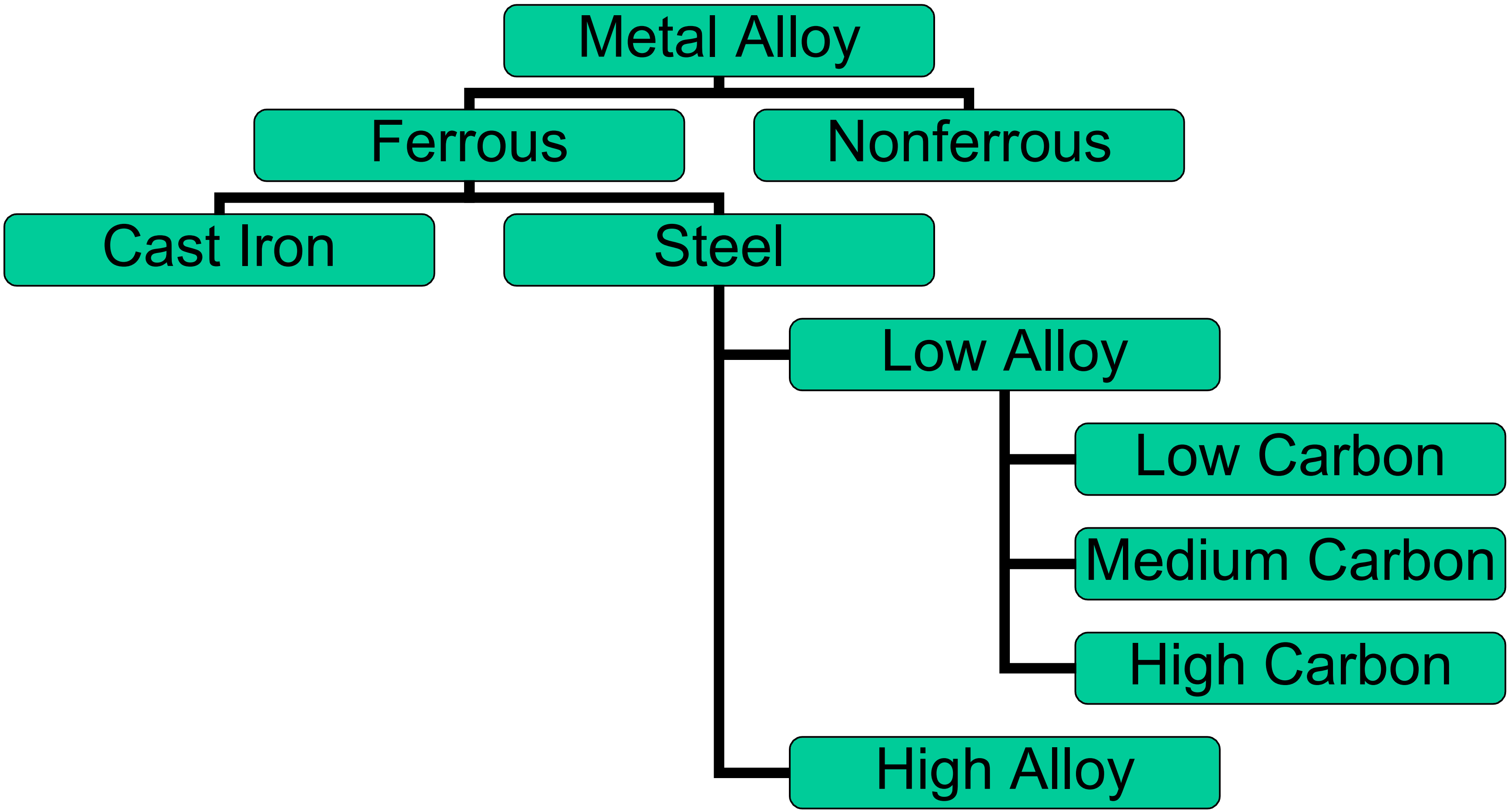
Types of Materials

- **Metals**:
  - Strong, ductile
  - high thermal & electrical conductivity
  - opaque

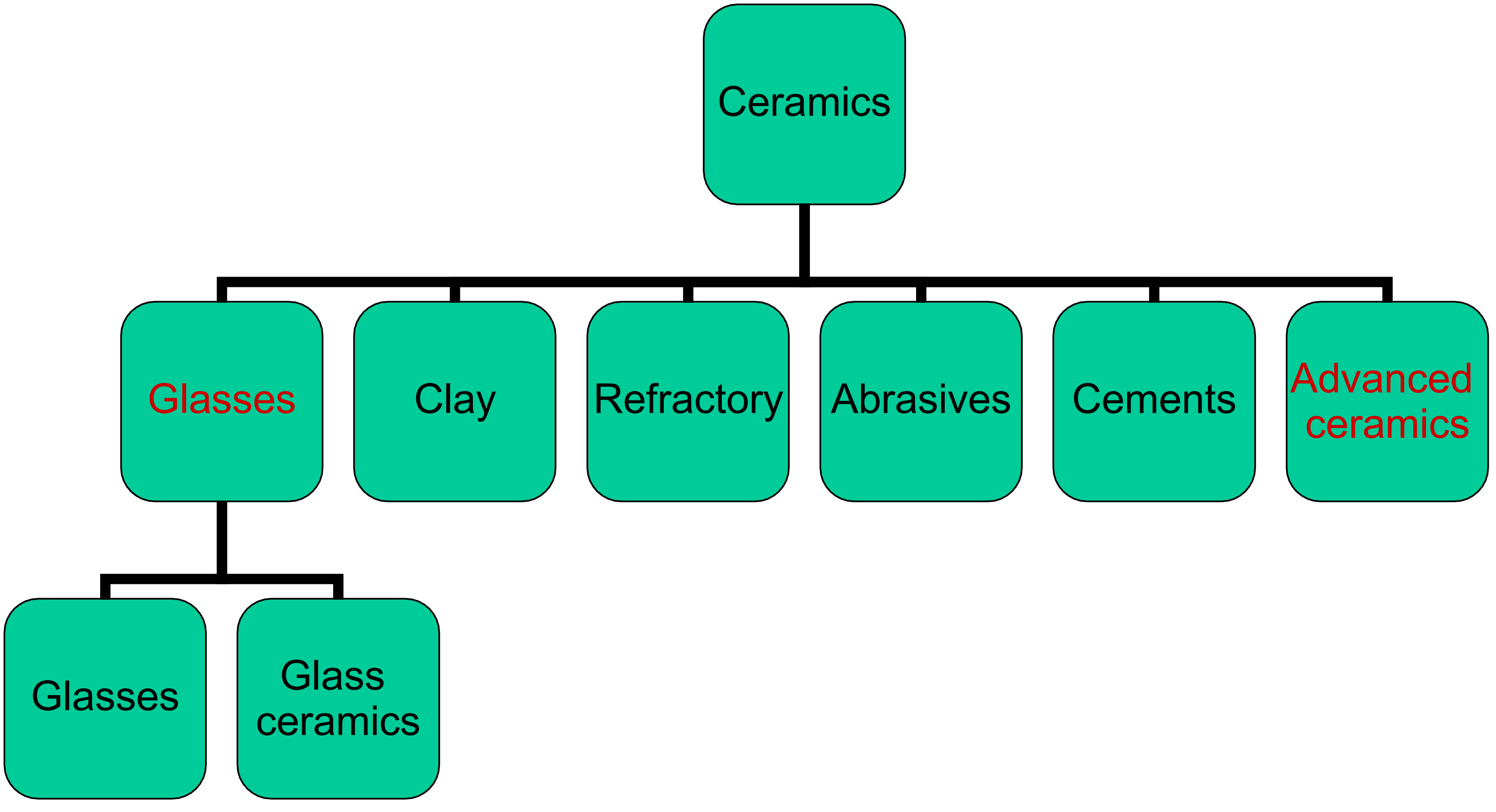
- **Polymers/plastics**: Covalent bonding → sharing of e's
  - Soft, ductile, low strength, low density
  - thermal & electrical insulators
  - Optically translucent or transparent.

- **Ceramics**: ionic bonding (refractory) – compounds of metallic & non-metallic elements (oxides, carbides, nitrides, sulfides)
  - Brittle, glassy, elastic
  - non-conducting (insulators)

