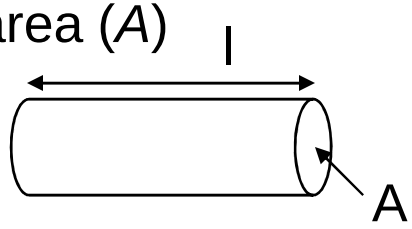
FE Review
Materials Properties

Jeffrey W. Fergus
Materials Engineering
Office: 284 Wilmore
Phone: 844-3405
email: jwfergus@eng.auburn.edu

Electrical Properties

- Electrical resistance
  - resistance (R) = resistivity (ρ) length (l) / area (A)
  - resistivity is a material property
  - conductivity (σ) = 1 / resistivity (ρ)



- Temperature dependence – with increasing temperature…
  - metals: resistance increases (conductivity decreases)
  - semiconductors: conductivity increases (resistivity decreases)
    - extrinsic: like metals in intermediate temperatures
  - insulators: conductivity increases (resistivity decreases)

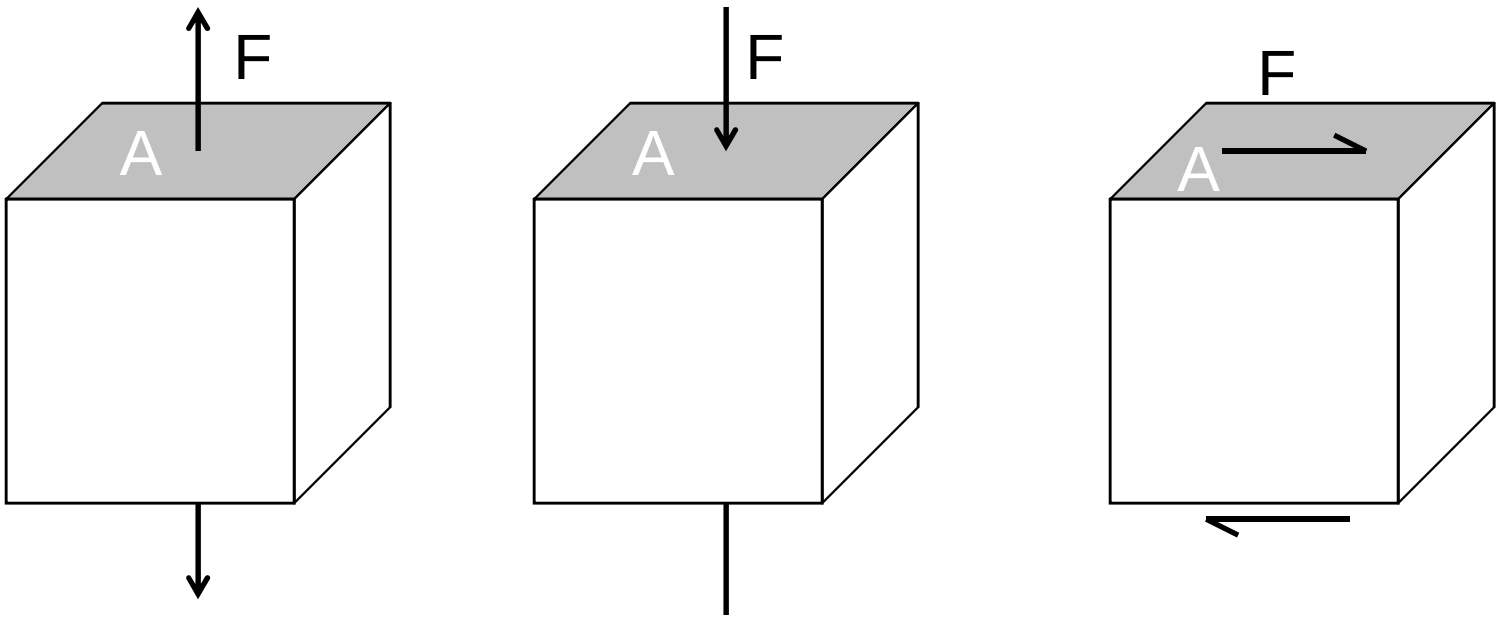
Mechanical Properties

- Stress-strain relationships
  - engineering stress and strain
  - stress-strain curve
- Testing methods
  - tensile test
  - endurance test
  - impact test

Stress

$$\text{Normal} = \sigma = \frac{F}{A}$$

$$\text{Shear} = \tau = \frac{F}{A}$$

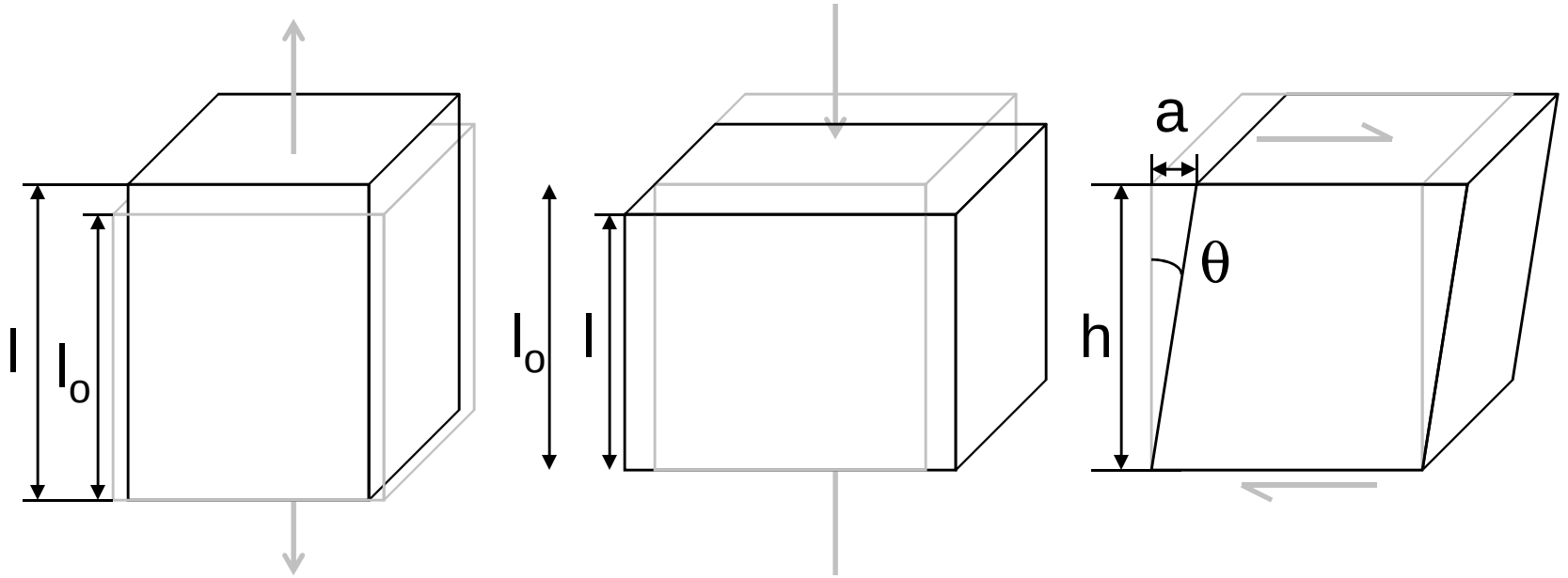


Tension: $\sigma>0$ Compression: $\sigma<0$

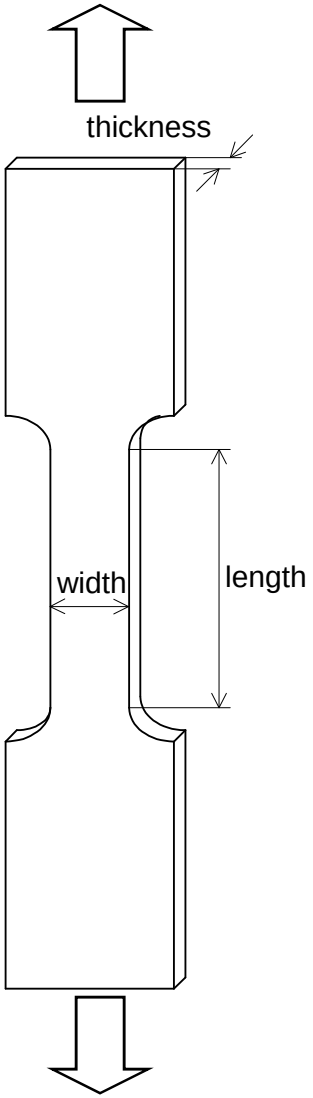
Strain

$$\text{Strain} = \varepsilon = \frac{l - l_o}{l_o} = \frac{\Delta l}{l_o}$$

$$\text{Shear strain} = \gamma = \frac{a}{h} = \tan\theta$$



Tensile Test



Control length (l)

