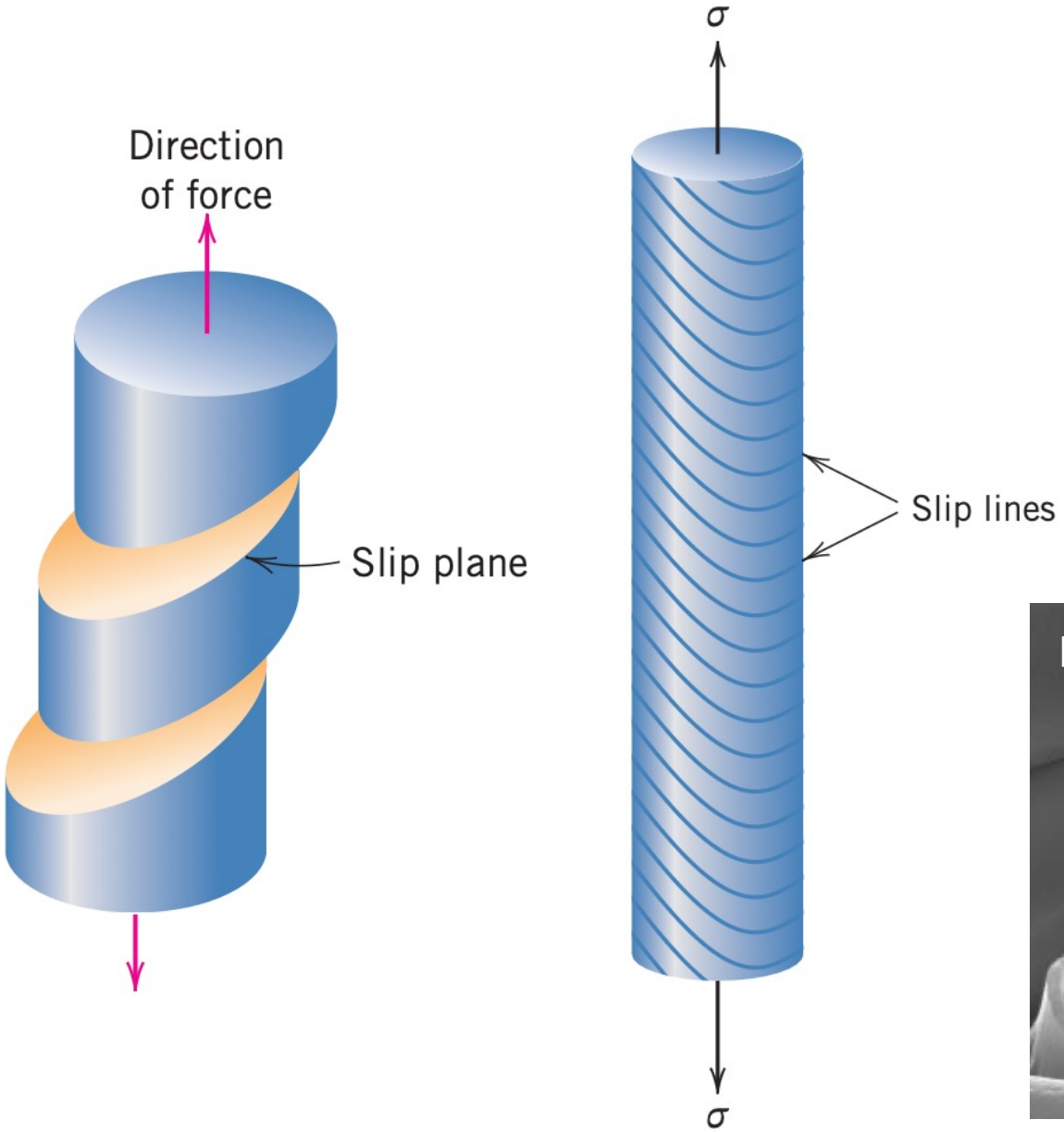
The critical resolved shear stress is closely related to the yield strength of a material:

$$\sigma_y = \frac{\tau_{\text{crss}}}{(\cos\phi \cos\lambda)_{\text{max}}}$$

If a high stress is needed to cause slip, the material will have a high yield strength

This implies that mechanical strength has a **strong dependence on direction…**
Is that reasonable?

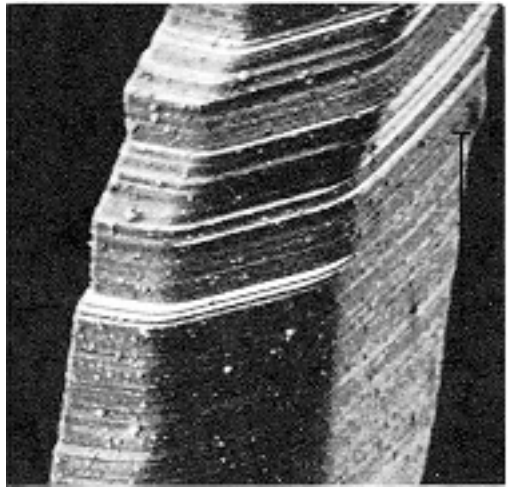
Plastic deformation in single crystals

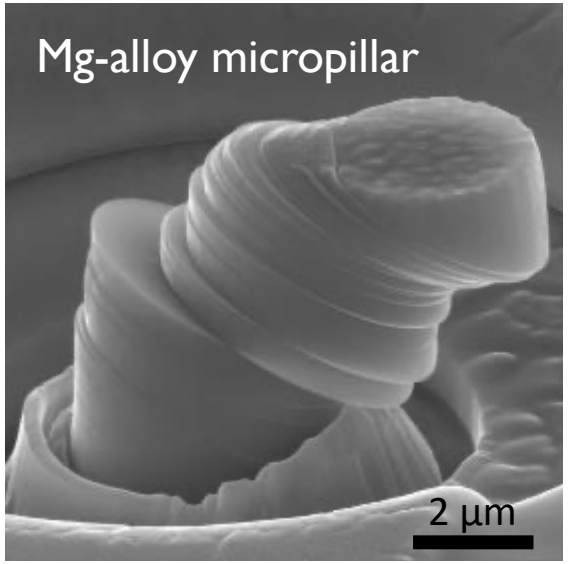


For **single crystals** – yes!
We can observe this directly.



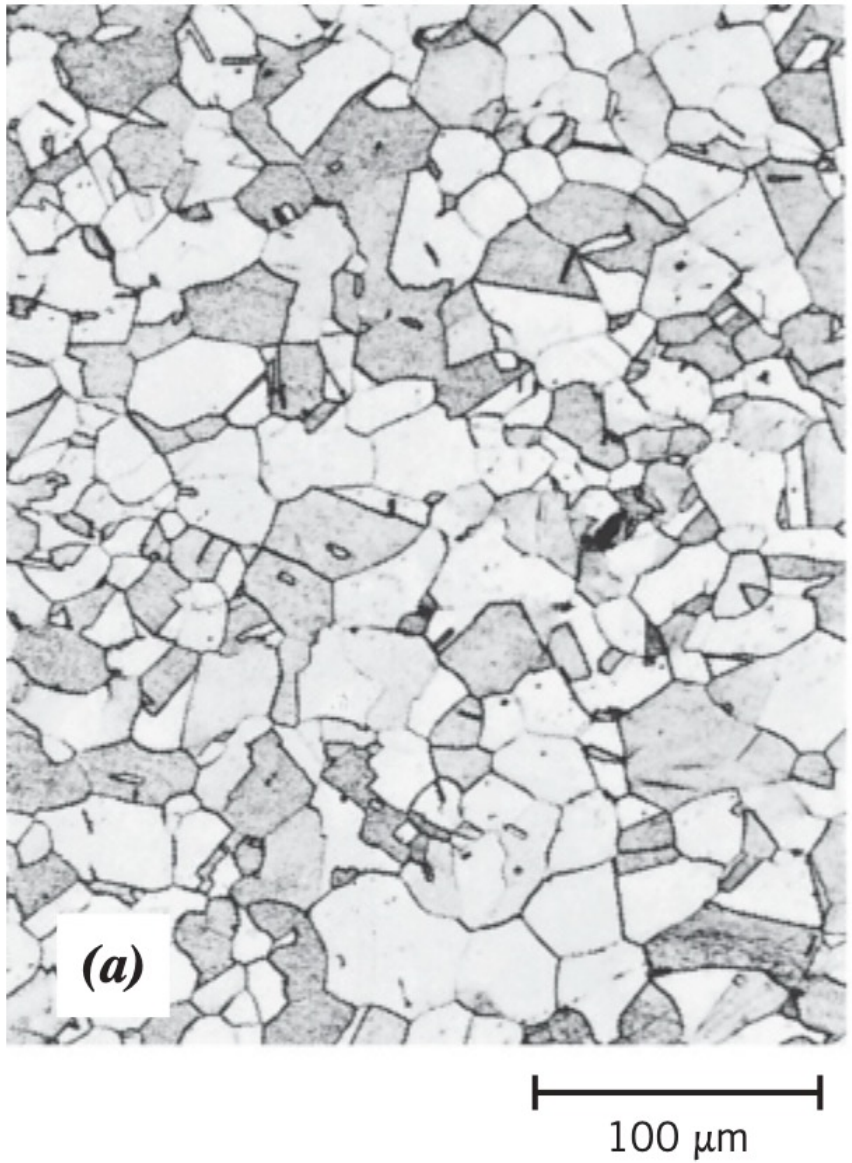
Single-crystal cobalt





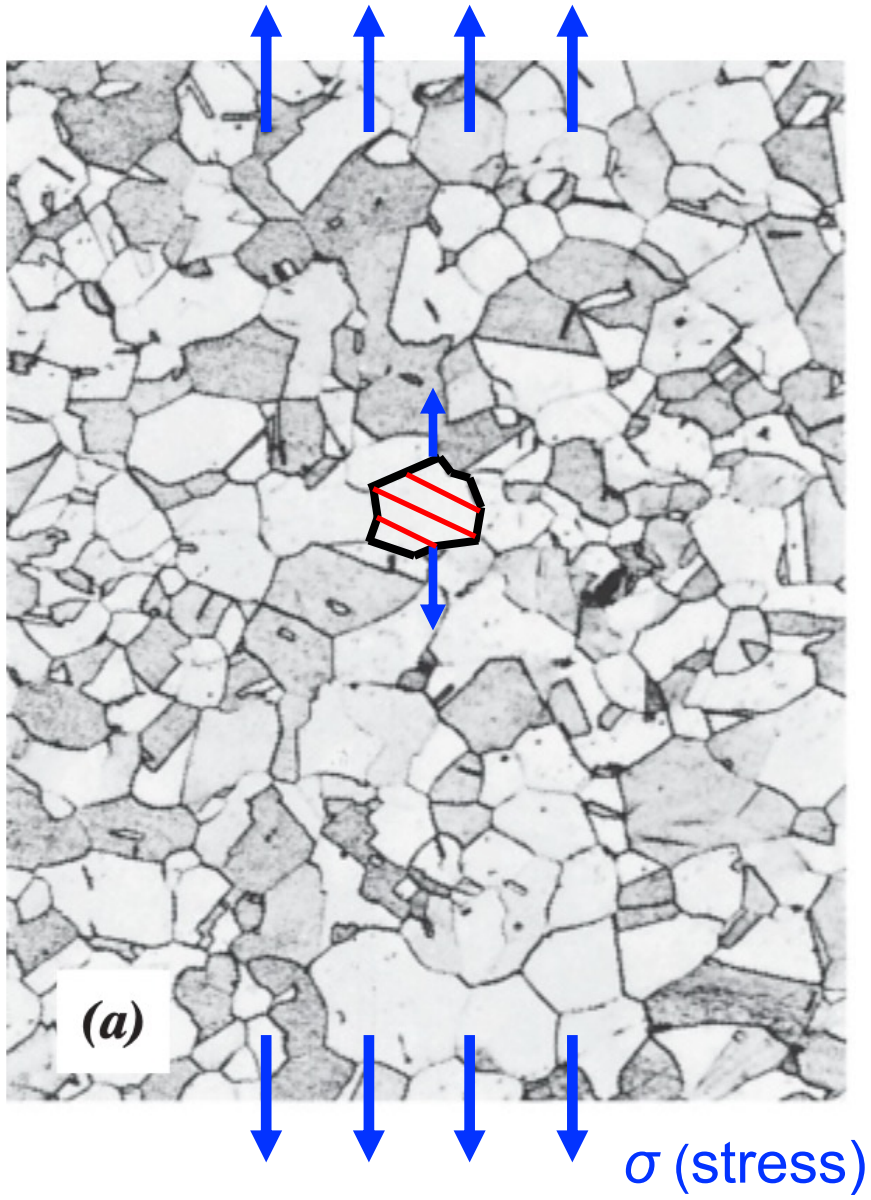
But remember,
most materials are *not* single crystals

Plastic deformation in polycrystalline materials



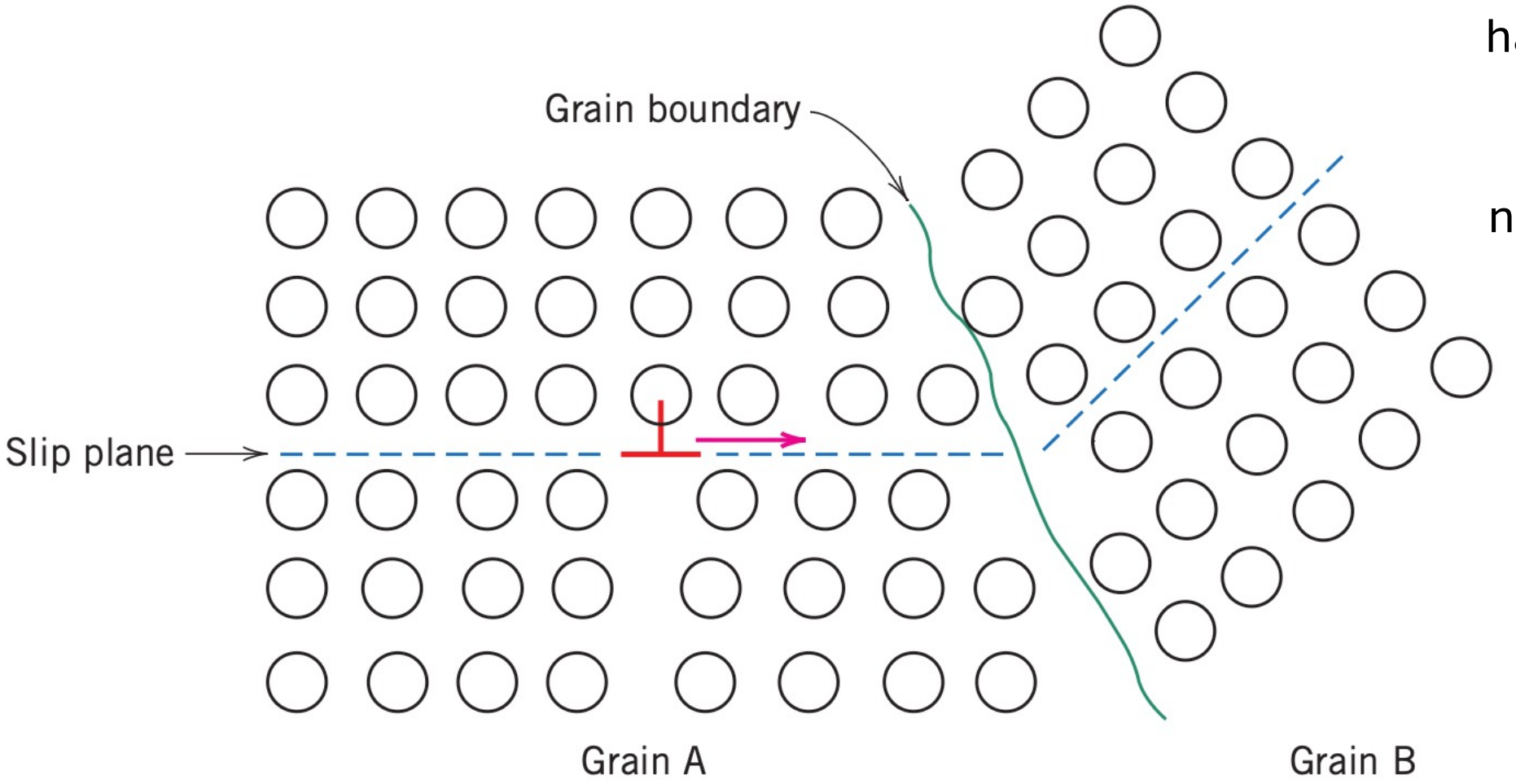
- Think of polycrystalline materials as being composed of ***many*** **single crystals (grains)**, glued together in **random orientations**

Plastic deformation in polycrystalline materials



- Think of polycrystalline materials as being composed of ***many*** **single crystals (grains)**, glued together in **random orientations**
- As we pull on this material, each grain experiences some part of the force, and **each grain has its own unique:**
  - **Preferred slip plane and direction**
  - **Critical resolved shear stress**
- Dislocations can still move within each grain, but now they have to "hop" across grains

Dislocation motion (slip) across grain boundaries



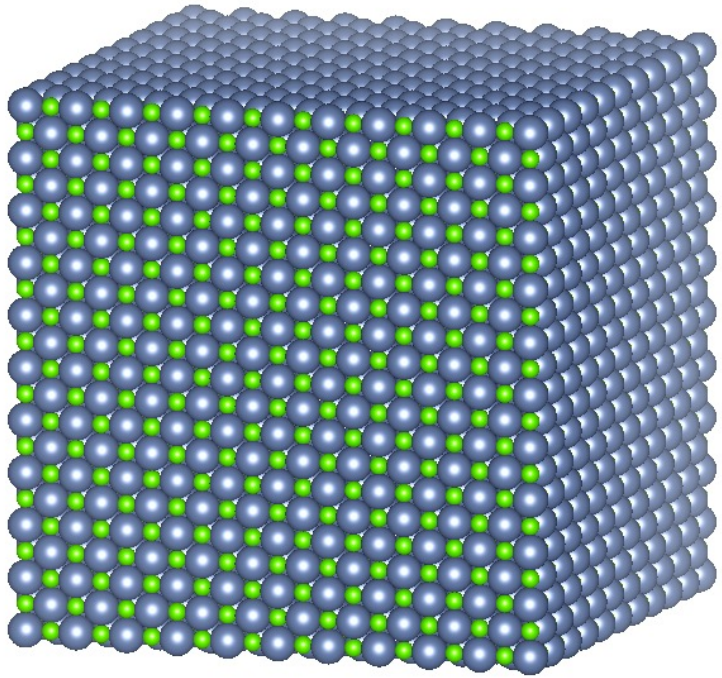
Enough dislocations have to "pile up" at the boundary to cause enough stress in the nearby grain – creating *new* dislocations

This happens but it is **more difficult than slip in single crystals**

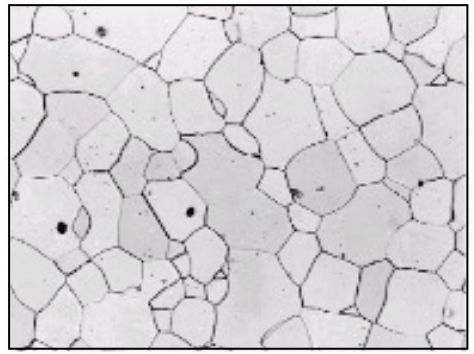
Small grains provide a *strengthening* mechanism

Polycrystalline materials (especially those with **small grains**) are **generally more resistant to plastic deformation** than single crystals