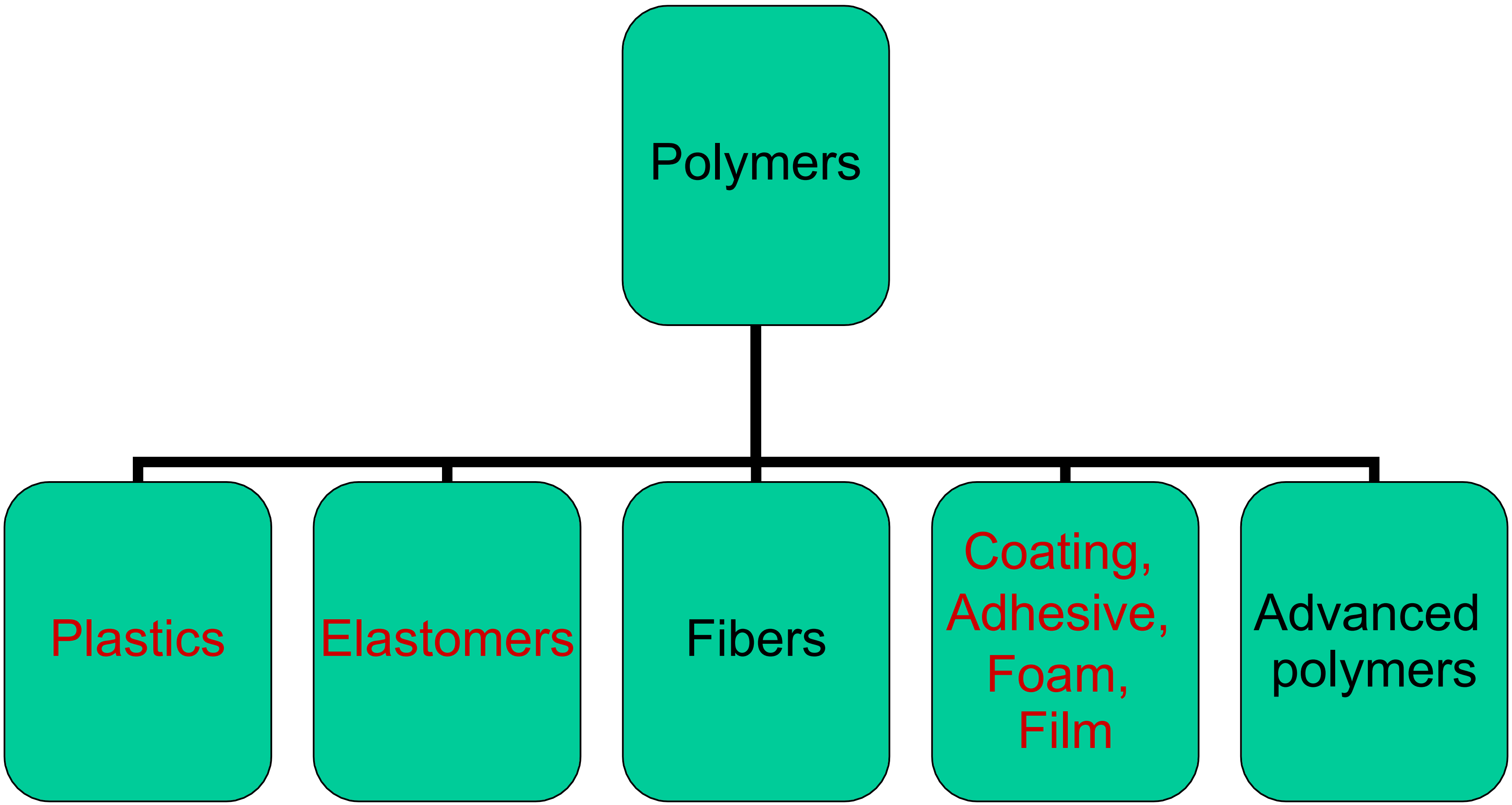
Metal Classification



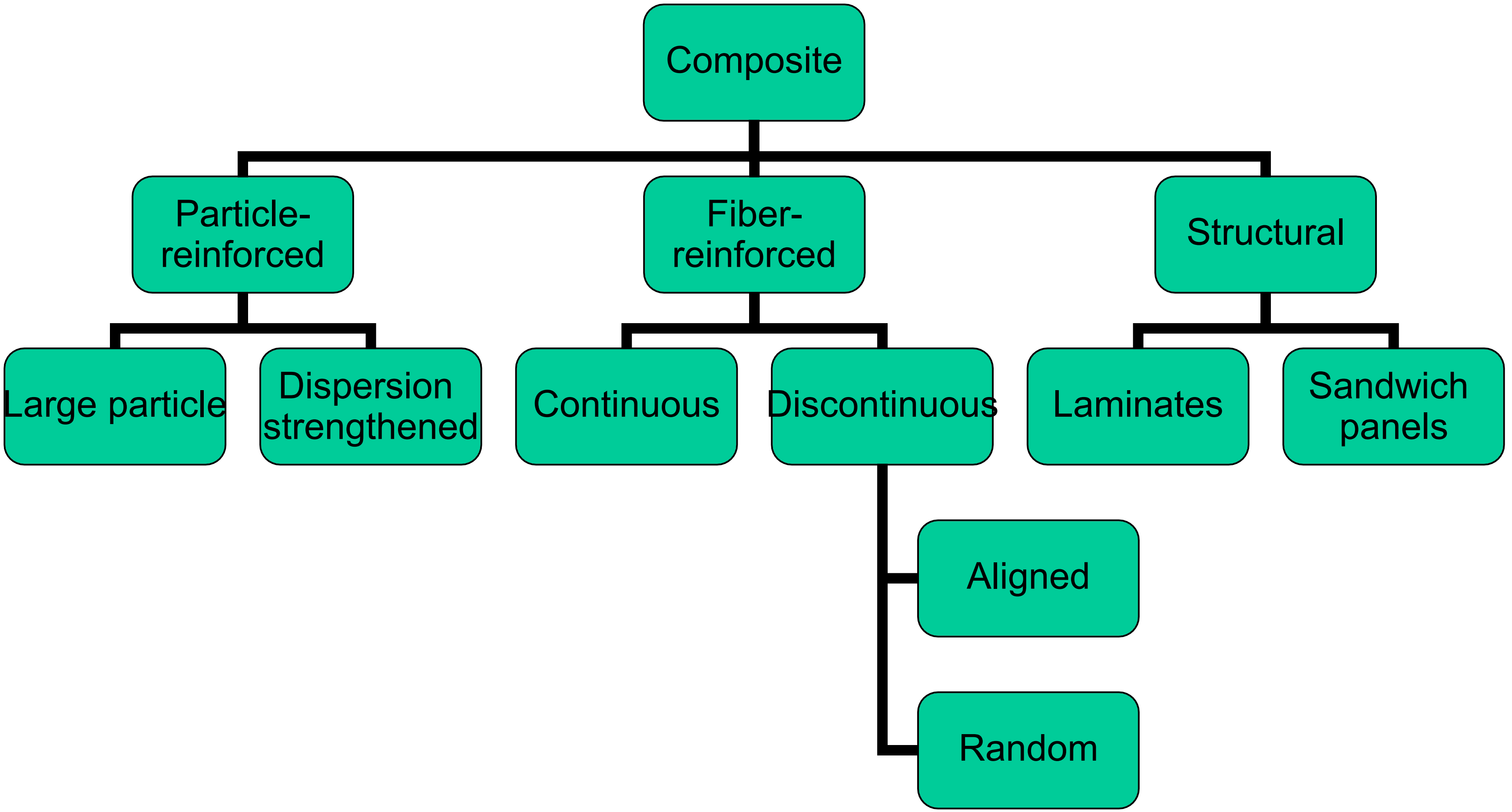
Ceramic Classification



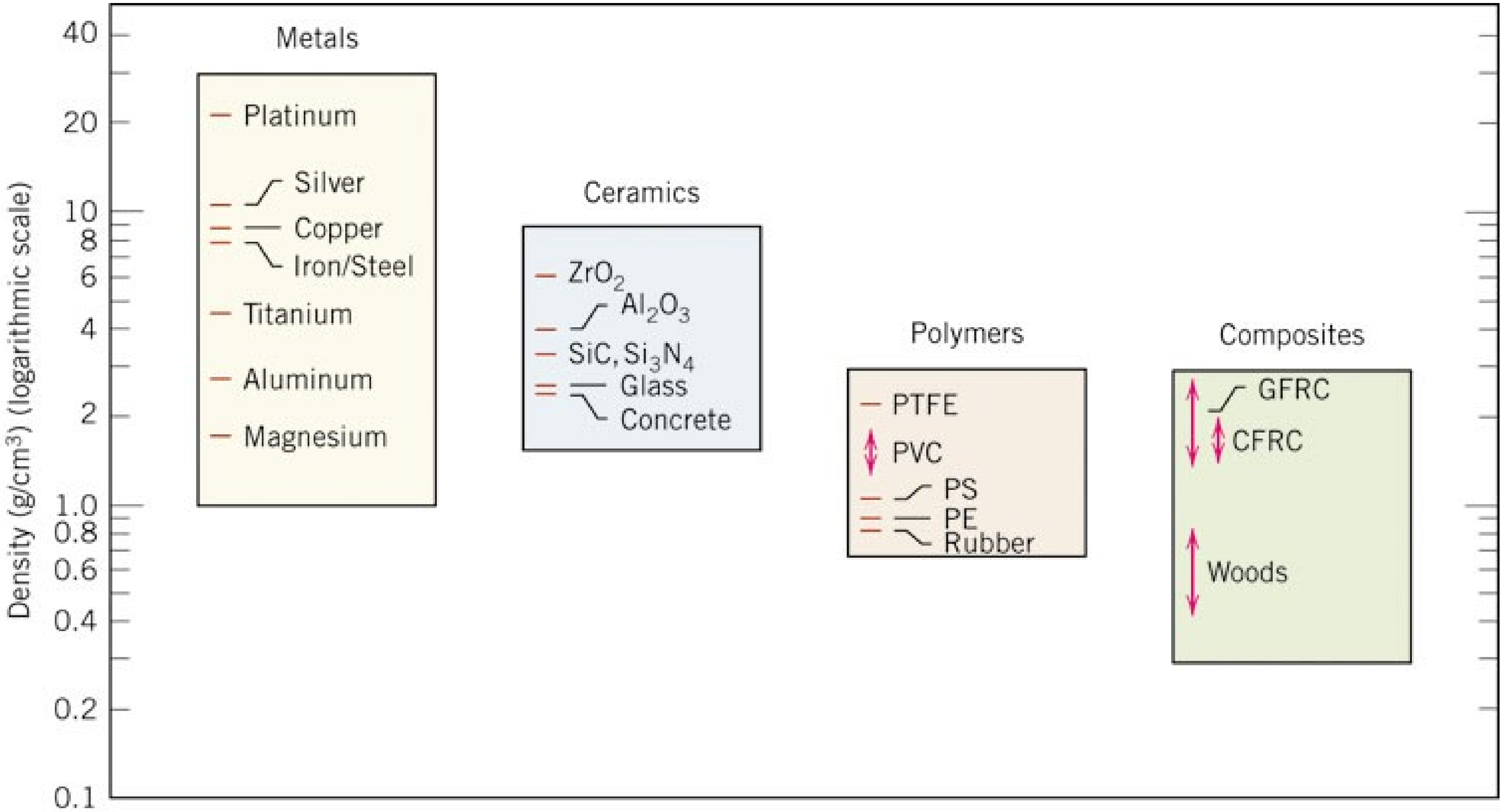
Polymer Classification



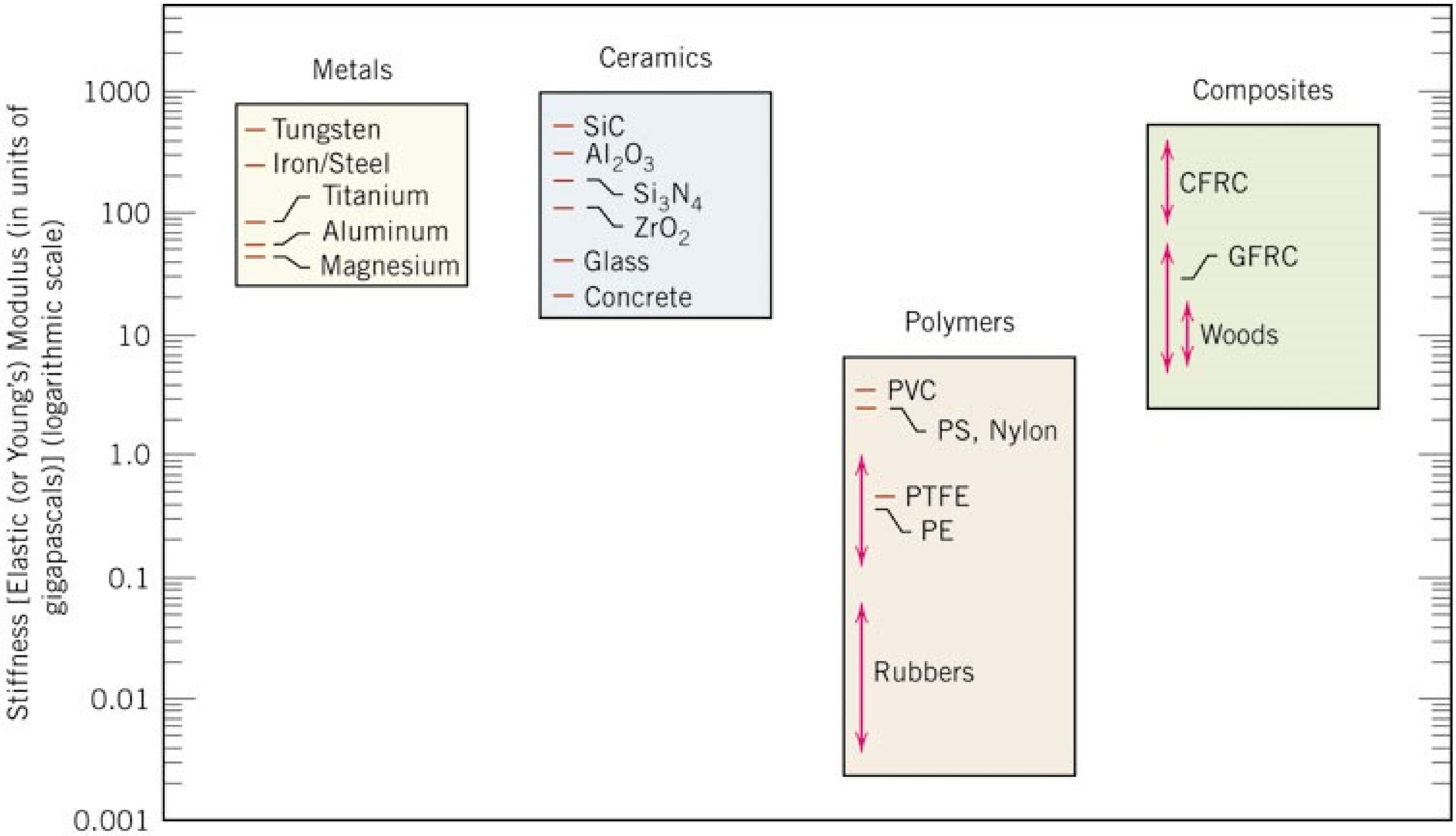
Composite classification



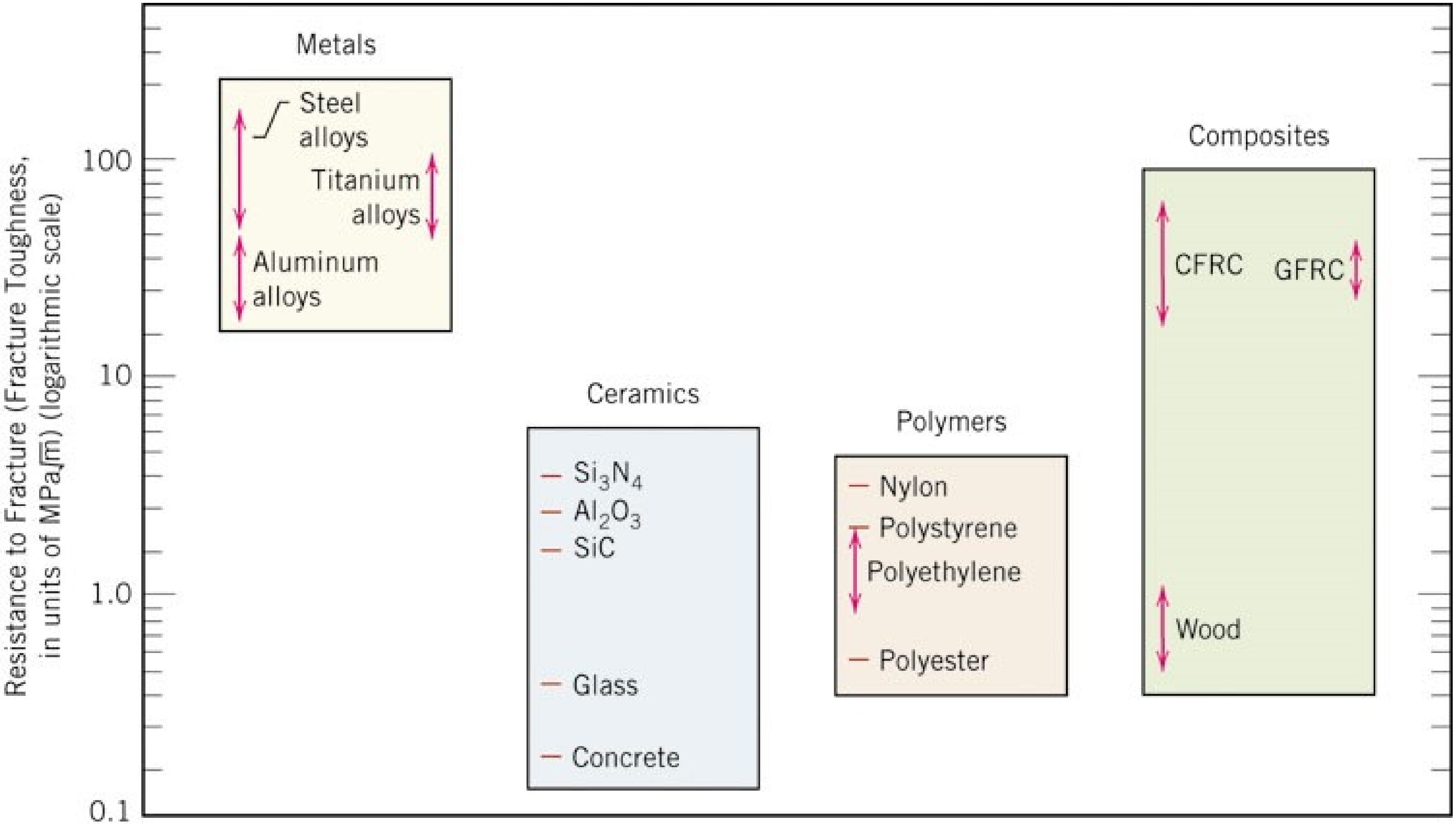
Material Density



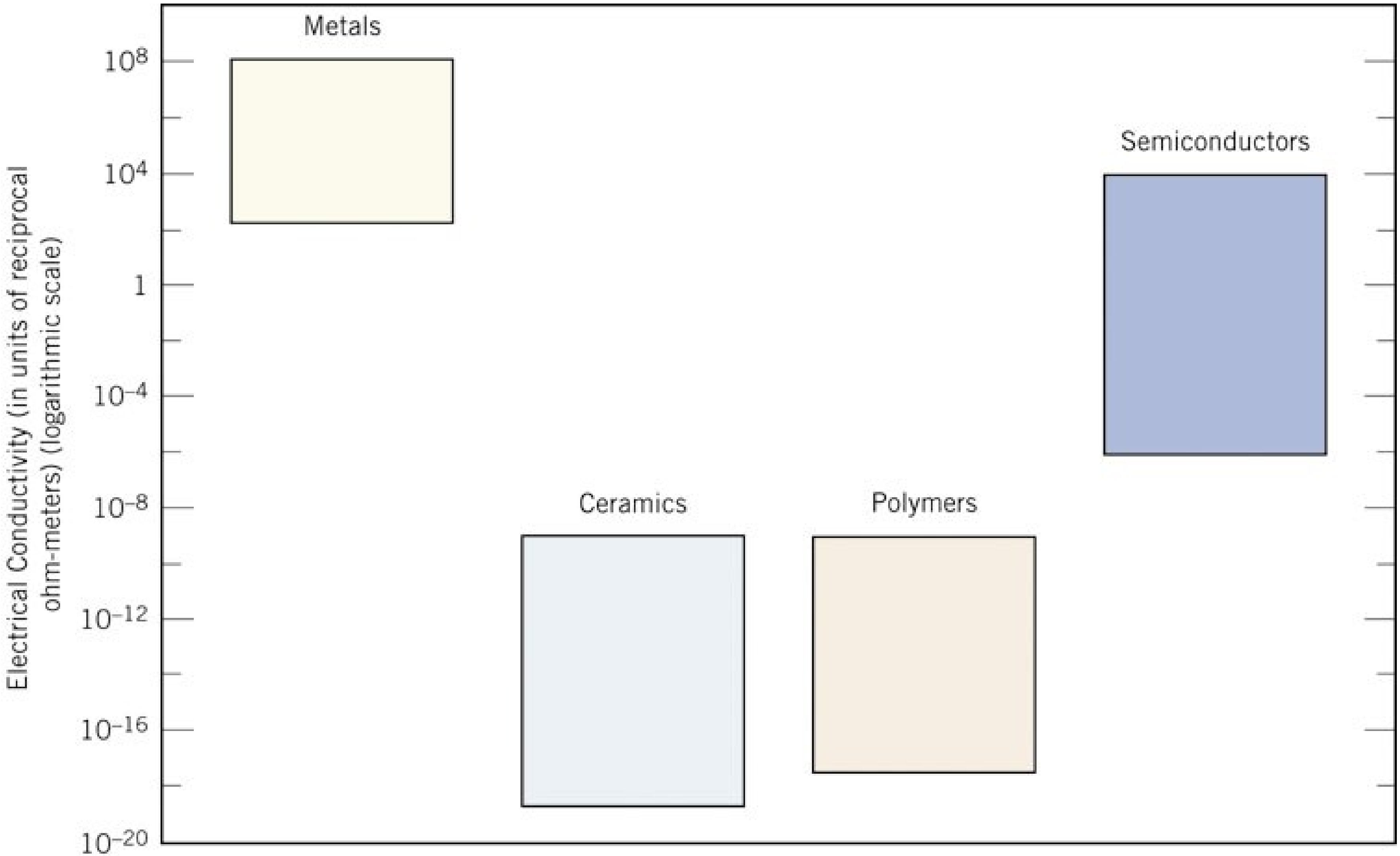
Material Stiffness



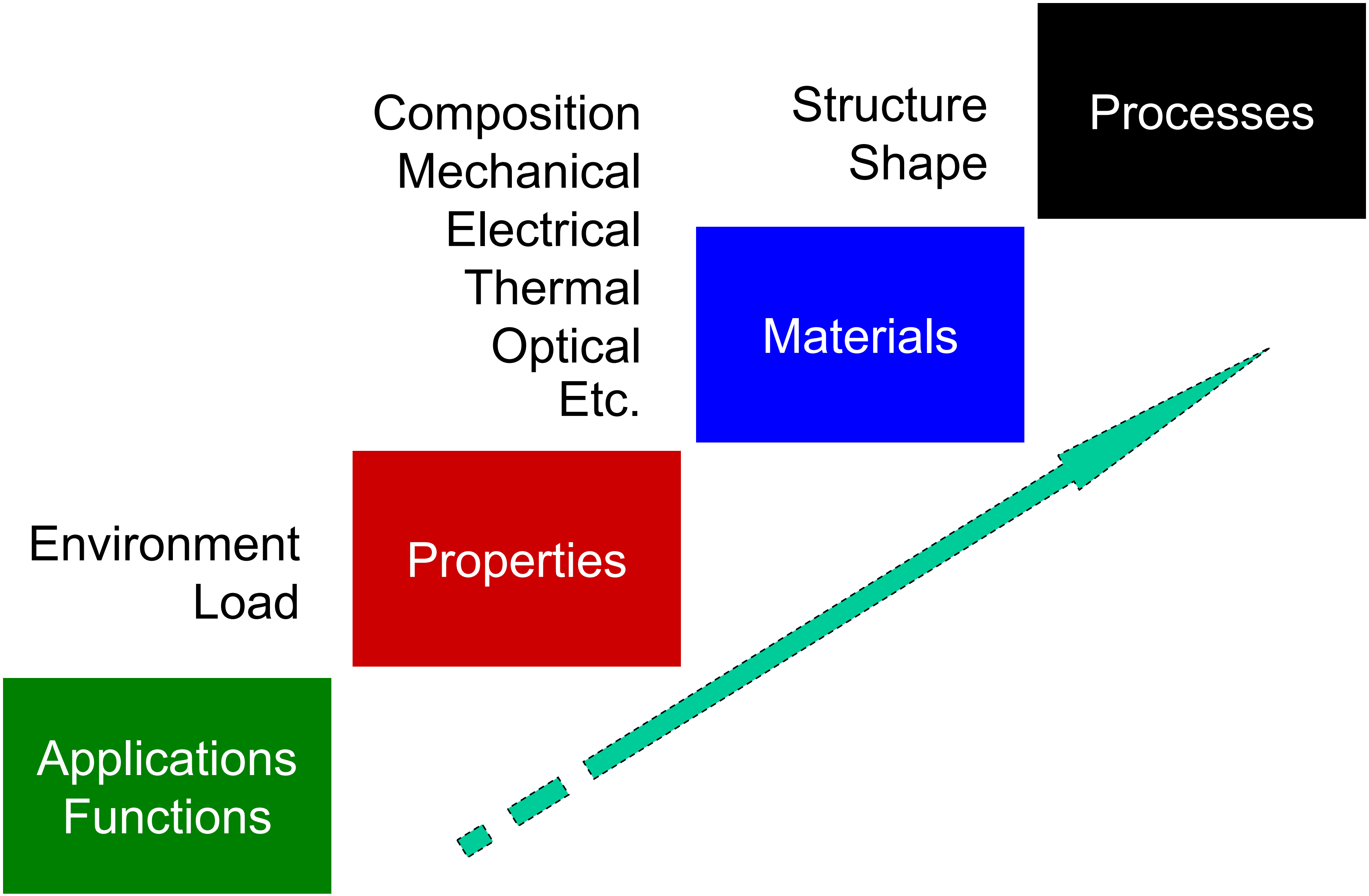
Material Resistance to Fracture



Material Electrical Conductivity

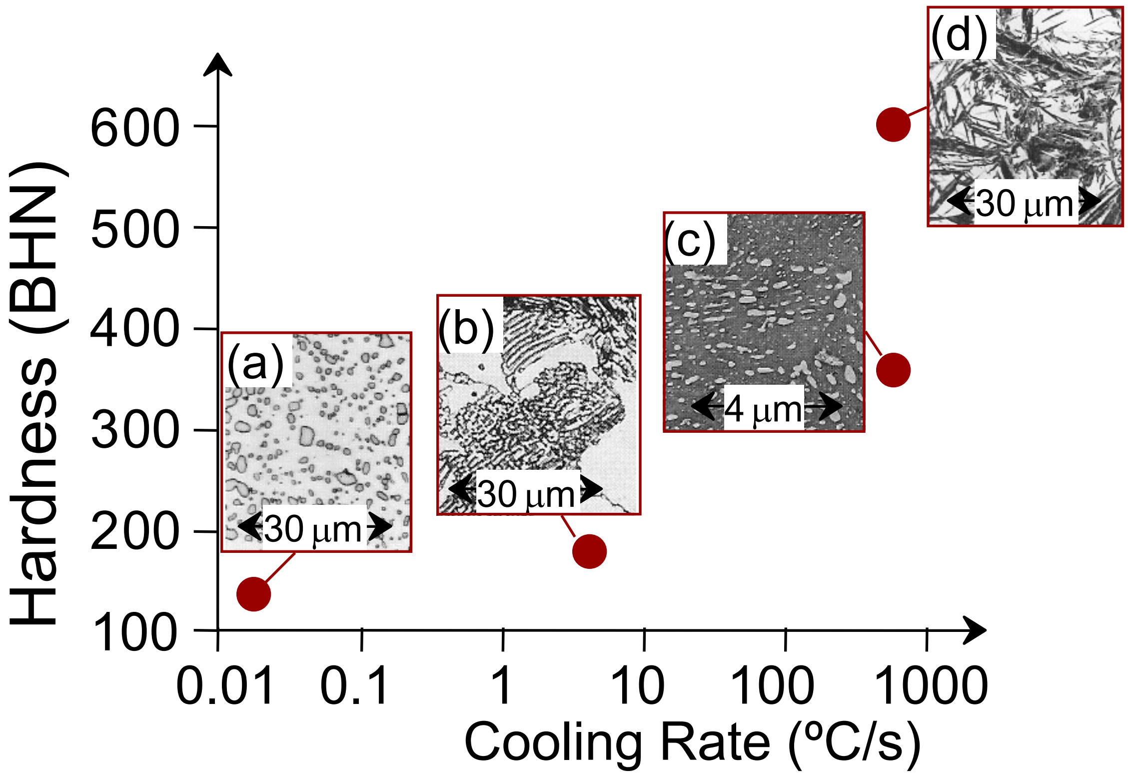


The Materials Selection Process



Structure, Processing, & Properties

- Properties depend on structure
  ex: hardness vs structure of steel



Steel with 0.4 wt% C

d) Martensite

c) Martensite
(tempered at 371 C)

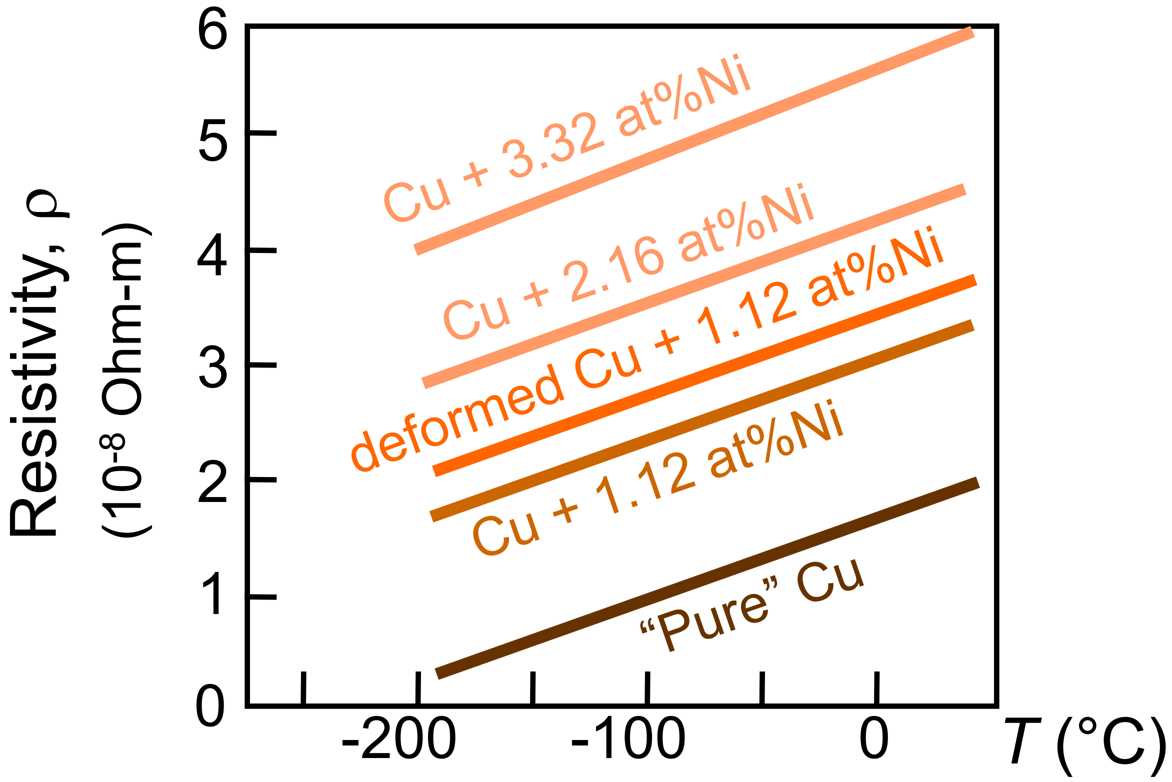
b) Fine pearlite

a) Spheroidite

- Processing can change structure
  ex: structure vs cooling rate of steel

ELECTRICAL

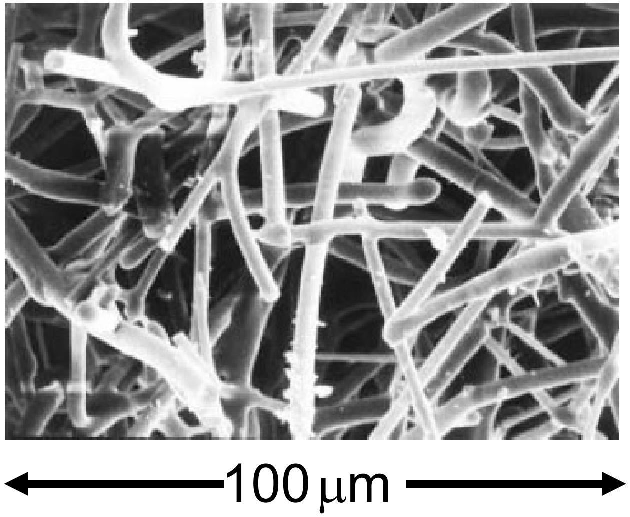
- Electrical Resistivity of Copper:



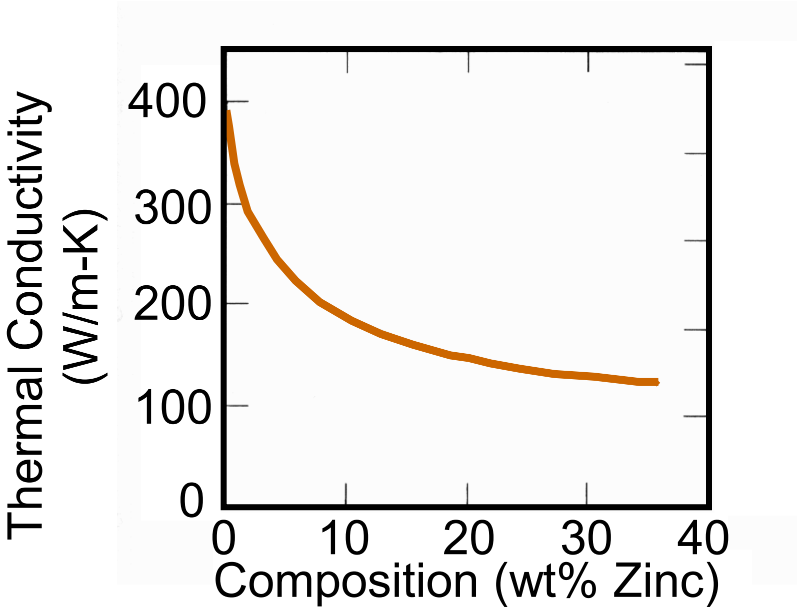
- Adding "impurity" atoms to Cu increases resistivity.
- Deforming Cu increases resistivity.

THERMAL

- Space Shuttle Tiles:
  --Silica fiber insulation
  offers low heat conduction.

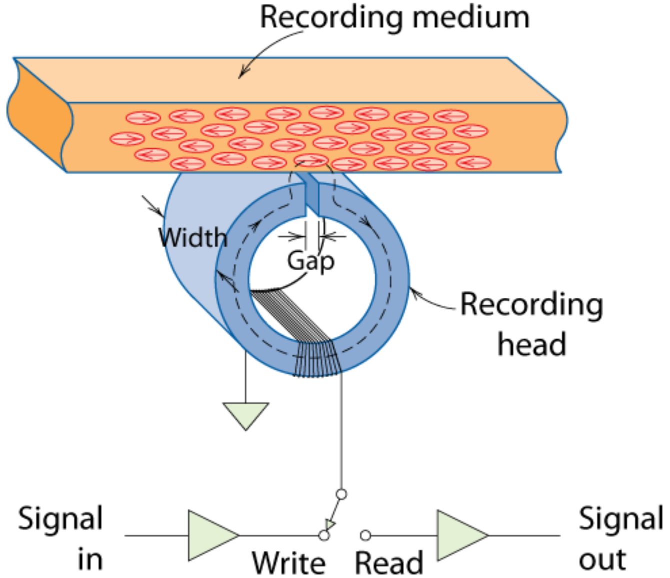


- Thermal Conductivity of Copper:
  --It decreases when
  you add zinc!

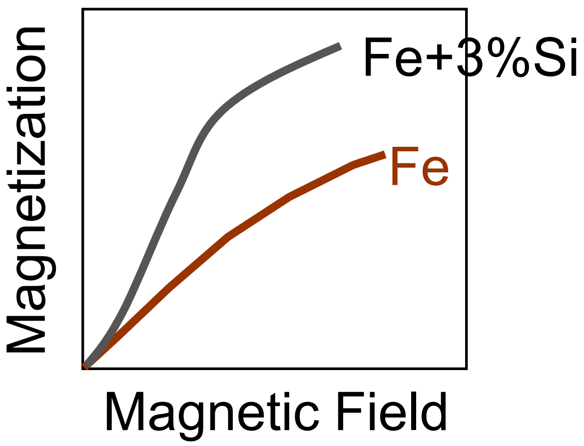


MAGNETIC

- Magnetic Storage:
  --Recording medium is magnetized by recording head.