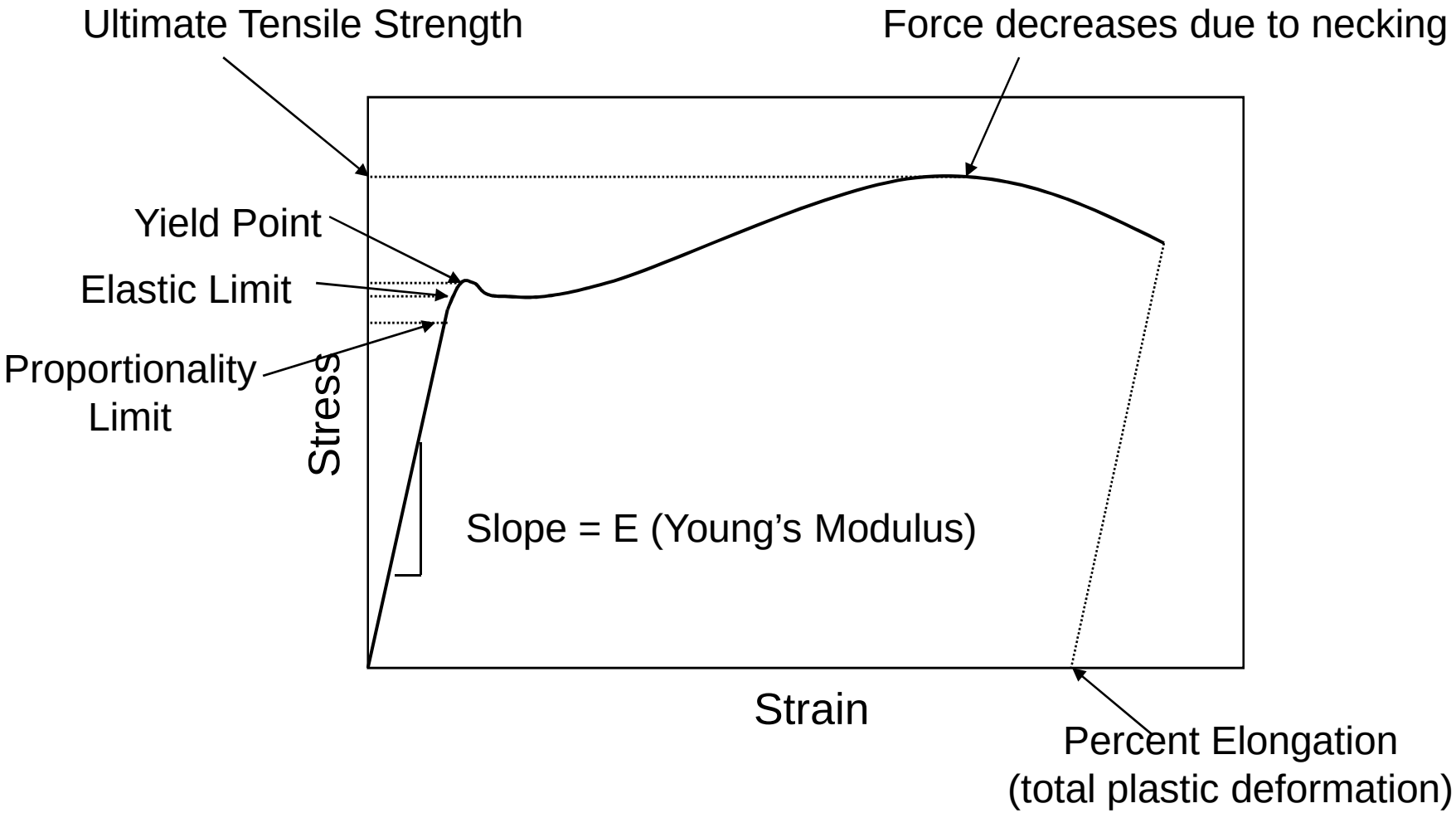
$$\text{Strain} = \varepsilon = \frac{l - l_o}{l_o} = \frac{\Delta l}{l_o}$$

Measure force (F) with load cell

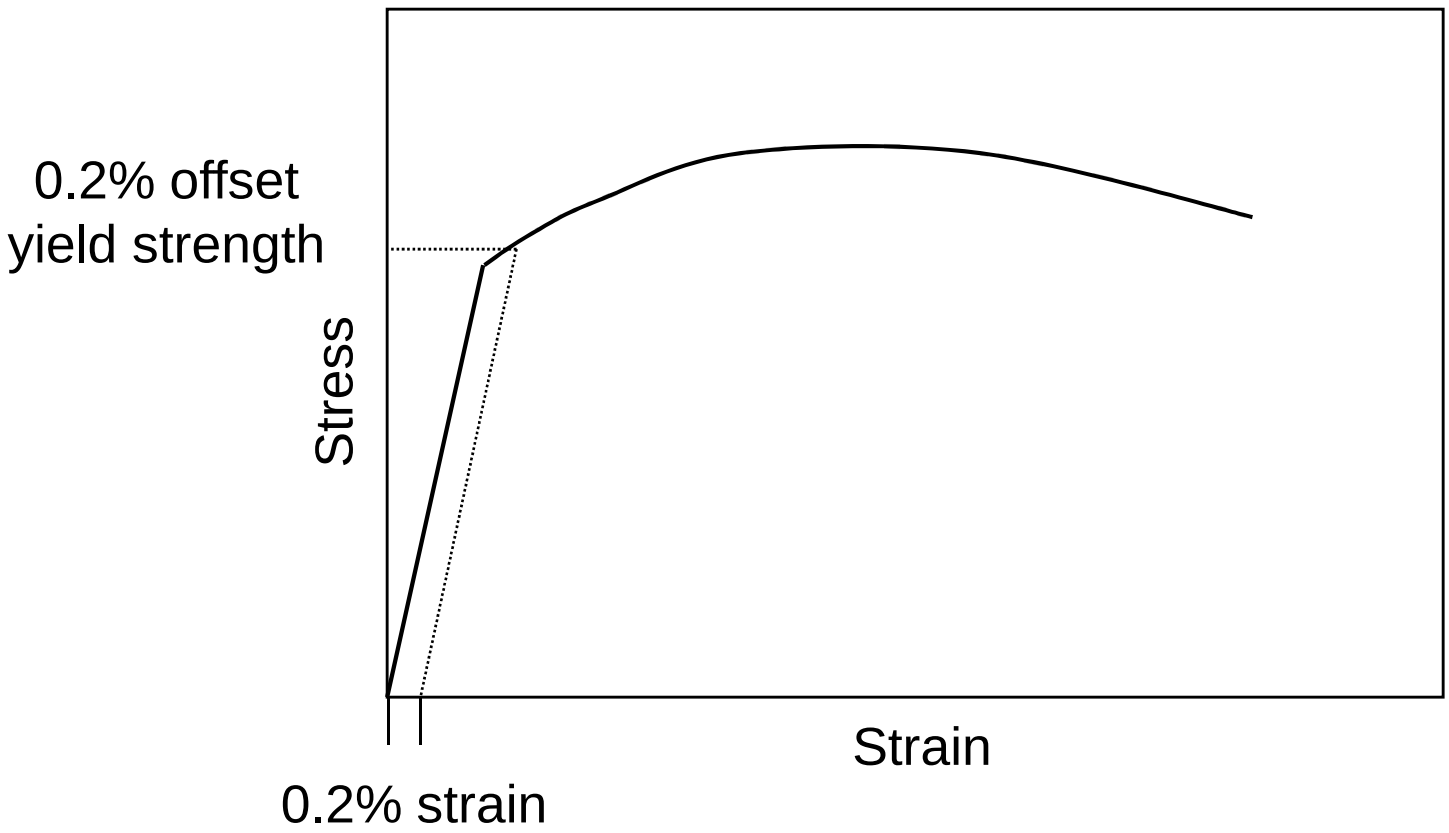
$$\text{Stress} = \sigma = \frac{F}{A} = \frac{F}{w \cdot t}$$