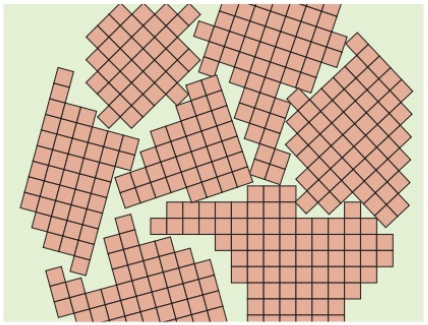


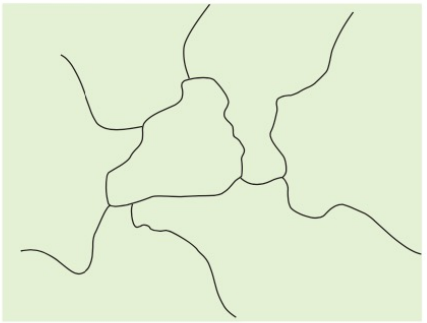


Dislocations move easily through single crystals









Dislocations move ***less*** easily through polycrystalline materials

Small grains provide a *strengthening* mechanism

A fine-grained material (one that has small grains) is harder and stronger than one that is coarse grained because the former has a greater total grain boundary area to impede dislocation motion. For many materials, the yield strength σ_y varies with grain size according to

$$\sigma_Y = \sigma_0 + k_Y d^{-1/2}$$

Hall-Petch Equation

Material-dependent constants

Yield strength

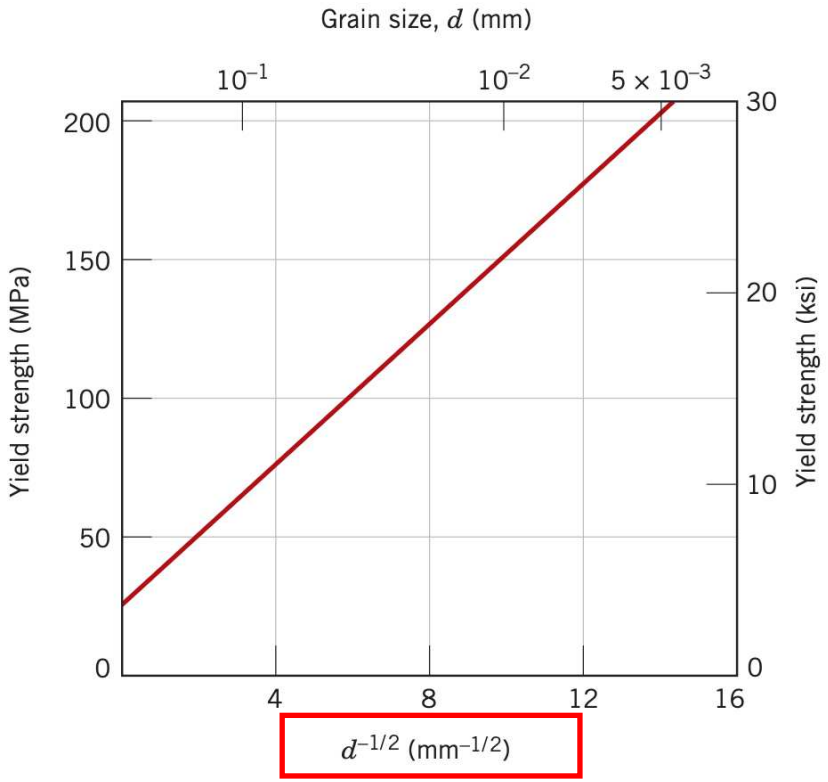
Inverse grain size

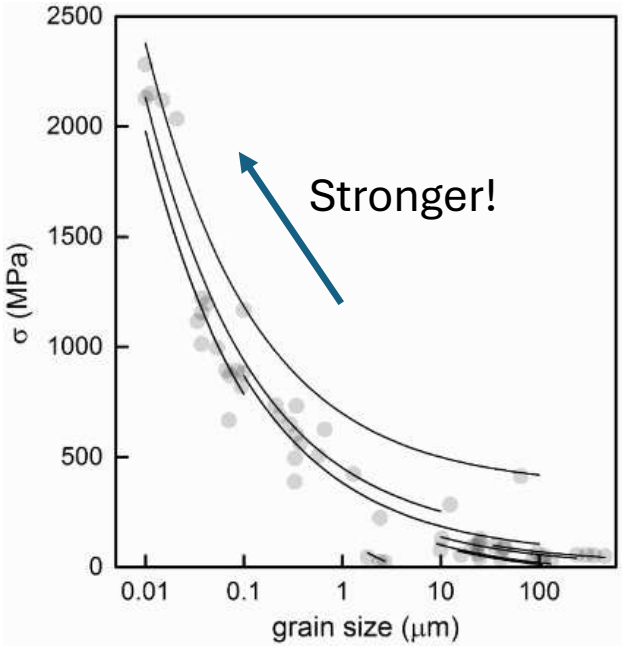
Small grains provide a *strengthening* mechanism

A fine-grained material (one that has small grains) is harder and stronger than one that is coarse grained because the former has a greater total grain boundary area to impede dislocation motion. For many materials, the yield strength σ_y varies with grain size according to

$$\sigma_Y = \sigma_0 + k_Y d^{-1/2}$$

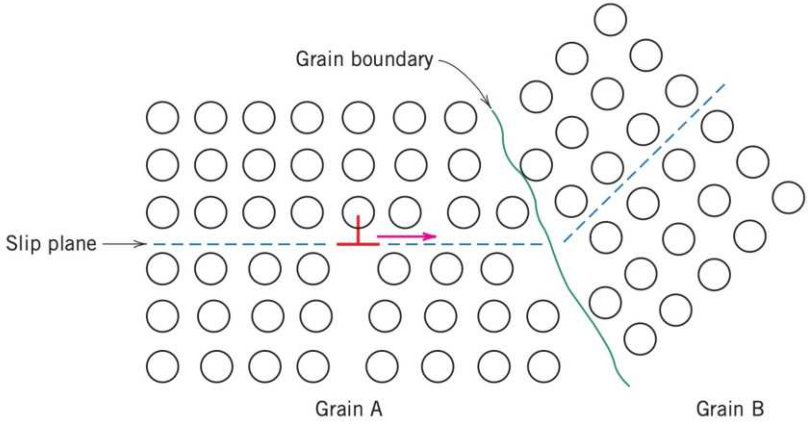
Hall-Petch Equation



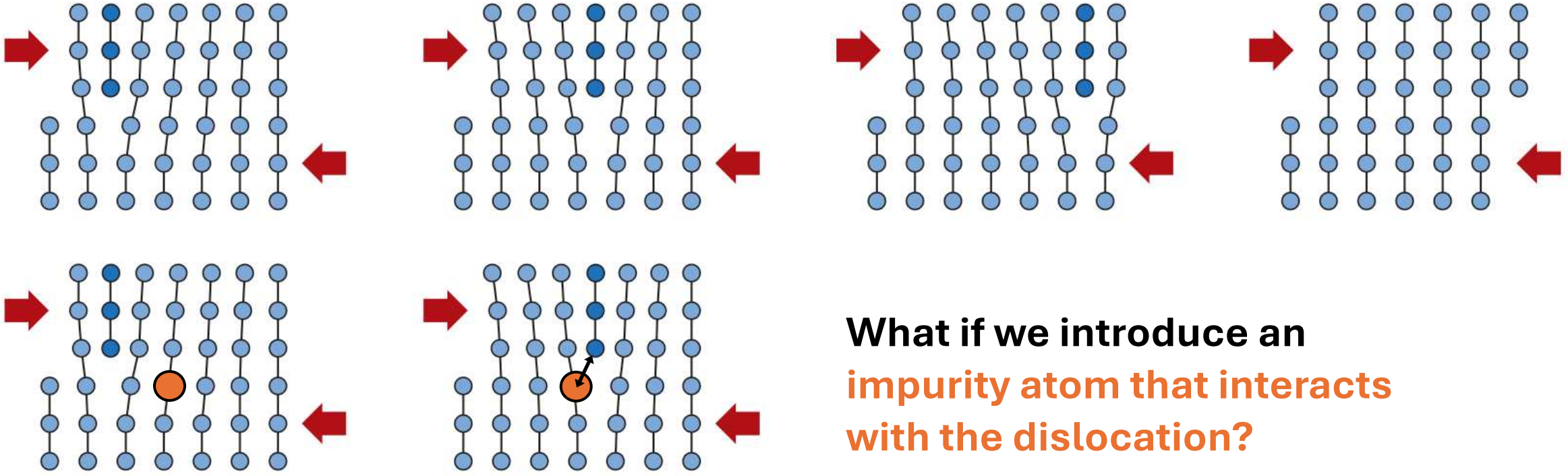


Real data does not perfectly follow the Hall-Petch equation, but it is a good rule of thumb: smaller grains = stronger material.

Strengthening mechanism #2: solid solutions

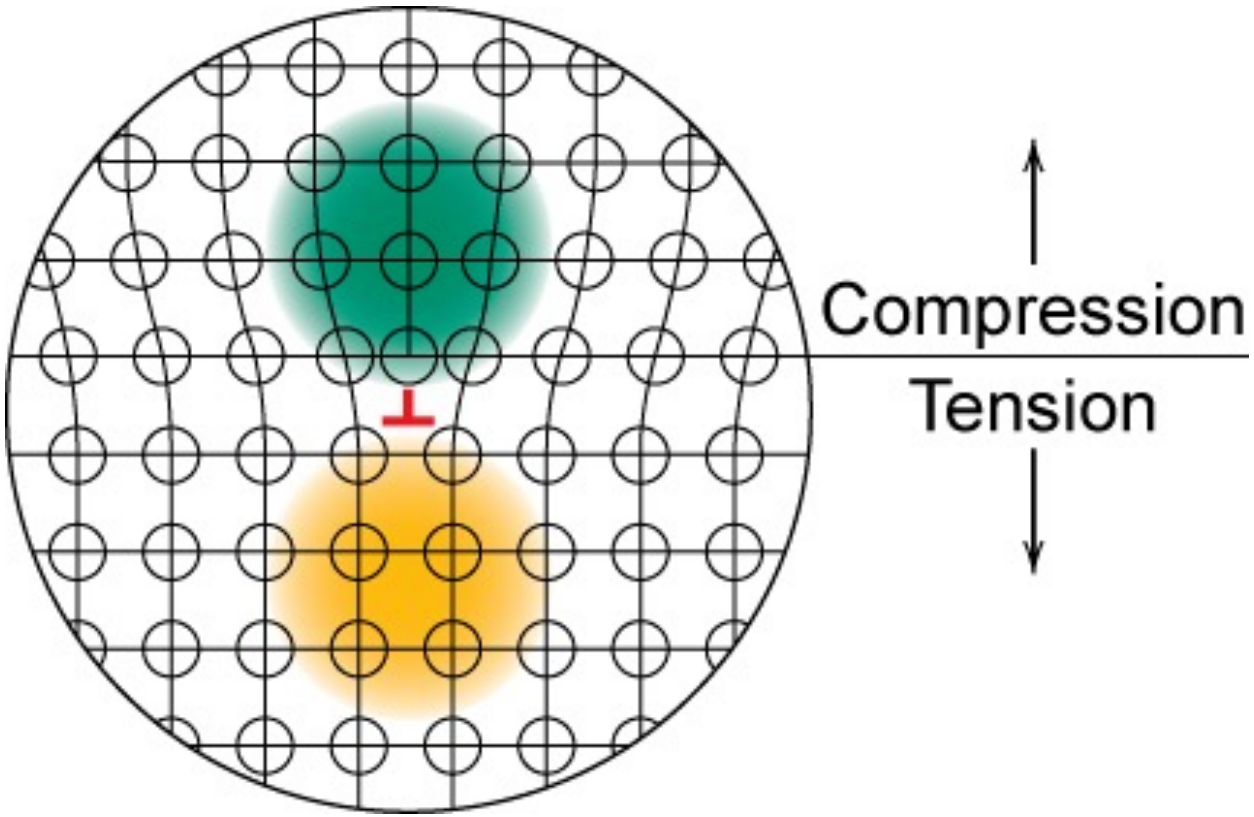


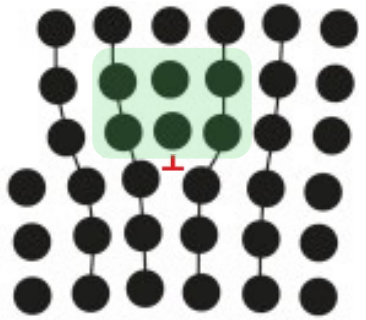
Grain boundaries cause strength strengthening by **impeding dislocation motion.** How else can we accomplish this?



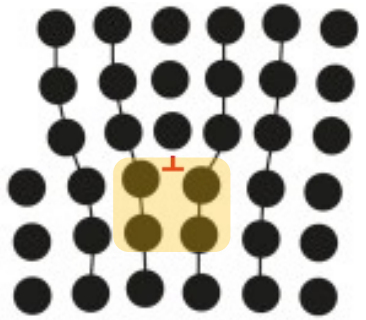
What if we introduce an impurity atom that interacts with the dislocation?

Dislocations lead to compression and tension



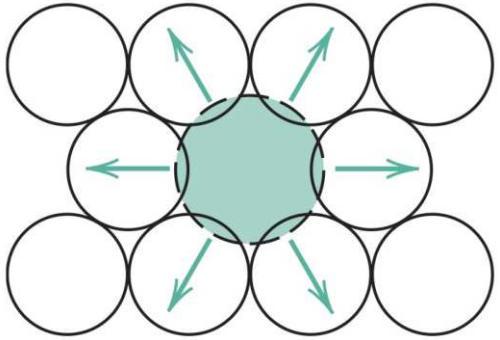


Atoms above ⊥ are pushed together **(compression)**



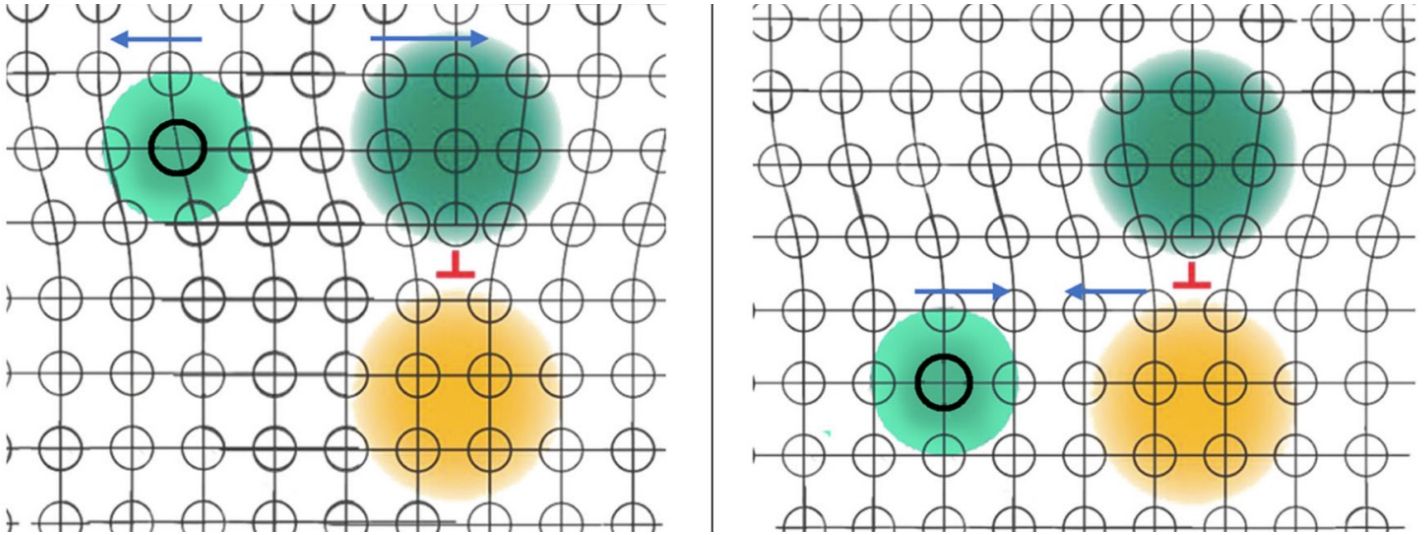
Atoms below ⊥ are pulled apart **(tension)**

Substitutional elements *also* create stress fields



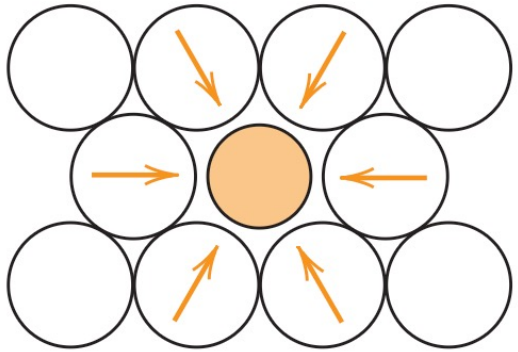
Consider an impurity that is larger than the host lattice, leading to **compressive stress**

This stress field can interact with impurity atoms



Repulsion **Attraction**

Both impede dislocation motion!