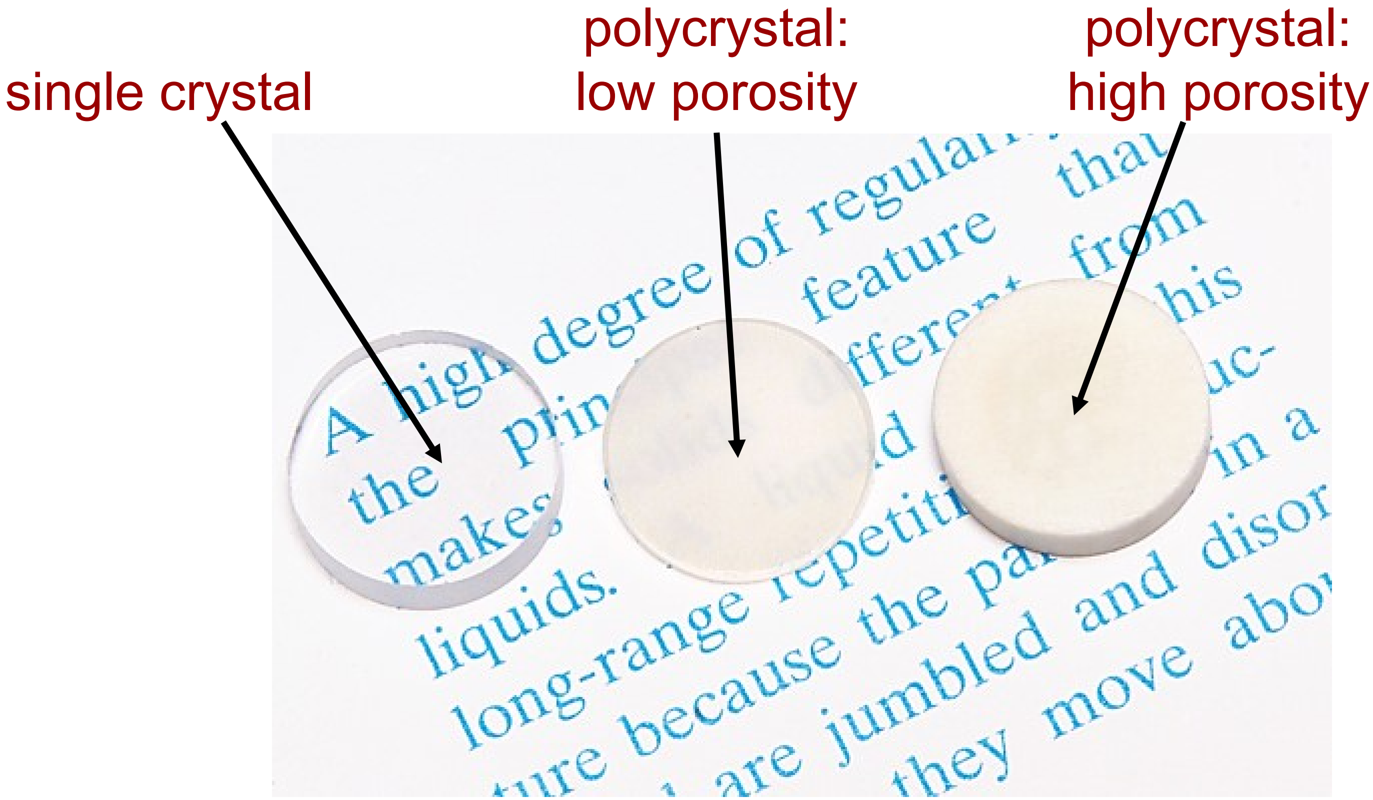


- Magnetic Permeability vs. Composition:
  --Adding 3 atomic % Si makes Fe a better recording medium!



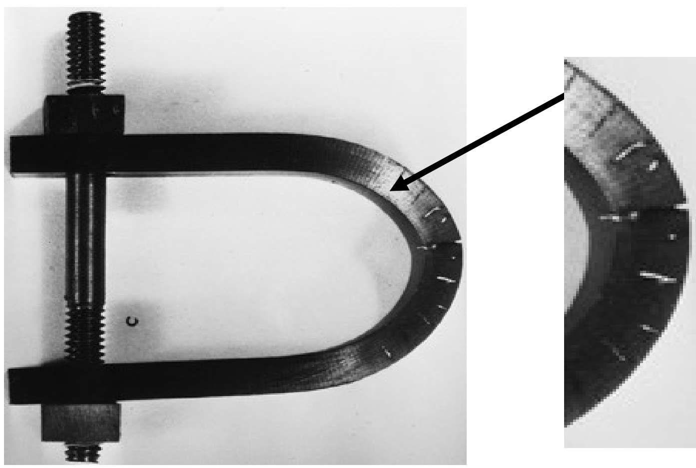
OPTICAL

- Transmittance:
  --Aluminum oxide may be transparent, translucent, or opaque depending on the material structure.

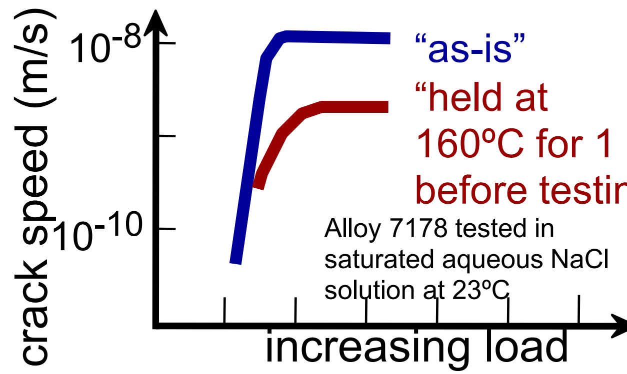


DETERIORATIVE

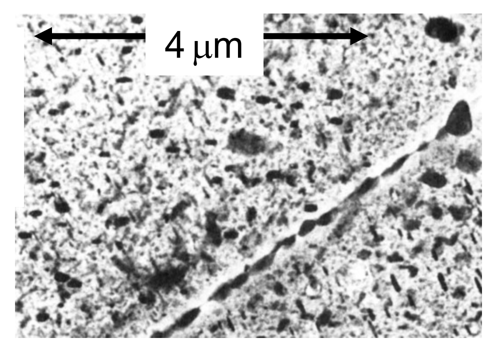
- Stress & Saltwater...
  --causes cracks!



- Heat treatment: slows
  crack speed in salt water!

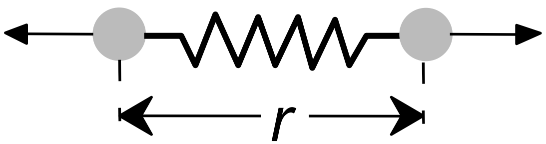


--material:
7150-T651 Al "alloy"
(Zn,Cu,Mg,Zr)

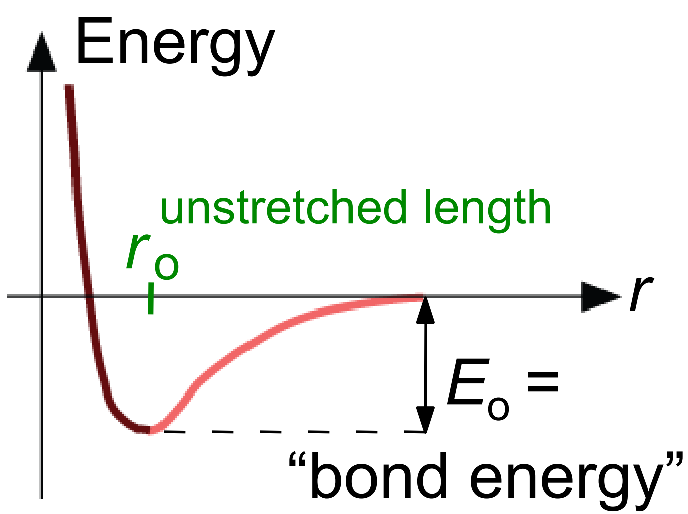


Properties From Bonding: T_m

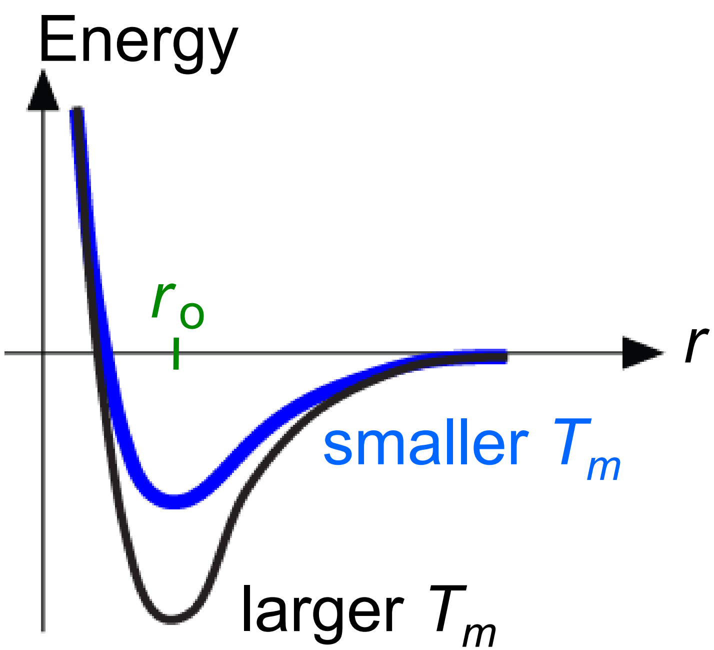
- Bond length, r



- Bond energy, E_o



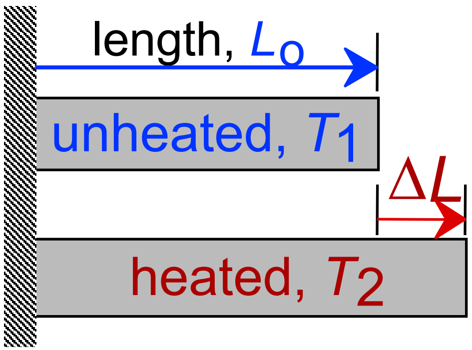
- Melting Temperature, T_m



T_m is larger if E_o is larger.

Properties From Bonding : α

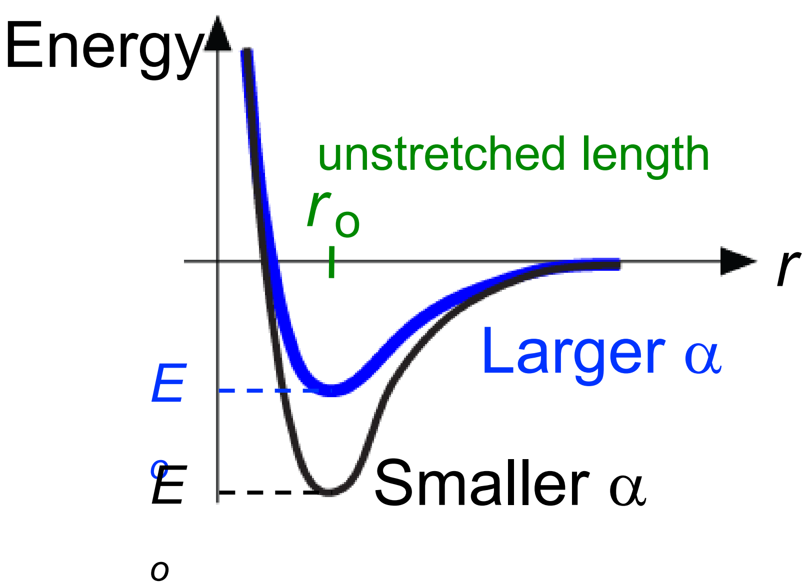
- Coefficient of thermal expansion, α



coeff. thermal expansion

$$\frac{\Delta L}{L_o} = \alpha\,(T_2 - T_1)$$

- α ~ symmetry at r_o



α is larger if E_o is smaller.

Summary: Primary Bonds

Ceramics

(Ionic & covalent bonding):

Large bond energy
- large T_m
- large E
- small α

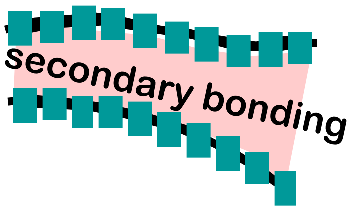
Metals

(Metallic bonding):

Variable bond energy
- moderate T_m
- moderate E
- moderate α

Polymers

(Covalent & Secondary):

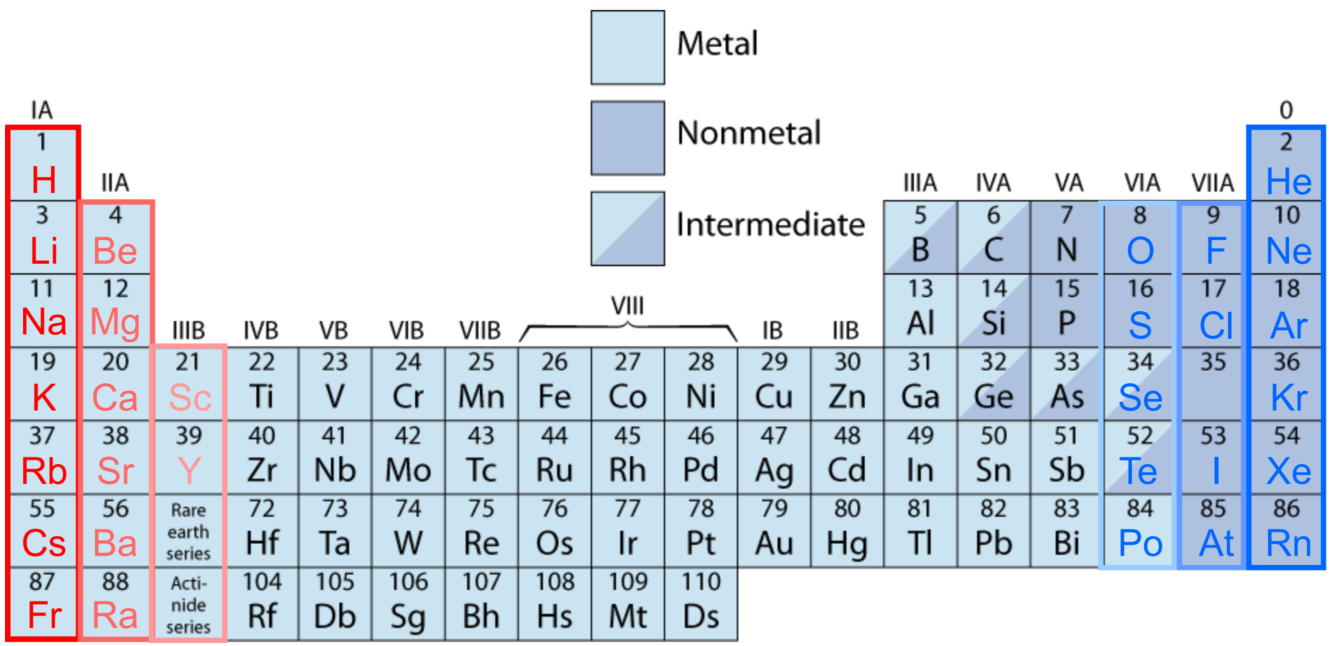


Secondary bonding dominates
- small T_m
- small E
- large α

Brief of Metal

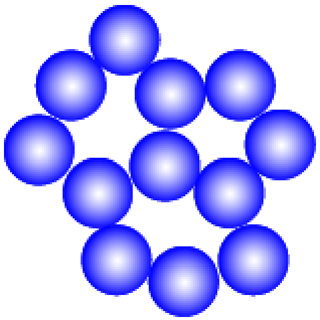
The Periodic Table

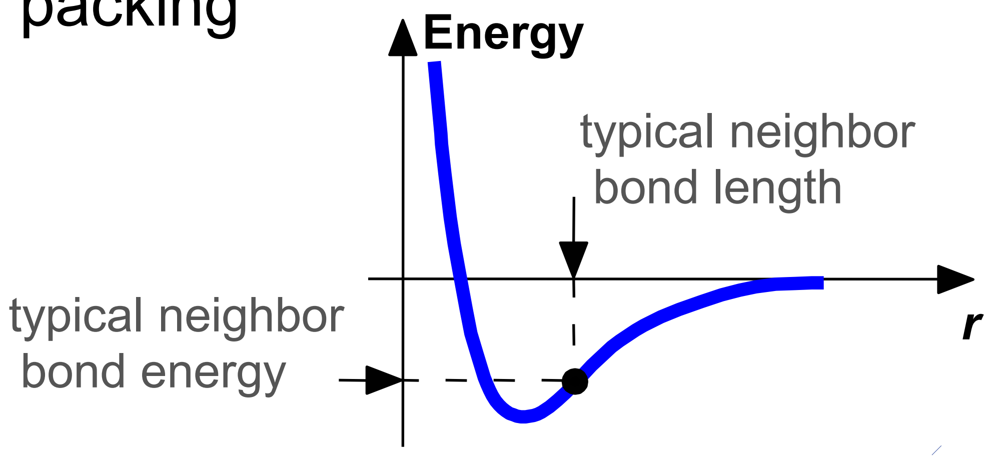
- Columns: Similar Valence Structure



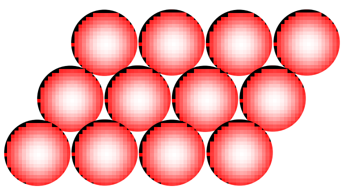
Energy and Packing

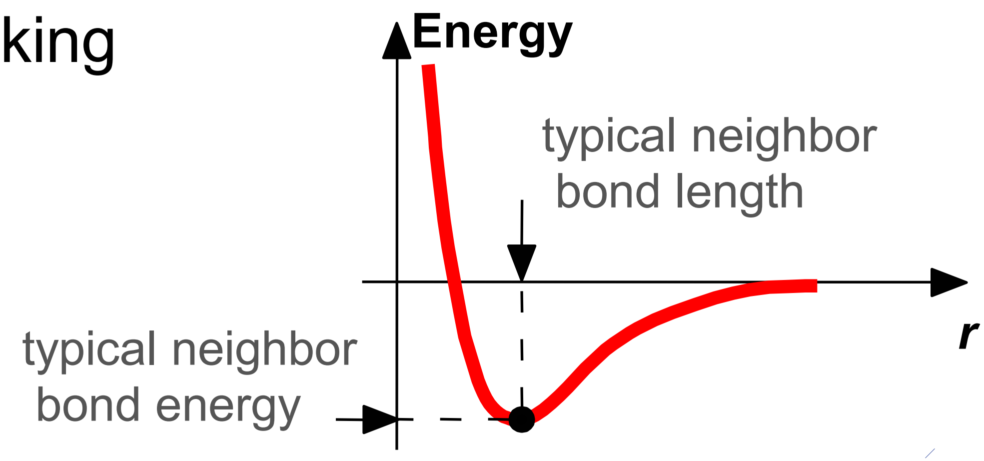
- Non dense, random packing





- Dense, ordered packing



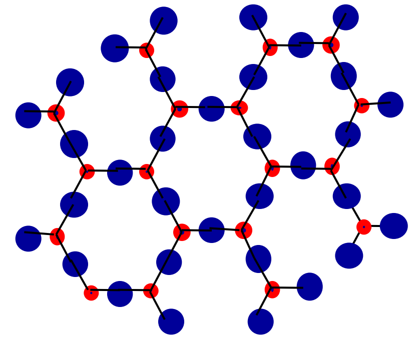


Dense, ordered packed structures tend to have lower energies.

Materials and Packing

Crystalline materials...

- atoms pack in periodic, 3D arrays
- typical of: -metals
  -many ceramics
  -some polymers

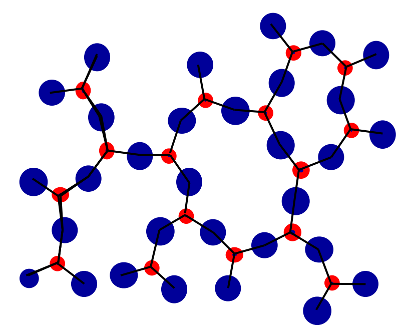


crystalline SiO_2

• Si ● Oxygen

Noncrystalline materials...

- atoms have no periodic packing
- occurs for: -complex structures
  -rapid cooling



noncrystalline SiO_2

"Amorphous" = Noncrystalline

Types of Imperfections

- Vacancy atoms
- Interstitial atoms
- Substitutional atoms

Point defects

- Dislocations

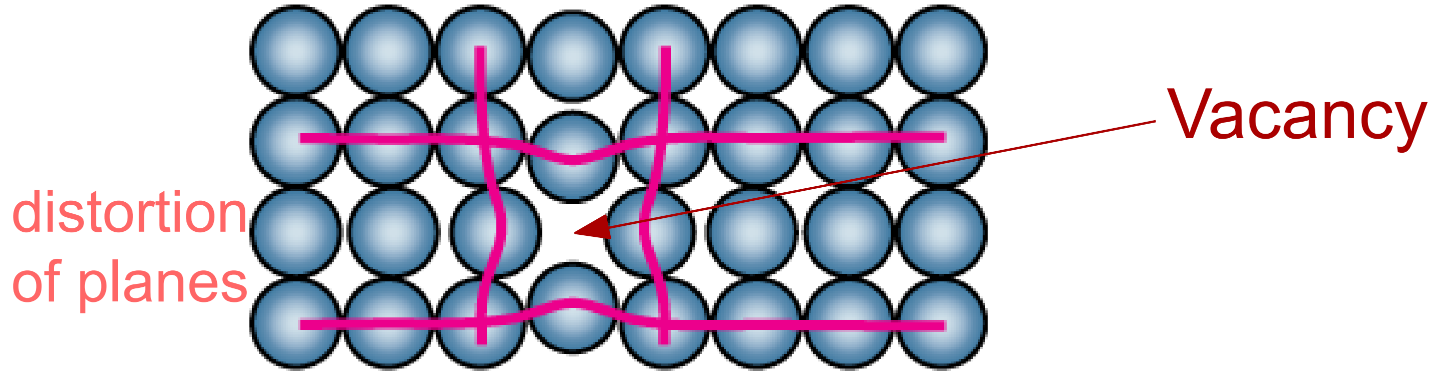
Line defects

- Grain Boundaries

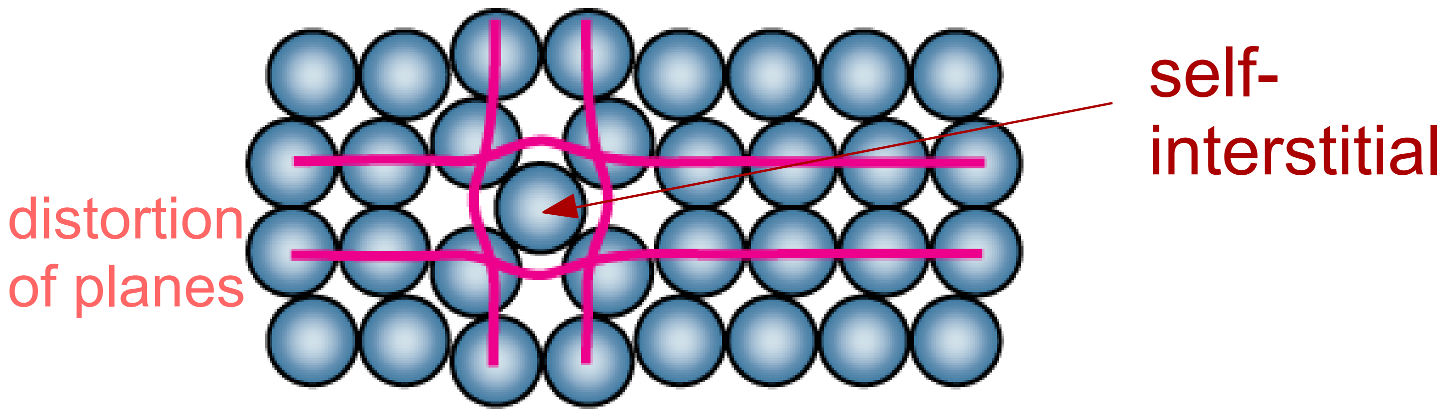
Area defects

Point Defects

- Vacancies:
  -vacant atomic sites in a structure.