Reduced section used to limit portion of sample undergoing deformation

Stress-Strain Curve



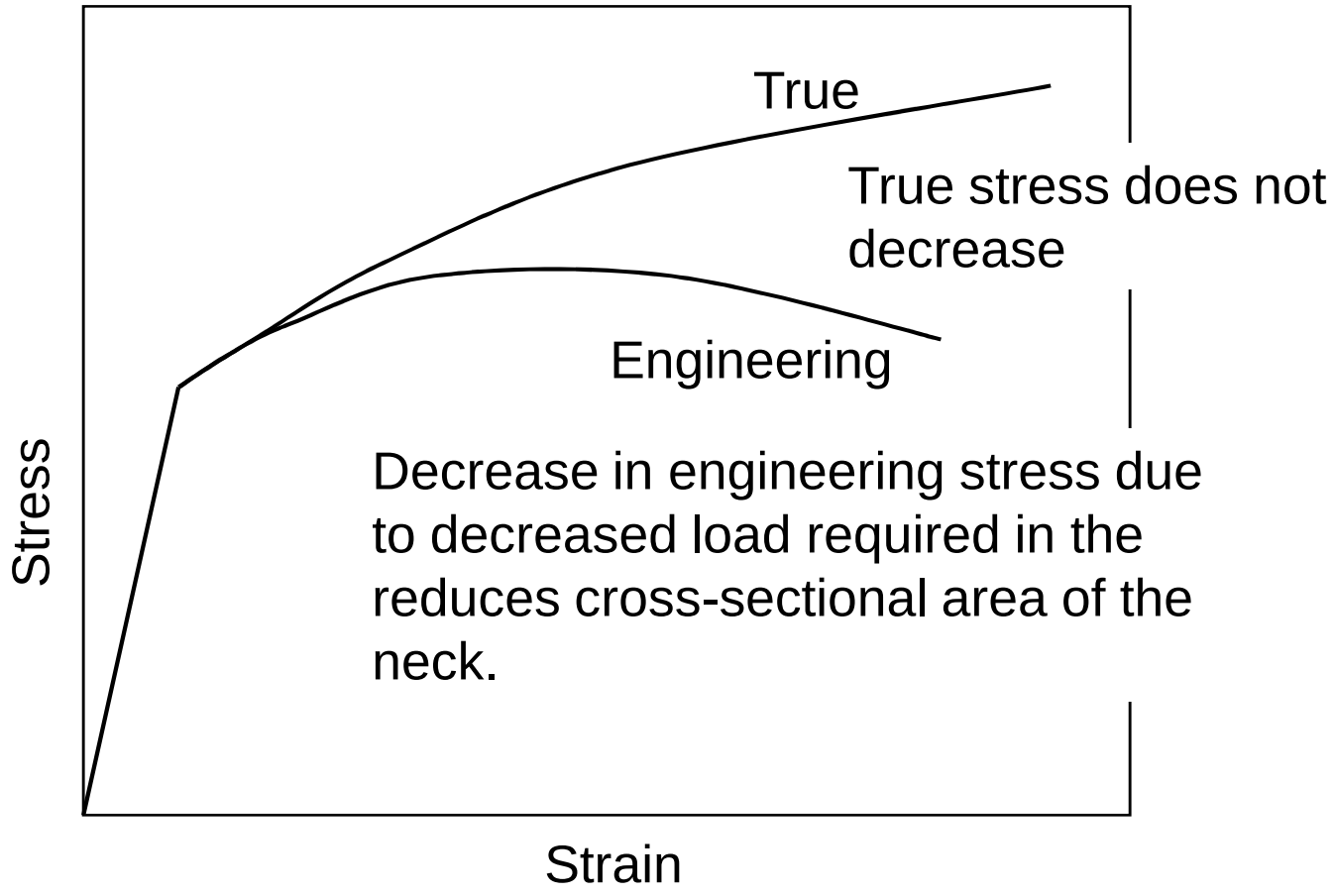
0.2% Offset Yield Strength



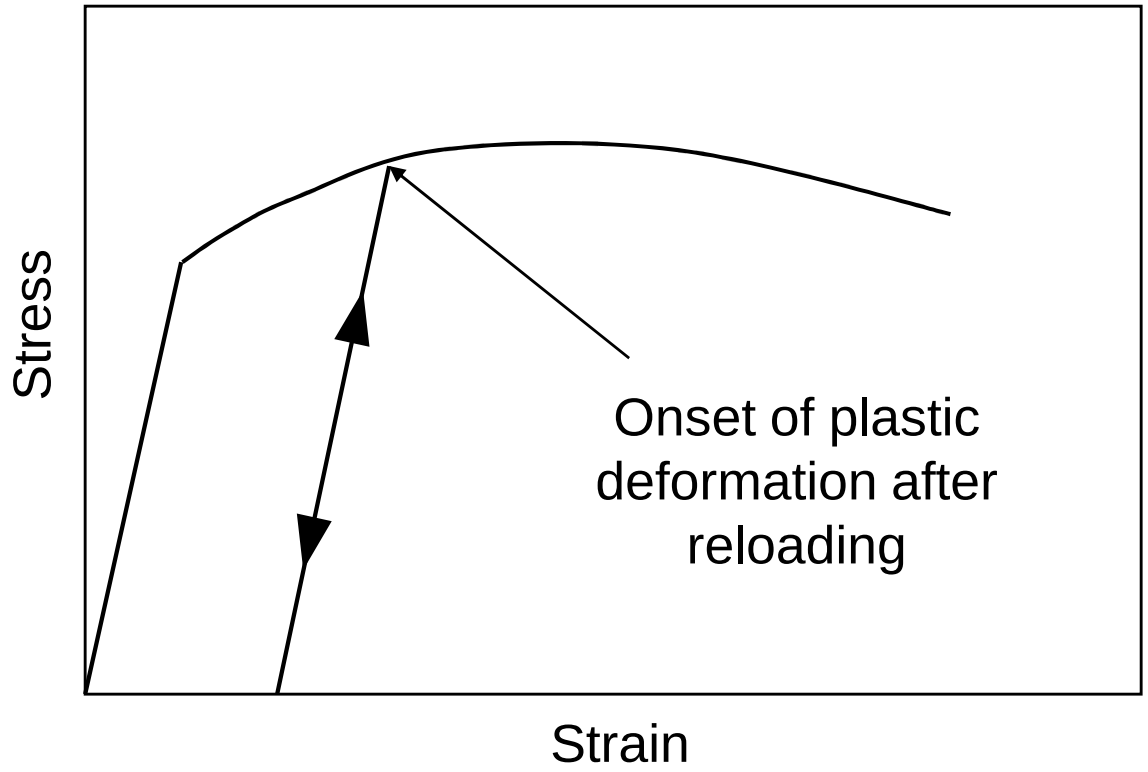
True/Engineering Stress/Strain

	Stress	Strain
Engineering (initial dimensions)	$\sigma_E = \frac{F}{A_o}$	$\varepsilon_E = \frac{l - l_o}{l_o} = \frac{\Delta l}{l_o}$
True (instantaneous dimensions)	$\sigma_T = \frac{F}{A_i}$	$\varepsilon_T = \int_{l_o}^{l_i} \frac{dl}{l} = ln\left(\frac{l_i}{l_o}\right)$
	Using $\longrightarrow$ and $A_i \cdot l_i = A_o \cdot l_o$ $\sigma_T = \sigma_E(1+\varepsilon_E)$	$\longrightarrow$ $\varepsilon_T = ln(\varepsilon_E + 1)$

True/Engineering Stress/Strain



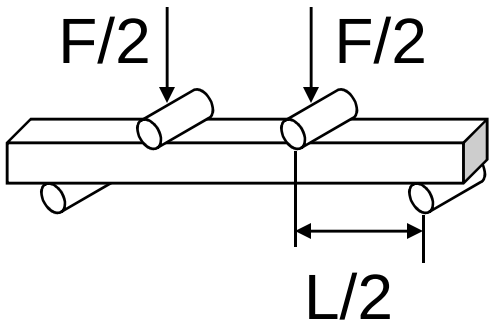
Strain Hardening



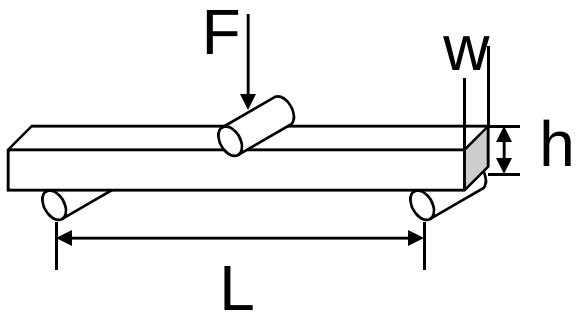
Plastic deformation require larger load after deformation. Sample dimensions are decreased, so stress is even higher