Similar effects occur for impurities that are smaller than the host lattice, leading to **tensile stress**

Solid solution strengthening

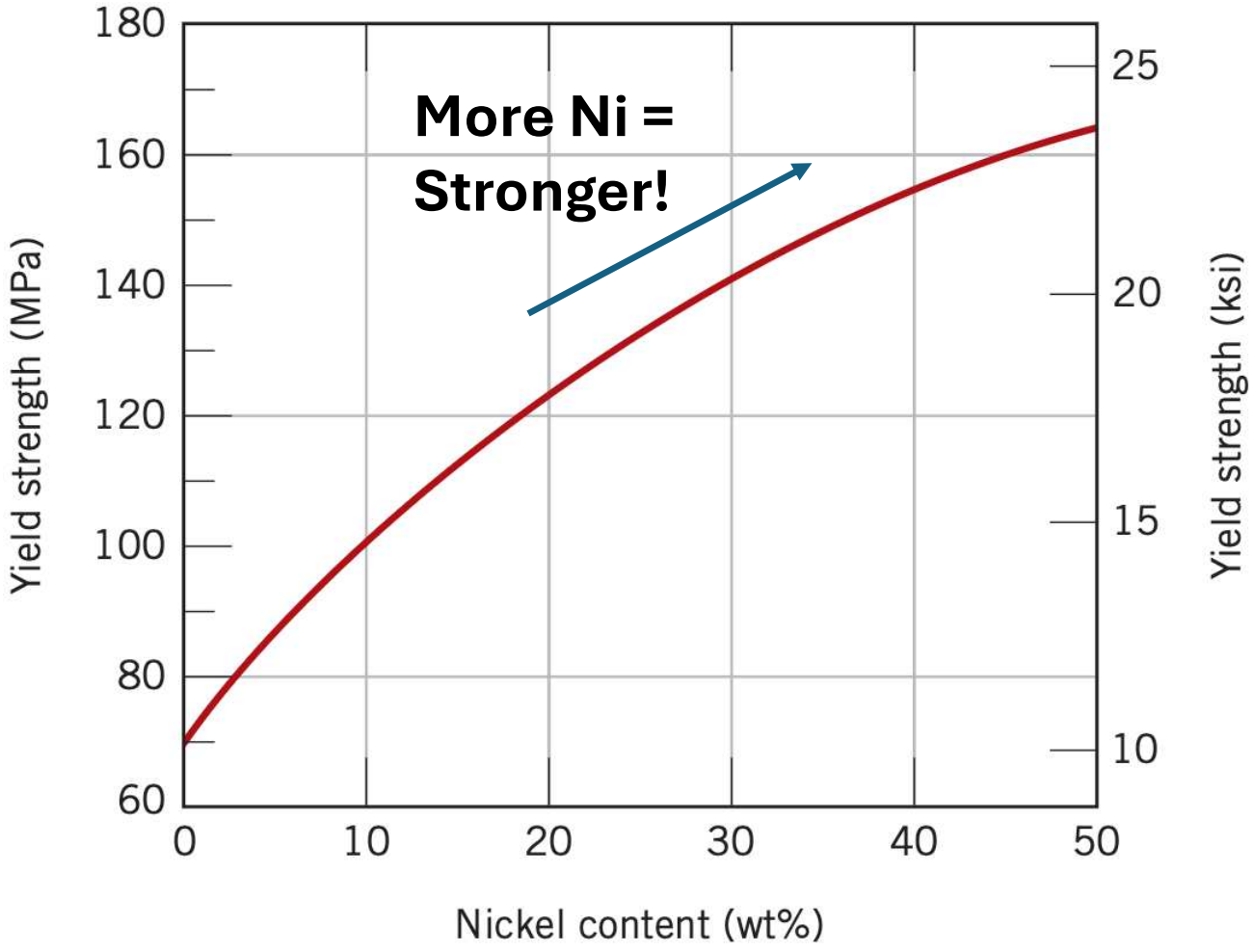
As you introduce a second element into a pure material, that material's yield strength will increase

Empirically:

$$\sigma_Y \propto c^{1/2}$$

Concentration of the solute

Example: Cu alloyed with Ni



Strengthening mechanism #3: strain hardening

So far, we have discussed two things that **impede dislocation motion:**

1) Grain boundaries

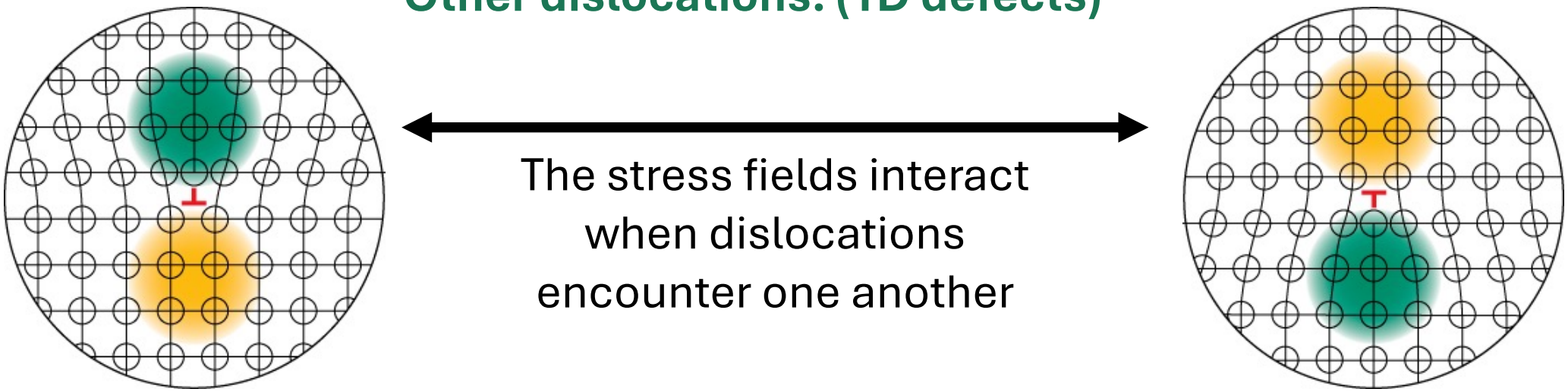
(2D defects)

2) Impurity atoms (solutes)

(0D defects)

What are we missing?

Other dislocations! (1D defects)



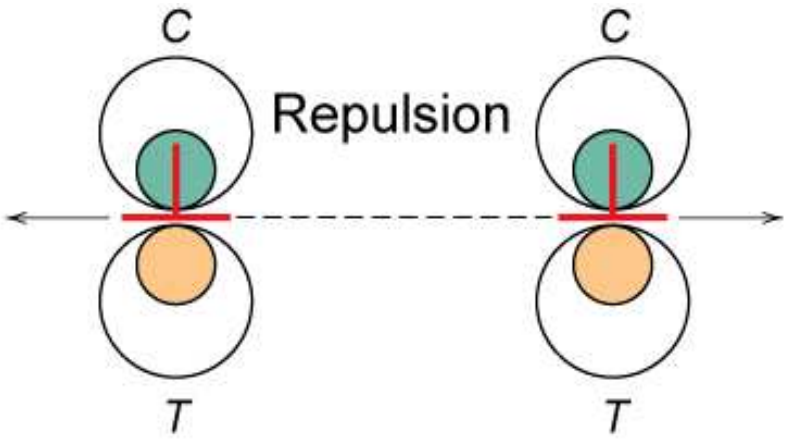
The stress fields interact when dislocations encounter one another

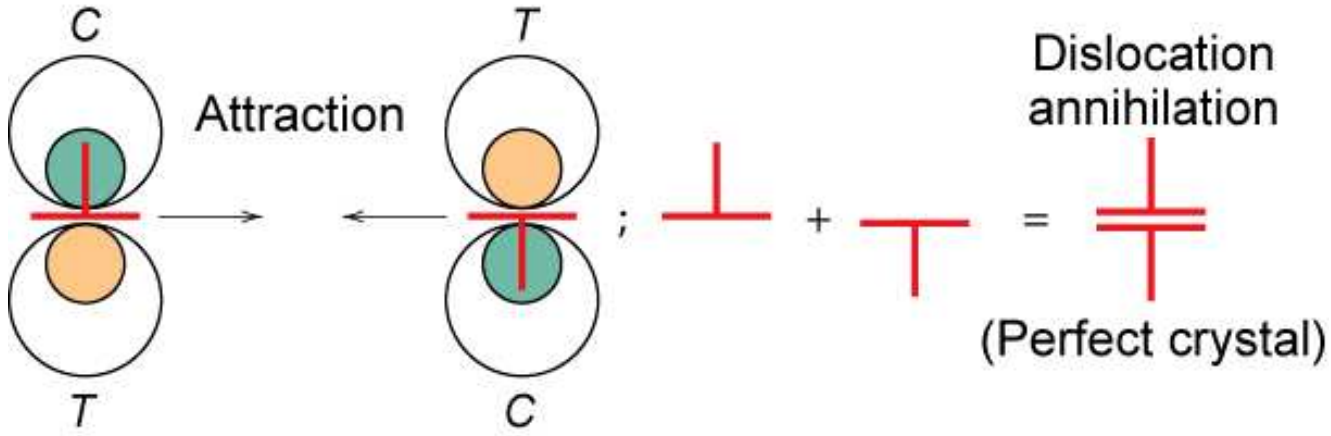
Strengthening mechanism #3: strain hardening

When the two dislocations are aligned, **they repel one another**

- Compression + compression = *more* compression
- Tension + Tension = *more* tension

→ Less dislocation motion → stronger material





The extra half-planes meet and form a new full-plane

When the two dislocations are oppositely aligned, **they cancel one another**

- Compression + tension = 0

→ Some dislocation motion is lost
→ stronger material

Strengthening mechanism #3: strain hardening

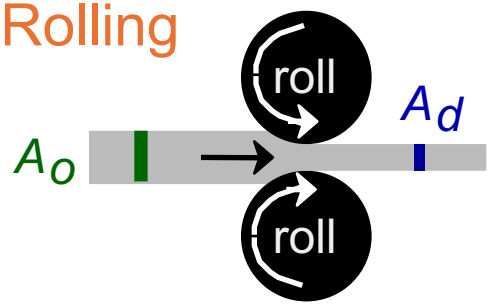
Result: more dislocations → stronger material

How can we introduce more dislocations?

Plastically deform a material at room temperature – otherwise known as ***cold working***



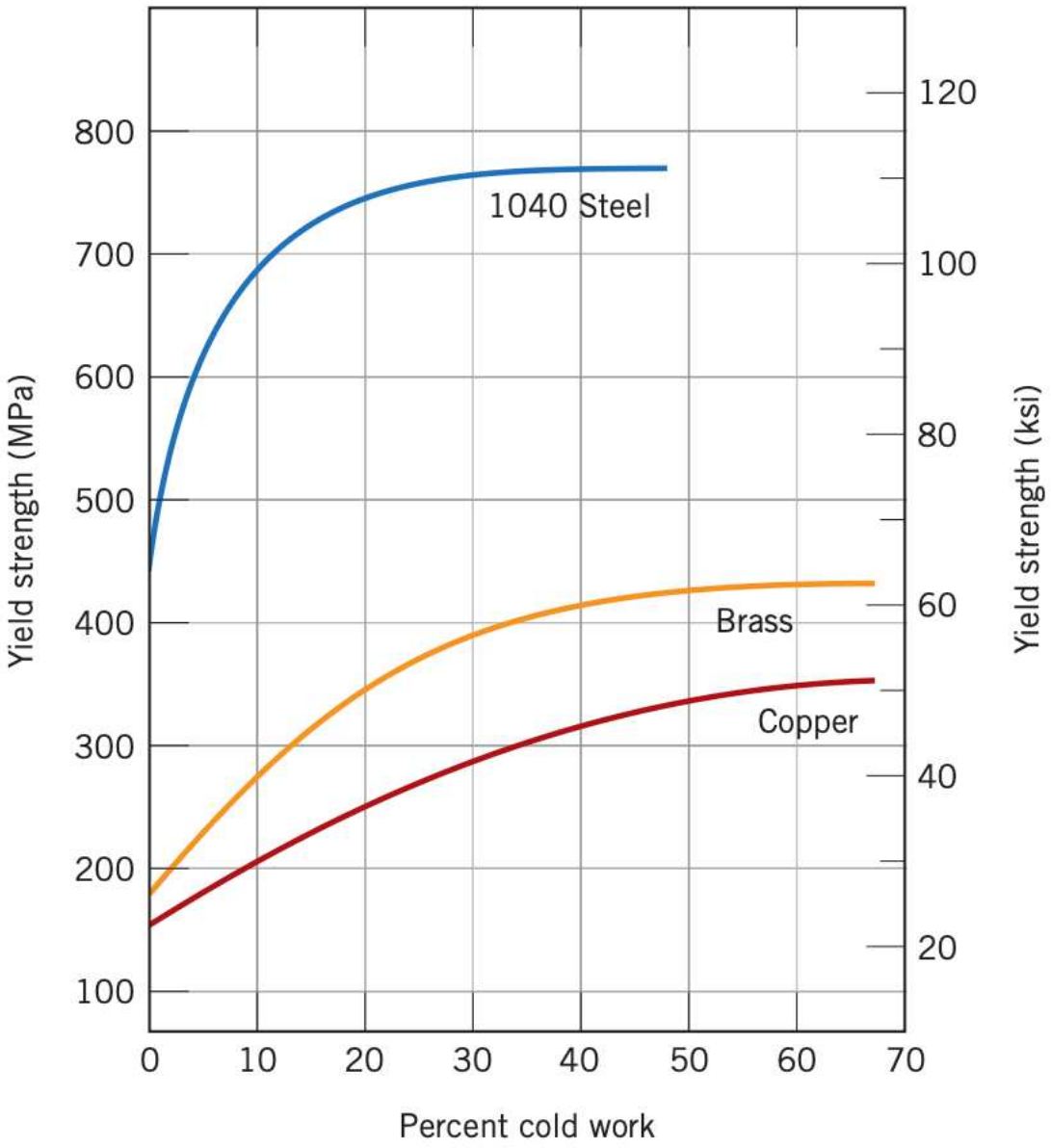
Rolling

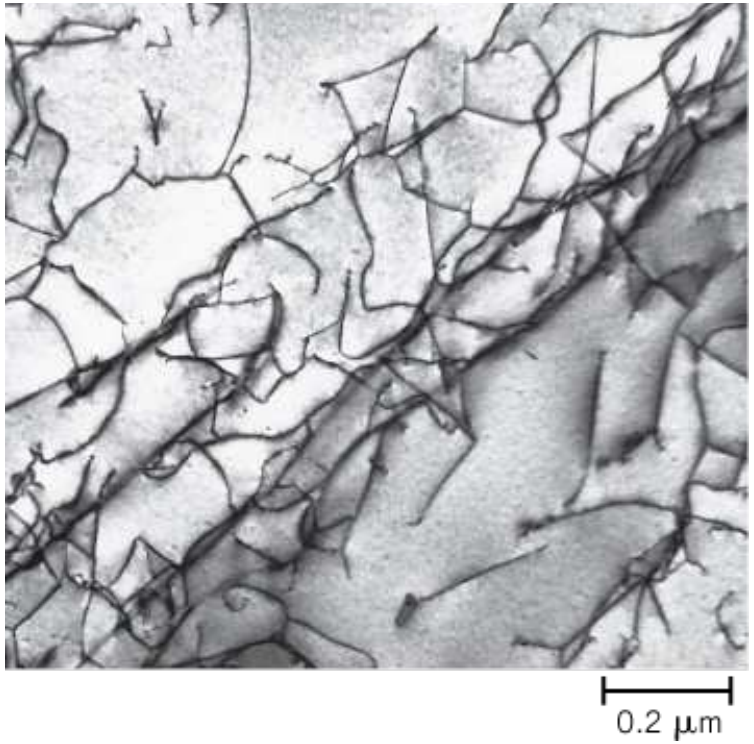


It is sometimes convenient to express the degree of plastic deformation as *percent cold work* rather than as strain. Percent cold work (%CW) is defined as

$$\%\text{CW} = \left(\frac{A_0 - A_d}{A_0}\right) \times 100$$

Strengthening mechanism #3: strain hardening





Electron microscopy image of a heavily cold worked material

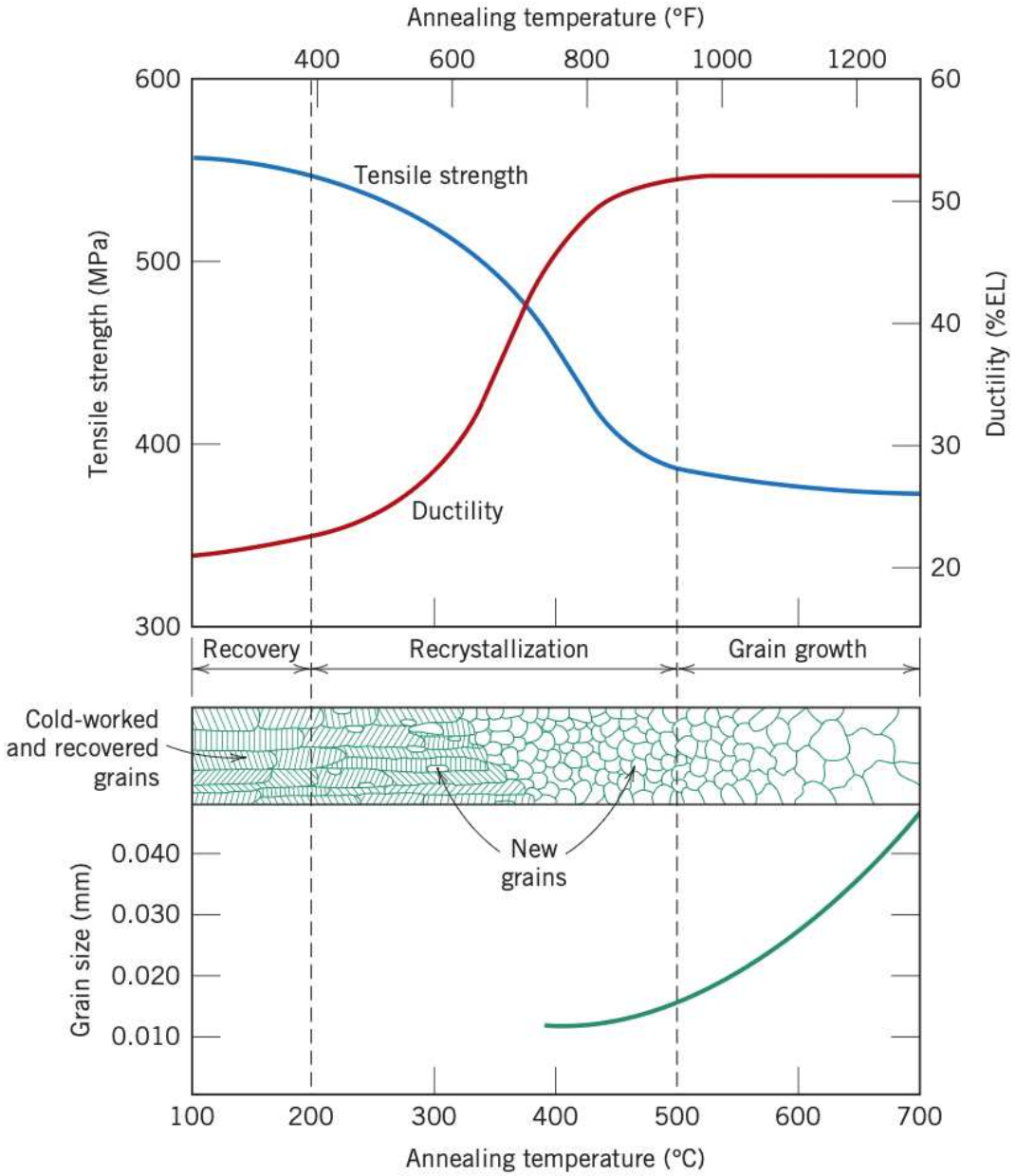
With lots of dislocations clearly visible

Dislocation density = $\frac{\text{total dislocation length}}{\text{unit volume}}$

Can range from 10^4 mm^{-2} (before cold work) to 10^{10} mm^{-2} (after cold work) – huge increase!