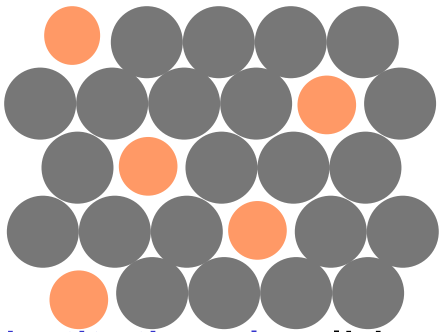
- Self-Interstitials:
  -"extra" atoms positioned between atomic sites.



Point Defects in Alloys

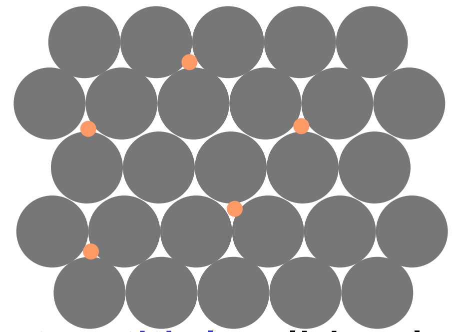
Two outcomes if impurity (B) added to host (A):

- Solid solution of B in A (i.e., random dist. of point defects)



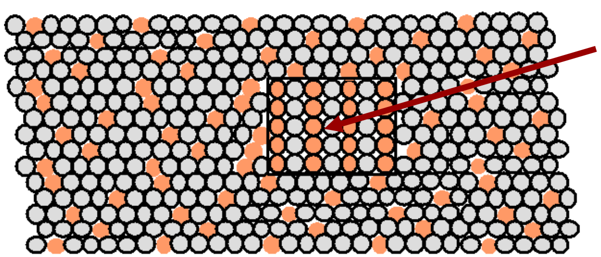
Substitutional solid soln.
(e.g., Cu in Ni)

OR



Interstitial solid soln.
(e.g., C in Fe)

- Solid solution of B in A plus a new phase (usually for a larger amount of B)



Second phase particle
--different composition
--often different structure.

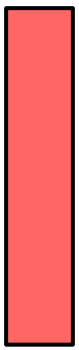
Line Defects

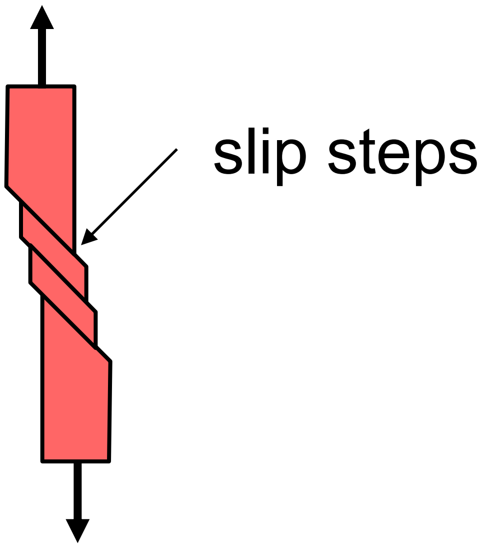
Dislocations:

- are line defects,
- slip between crystal planes result when dislocations move,
- produce permanent (plastic) deformation.

Schematic of Zinc (HCP):

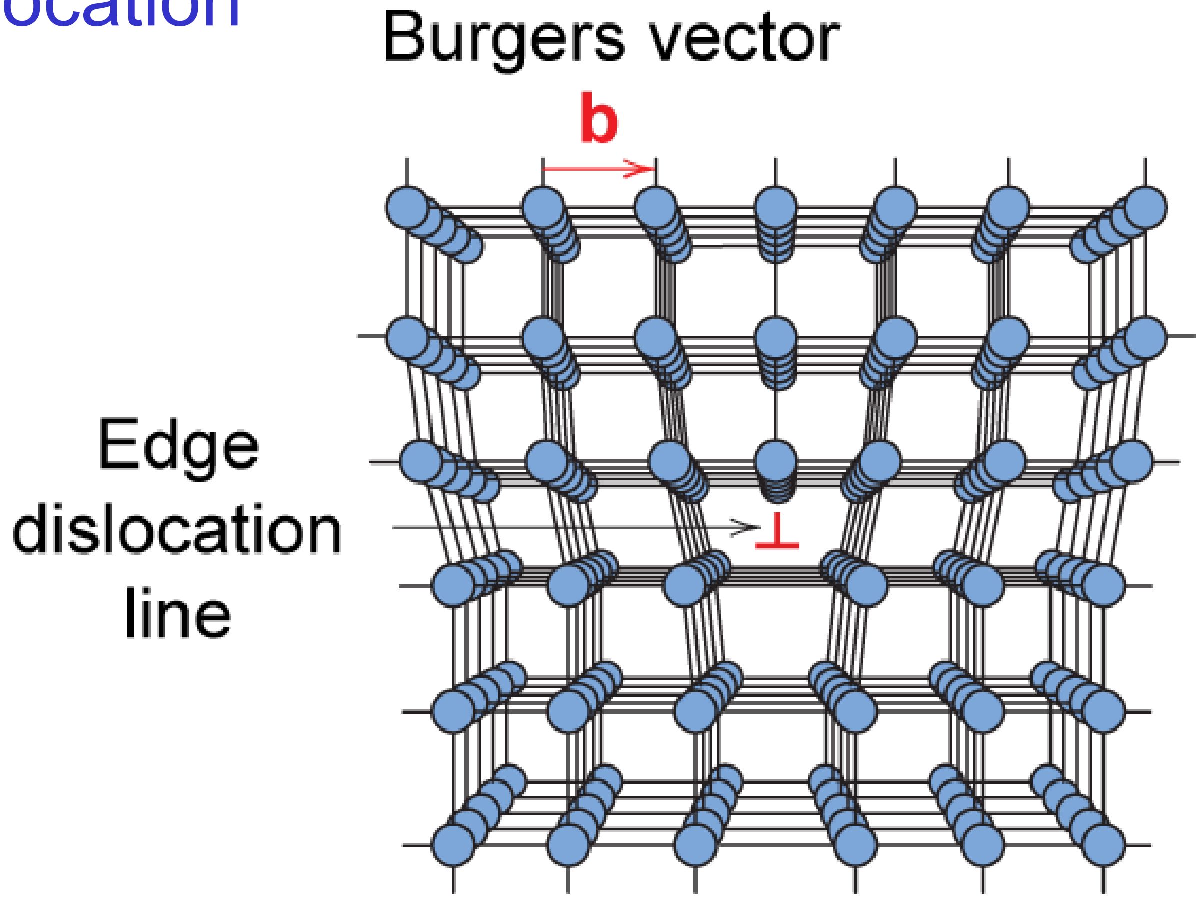
- before deformation
- after tensile elongation





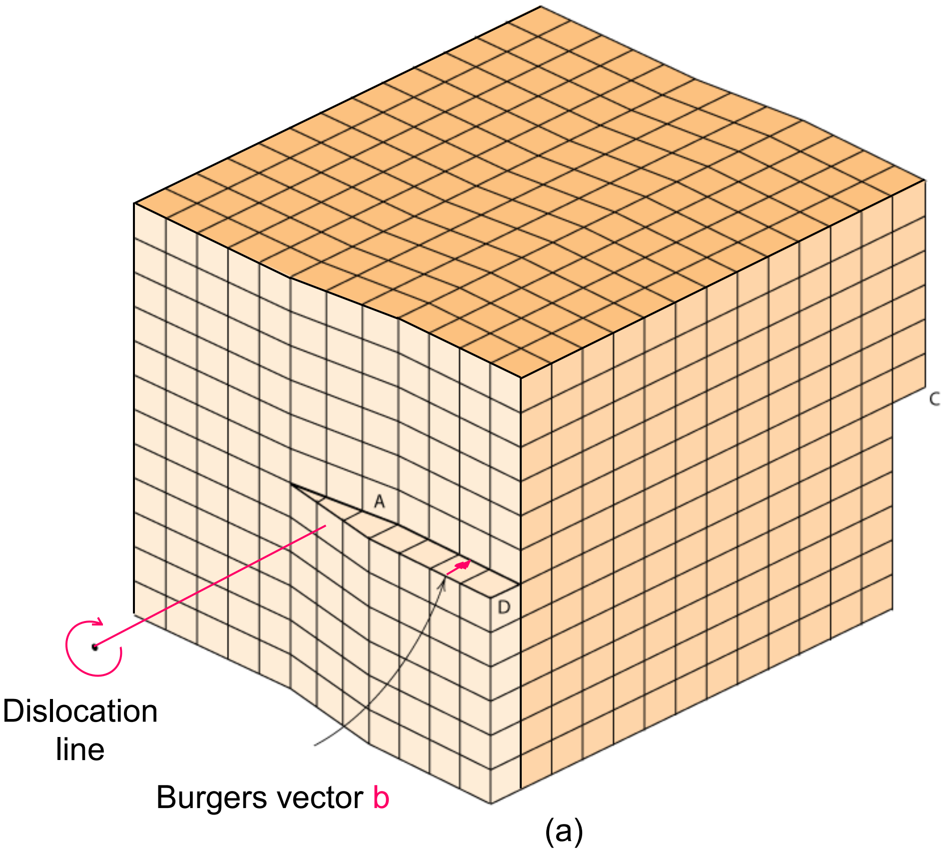
Imperfections in Solids

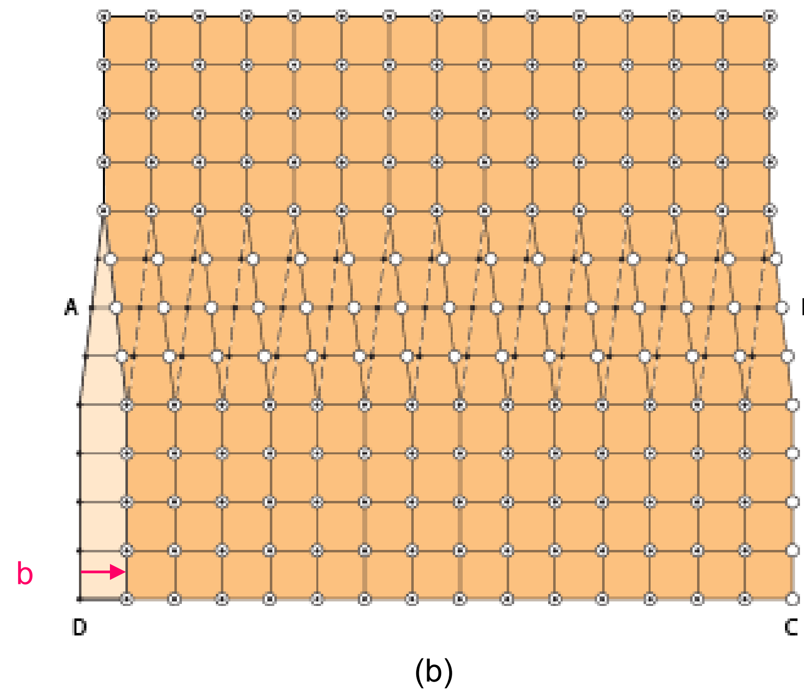
Edge Dislocation



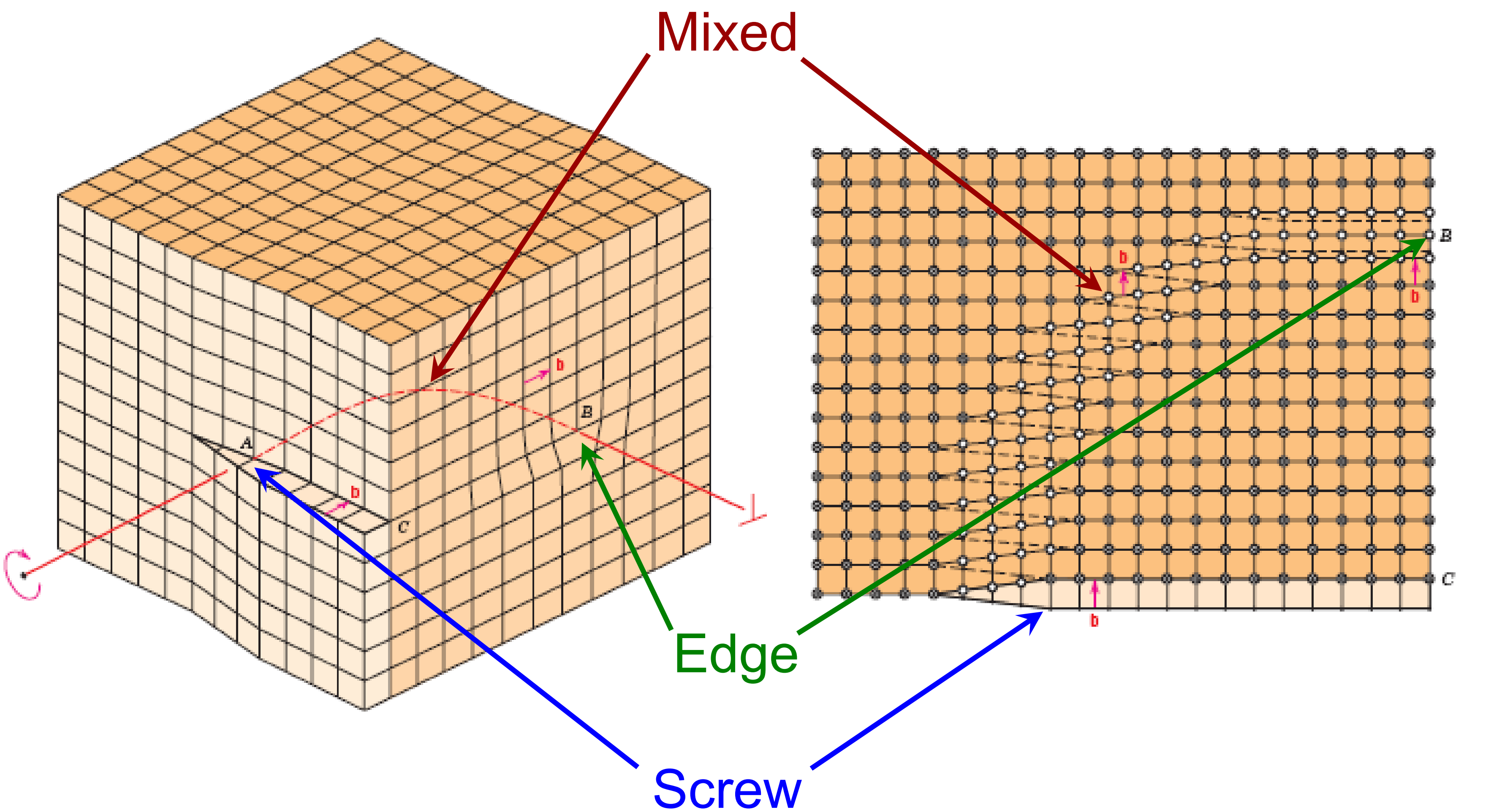
Imperfections in Solids

Screw Dislocation



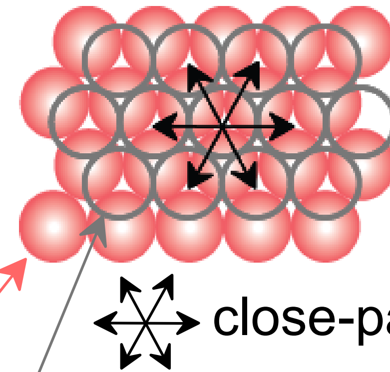


Edge, Screw, and Mixed Dislocations



Dislocations & Crystal Structures

- Structure: close-packed planes & directions are preferred.



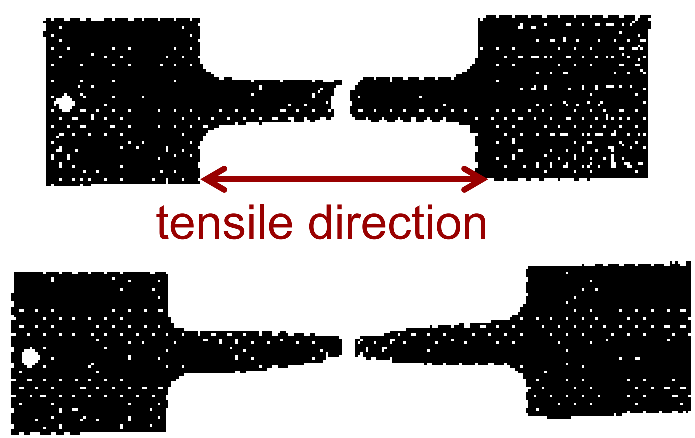
view onto two close-packed planes.

close-packed directions

close-packed plane (bottom)   close-packed plane (top)

- Comparison among crystal structures:
  - HCP: few slip systems/directions;
  - FCC: many slip systems/directions;
  - BCC: the most slip systems/directions

- Specimens that were tensile tested.



Mg (HCP)

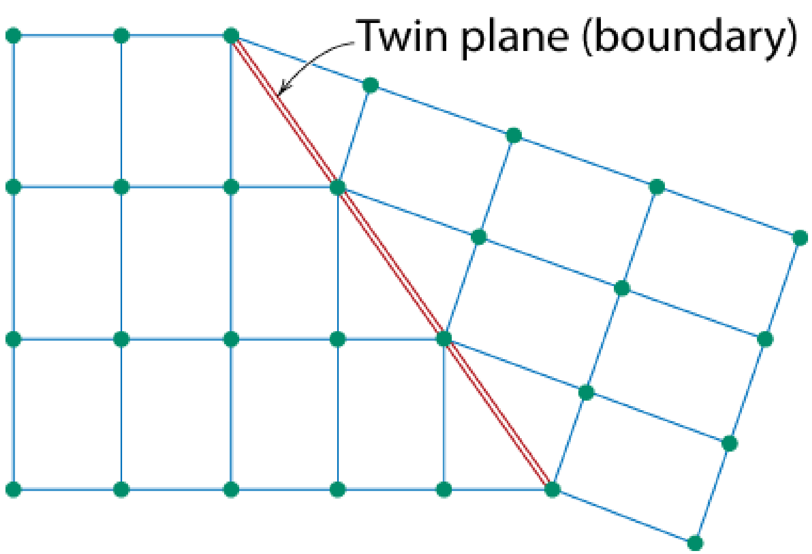
Al (FCC)

Planar Defects in Solids

- External Surfaces

  The most obvious
- Grain Boundary

  Different crystal orientation between grains

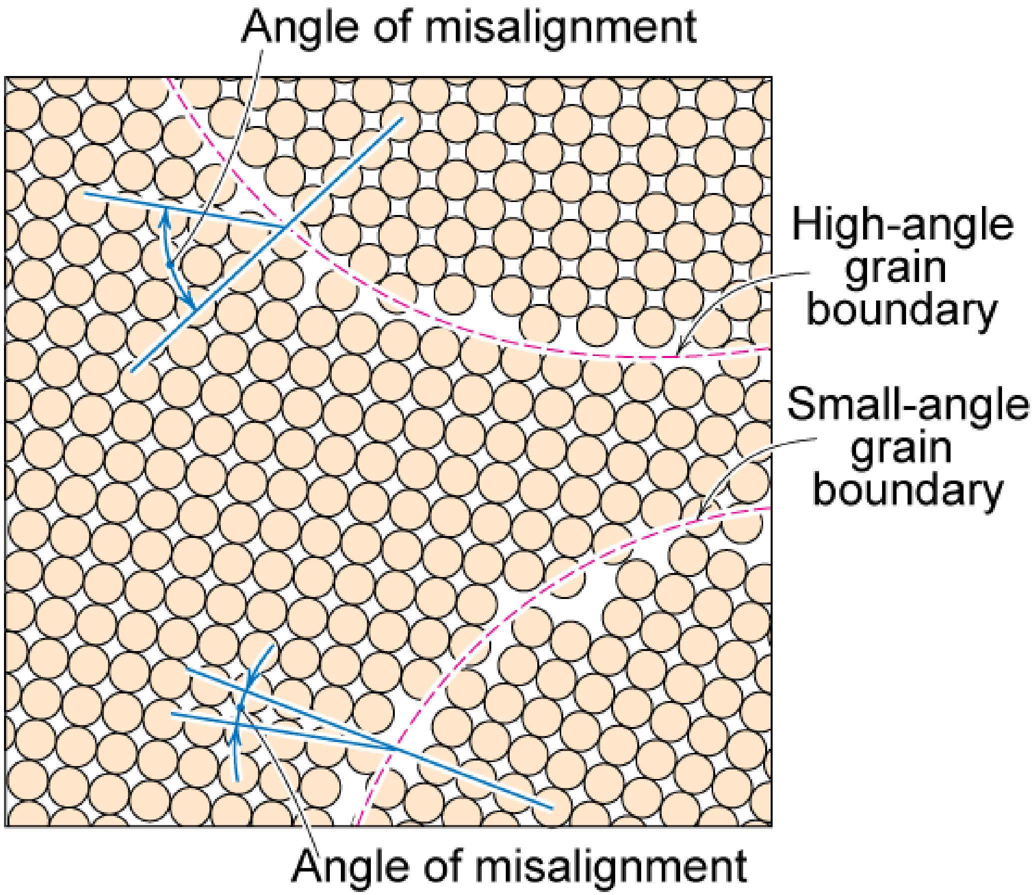


- twin boundary (plane)
  - Essentially a reflection of atom positions across the twin plane.
- Stacking faults
  - For FCC metals an error in ABCABC packing sequence
  - Ex: ABCABABC
- Phase boundary
  - In multiphase materials