Bending Test

Four-point



Three-point



By summing moment in cantilever beam

$$\sigma_{max} = \frac{3FL}{2wh^2}$$

Tension at bottom, compression at top

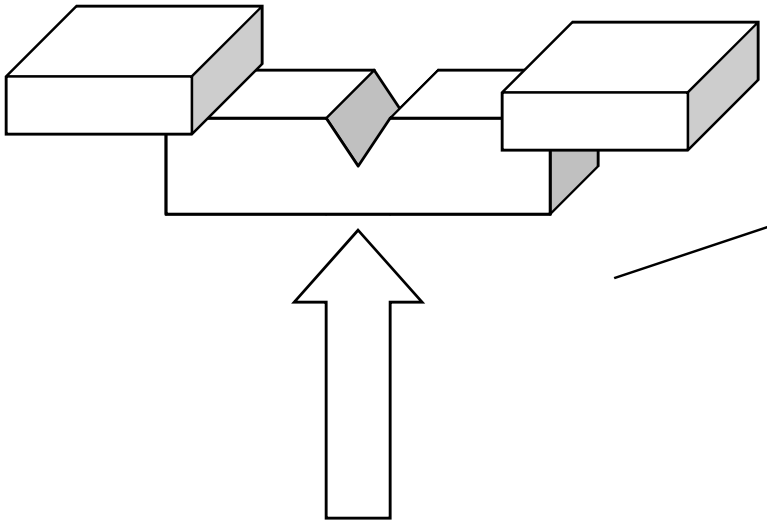
Hardness

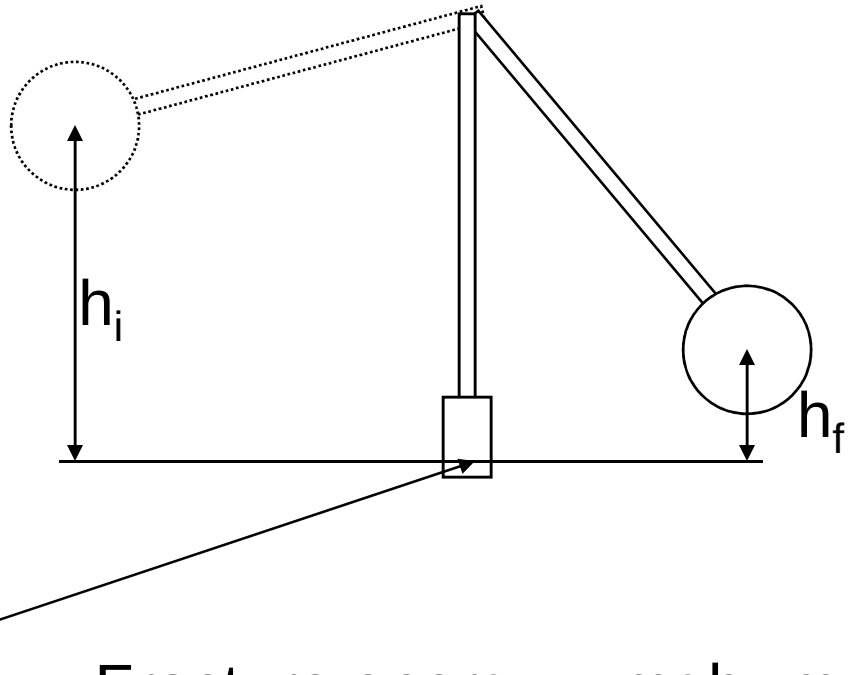
- Resistance to plastic deformation
- Related to yield strength
- Most common indentation test
  - make indentation
  - measure size or depth of indentation
  - macro- and micro- tests
- Scales: Rockwell, Brinell, Vickers, Knoop

Impact

Toughness: combination of strength and ductility - energy for fracture

Charpy V-notch

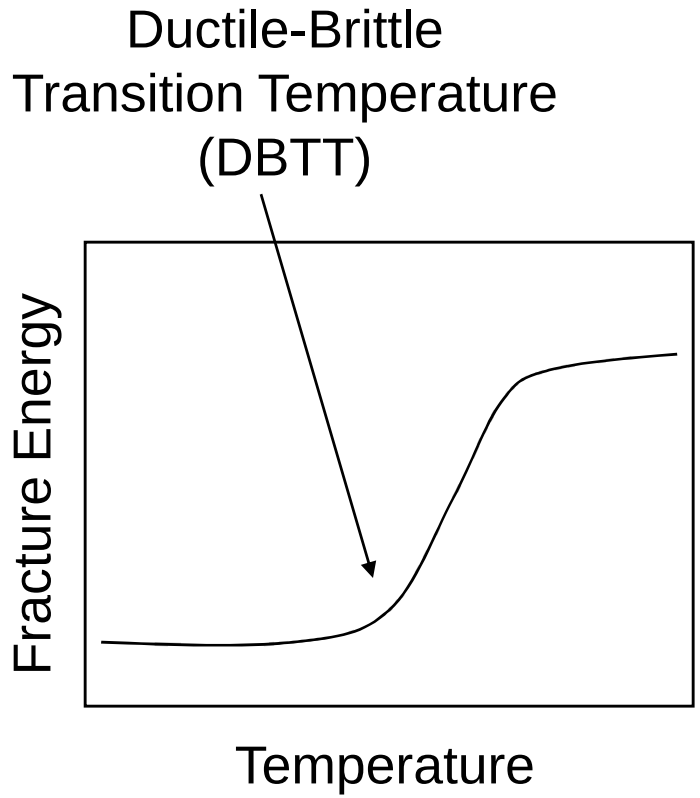




Fracture energy = $mgh_i - mgh_f$

Ductile-Brittle Failure

- Ductile
  - plastic deformation
  - cup-cone / fibrous fracture surface
- Brittle
  - little or no plastic deformation
  - cleaved fracture surface

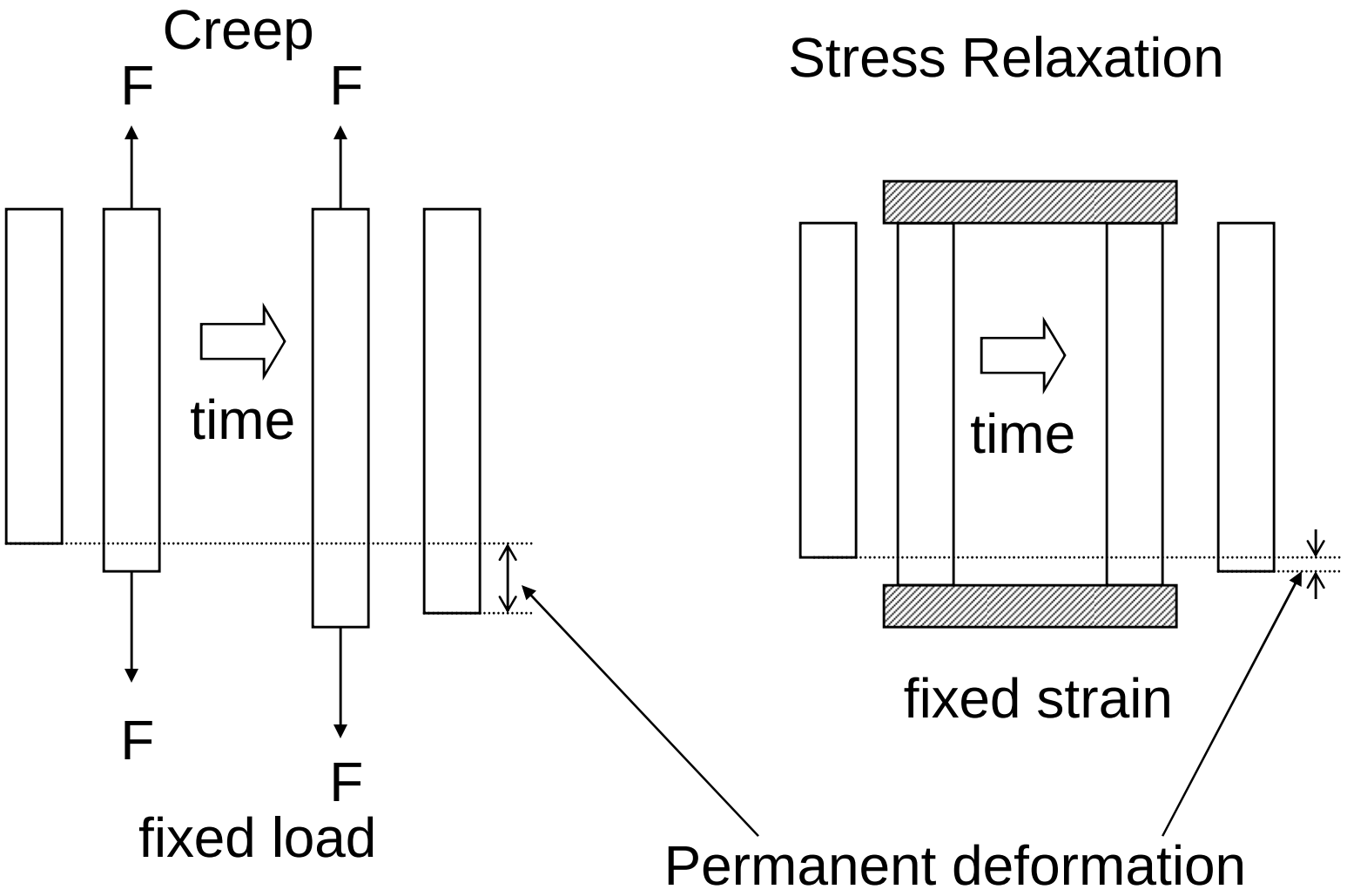


Creep / Stress Relaxation

- Load below yield strength - elastic deformation only
- Over long time plastic deformation occurs
- Requires diffusion, so usually a high-temperature process
- Activation energy, Q (or E_A)