DEMO

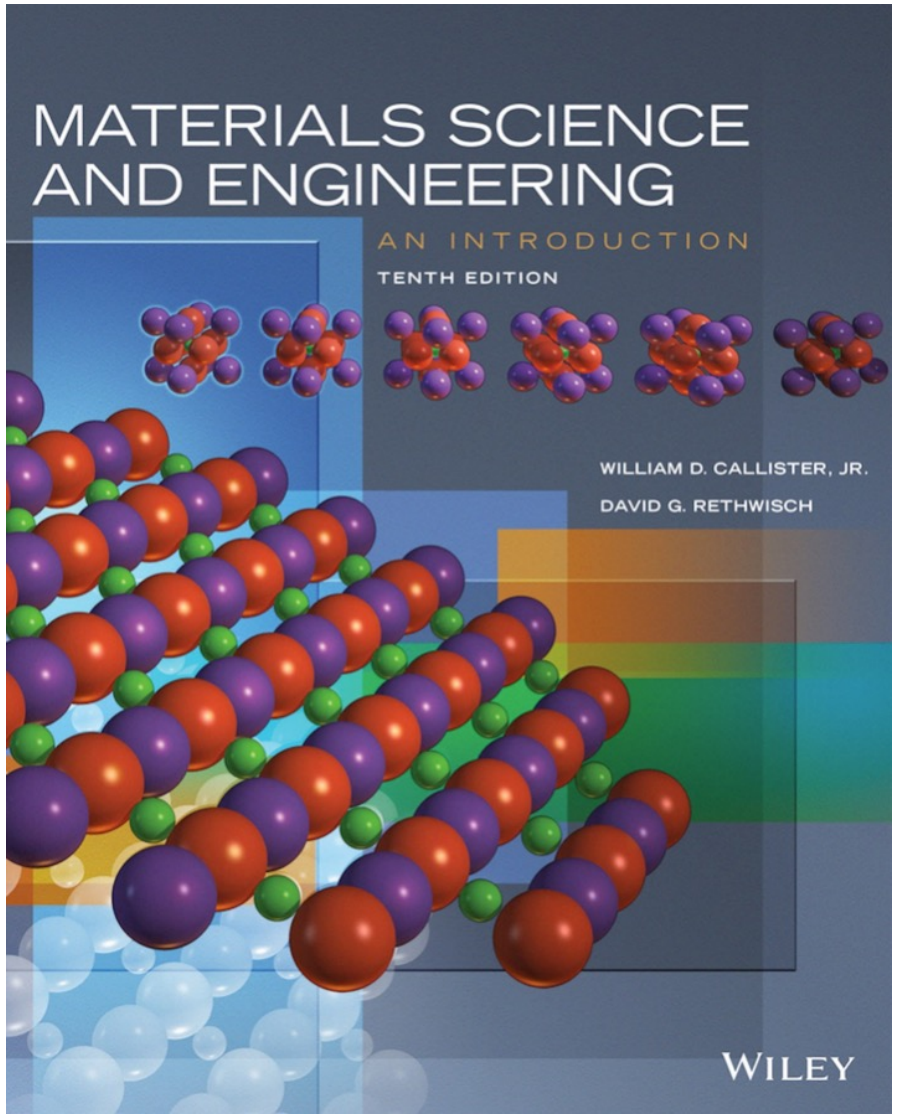
Recrystallization → larger, more relaxed grains



- Grain boundaries and dislocations make a material **stronger but more brittle**
- These are **non-equilibrium defects** left over from synthesis & processing
- We can "**anneal** them out" – heat the material up so diffusion removes some dislocations and grows larger grains
- This process – ***recrystallization*** – leads to lower strength but higher ductility

Time check

Reading for this subject

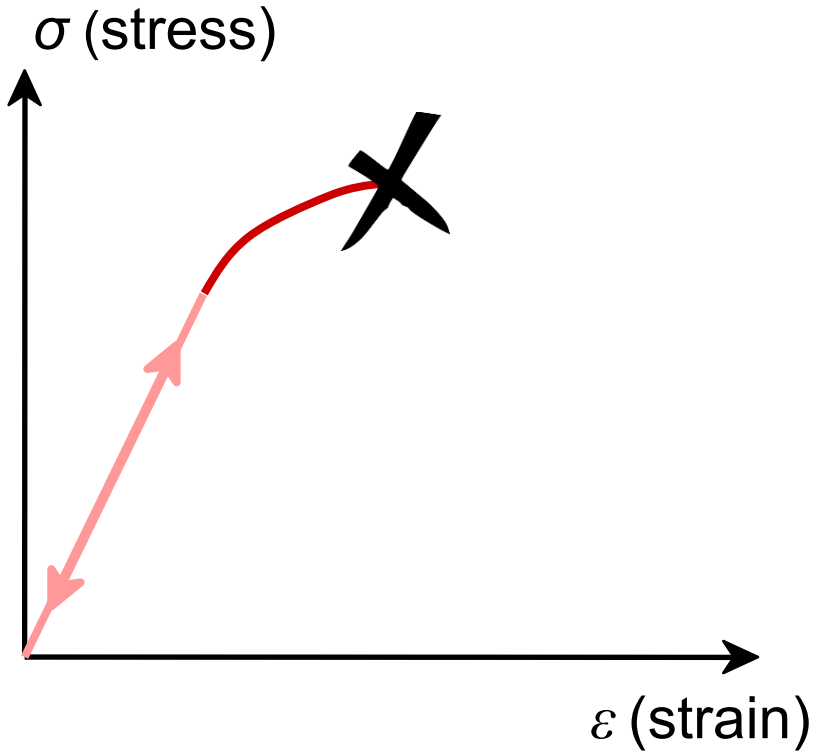


Chapter 8 Failure

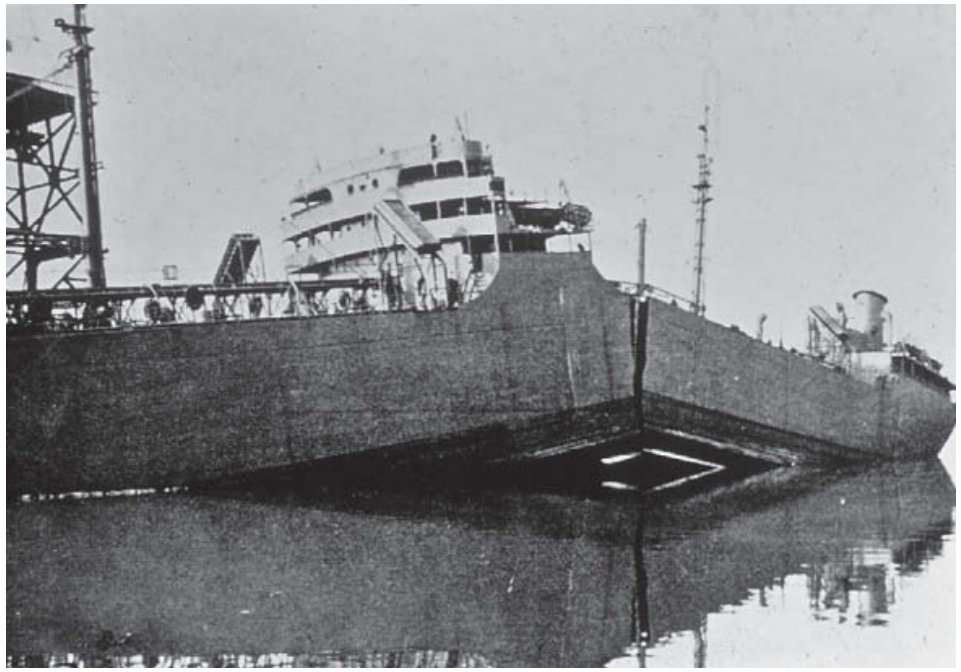
This discussion will closely follow **Chapter 8** of Callister, **pages 210-246** of the 10th edition.

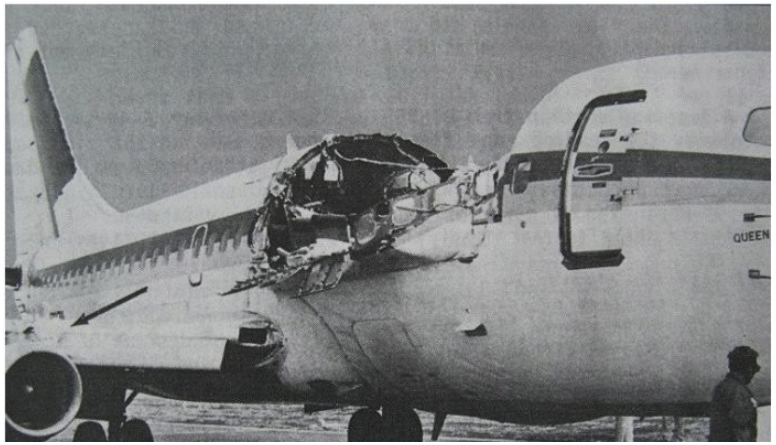
At large enough stress/strain, *fracture* will occur





At large enough stress/strain, *fracture* will occur

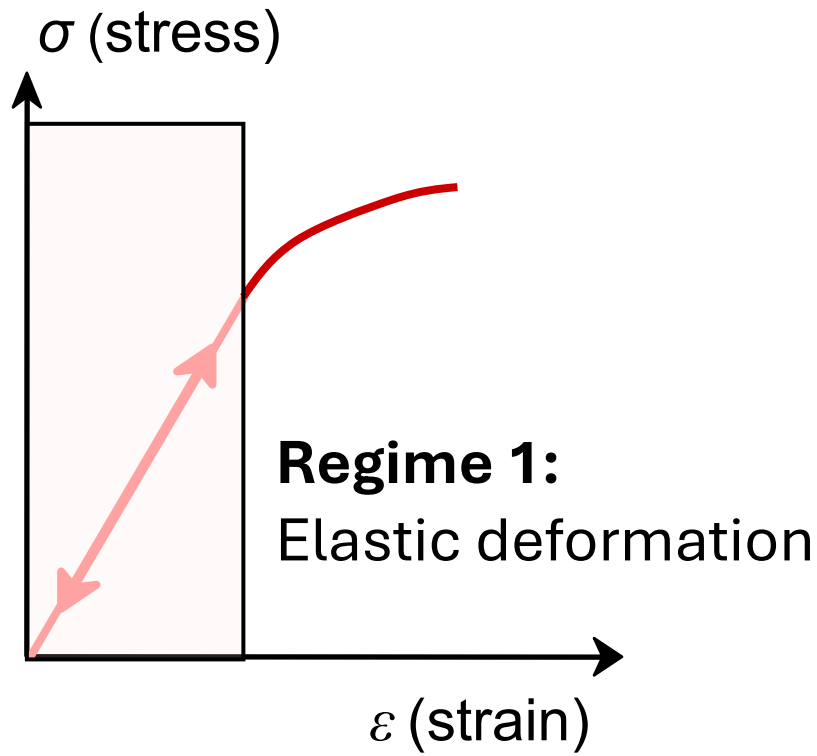




Fracture is something we'd like to understand so we can avoid it



Two general types of fracture: ductile and brittle

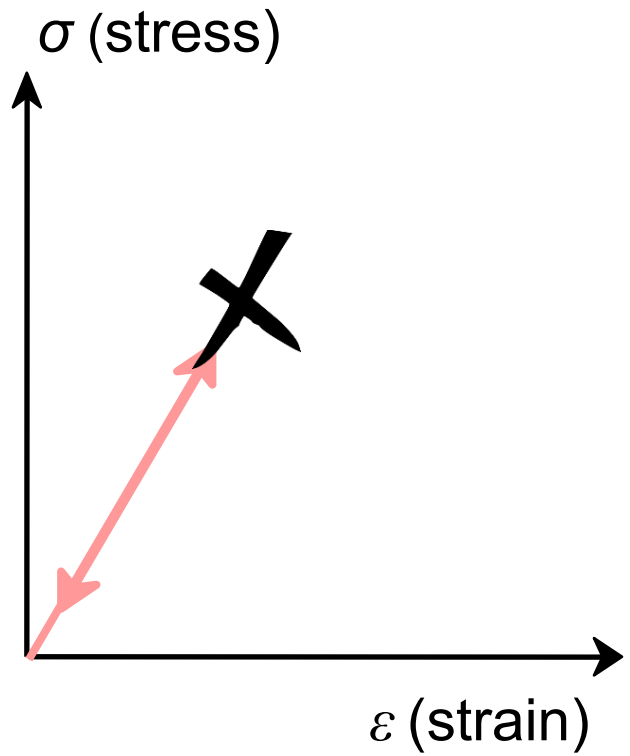


Two general types of fracture: ductile and brittle

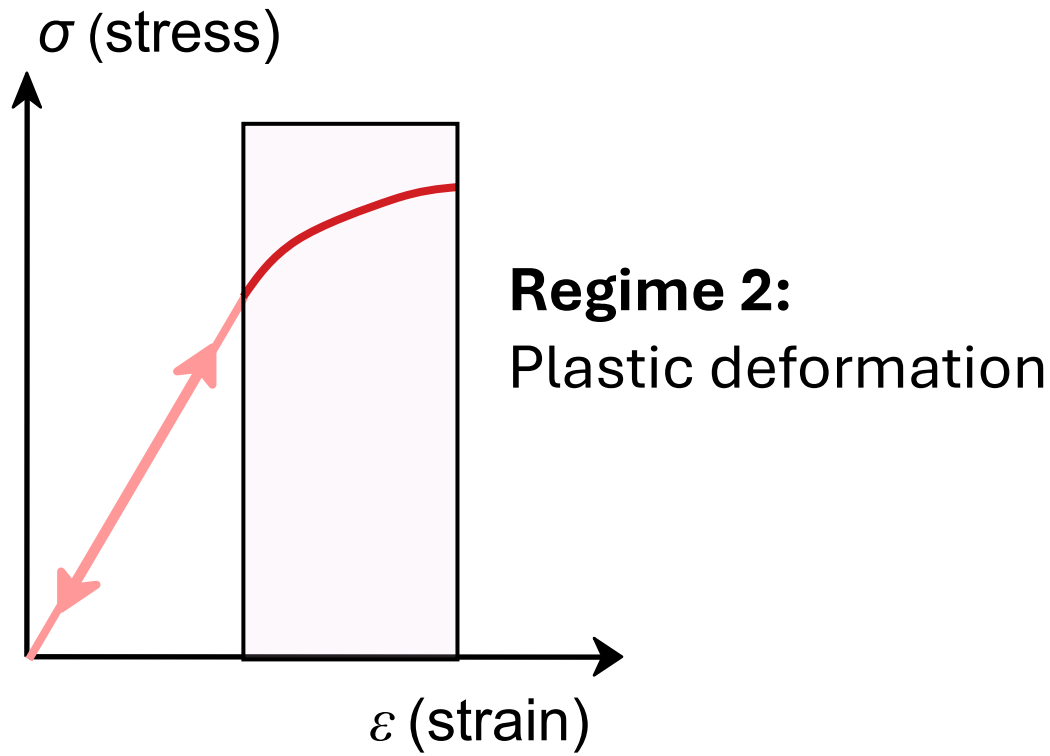
If failure occurs *before* any plastic deformation takes place: it is called **brittle fracture**

- Rapid crack propagation
- Fails without warning





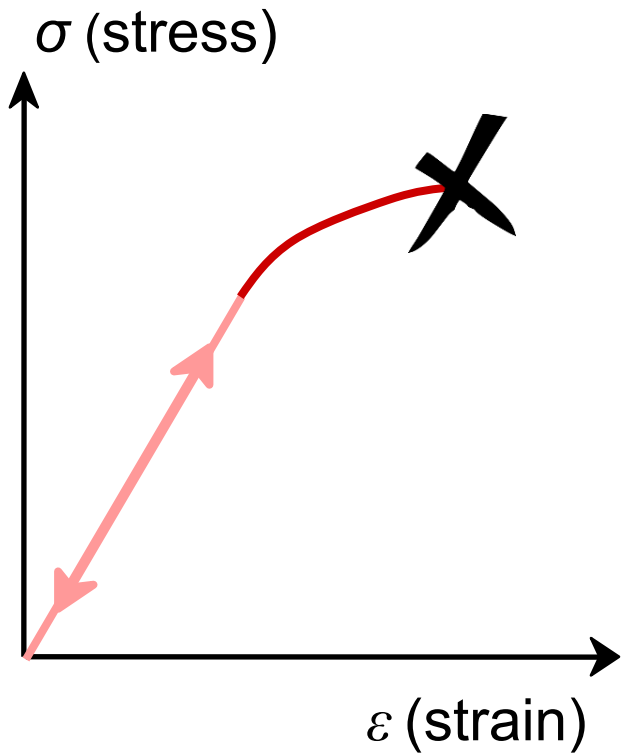
Two general types of fracture: ductile and brittle



Two general types of fracture: ductile and brittle

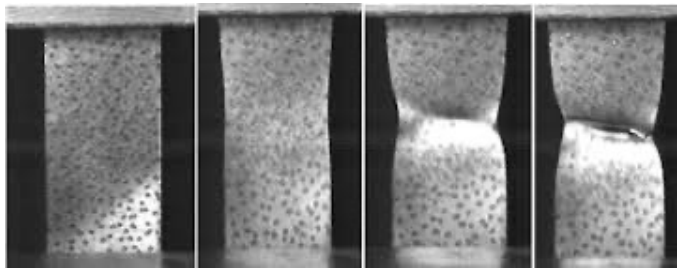
If failure occurs *before* any plastic deformation takes place: it is called **brittle fracture**

- Rapid crack propagation
- Fails without warning



If failure occurs *after* some plastic deformation takes place: it is called **ductile fracture**