Polycrystalline Materials

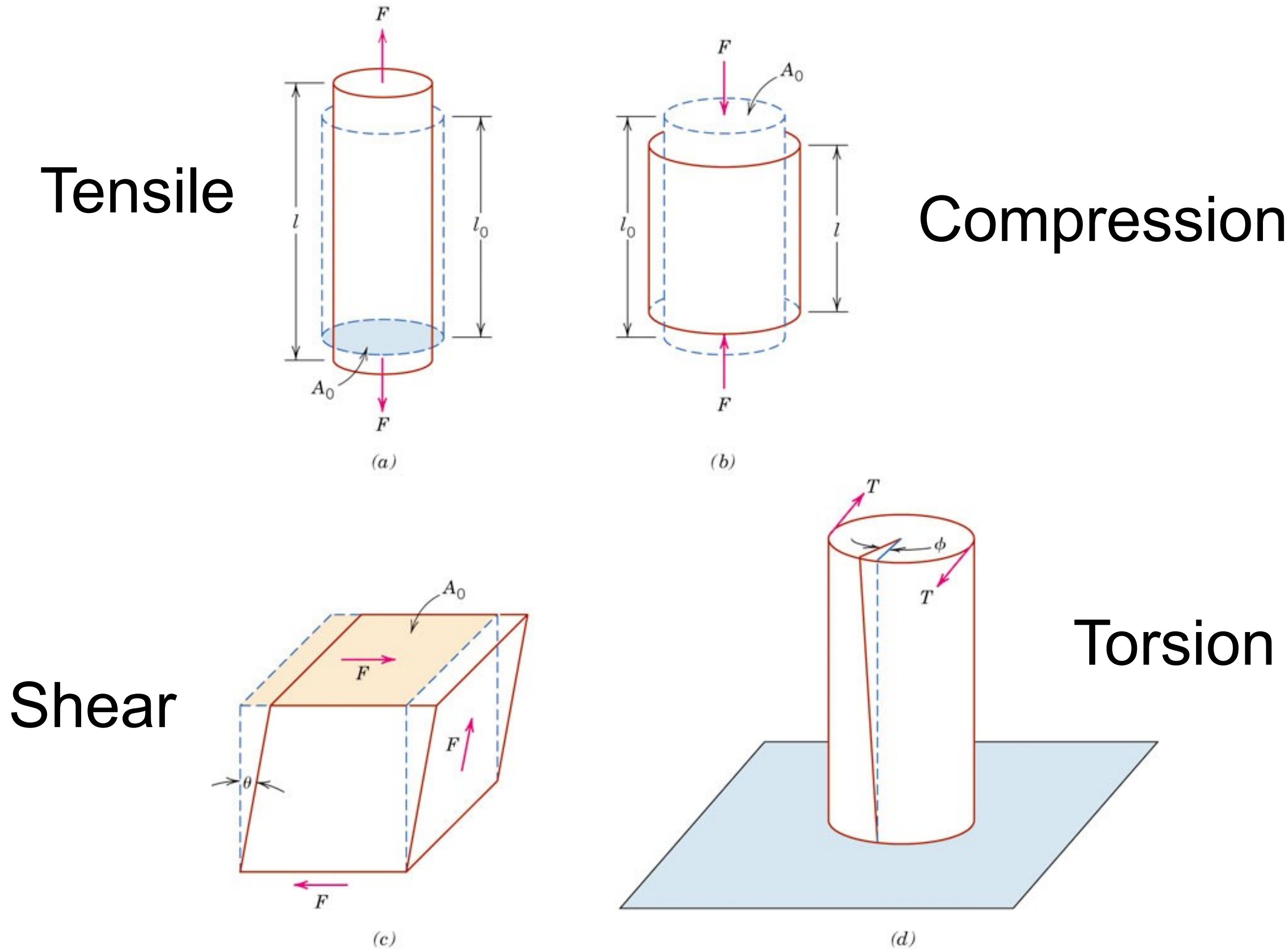
Grain Boundaries

- regions between crystals
- transition from lattice of one region to that of the other
- slightly disordered
- low density in grain boundaries
  - high mobility
  - high diffusivity
  - high chemical reactivity

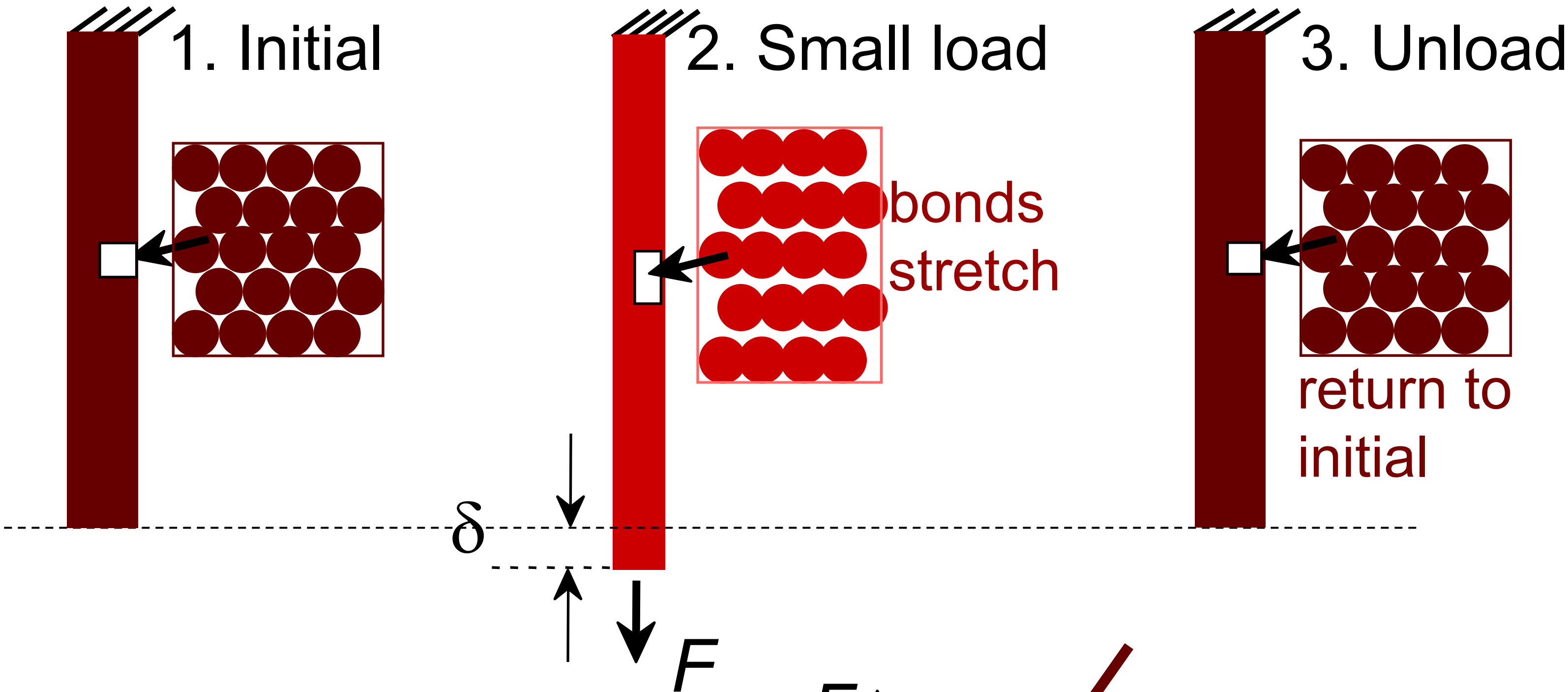


Mechanical Properties

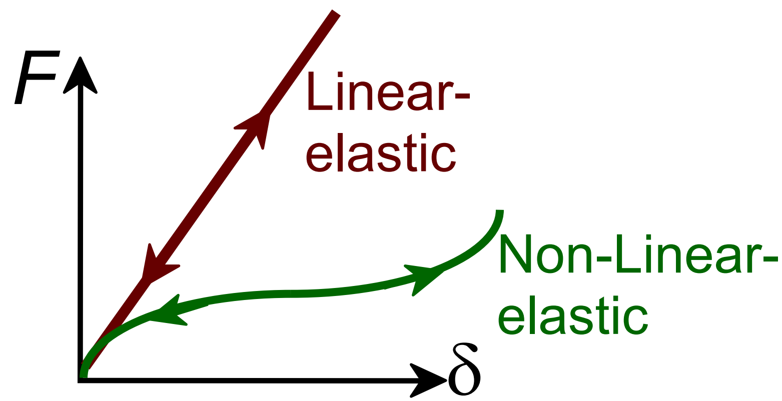
Load and Deformation



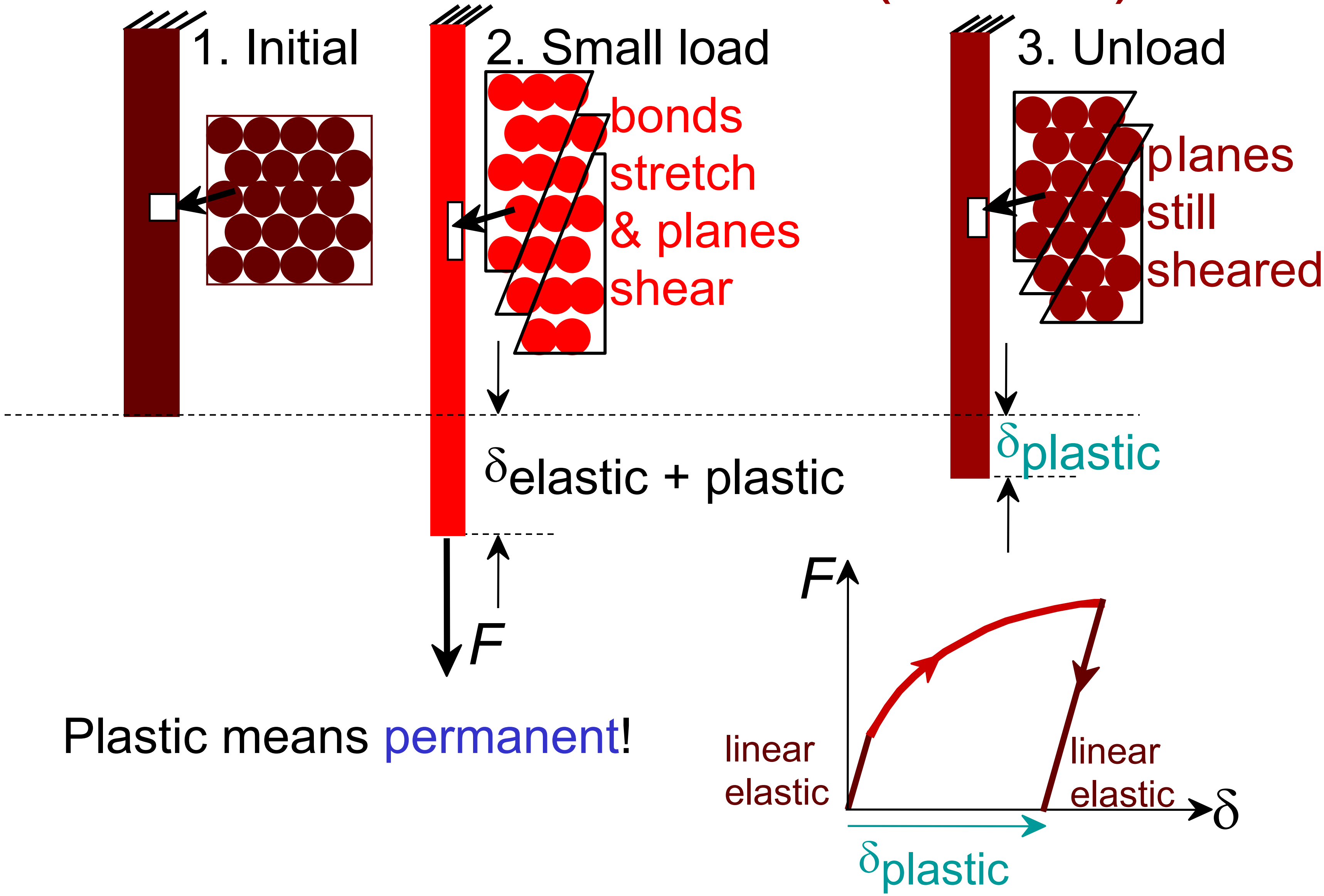
Elastic Deformation



Elastic means reversible!



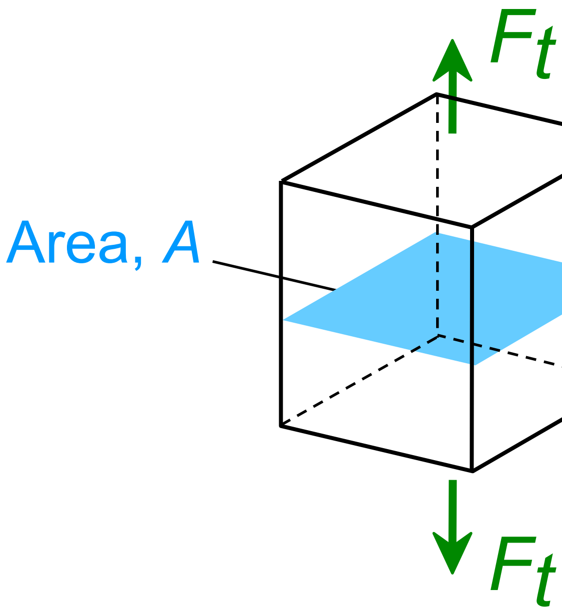
Plastic Deformation (Metals)



Plastic means permanent!

Engineering Stress

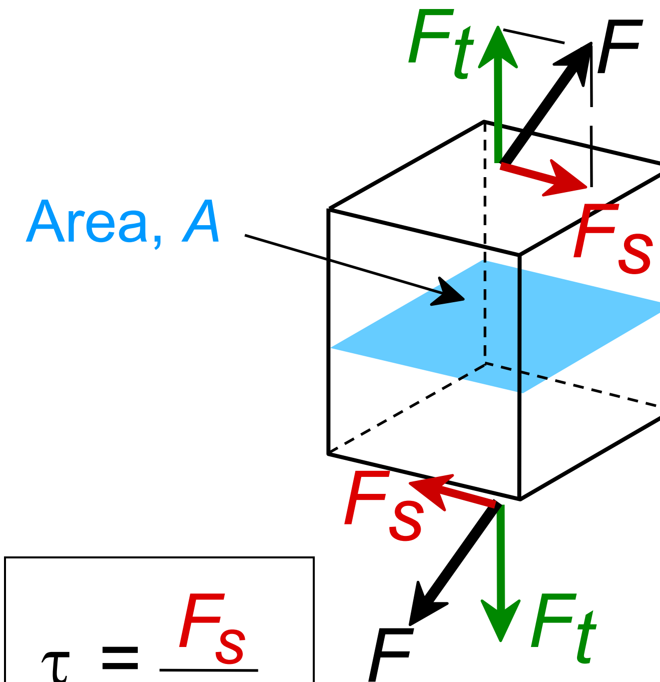
- Tensile stress, σ:



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

original area
before loading

- Shear stress, τ:

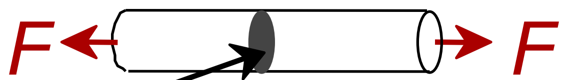


$$\tau = \frac{F_s}{A_o}$$

$\therefore$ Stress has units:
N/m2 or lb_f/in2

Common States of Stress

- **Simple tension: cable**

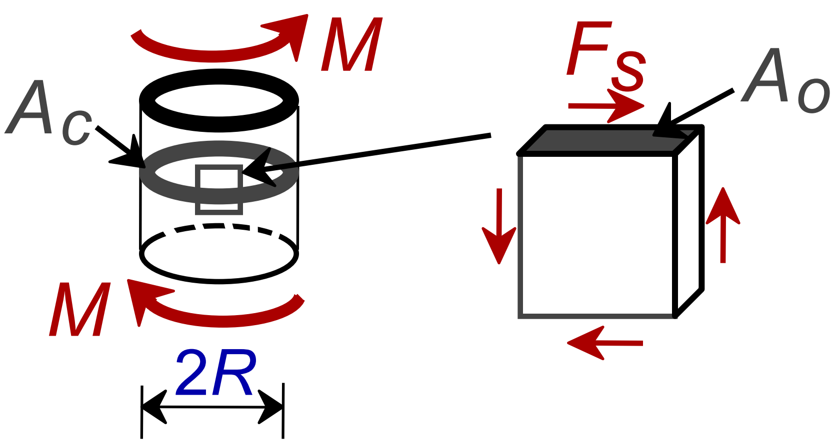


A_o = cross sectional area (when unloaded)

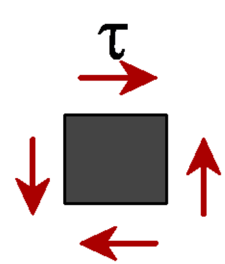
$$\sigma = \frac{F}{A_o}$$

Ski lift

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



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



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

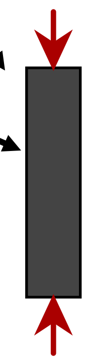
OTHER COMMON STRESS STATES (1)

- **Simple compression:**

Balanced Rock, Arches National Park

Canyon Bridge, Los Alamos, NM

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



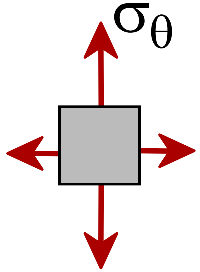
Note: compressive structure member ($\sigma < 0$ here).

OTHER COMMON STRESS STATES (2)

- **Bi-axial tension:**

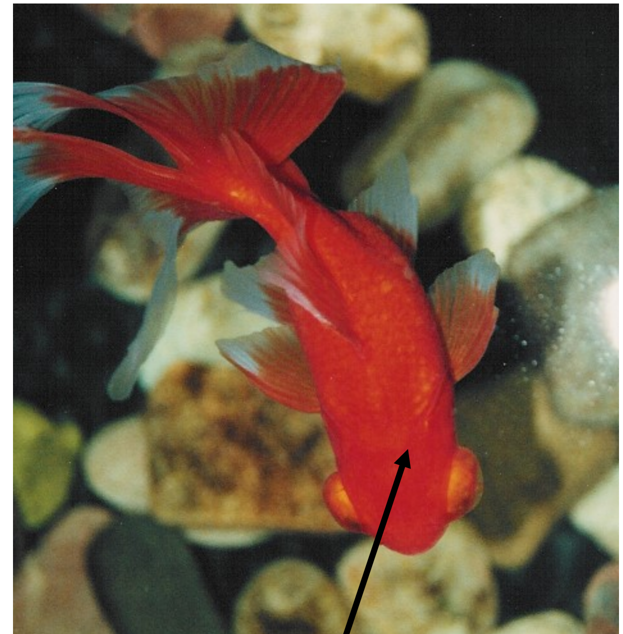
Pressurized tank

$\sigma_\theta > 0$



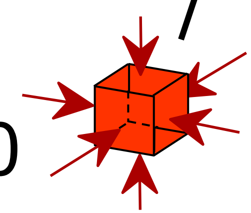
$\sigma_z > 0$

- **Hydrostatic compression:**



Fish under water

$\sigma_h < 0$



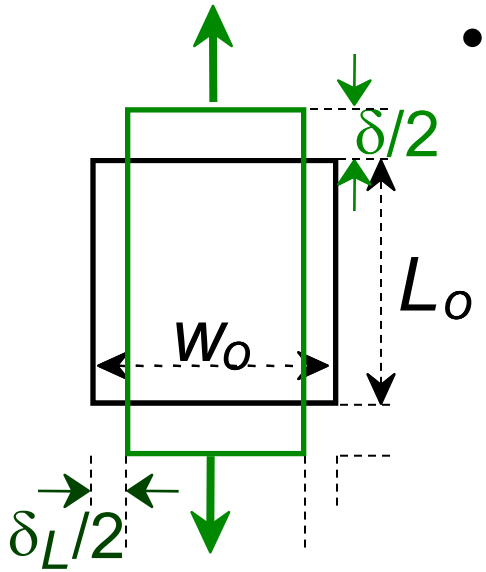
Engineering Strain

- **Tensile strain:**

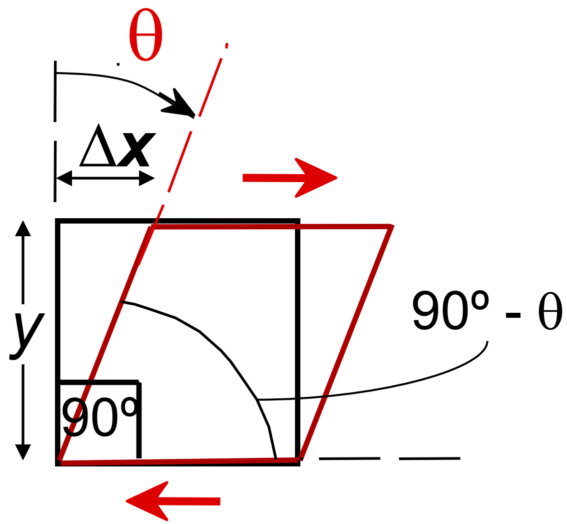
$$\varepsilon = \frac{\delta}{L_o}$$

- **Lateral strain:**

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



- **Shear strain:**

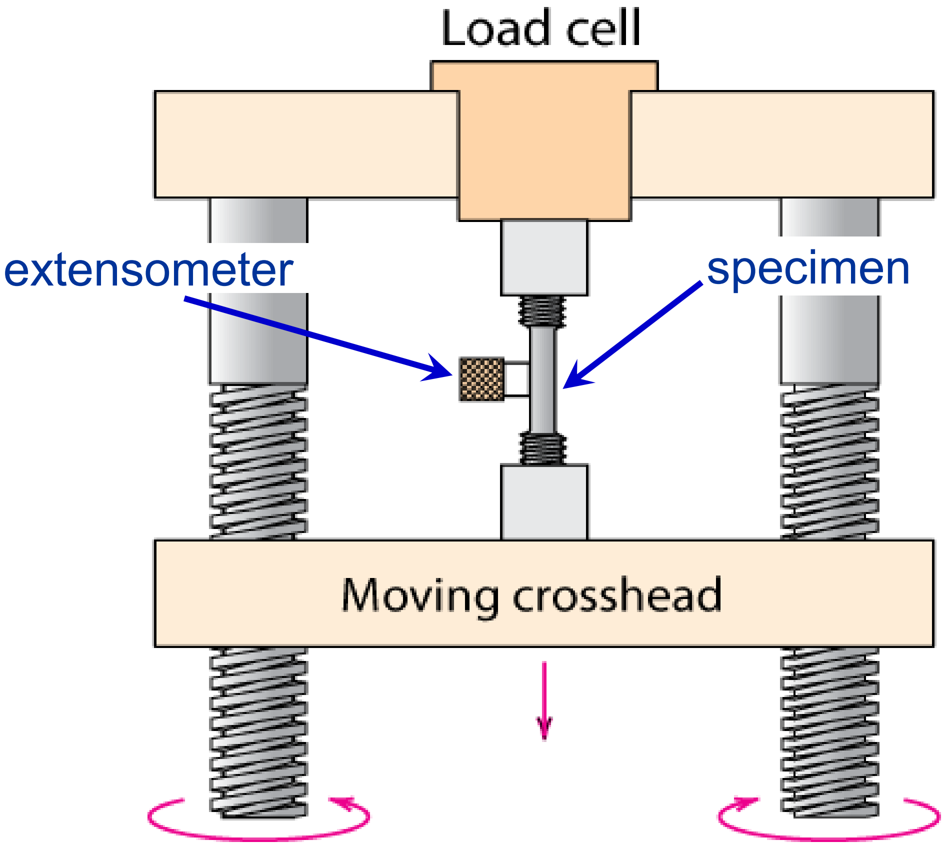


$$\gamma = \Delta x / y = \tan\theta$$

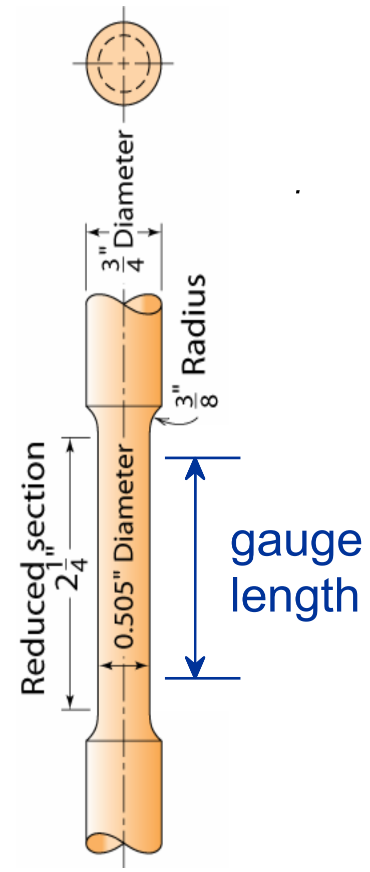
Strain is always dimensionless.