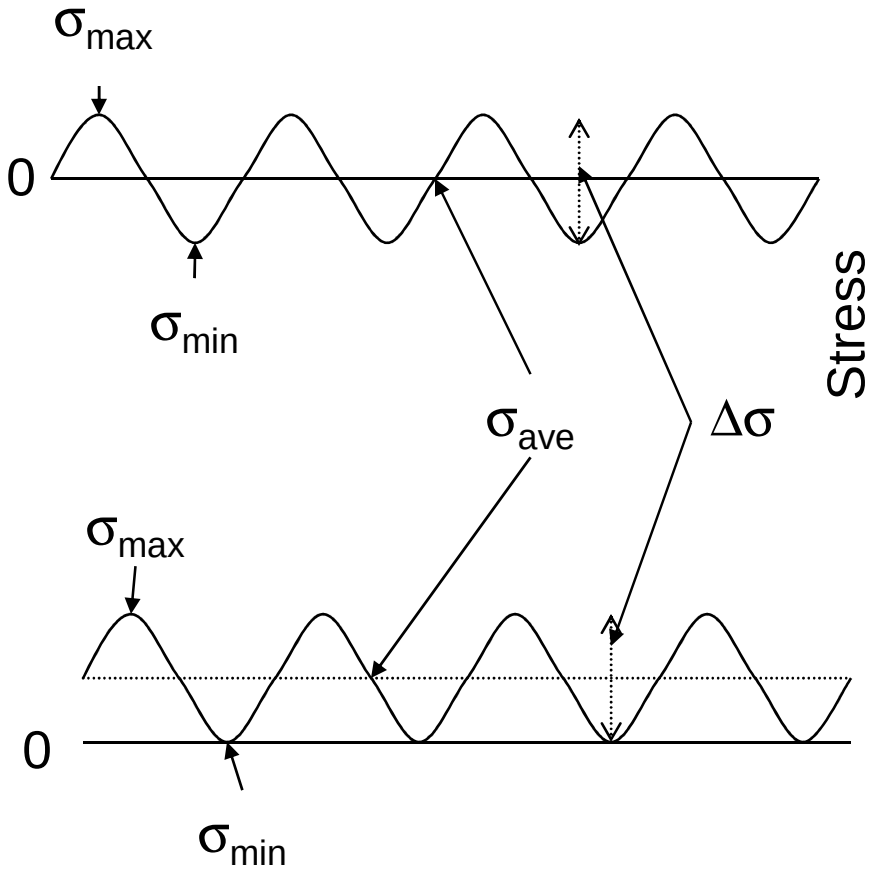
$$\text{creep rate} = \dot{\varepsilon} = A \cdot exp\left(\frac{-Q}{RT}\right) = A \cdot exp\left(\frac{-E_A}{kT}\right)$$

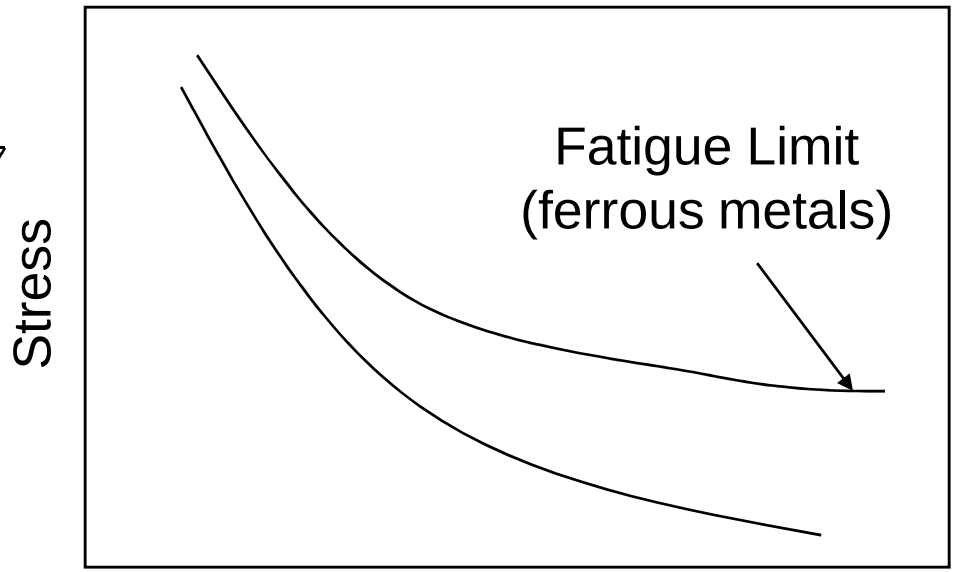
Creep /Stress Relaxation



Fatigue

Repeated application of load - number of cycles, rather than time important.





Corrosion Resistance

- Thermodynamics vs. Kinetics
  - thermodynamics - stable phases
  - kinetic - rate to form stable phases
- Active vs. Passive
  - active: reaction products ions or gas - non protective
  - passive: reaction products - protective layer
- Corrosion resistance
  - inert (noble): gold, platinum
  - passivation: aluminum oxide (alumina) on aluminum, chromia on stainless steel

Electrode Potential

- Tendency of metal to give up electron
- Oxidation (anode)
  - $M = M^{2+} + 2e^-$ (loss electrons)
- Reduction (cathode)
  - $M^{2+} + 2e^- = M$ (gain electrons)
- LEO (loss electrons oxidation) goes GER (gain electrons reduction)

Corrosion Reactions

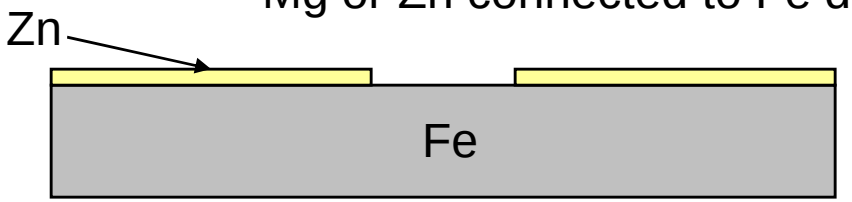
- Oxidation - metal (anode)
  - $M = M^{2+} + 2e^-$
- Reduction - in solution (cathode)
  - $2H^+ + 2e^- = H_2$
  - $2H^+ + ½O_2 + 2e^- = H_2O$
  - $H_2O + ½O_2 + 2e^- = 2OH^-$
- Overall Reactions
  - $M + 2H^+ = M^{2+} + H_2$
  - $M + 2H^+ + ½O_2 = M^{2+} + H_2O$
  - $M + H_2O + ½O_2 = M^{2+} + 2OH^- = M(OH)_2$

Electromotive Force

- Gibbs Free Energy (ΔG) =-nFE (Electromotive Force)
  - n = number of electrons, F = Faraday's Constant
  - favorable: energy decrease (-) = positive voltage
- $Fe^{2+} + 2e^- = Fe$: $E_{red} = +0.440$ V
- $Fe = Fe^{2+} + 2e^-$: $E_{ox} = -0.440$ V
- $H_2O = 2H^+ + ½O_2 + 2e$-: $E_{red} = +1.229$ V
- $Fe + 2H^+ + ½O_2 = Fe^{2+} + H_2O$: $E = 0.789$ V
  - E does not change with number of moles (ΔG does)
  - E must be corrected for non-standard state
    - concentration of H^+ (i.e. pH), oxygen pressure…

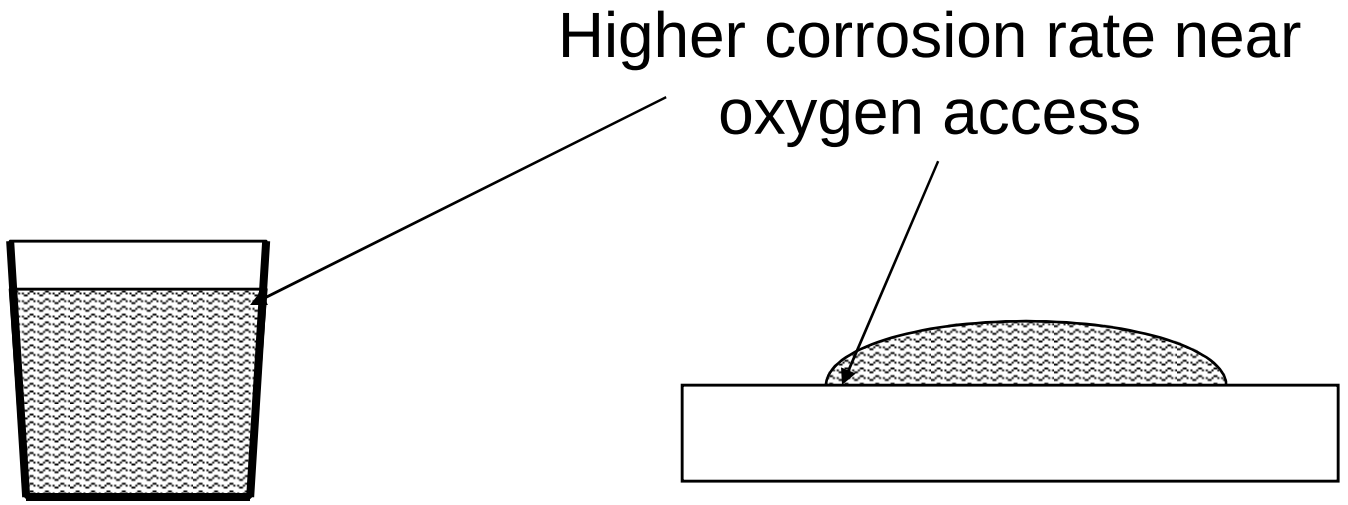
Galvanic Corrosion / Protection

- At joint between dissimilar metals
  - reaction rate of active metal increases
  - reaction of less active metal decreases
- Galvanic corrosion
  - high corrosion rate at galvanic couple
    - presence of Cu increase the local corrosion rate of Fe
- Galvanic protection
  - galvanized steel
    - presence of Zn decreases the local corrosion rate of Fe
  - galvanic protection
    - Mg or Zn connected to Fe decrease corrosion rate