- *Slow* crack propagation
- Usually shows early warning signs

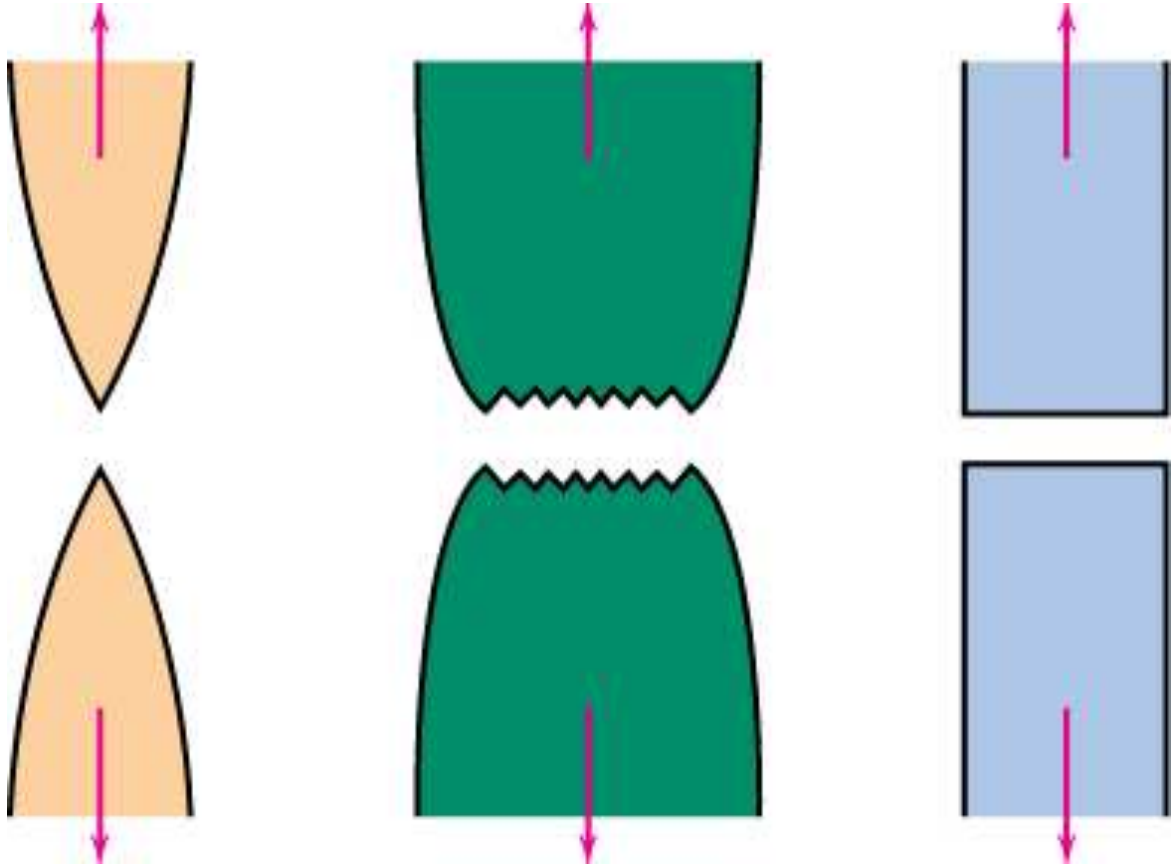


These mechanisms have distinct fracture profiles

Very Ductile

Moderately Ductile

Brittle



The material was clearly stretched prior to breaking

No signs of plastic defamation prior to crack formation

These mechanisms have distinct fracture profiles

“Cup-and-cone” structure



Ductile fracture



Brittle fracture

These mechanisms have distinct fracture profiles

“Cup-and-cone” structure



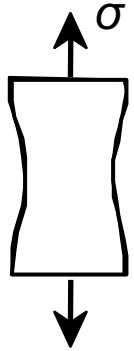
Ductile fracture



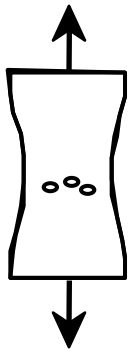
Brittle fracture

Stages of ductile failure

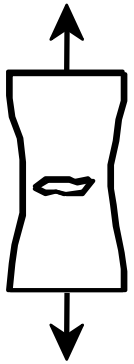
necking



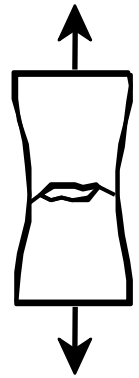
void nucleation



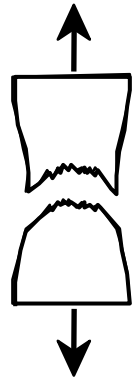
void growth and coalescence

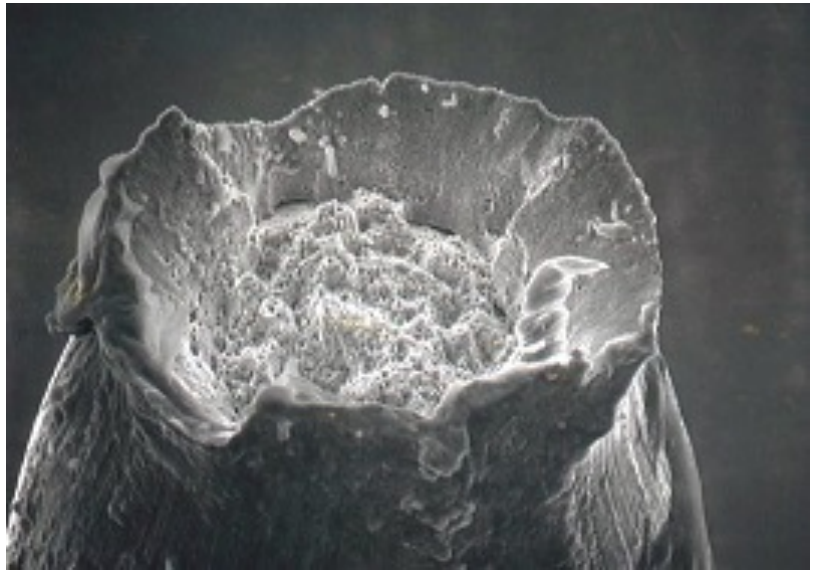


crack propagation



fracture





These mechanisms have distinct fracture profiles



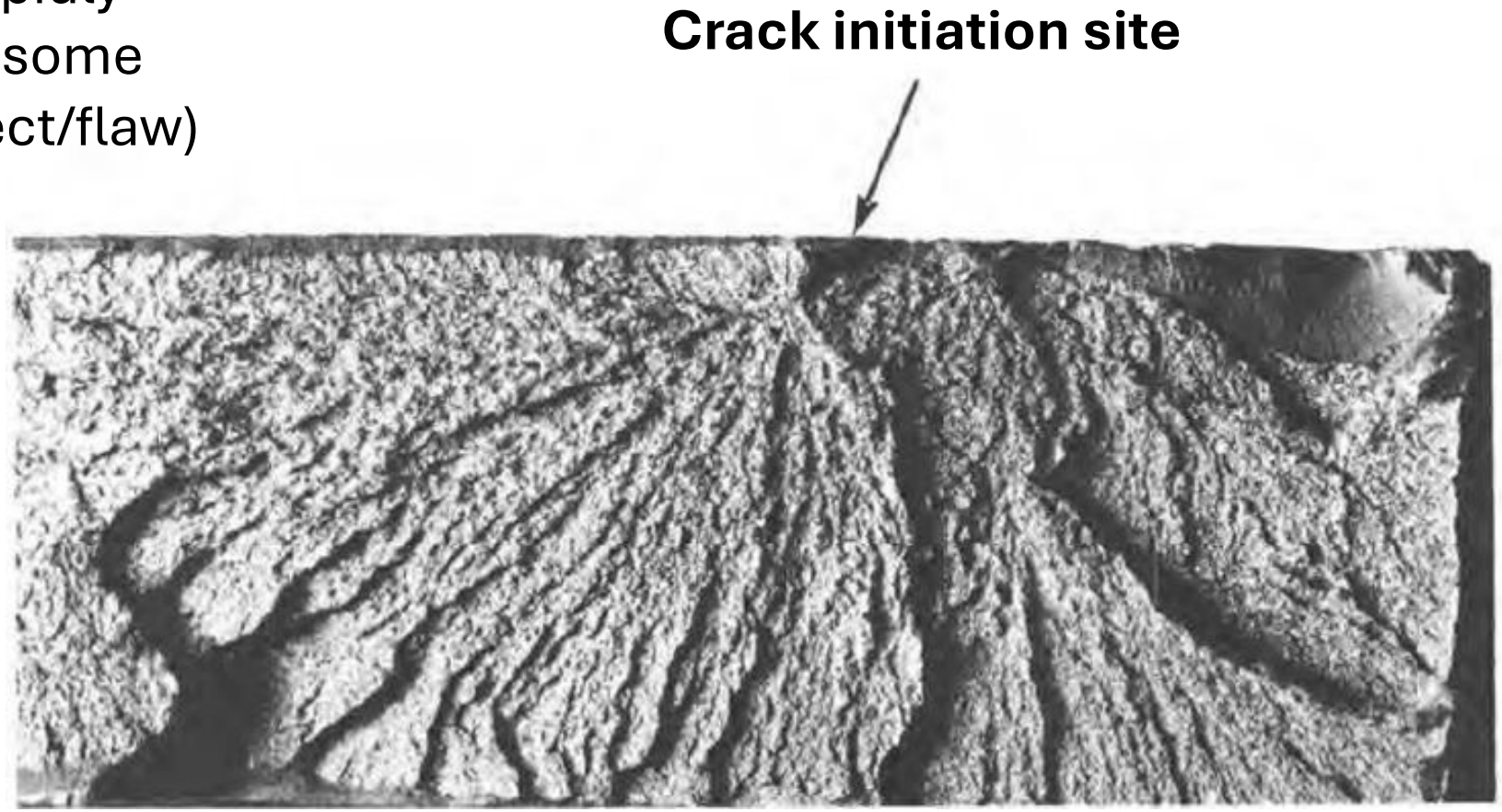
Ductile fracture



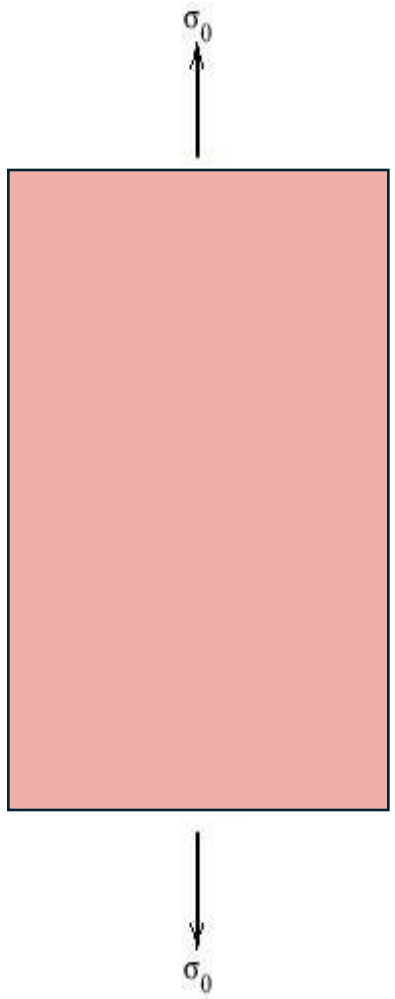
Brittle fracture

Signs of brittle failure

- Brittle facture surfaces often have V-shaped “chevron” markings
- This happens as cracks rapidly propagate outwards from some initiation site (often a defect/flaw)
- Because the material is brittle, there is **no plastic deformation to slow the cracks down**



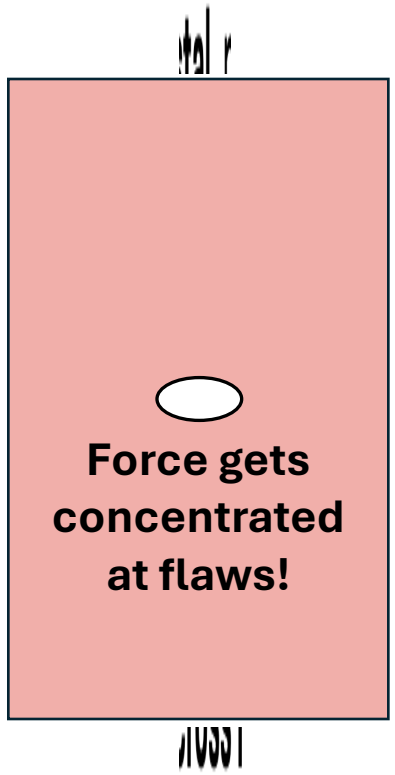
Principles of fracture mechanics



Suppose we tried to pull apart a **perfect crystal**, meaning tensile stress is **applied uniformly** to its cross section. Based on this understanding, we would predict that *very* large forces are required to cause failure.

- **Uniform stress → small forces spread across many bonds**

Principles of fracture mechanics



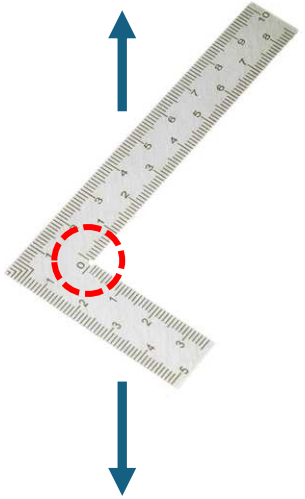
Suppose we tried to pull apart a **perfect crystal**, meaning tensile stress is **applied uniformly** to its cross section. Based on this understanding, we would predict that *very* large forces are required to cause failure.

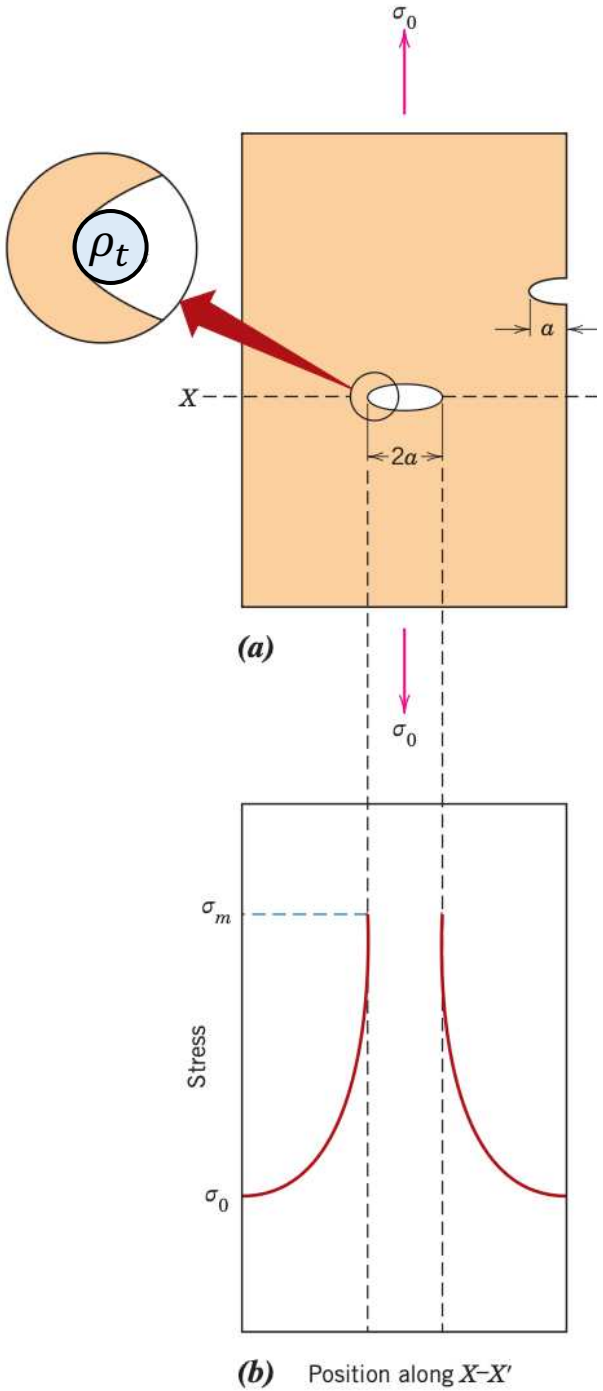
- **Uniform stress → small forces spread across many bonds**

In reality, **there are *always* minor flaws in the material** (like small voids) that act as a **stress concentrators**, leading to failure at much lower forces.

- **Concentrated stress → high forces at a few specific bonds**

Fracture mechanics: It is the propagation of cracks, starting at these flaws, that cause failure.





Stress concentration

We can quantify the stress at the tip of the flaw by assuming it is approximately spherical:

$$\sigma_m = 2\sigma_o \left(\frac{a}{\rho_t} \right)^{1/2}$$

$$K_t = \frac{\sigma_m}{\sigma_o} > 1$$

Stress concentration factor

Where:

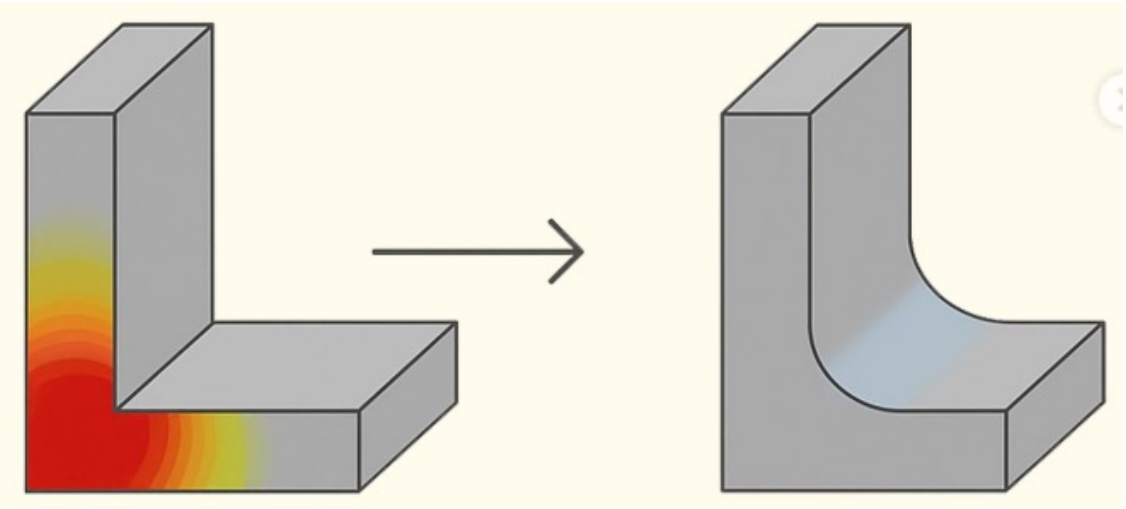
ρ_t = radius of curvature

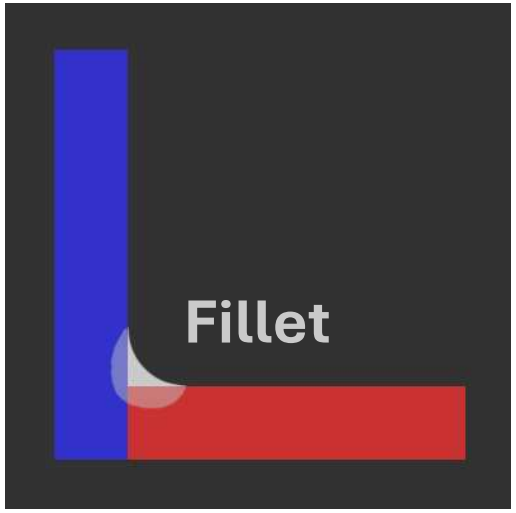
σ_o = applied stress

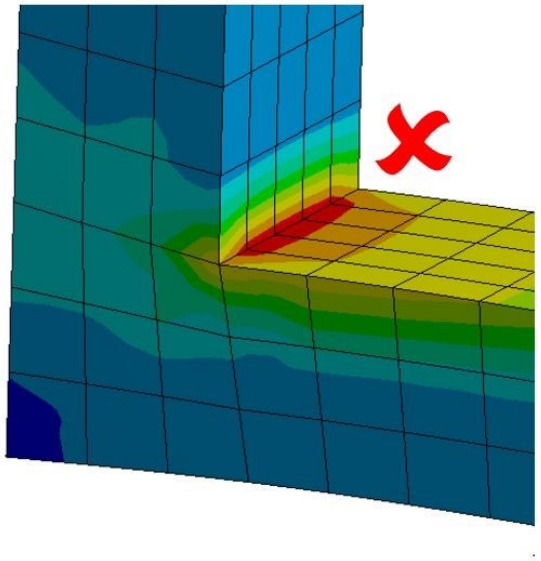
σ_m = stress at crack tip

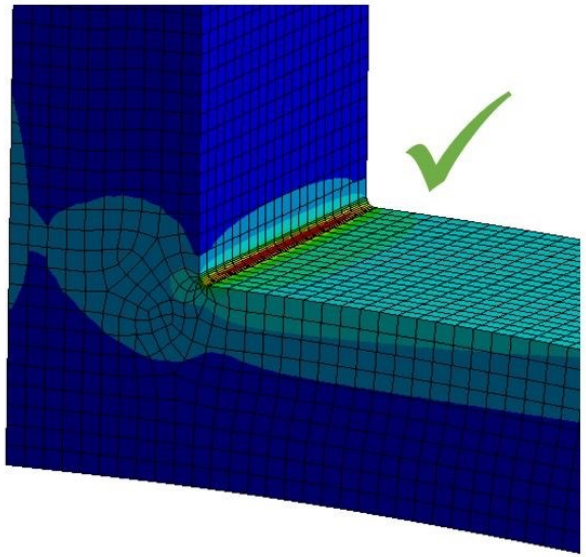
Sharper tip → smaller radius → more stress concentration

Design tip: avoid sharp corners!





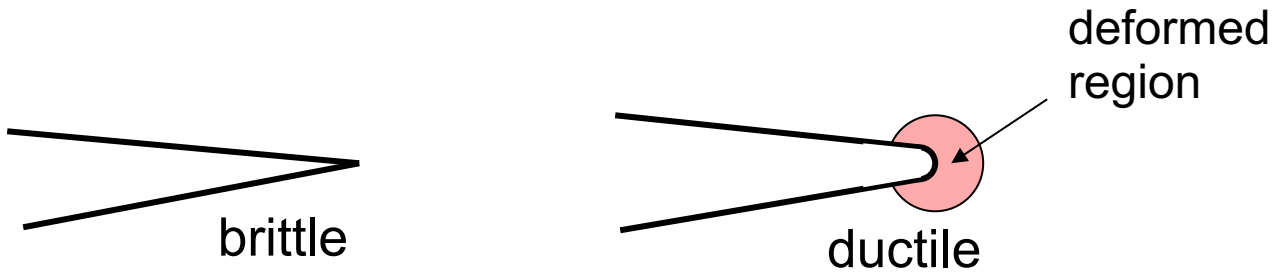




Make components with **rounded corners/edges** alleviates stress concentration

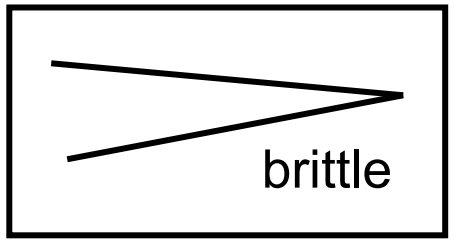
Ductile materials are more resistant to crack propagation than brittle materials

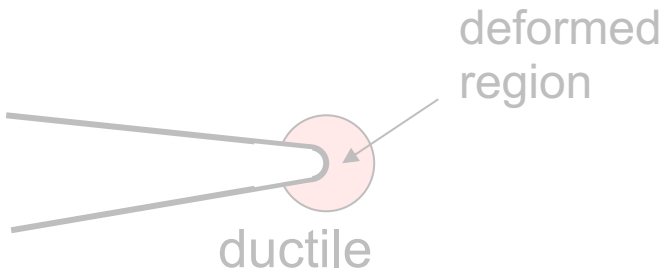
Ductile materials can (and will) **plastically deform to blunt the flaw tip**, thereby reducing stress concentration



Ductile materials are more resistant to crack propagation than brittle materials

Ductile materials can (and will) **plastically deform to blunt the flaw tip**, thereby reducing stress concentration





In brittle materials: the crack will grow very quickly when the applied stress exceeds some critical value (call it σ_C) for the material

The critical stress for crack propagation.