Stress-Strain Testing

- **Typical tensile test machine**



- **Typical tensile specimen**

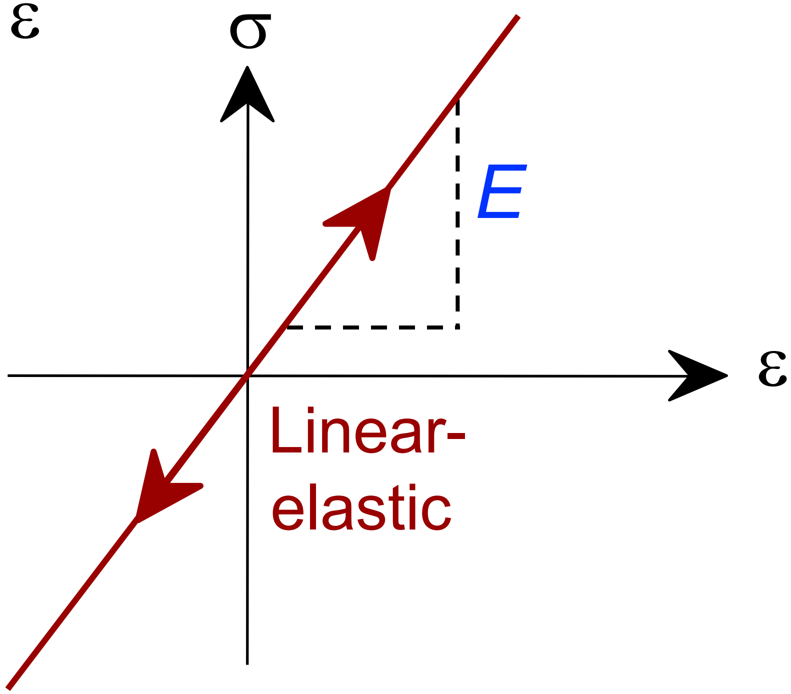


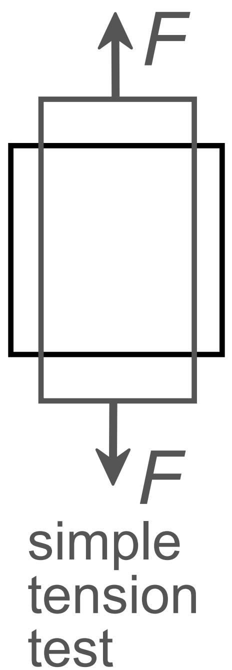
Linear Elastic Properties

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

- **Hooke's Law:**

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

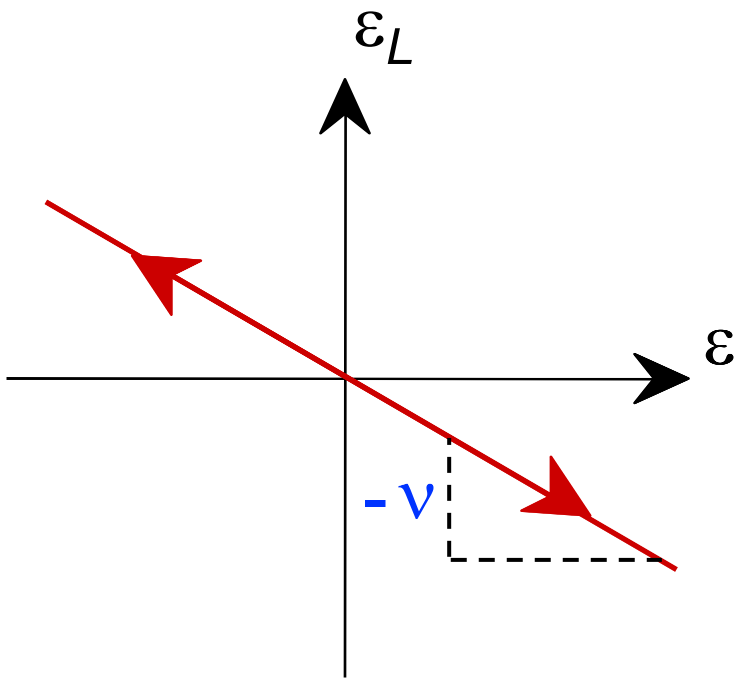




Poisson's ratio, ν

- **Poisson's ratio, ν:**

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

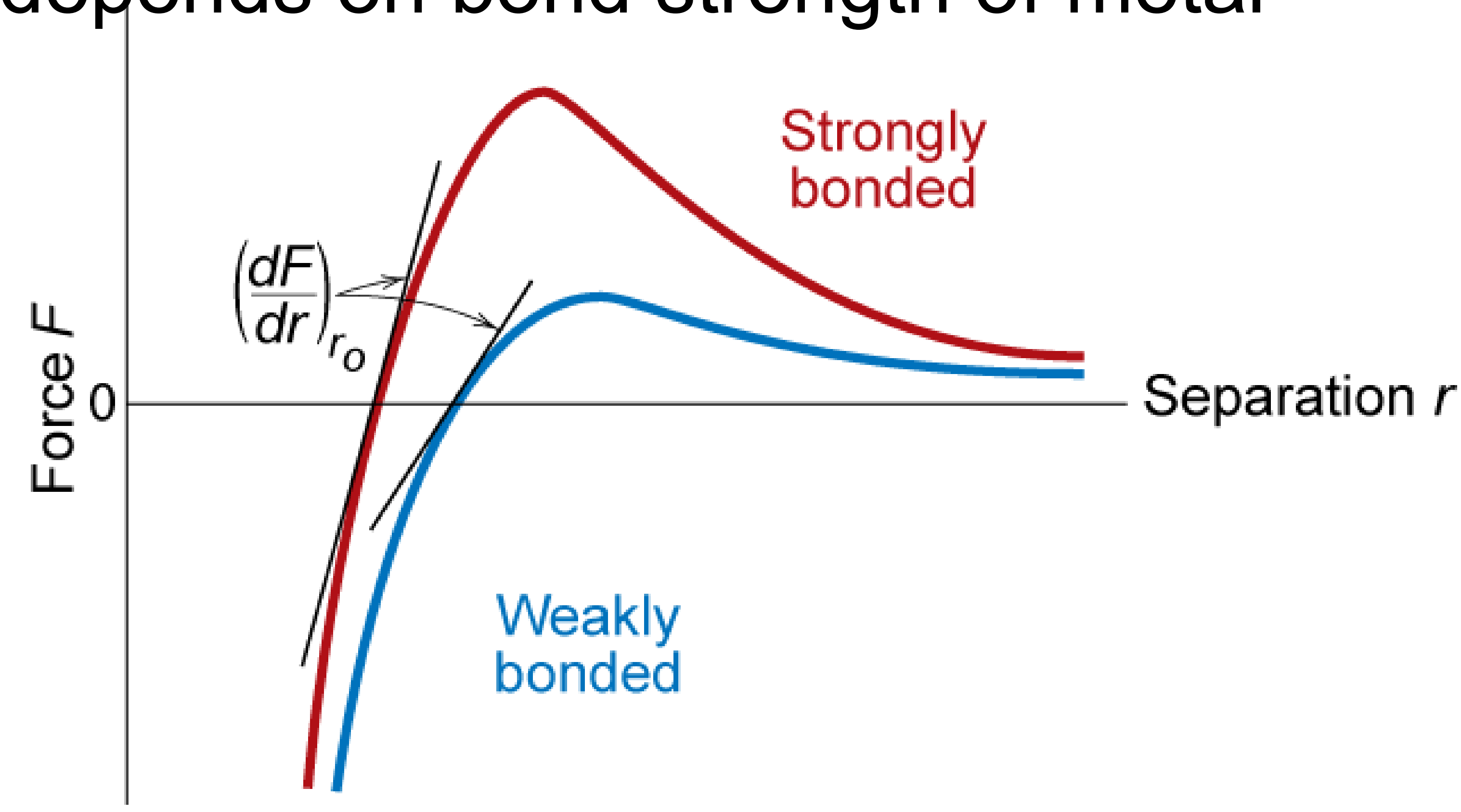


metals: ν ~ 0.33
ceramics: ν ~ 0.25
polymers: ν ~ 0.40

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

Mechanical Properties

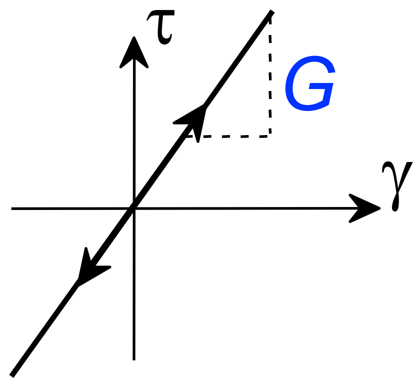
- Slope of stress strain plot (which is proportional to the elastic modulus) depends on bond strength of metal

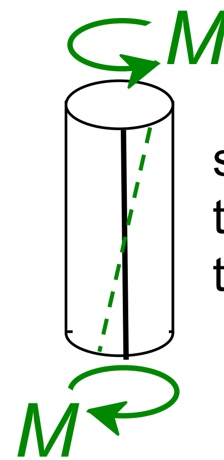


Other Elastic Properties

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

$$\tau = G\gamma$$

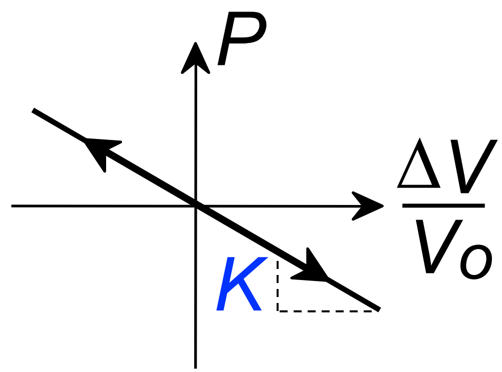


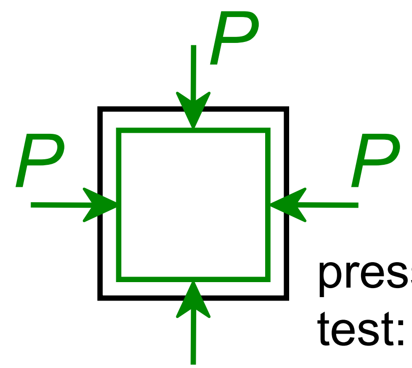


simple torsion test

- **Elastic Bulk modulus, K:**

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



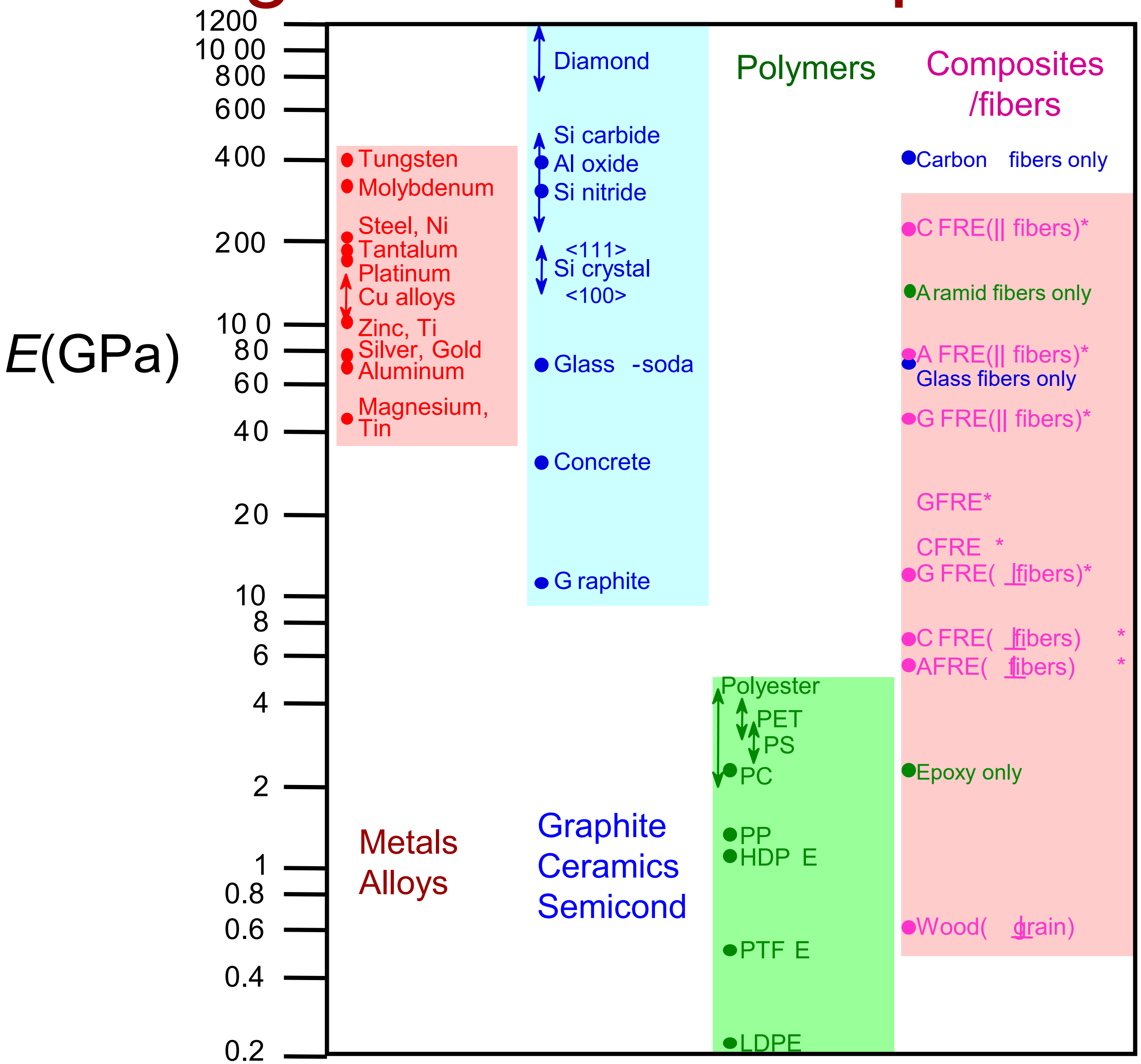


pressure test: Initial. vol $= V_o$, Vol change $= \Delta V$

- **Special relations for isotropic materials:**

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

Young's Moduli: Comparison



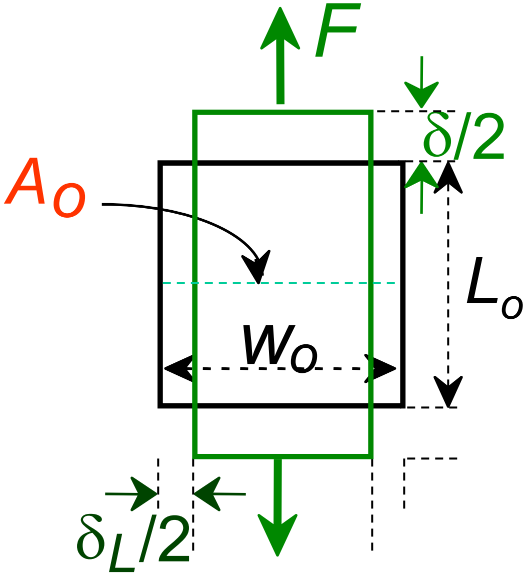
Modulus of Metal

Metal Alloy	Modulus of Elasticity GPa	Modulus of Elasticity 10^6 psi	Shear Modulus GPa	Shear Modulus 10^6 psi	Poisson's Ratio
Aluminum	69	10	25	3.6	0.33
Brass	97	14	37	5.4	0.34
Copper	110	16	46	6.7	0.34
Magnesium	45	6.5	17	2.5	0.29
Nickel	207	30	76	11.0	0.31
Steel	207	30	83	12.0	0.30
Titanium	107	15.5	45	6.5	0.34
Tungsten	407	59	160	23.2	0.28

Useful Linear Elastic Relationships

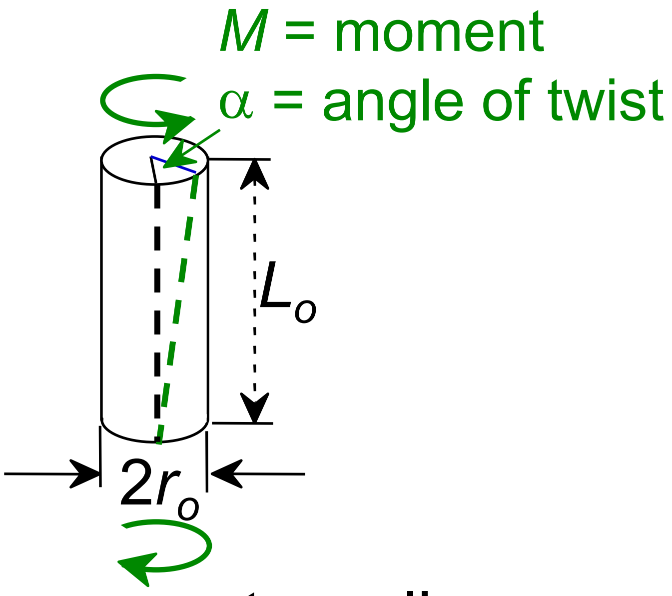
- **Simple tension:**

$$\delta = \frac{F L_o}{E A_o} \qquad \delta_L = -\nu \frac{F w_o}{E A_o}$$



- **Simple torsion:**

$$\alpha = \frac{2 M L_o}{\pi r_o^4 G} \qquad d\alpha = \frac{T}{JG} dx$$

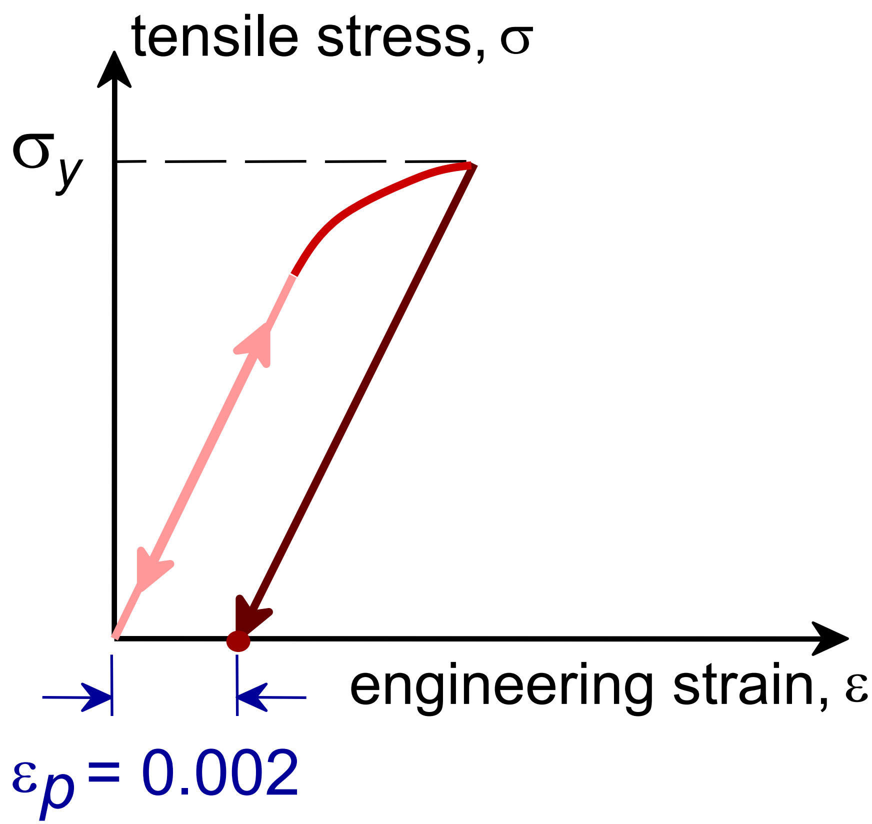


- Material, geometric, and loading parameters all contribute to deflection.
- Larger elastic moduli minimize elastic deflection.