Waterline Corrosion

- Oxygen concentration in water leads to variation in local corrosion rates



Rust just below water surface

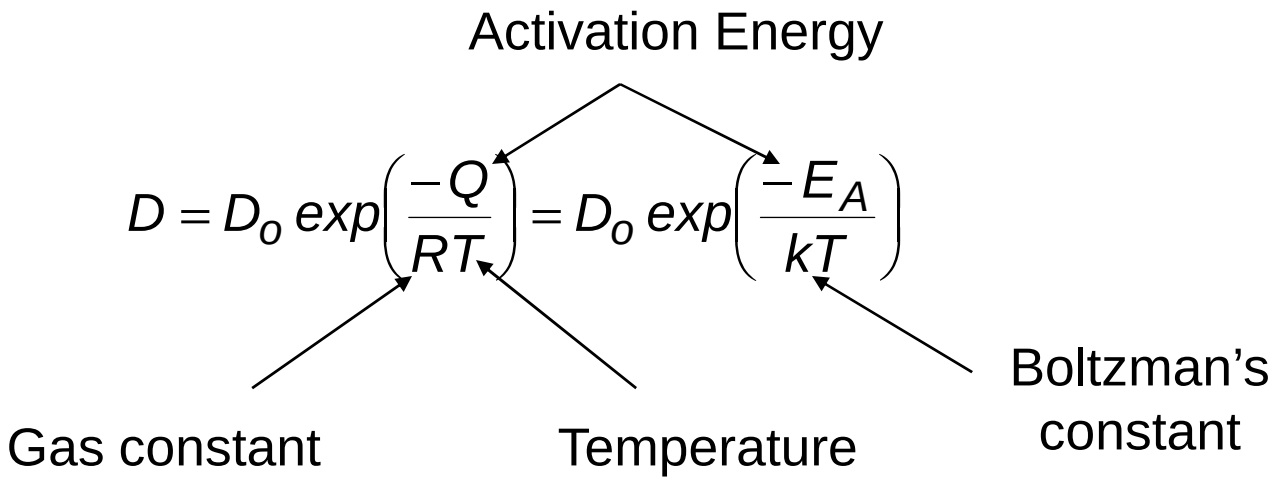
Rings of rust left from water drops

Materials Processing

- Diffusion
- Phase Diagrams
  - Gibb's phase rule
  - lever rule
  - eutectic system / microconstituents
  - Fe-Fe_3C diagram (ferrous metals)
- Thermal-mechanical processing

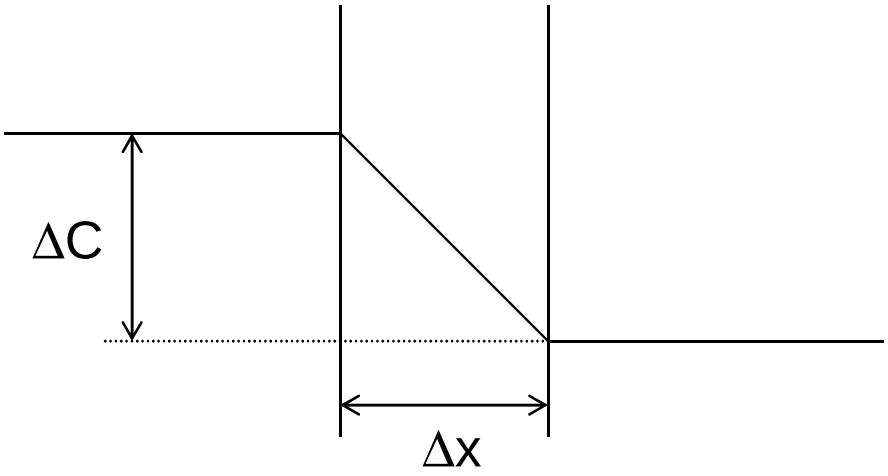
Diffusion

- Atoms moving within solid state
- Required defects (*e.g.* vacancies)
- Diffusion thermally activated
- Diffusion constant follows Arrhenius relationship



Steady-State Diffusion

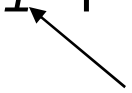
- Fick's first law (1-D) $$J = -D\left(\frac{\partial C}{\partial x}\right)$$
- J = flux (amount/area/time)
- For steady state $$J = -D\left(\frac{\Delta C}{\Delta x}\right)$$



$$J = -\left(\frac{m^2}{s}\right)\left(\frac{\frac{mass}{m^3}}{m}\right) = \frac{mass}{m^2 s}$$

Phase Equilibria

- Gibb's Phase Rule
- P + F = C + 2 (Police Force = Cops + 2)
  - P = number of phases
  - F = degrees of freedom
  - C = number of components (undivided units)
  - 2: Temperature and Pressure
- One-component system
  - F = 1 + 2 - P = 3 - P
- Two-component system
  - F = 2 + 2 - P = 4 - P
- Two-component system at constant pressure
  - F = 2 + *1* - P = 3 - P



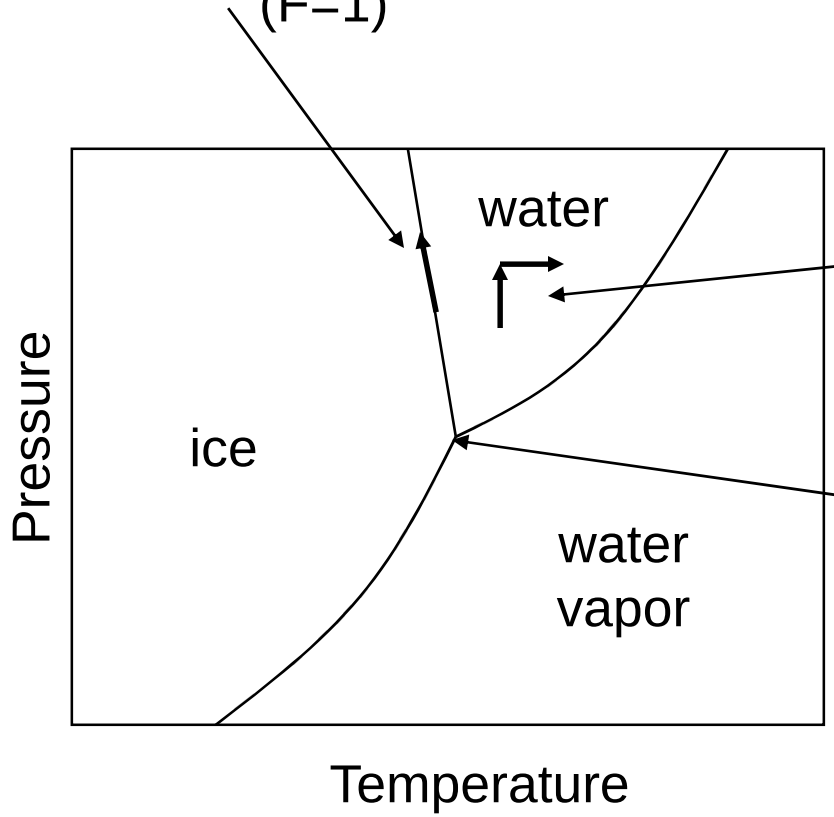
"2" becomes "1" at constant pressure

Pressure-Temperature Diagram

One component: H_2O

If formation of H_2 and O_2 were considered there would be two components (H and O)