Applying stress > σ_C causes failure!

Fracture toughness = resistance to brittle failure when a crack is present

Fracture toughness → $K_C = Y \sigma_C \sqrt{\pi a}$ ← Crack length

Dimensionless parameter that **depends on sample thickness/geometry**

Critical stress for crack propagation

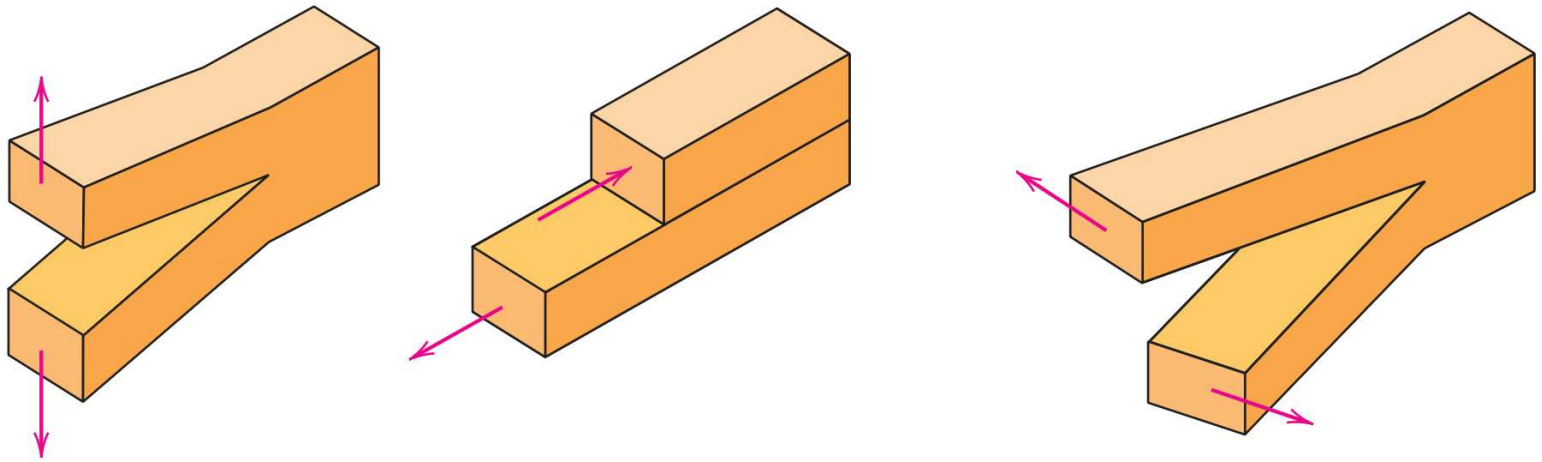
A higher fracture toughness tells us that more stress (or larger cracks) are needed to cause failure

Special case: *plane strain* fracture toughness

Plane-strain fracture toughness → $K_{IC} = Y \sigma_C \sqrt{\pi a}$ ← Crack length

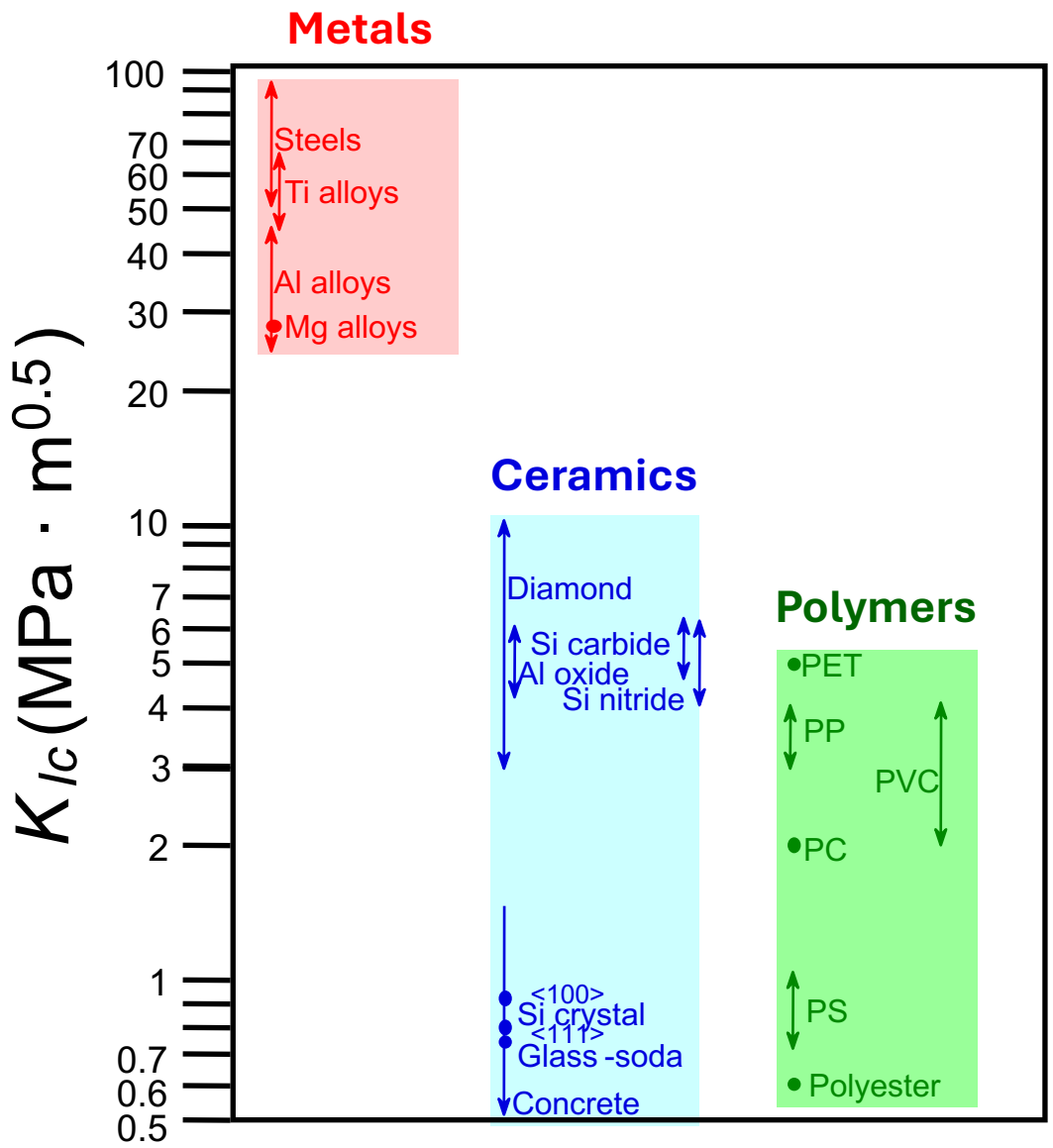
If sample is much thicker than any flaw, this becomes **independent of thickness**

Critical stress for crack propagation



K_{IC} is a fundamental material property that can be measured in various modes of stress

Fracture toughness by material class



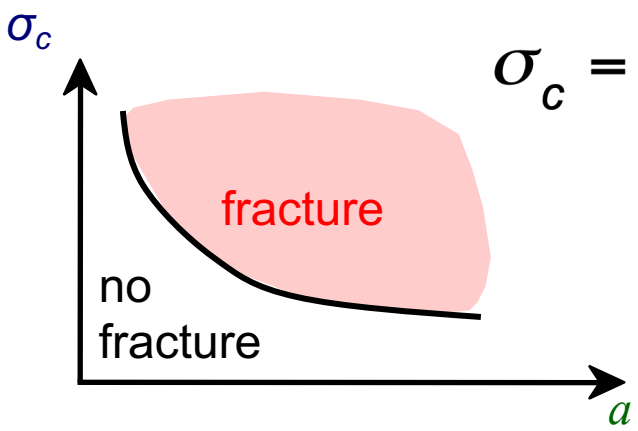
Metals tend to have the highest fracture toughness as they balance high strength with good ductility

Designing against fracture

$$K_{IC} = Y\sigma_C\sqrt{\pi a}$$

Scenario 1: fracture toughness and flaw size are specified

→This dictates how much stress we can apply to the specimen



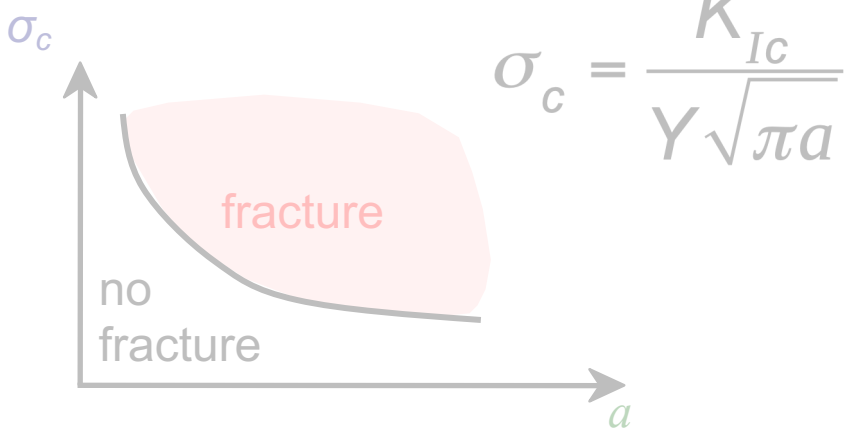
$$\sigma_c = \frac{K_{Ic}}{Y\sqrt{\pi a}}$$

Designing against fracture

$$K_{IC} = Y\sigma_C\sqrt{\pi a}$$

Scenario 1: fracture toughness and flaw size are specified

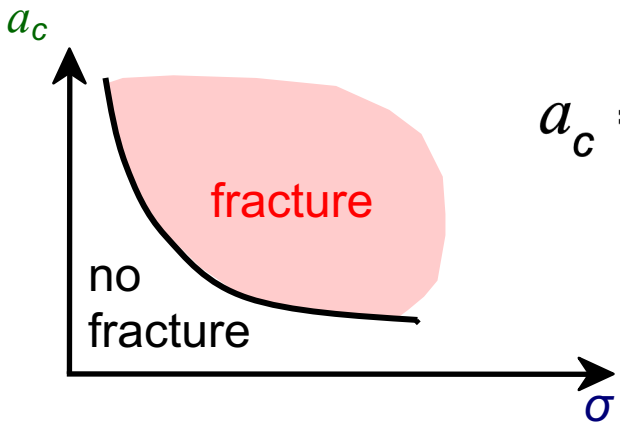
→This dictates how much stress we can apply to the specimen



$$\sigma_c = \frac{K_{Ic}}{Y\sqrt{\pi a}}$$

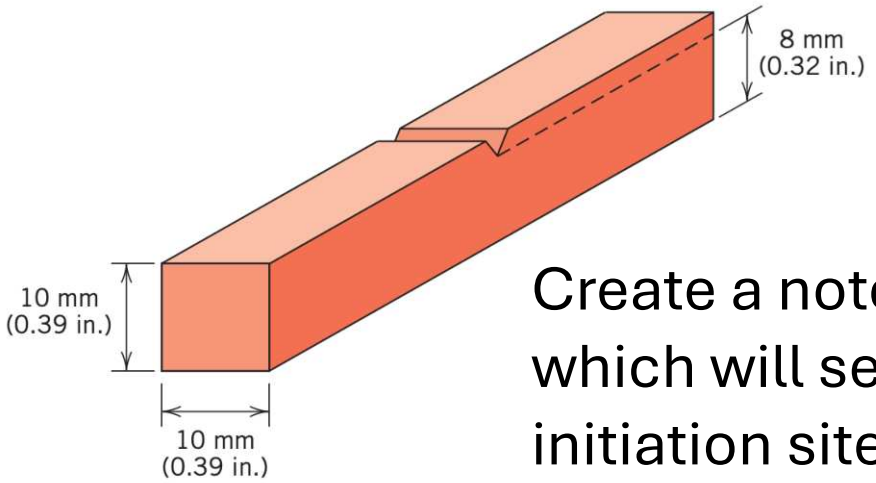
Scenario 2: fracture toughness and the anticipated stress level are specified

→This dictates the max flaw size we can allow in the specimen

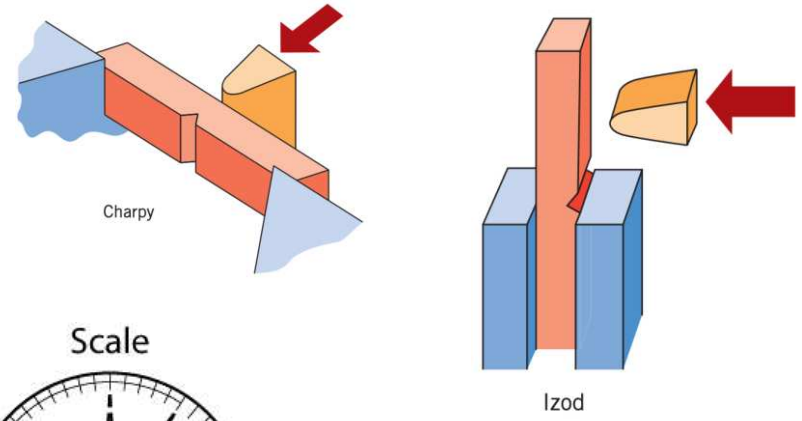


$$a_c = \frac{1}{\pi}\left(\frac{K_{Ic}}{Y\sigma}\right)^2$$

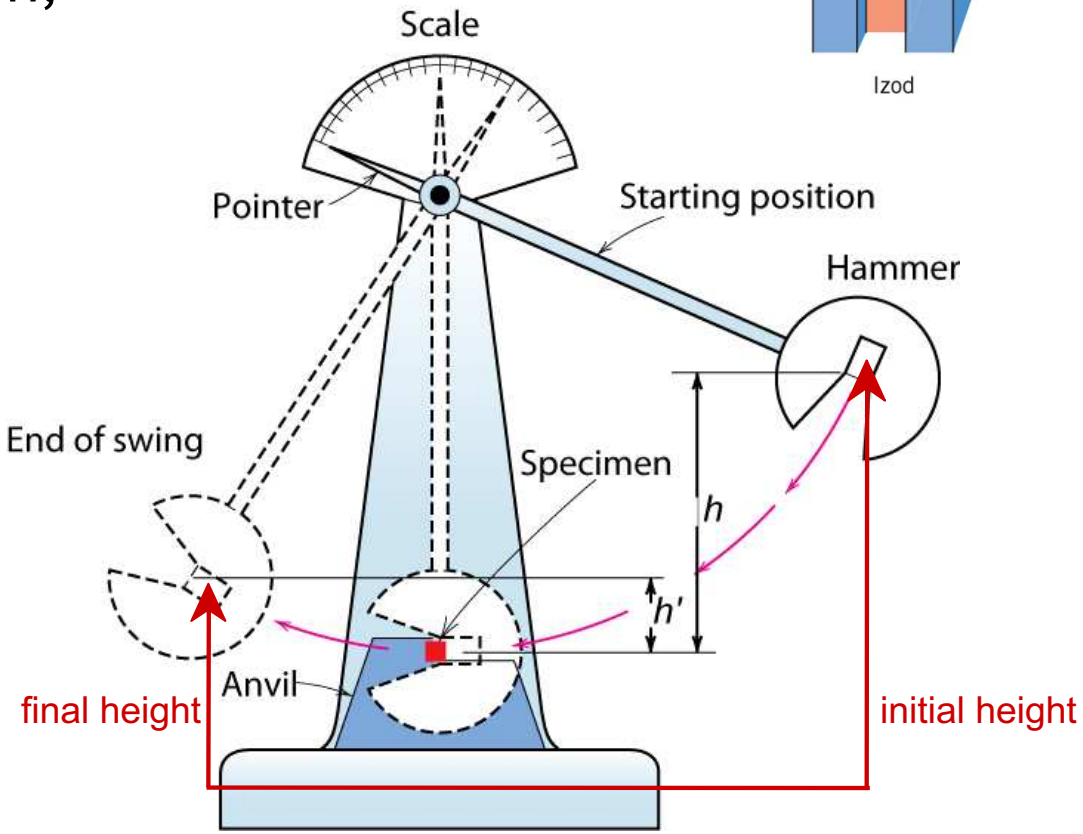
How do we test fracture toughness?



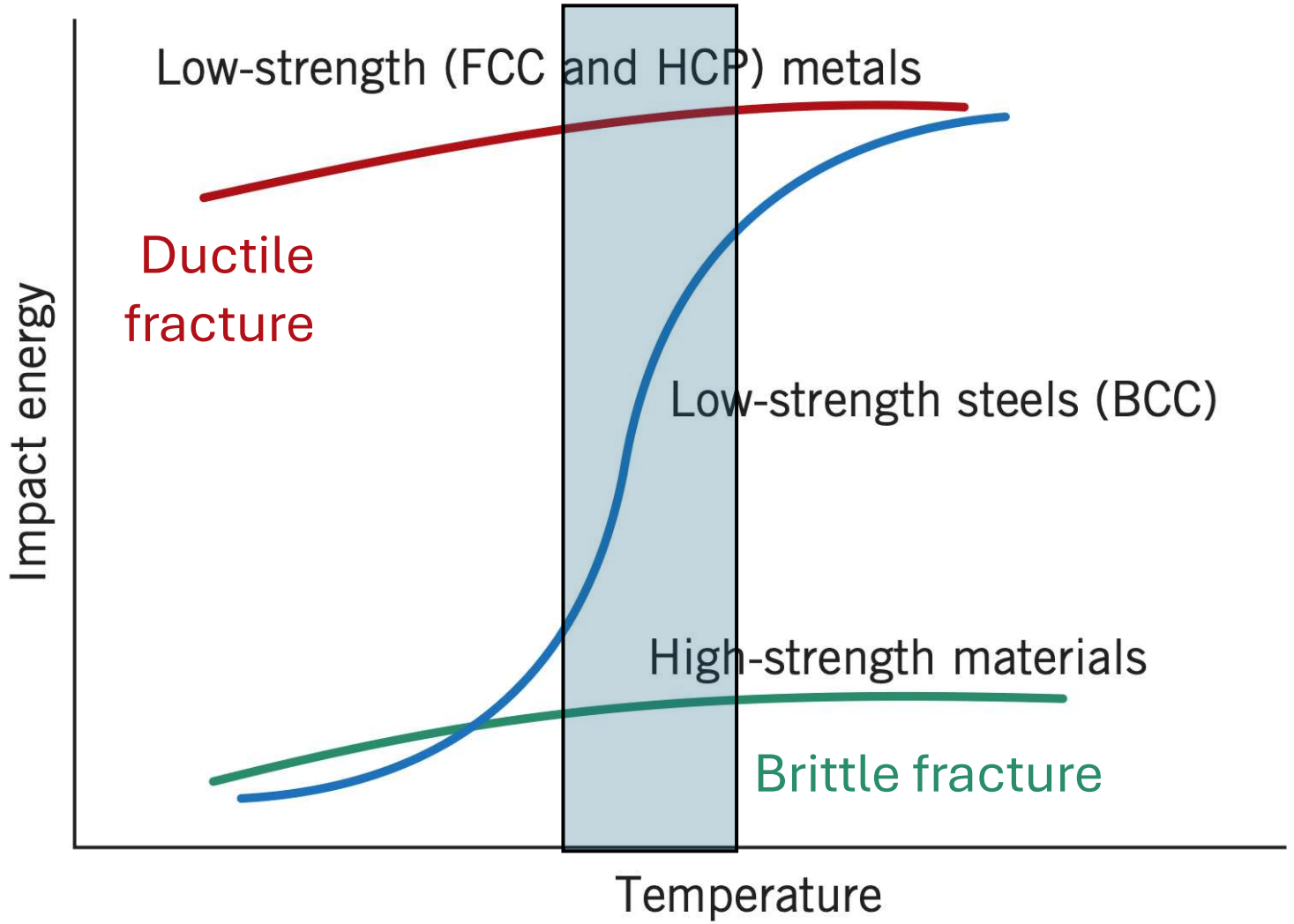
Create a notch in the specimen, which will serve as the crack initiation site



- Swing a pendulum at the sample, hard enough to fracture it
- Measure change in pendulum height to determine how much energy was absorbed – **impact energy**



The impact energy (and fracture toughness) can change substantially with temperature



Some materials exhibit **ductile-to-brittle transitions**

In such cases, do *not* use the materials at low temperature to avoid fracture!