Yield Strength, σ_y

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

when $\varepsilon_p = 0.002$



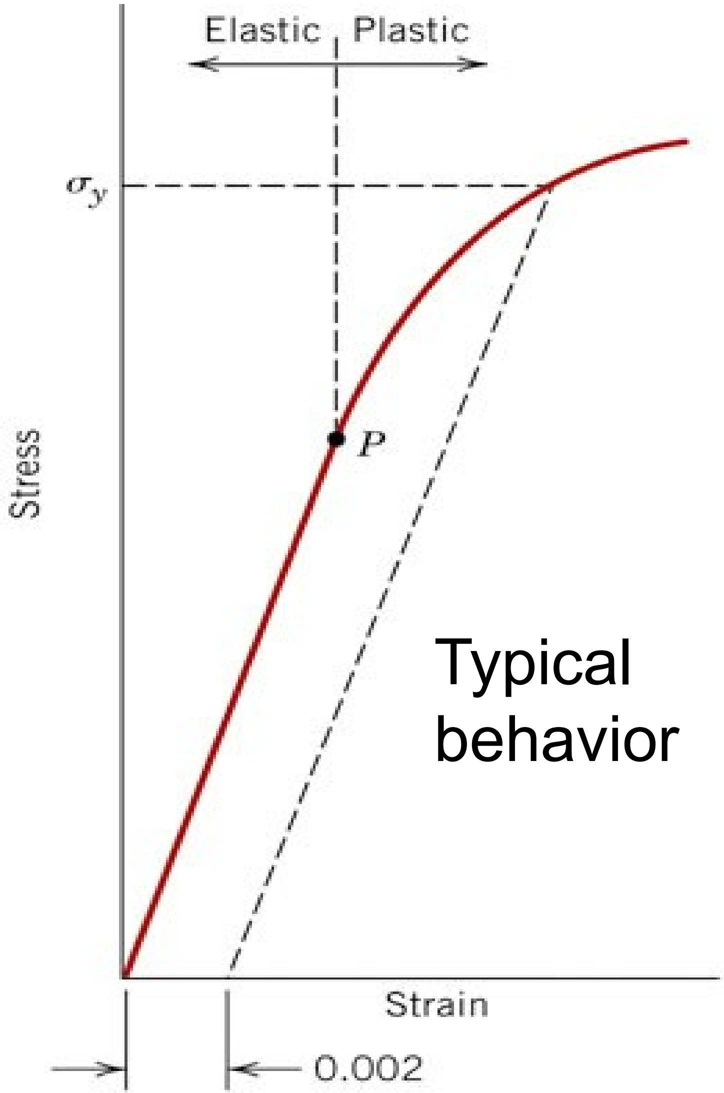
σ_y = yield strength

Note: for 2 inch sample

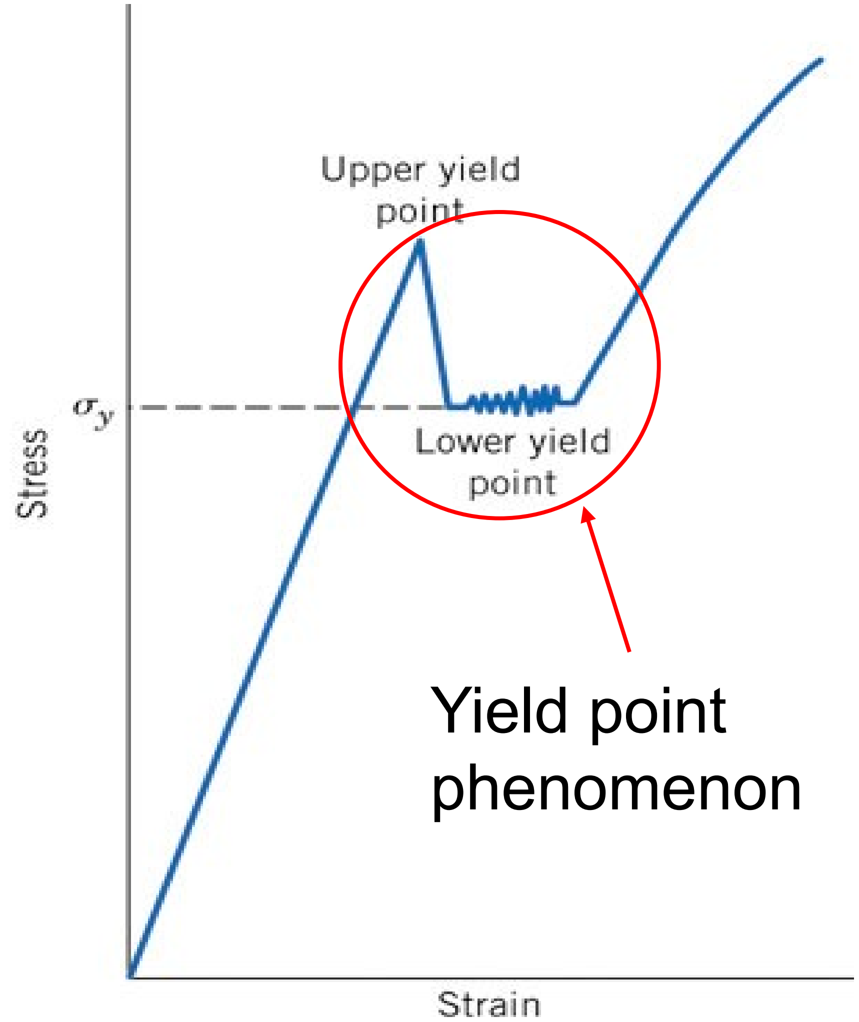
$\varepsilon = 0.002 = \Delta z/z$

$\therefore\ \Delta z = 0.004$ in

Stress-Strain Behavior

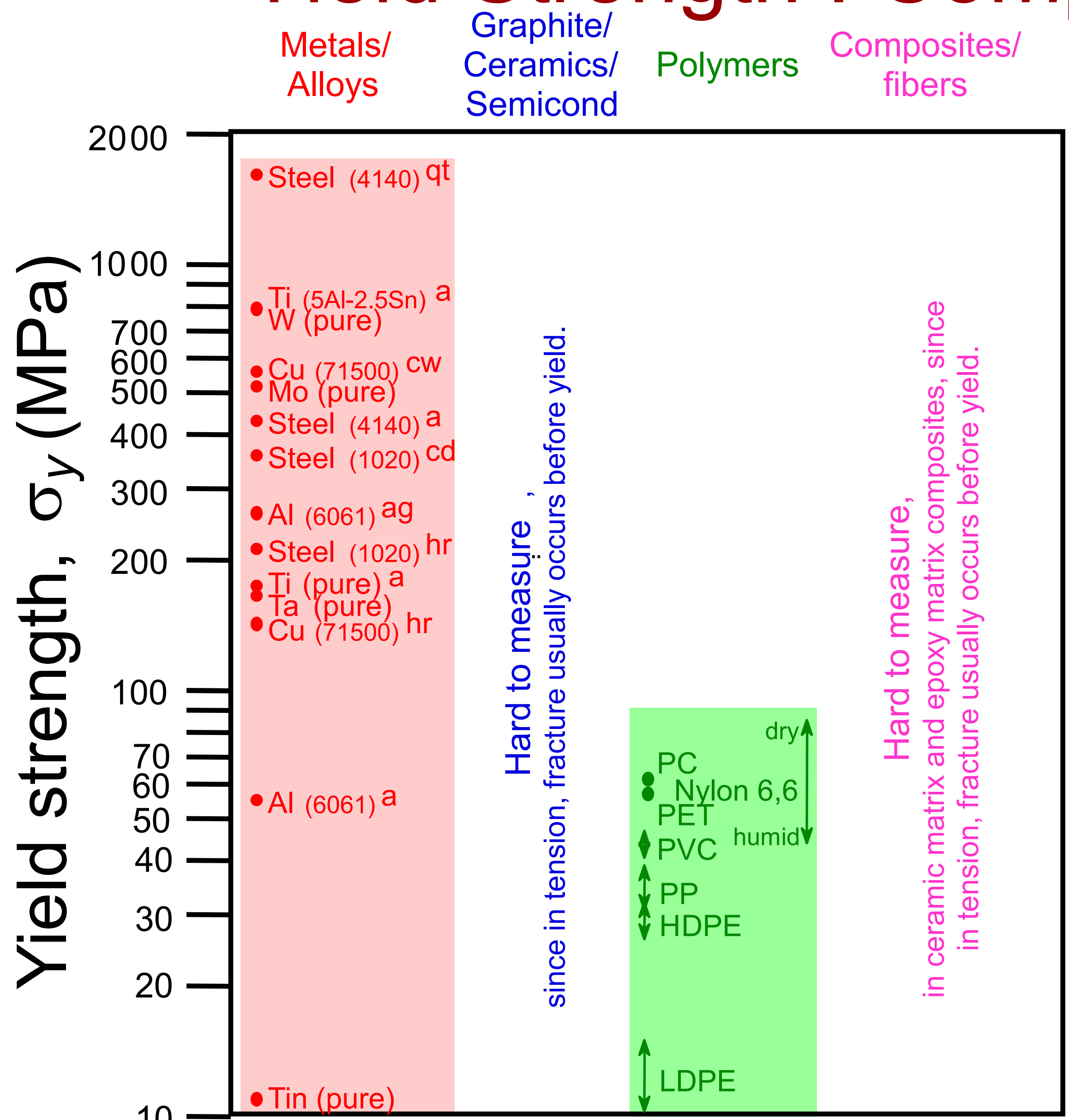


(a)



(b)

Yield Strength : Comparison



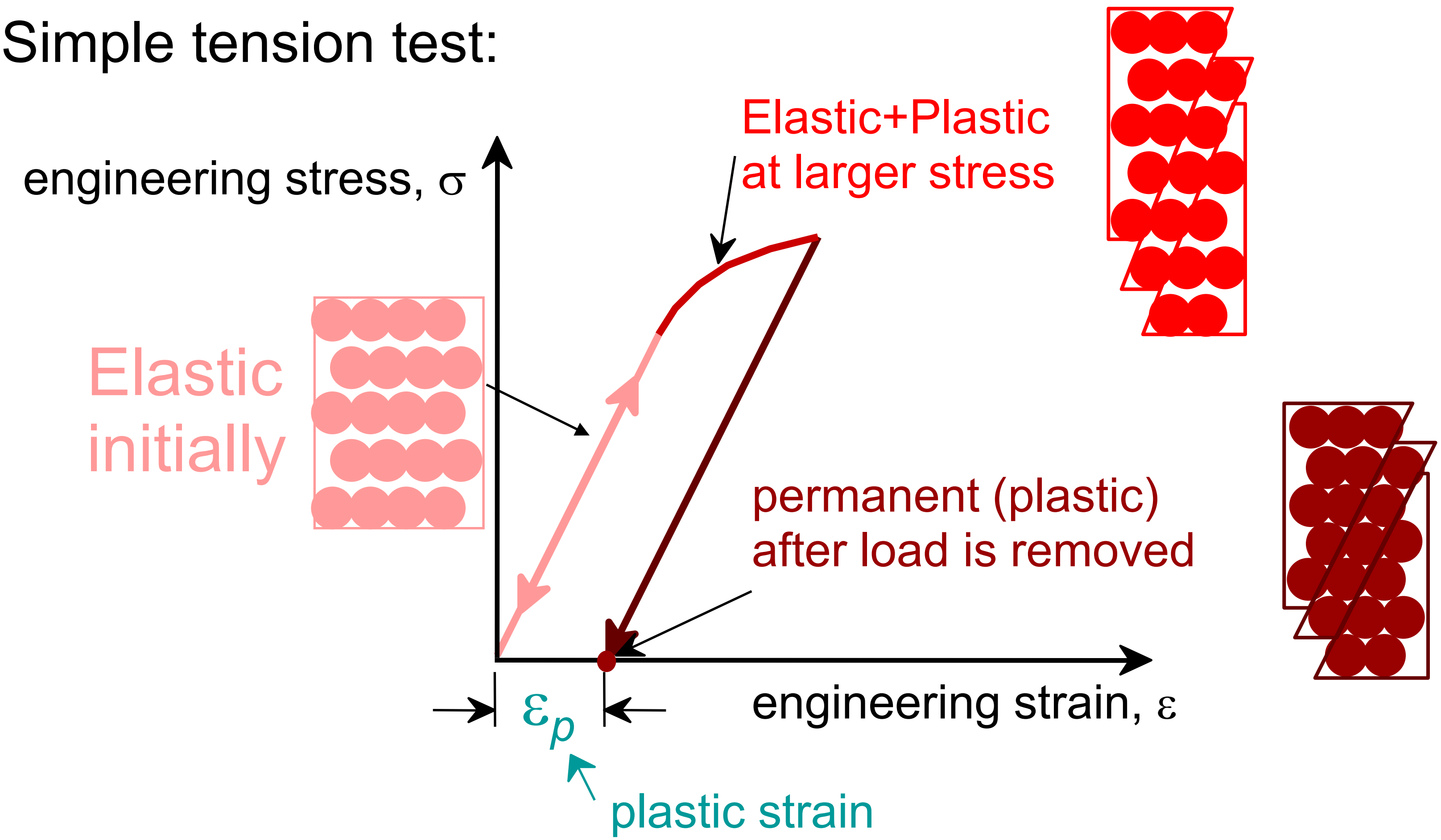
Room *T* values

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

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

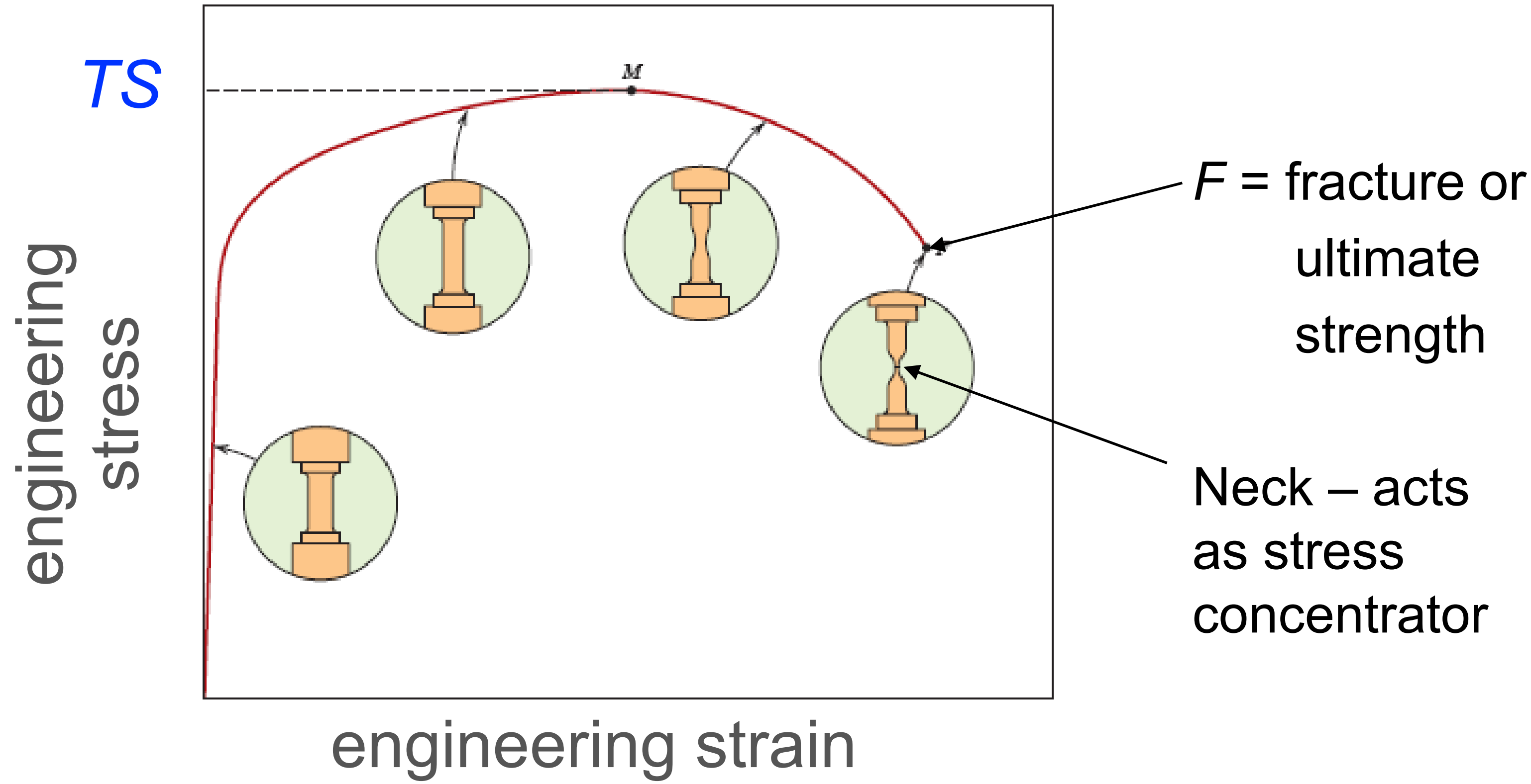
Plastic (Permanent) Deformation
(at lower temperatures, i.e. $T < T_{melt}/3$)

- Simple tension test:



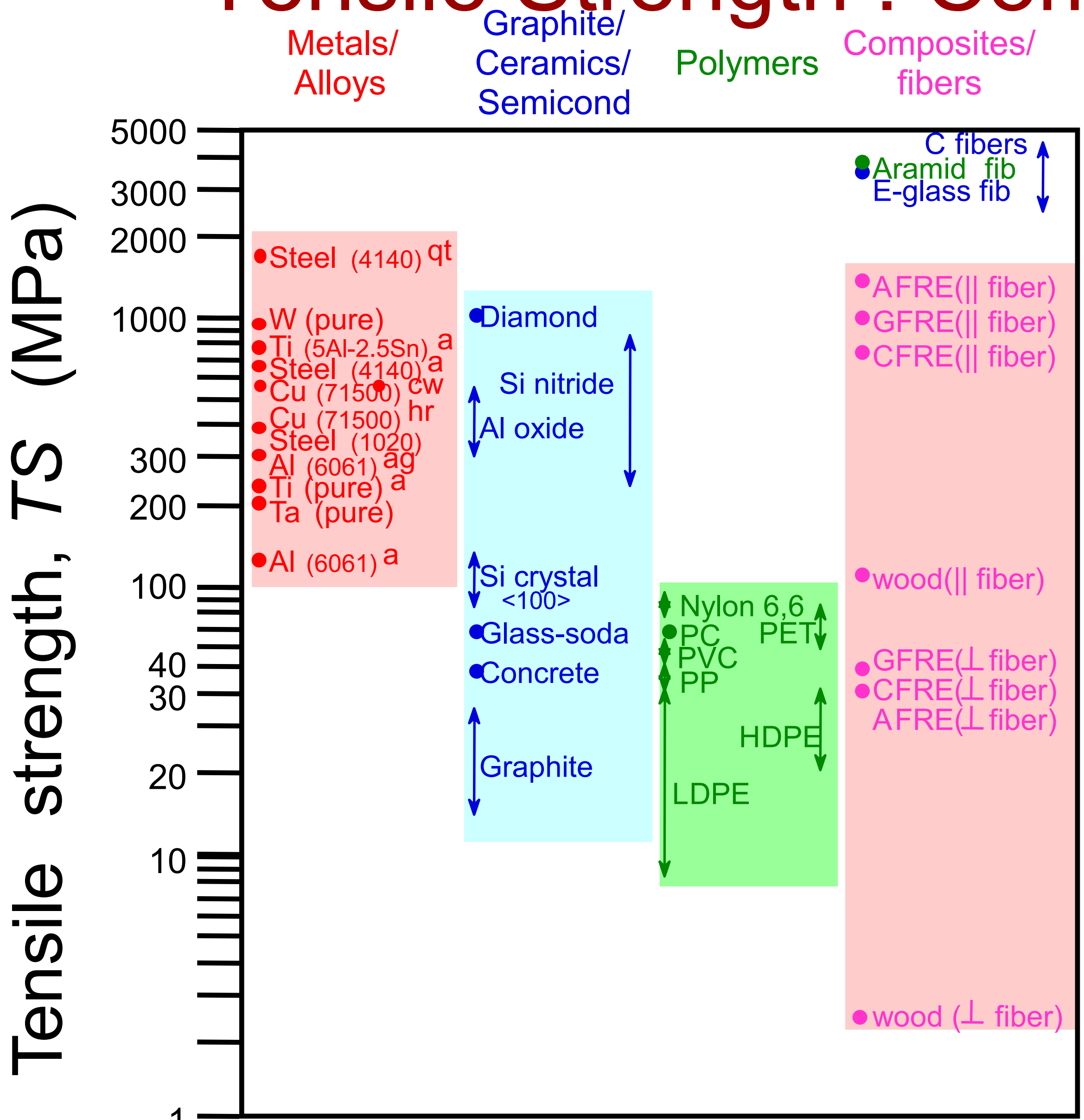
Tensile Strength, TS

• Maximum stress on engineering stress-strain curve.



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

Tensile Strength : Comparison



Room Temp. values

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

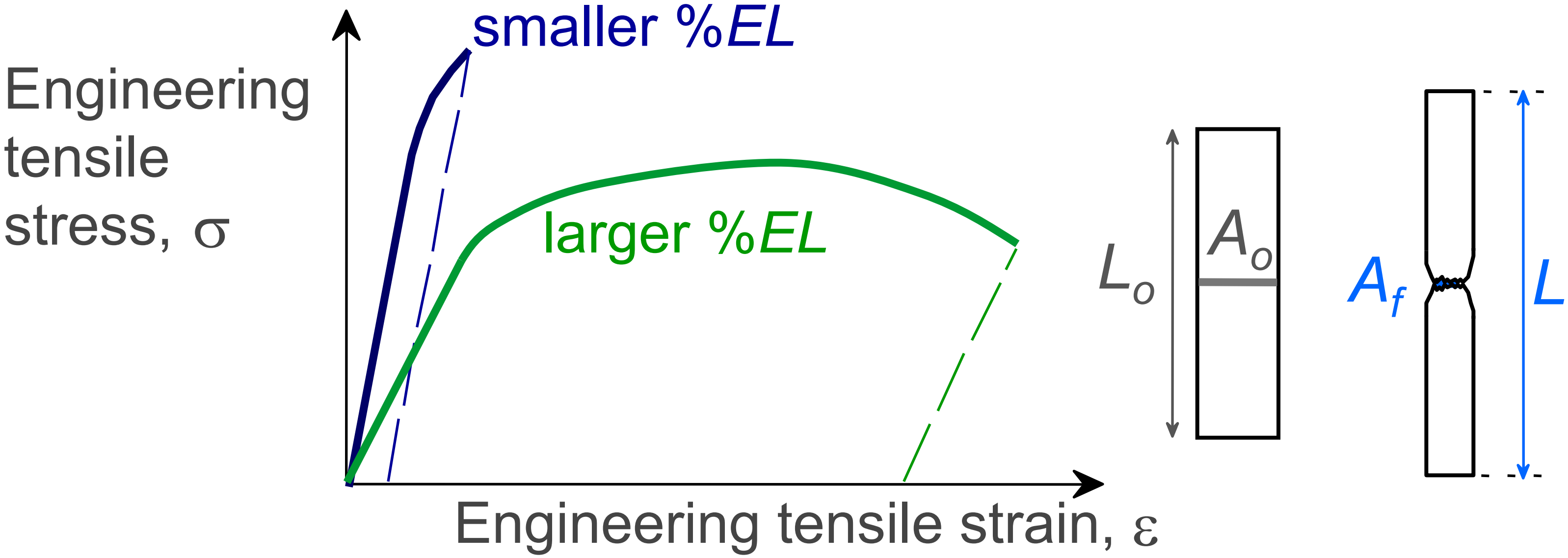
a = annealed
hr = hot rolled
ag = aged
cd = cold drawn
cw = cold worked
qt = quenched & tempered

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

Ductility

- Plastic tensile strain at failure:

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

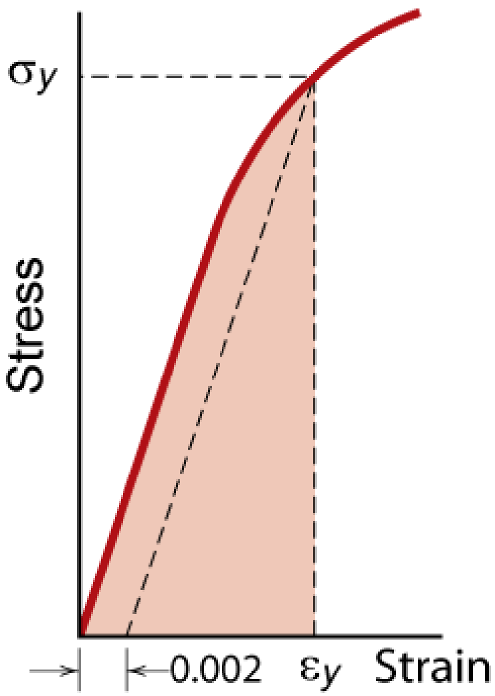


- Another ductility measure:

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

Resilience, U_r

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



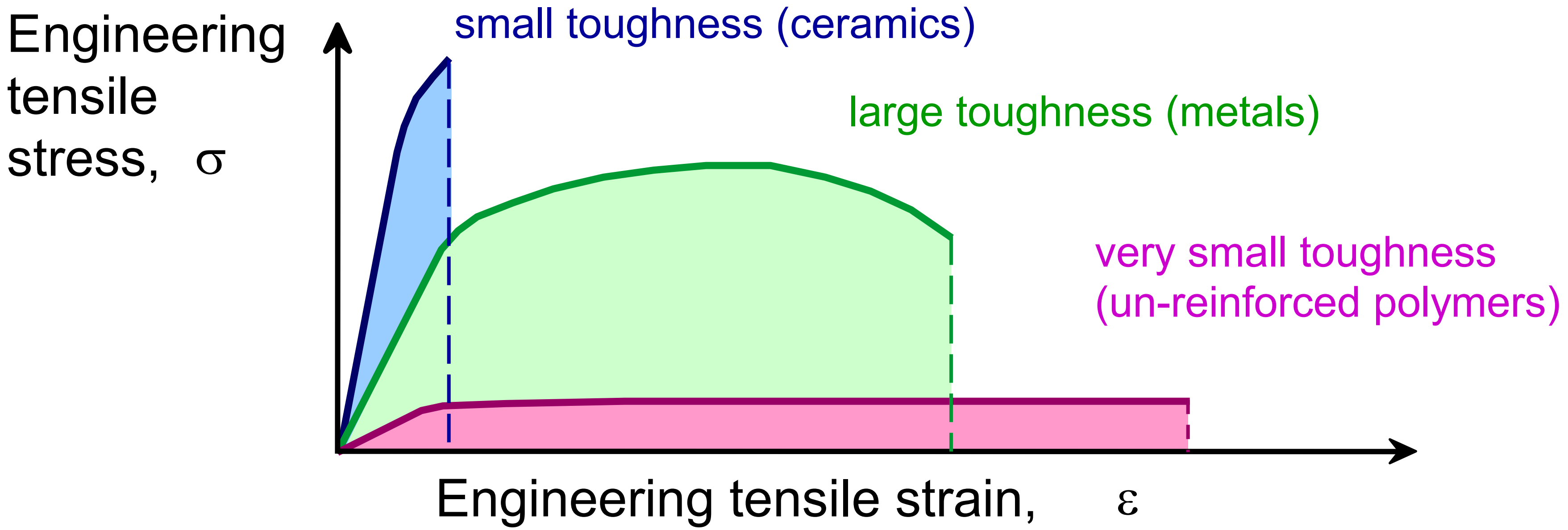
$$U_r = \int_0^{\varepsilon_y} \sigma d\varepsilon$$

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

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

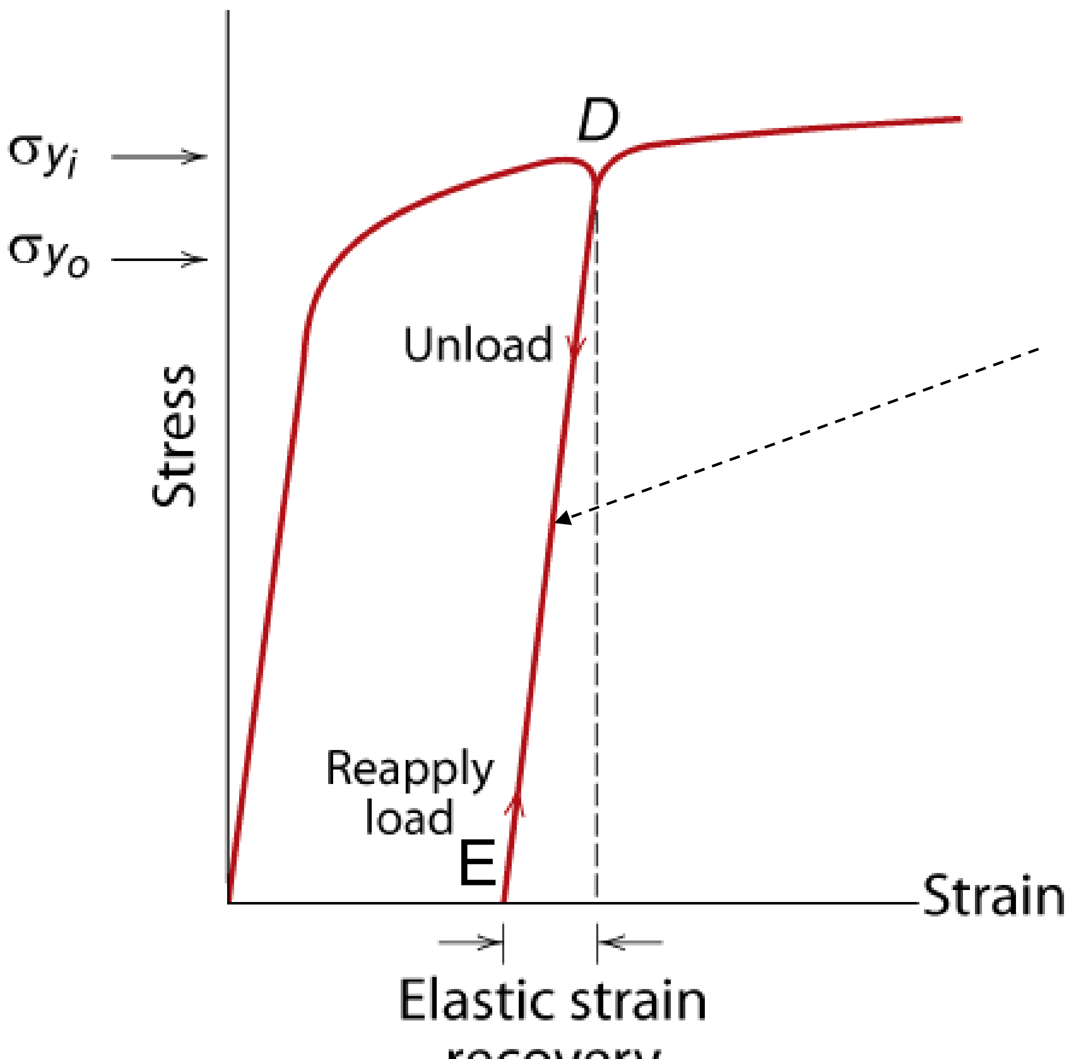
Toughness

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



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

Elastic Strain Recovery



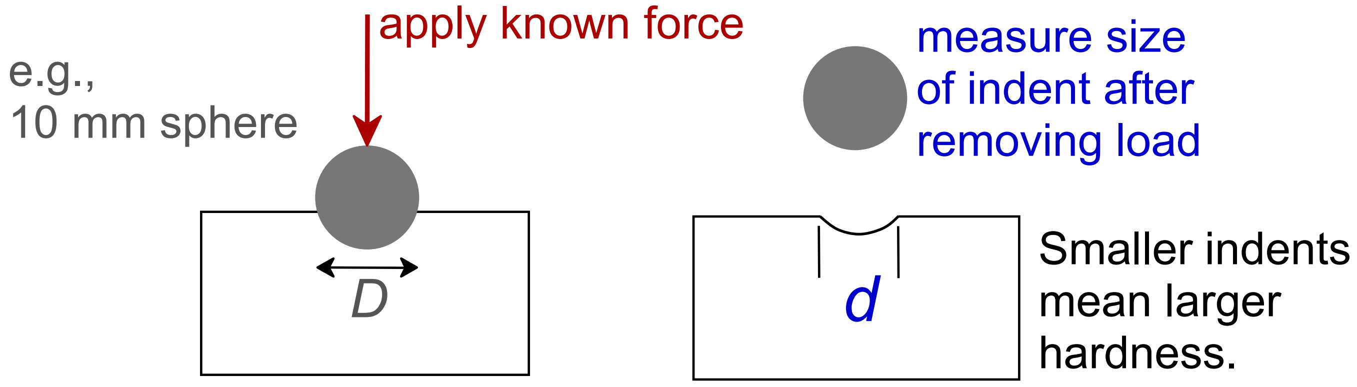
Strain hardening effect – the stress-strain curve will follow EF line when load is reapplied

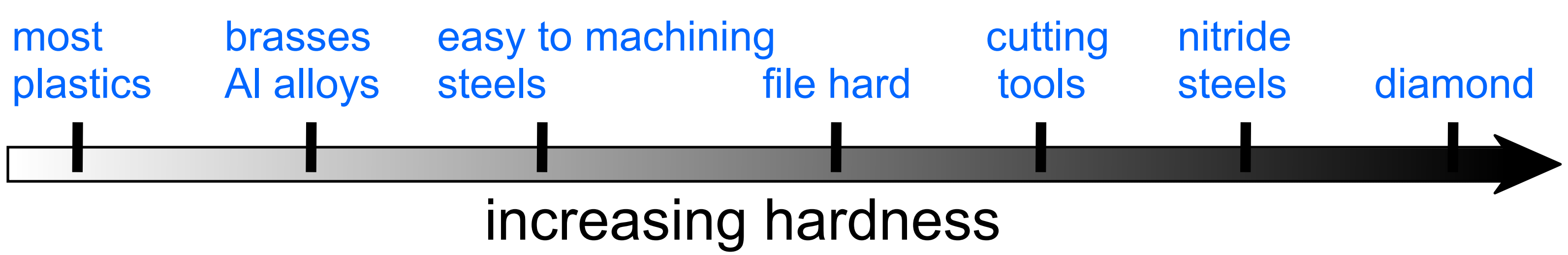
Strength of Metal

Metal Alloy	*Yield Strength MPa (ksi)*	*Tensile Strength MPa (ksi)*	*Ductility, %EL [in 50 mm (2 in.)]*
Aluminum	35 (5)	90 (13)	40
Copper	69 (10)	200 (29)	45
Brass (70Cu–30Zn)	75 (11)	300 (44)	68
Iron	130 (19)	262 (38)	45
Nickel	138 (20)	480 (70)	40
Steel (1020)	180 (26)	380 (55)	25
Titanium	450 (65)	520 (75)	25
Molybdenum	565 (82)	655 (95)	35

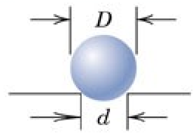
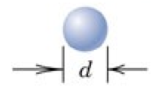
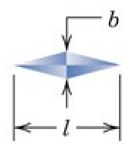
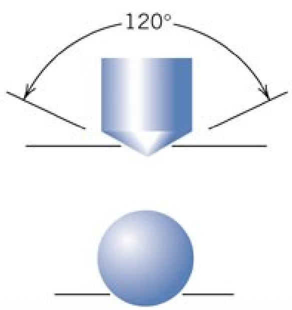
Hardness

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





Hardness: Measurement

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

[a] For the hardness formulas given, P (the applied load) is in kg, while D, d, d_1, and l are all in mm.

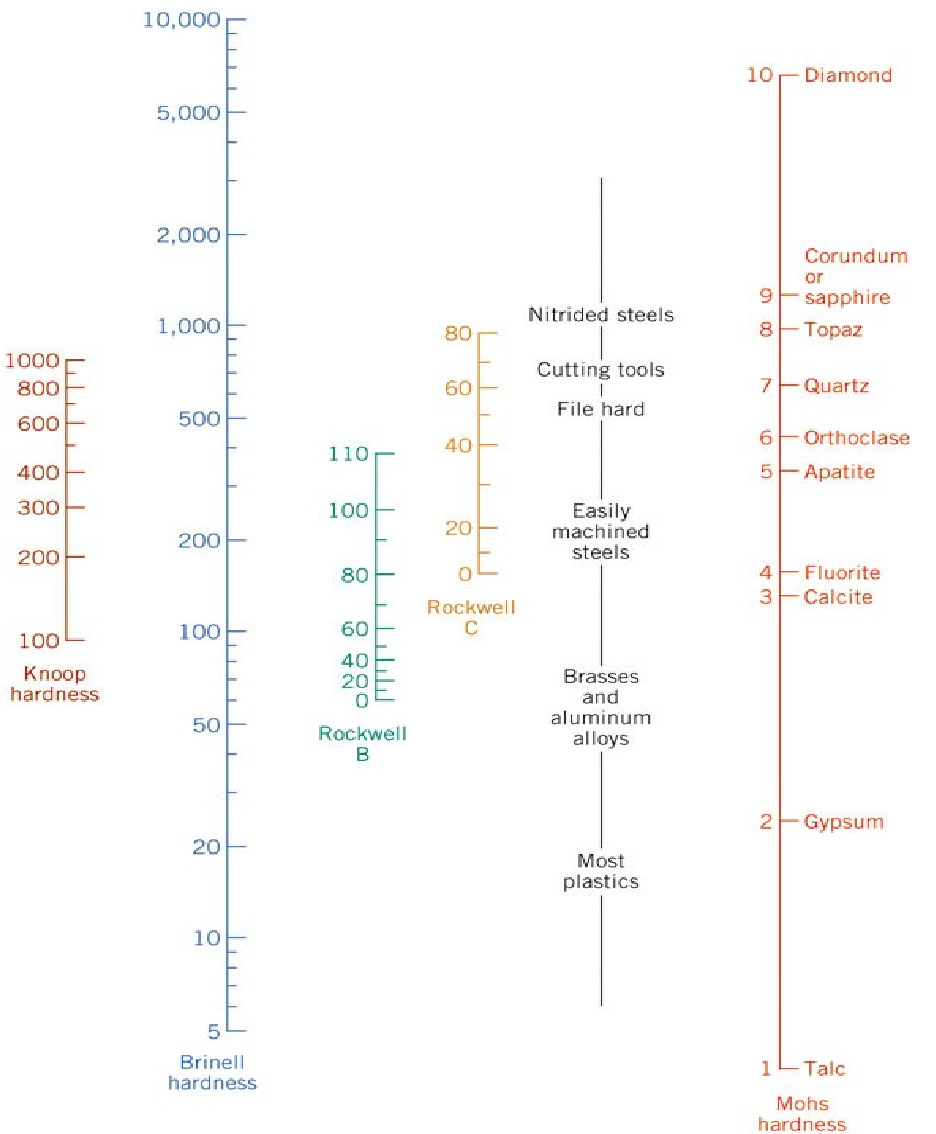
Source: Adapted from H. W. Hayden, W. G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*. Copyright © 1965 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.

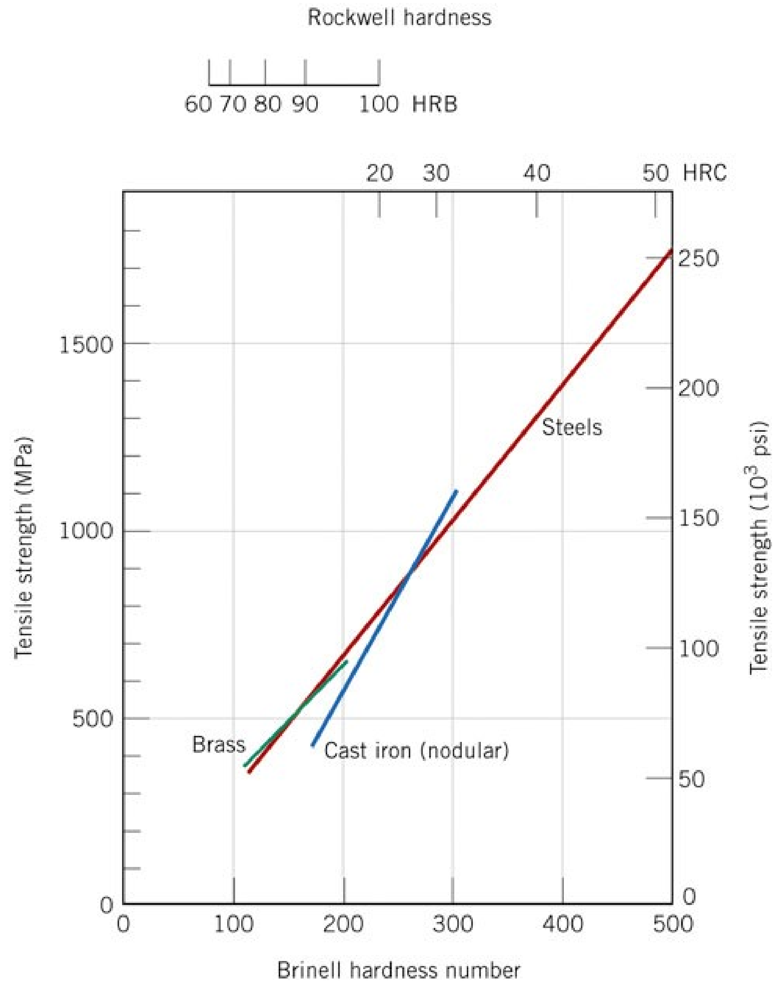
Hardness: Measurement

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

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

Hardness Scale Comparison

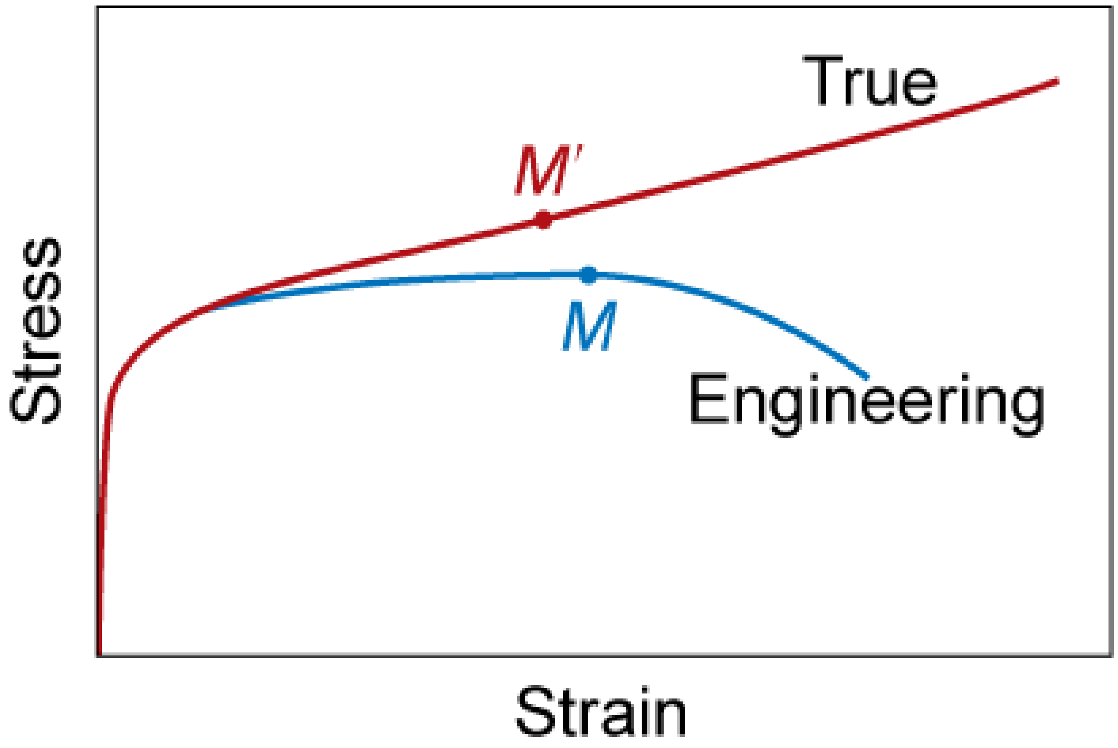




True Stress & Strain

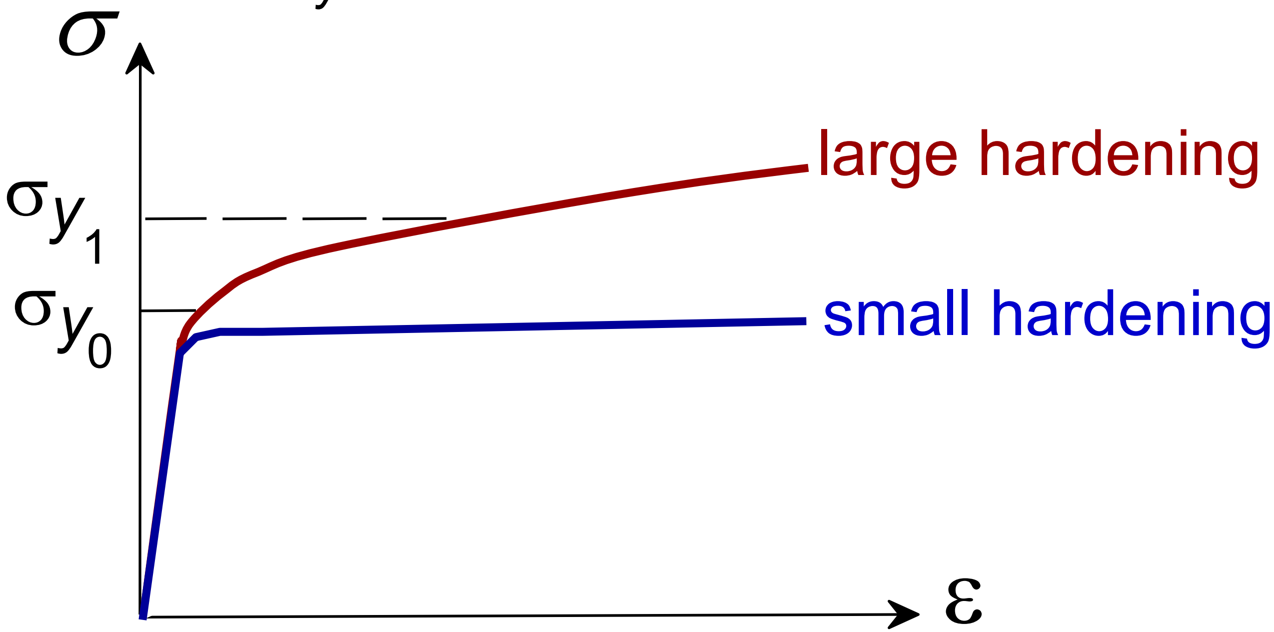
- True stress $\sigma_T = F/A_i$
- True strain $\varepsilon_T = \ln(\ell_i/\ell_o)$

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



Hardening

- An increase in σ_y due to plastic deformation.



- Curve fit to the stress-strain response:

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

"true" stress (F/A)

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

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

Fitting Parameters of Stress-Strain curve

		K	
Material	***n***	***MPa***	***psi***
Low-carbon steel (annealed)	0.21	600	87,000
4340 steel alloy (tempered @ 315°C)	0.12	2650	385,000
304 stainless steel (annealed)	0.44	1400	205,000
Copper (annealed)	0.44	530	76,500
Naval brass (annealed)	0.21	585	85,000
2024 aluminum alloy (heat treated—T3)	0.17	780	113,000
AZ-31B magnesium alloy (annealed)	0.16	450	66,000

Design or Safety Factors

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

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

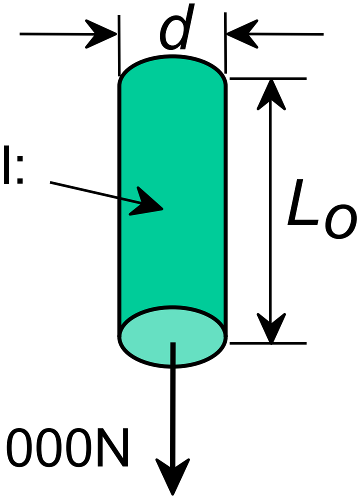
Often *N* is between 1.2 and 4

- 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.

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

$N = 5$

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



F = 220,000N

d = 0.067 m = 6.7 cm

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.