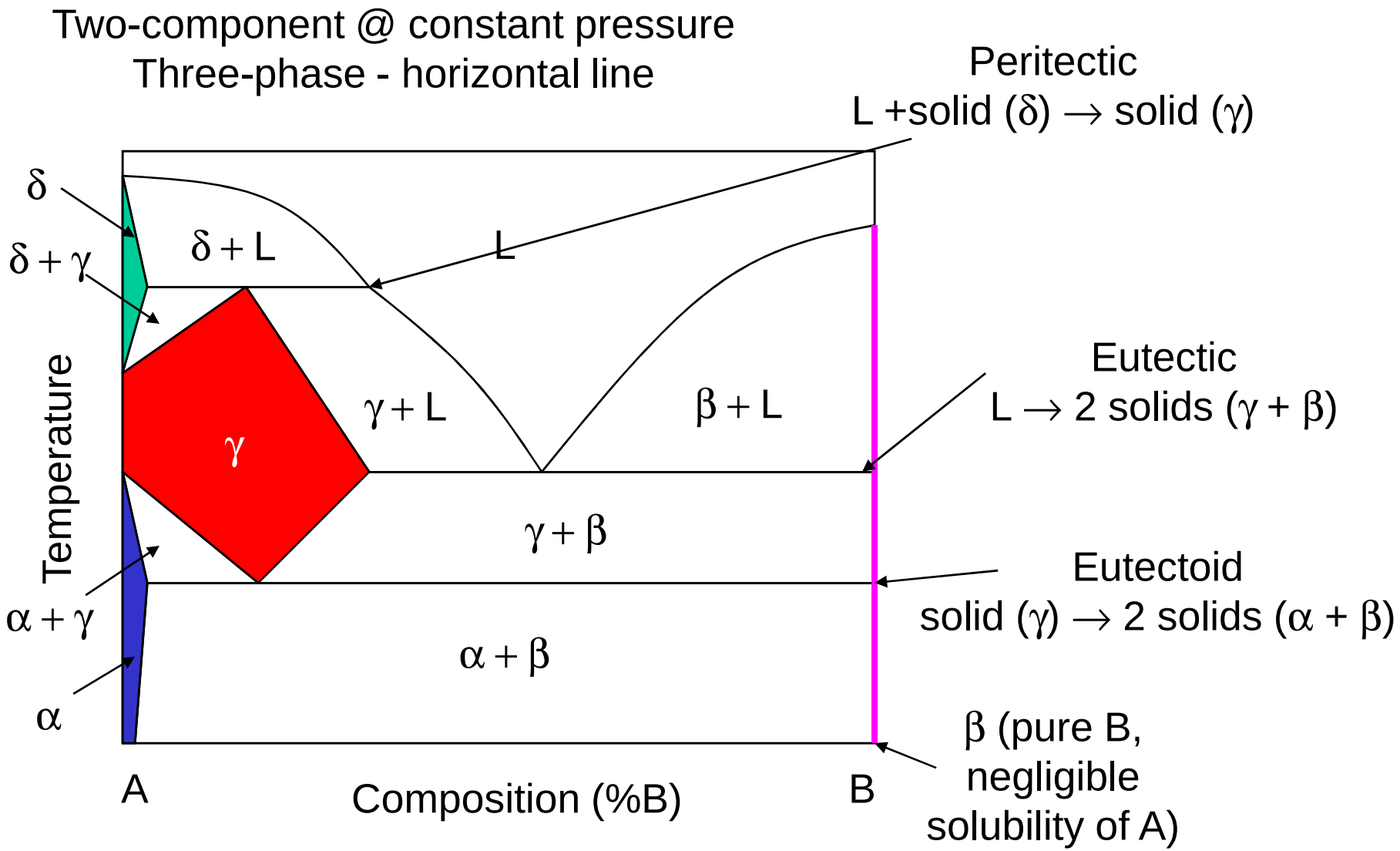
Two-phase line: Change T (P) require specific change in P (T) (F=1)



Single-phase area: can change T and P independently (F=2)

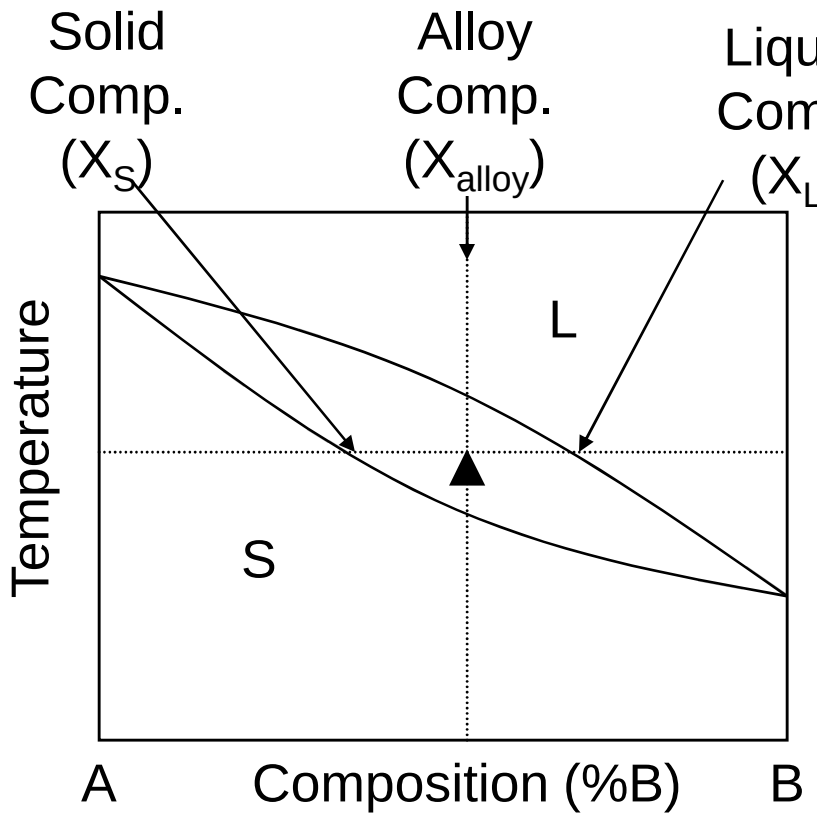
Three-phase point: One occurs at specific T and P (triple point) (F=0)

Phase Diagrams



Lever Law

- Phase diagram give compositions of phases
  - two-phase boundaries in 2-phase mixture
- Mass balance generate lever law