The impact energy (and fracture toughness) can change substantially with temperature



Ductile-to-brittle transitions can be catastrophic!



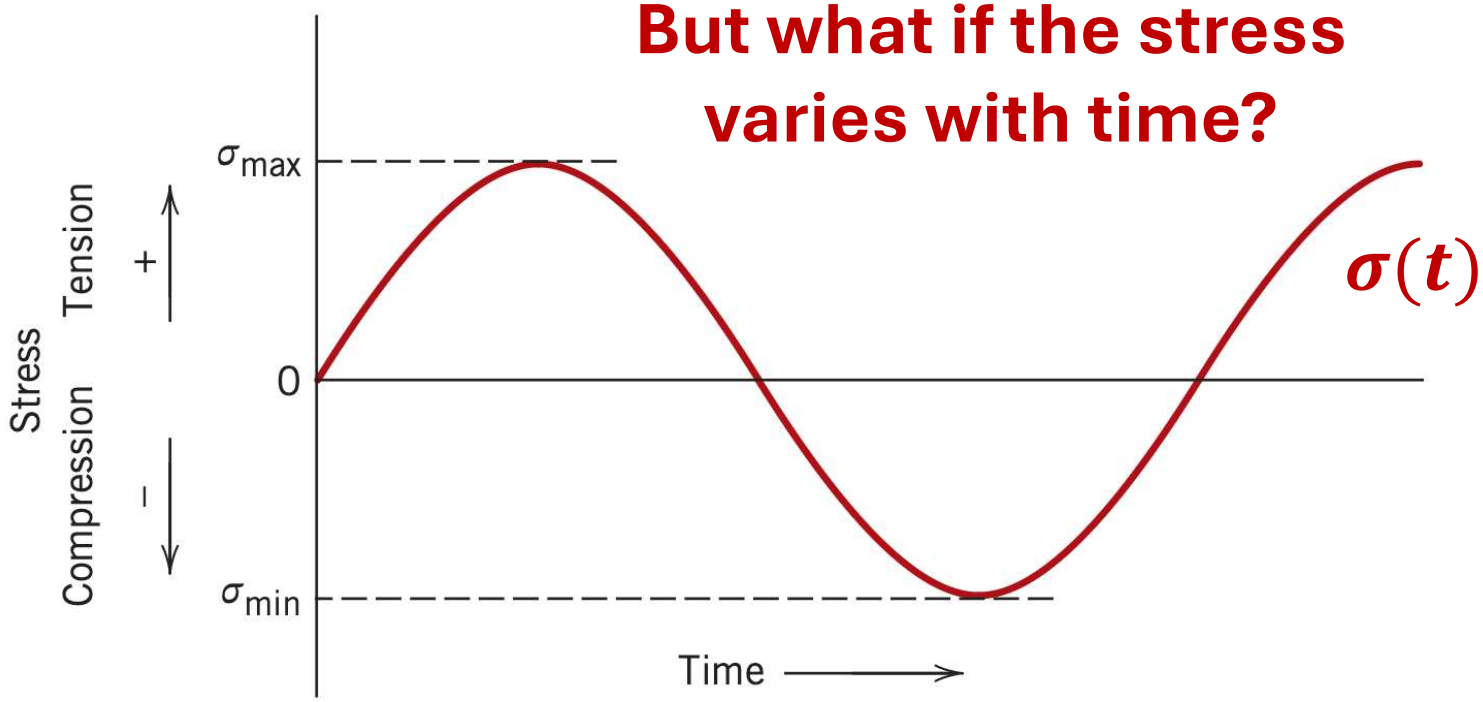


What if the load is applied repeatedly?



So far, we've focused primarily on a fixed amount of stress

But what if the stress varies with time?

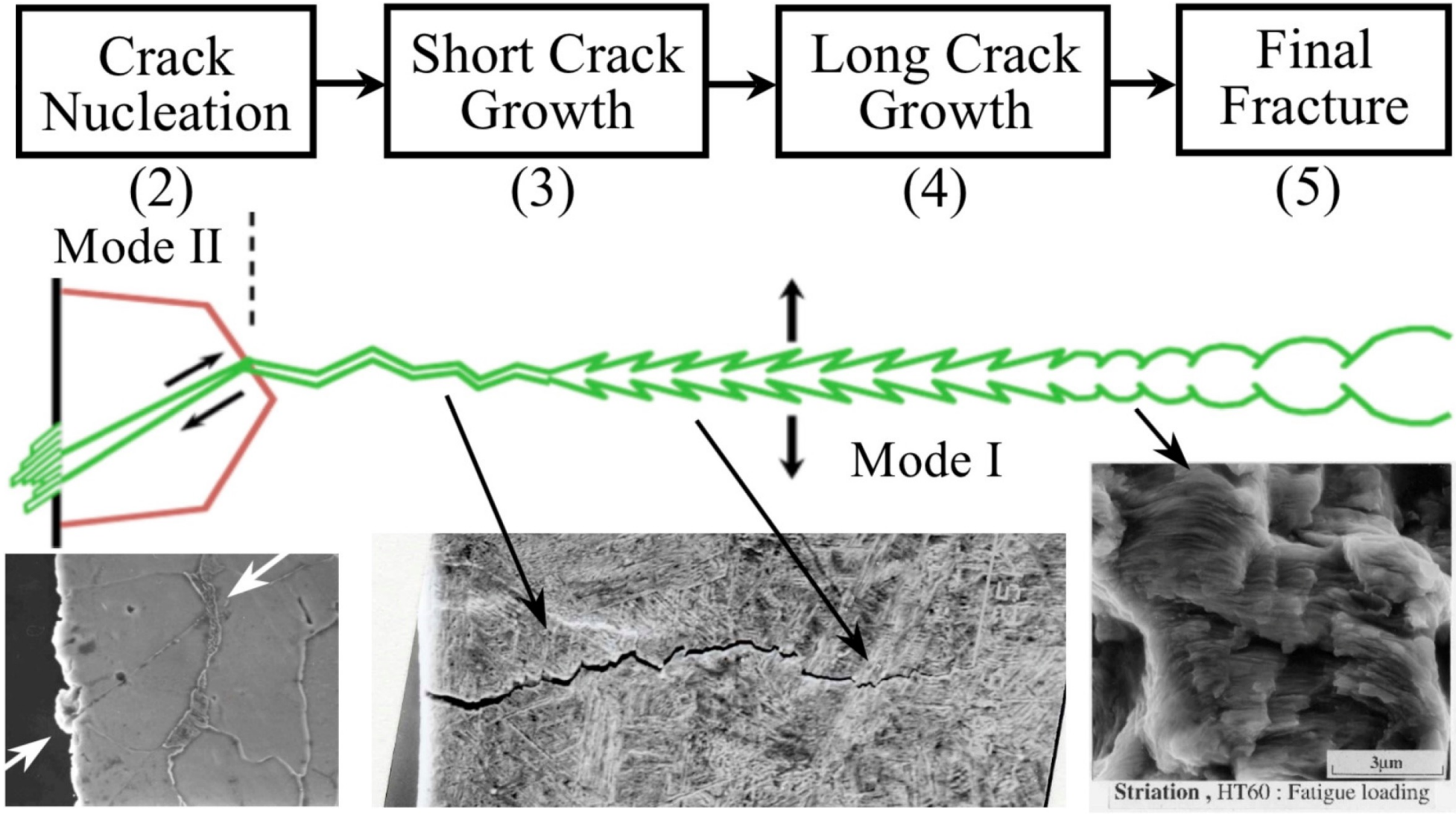




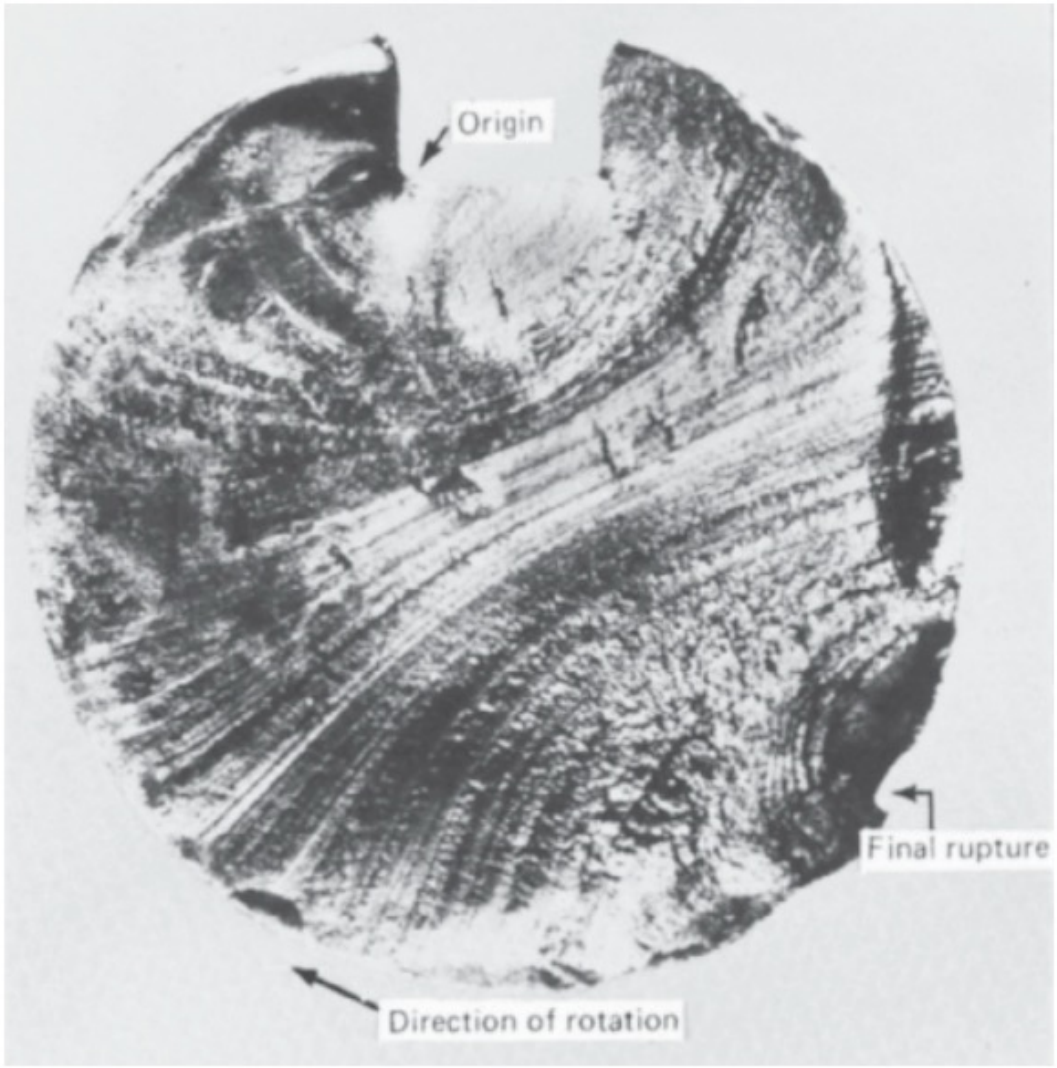


Repeated stresses are quite common!

Each stress cycle leads to incremental crack growth

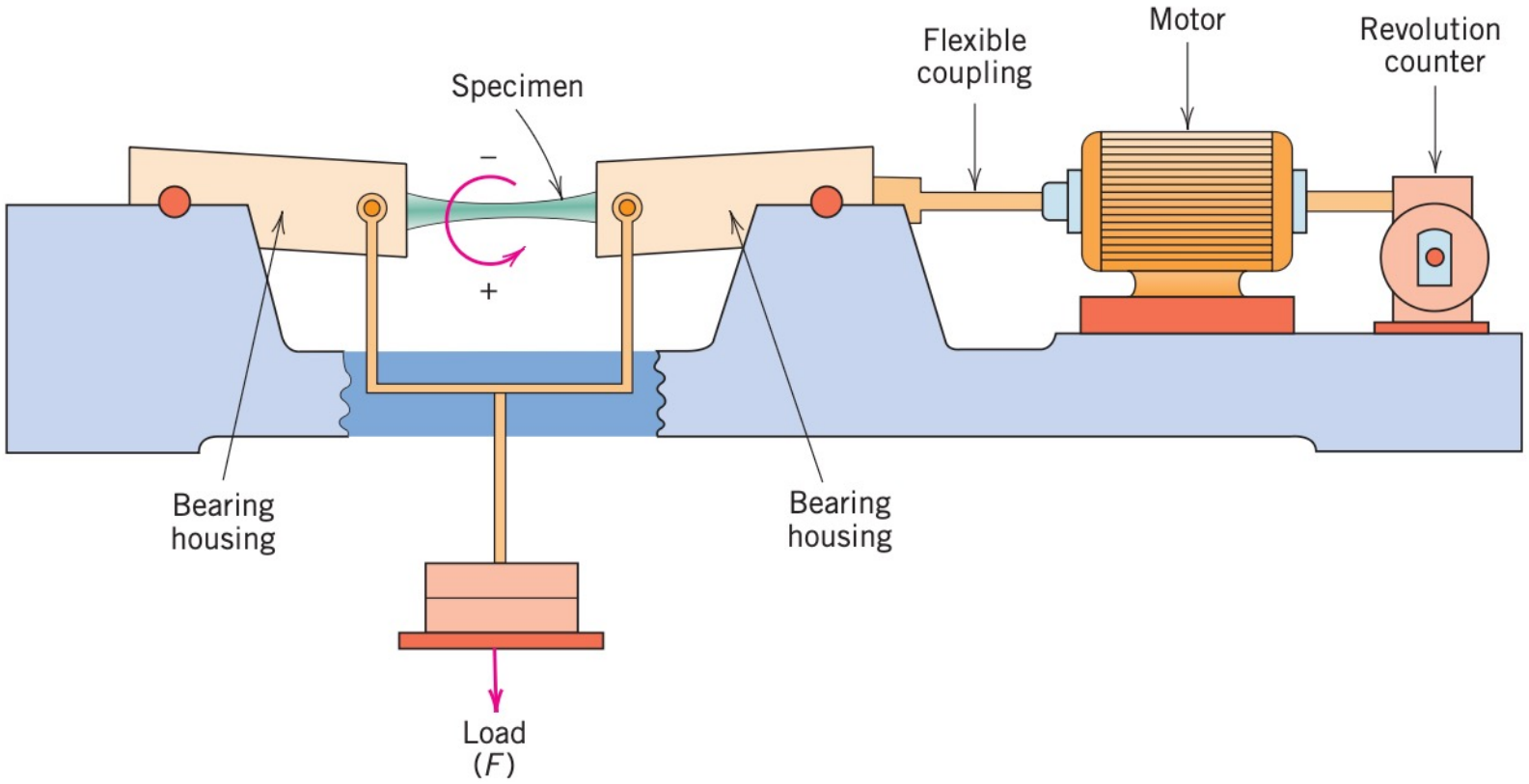


Each stress cycle leads to incremental crack growth

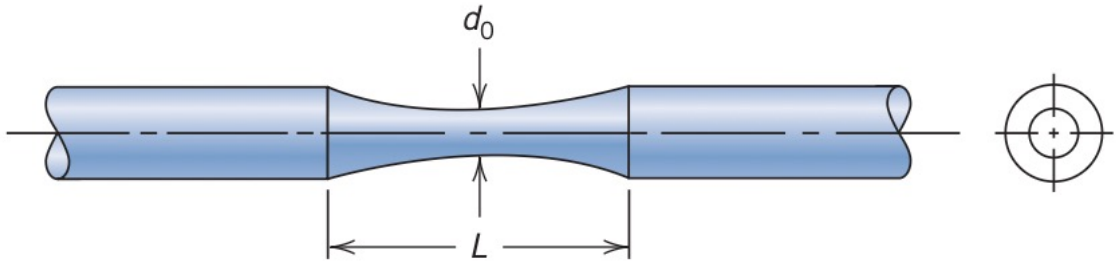




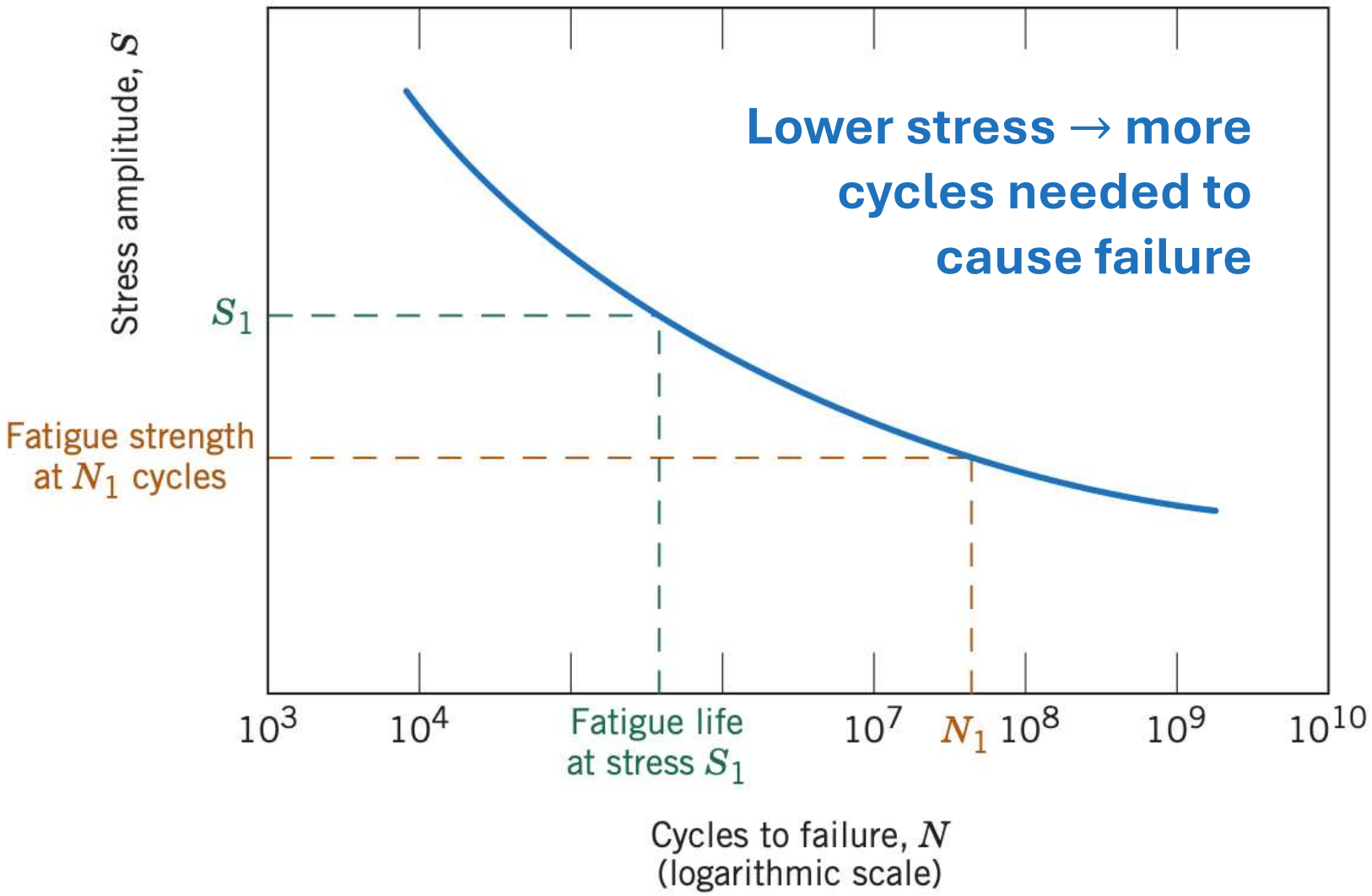
We can test fatigue in the lab



This tells us:
For a given stress amplitude (*S*), how many cycles (*N*) does it take to cause failure?

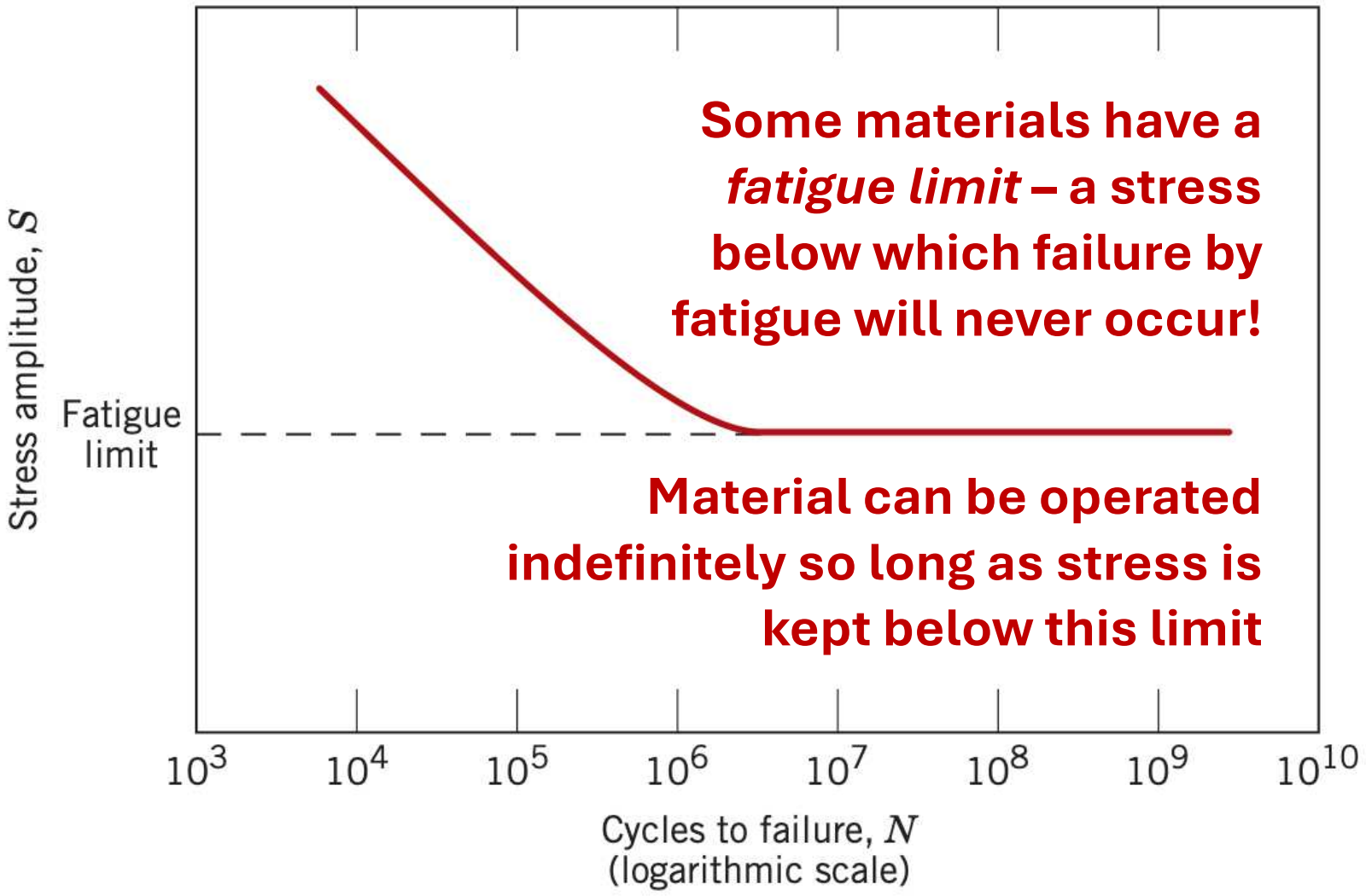


Fatigue is shown by S/N curves



This tells us:
For a given stress amplitude (*S*), how many cycles (*N*) does it take to cause failure?

Fatigue is shown by S/N curves



This tells us:
For a given stress amplitude (S), how many cycles (N) does it take to cause failure?

One other failure mechanism: *Creep*







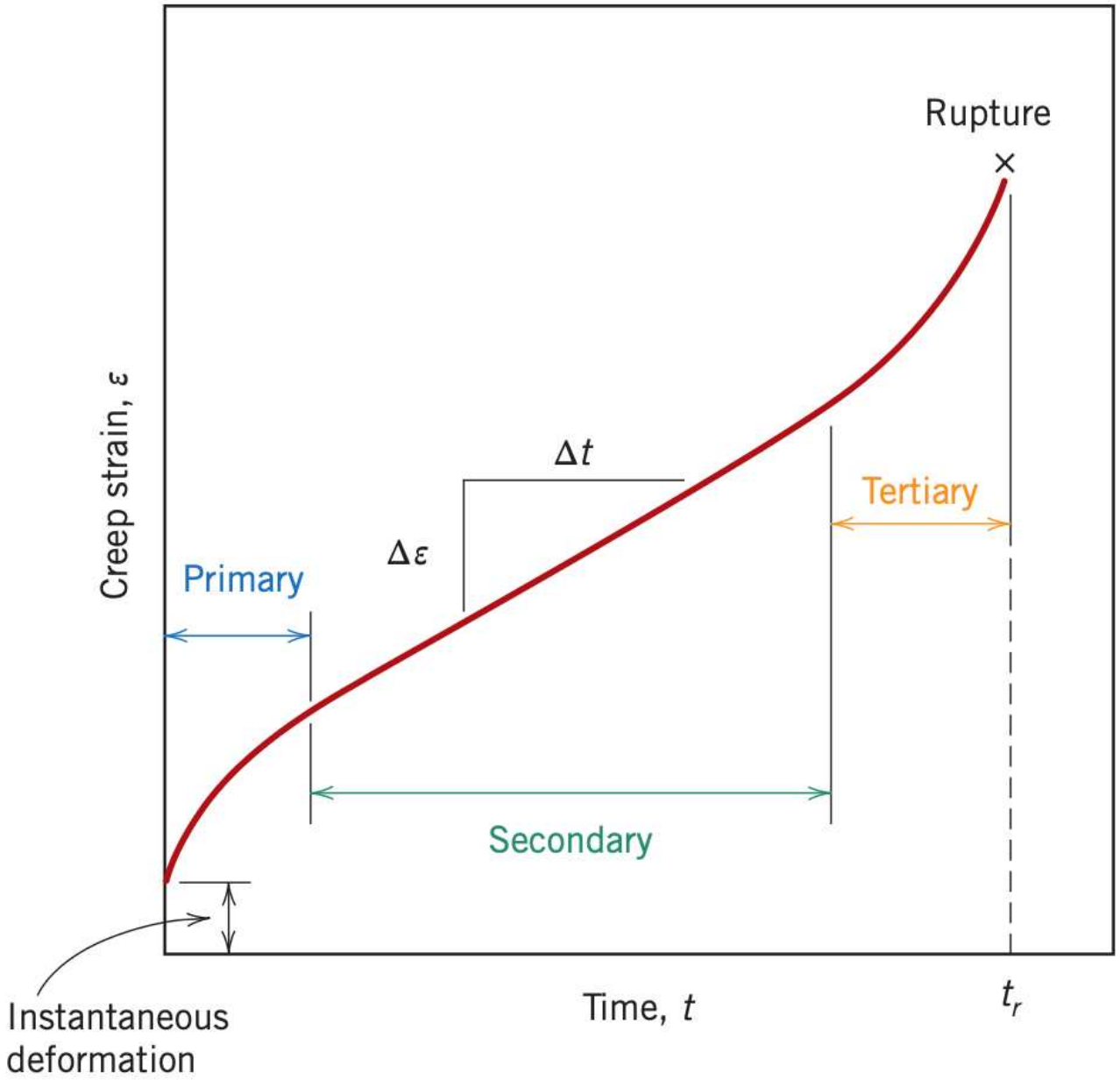
Suppose we apply a **fixed amount of stress**, but we keep that stress **applied for a long time at relatively high temperatures**





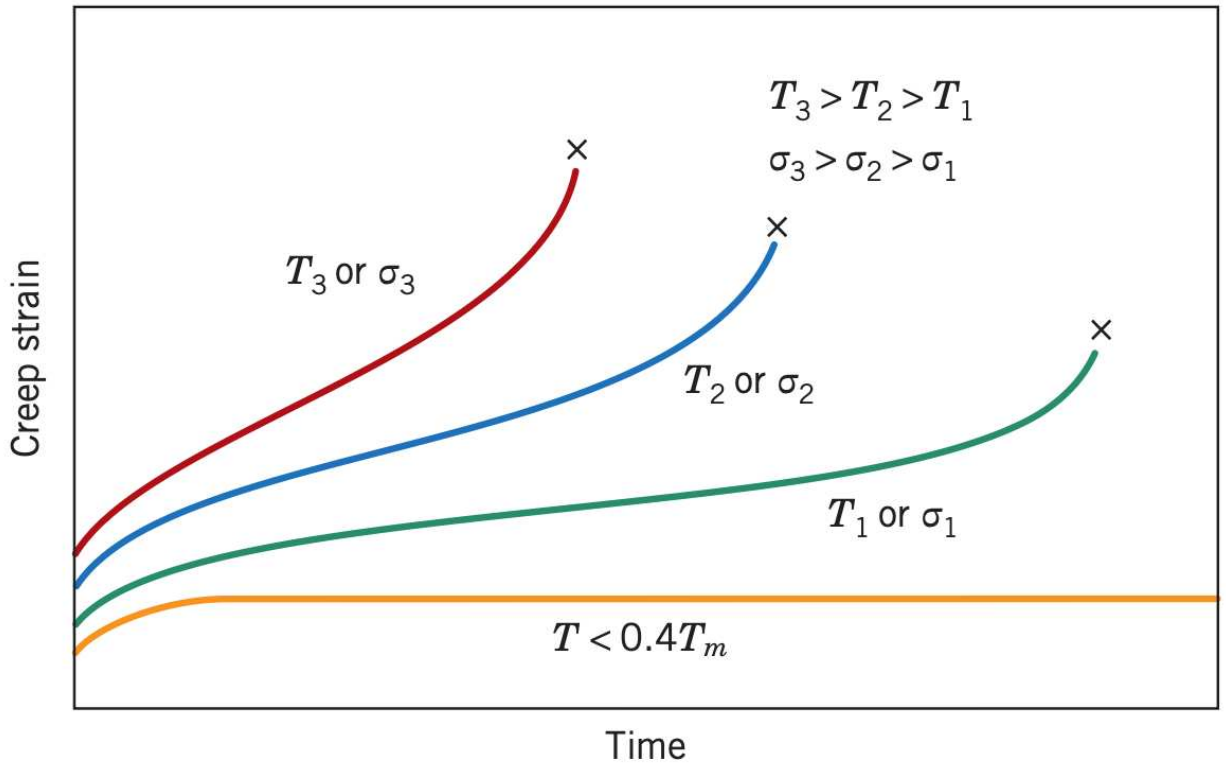
One other failure mechanism: *Creep*



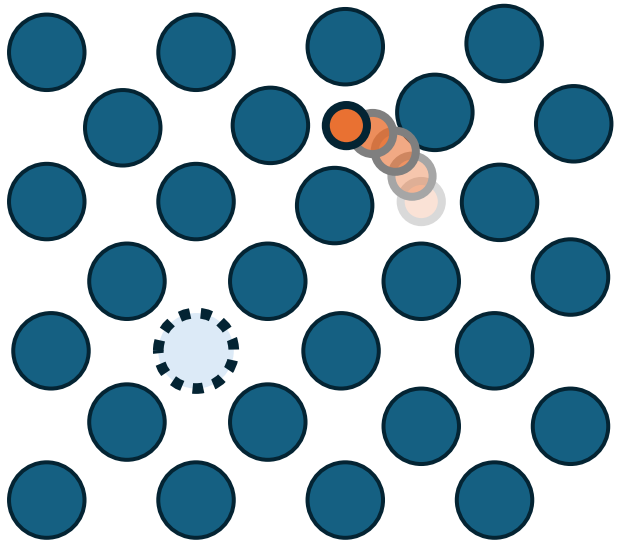


If the material is at high enough temperature (usually **> 0.4 T_M**) then it will slowly deform over time

Creep rate is *strongly* dependent on temperature



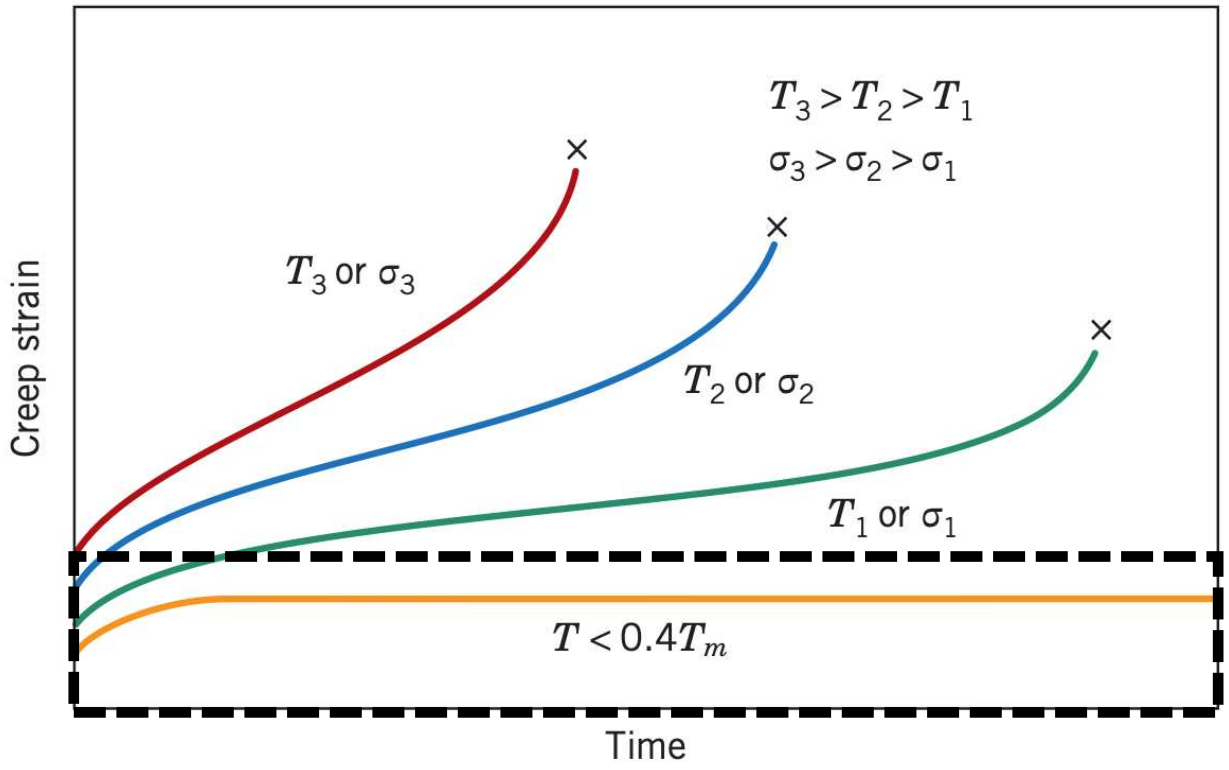
Creep is related to the diffusion of point defects – thermally activated!



Creep rate $\dot{\varepsilon}_s = K_2 \sigma^n \exp\left(-\frac{Q_c}{RT}\right)$

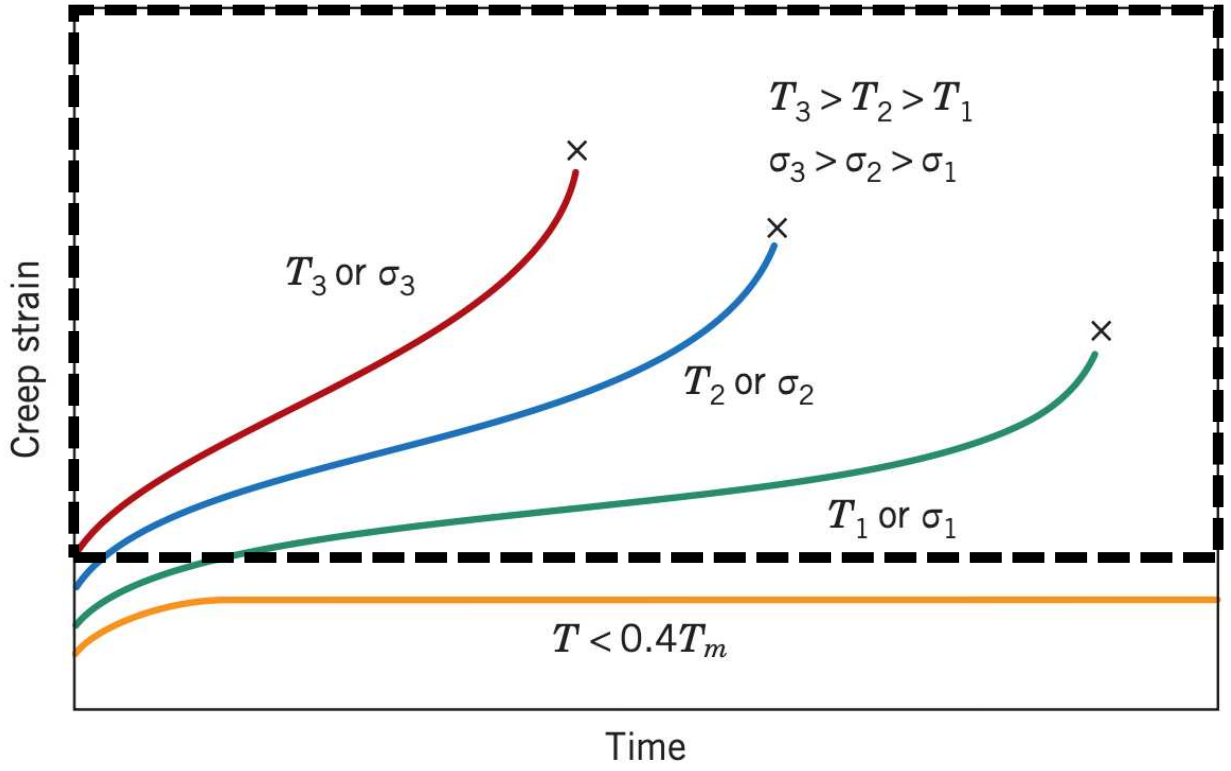
- stress exponent (material parameter)
- activation energy for creep (material parameter)
- material const.
- applied stress

Creep rate is *strongly* dependent on temperature



As long as we stay at low temperature, we do not need to worry about creep

Creep rate is *strongly* dependent on temperature



If we must operate at high temperature (*e.g.*, jet engines), then we should test and plan an operation lifetime

See Callister for some details on lifetime testing…