Opposite arm over total length

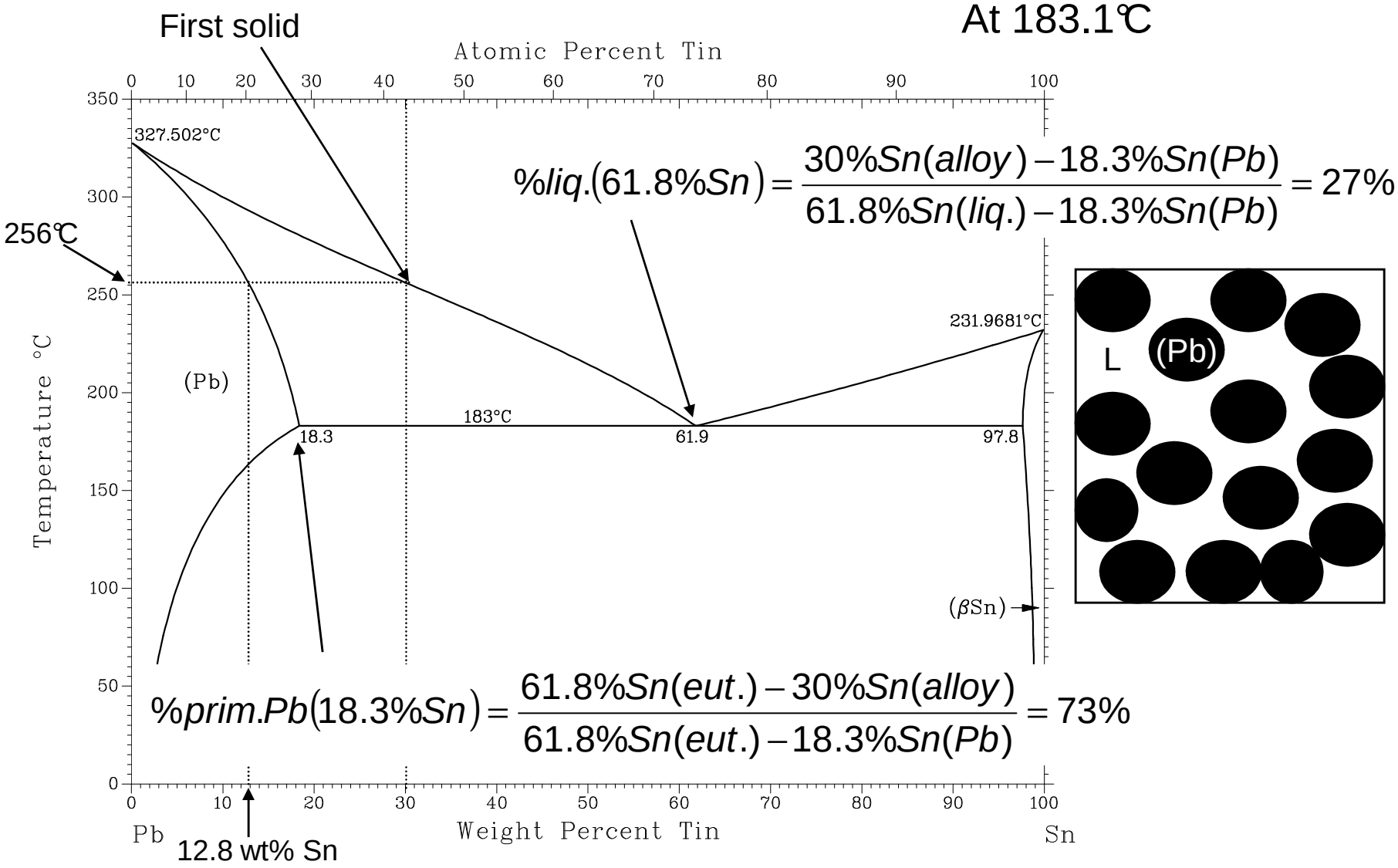
Right arm for solid

$$\%solid = \frac{X_L - X_{alloy}}{X_L - X_S}$$

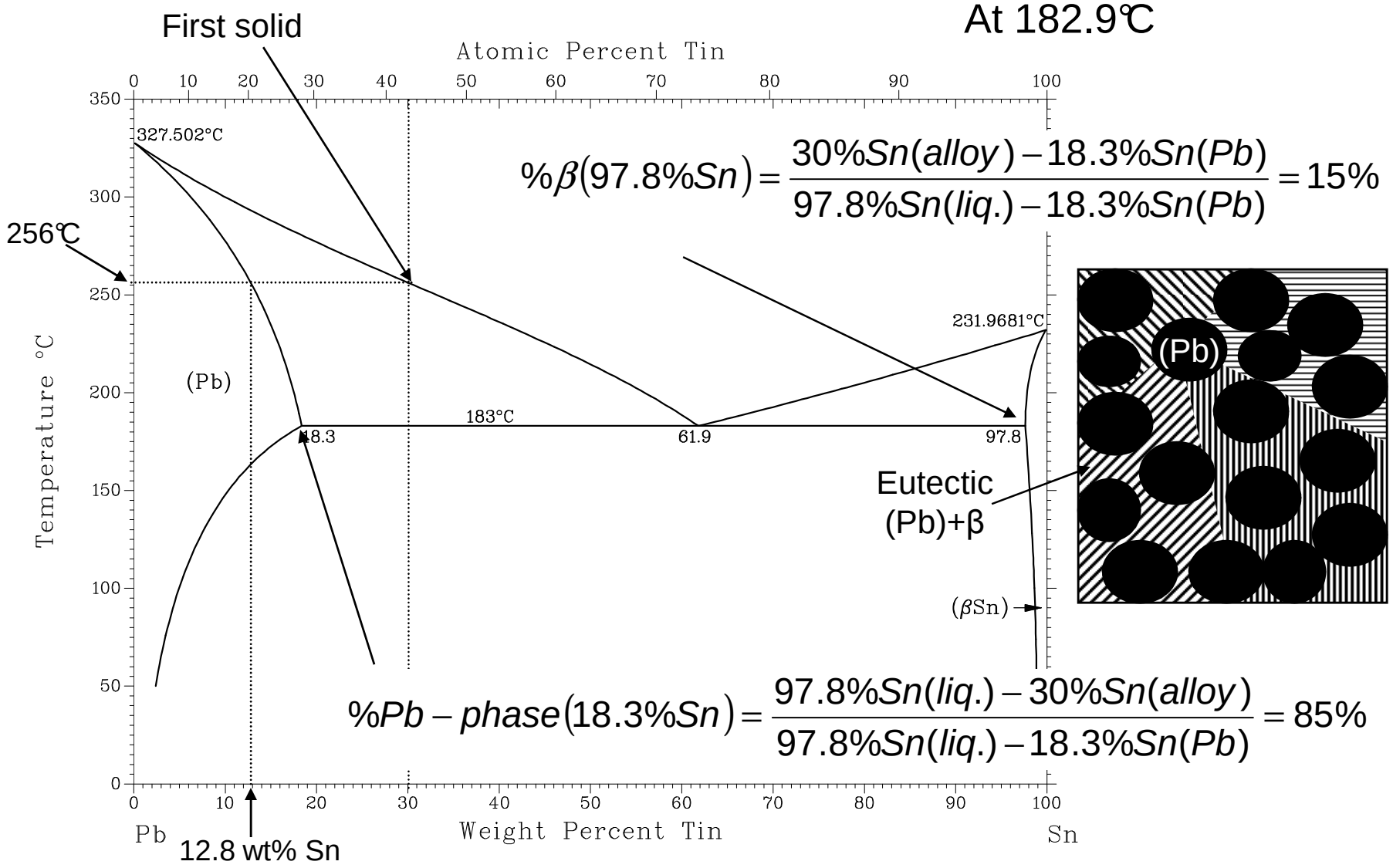
Left arm for liquid

$$\%liquid = \frac{X_{alloy} - X_S}{X_L - X_S}$$

70 wt% Pb - 30 wt% Sn



70 wt% Pb - 30 wt% Sn



Microconstituents

Primary Pb

$$\%\text{Prim.}Pb(18.3\%Sn) = \frac{61.8\%Sn(eut.) - 30\%Sn(alloy)}{61.8\%Sn(eut.) - 18.3\%Sn(Pb)} = 73\%$$

Eutectic Microsconstituent ((Pb)+βSn)

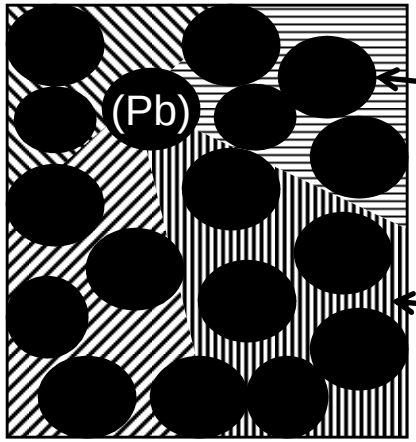
$$\%L(61.8\%Sn) = \frac{30\%Sn(alloy) - 18.3\%Sn(Pb)}{61.8\%Sn(liq.) - 18.3\%Sn(Pb)} = 27\%$$

Phases in Eutectic Microsconstituent

$$\%\beta_{in\,eut.}(97.8\%Sn) = \frac{61.8\%Sn(eut.) - 18.3\%Sn(Pb)}{97.8\%Sn(liq.) - 18.3\%Sn(Pb)} = 55\%$$

$$\%Pb_{in\,eut.}(18.3\%Sn) = \frac{97.8\%Sn(liq.) - 61.8\%Sn(eut.)}{97.8\%Sn(liq.) - 18.3\%Sn(Pb)} = 45\%$$

Phases in Microconstituents



73 g primary (Pb)

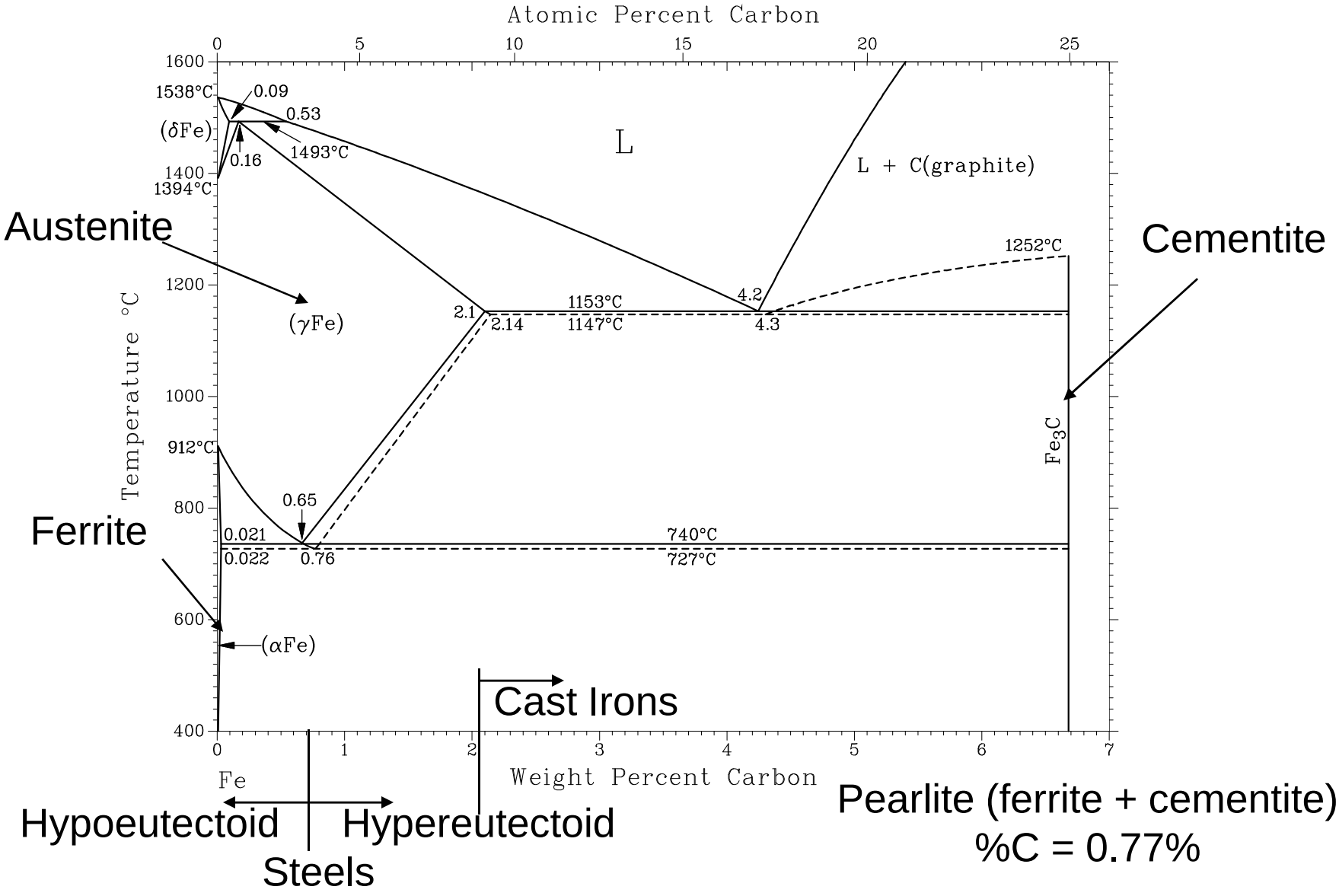
27 g eutectic
(Pb) + βSn

12 g (Pb) (45% of 27 g)

15 g βSn (55% of 27 g)

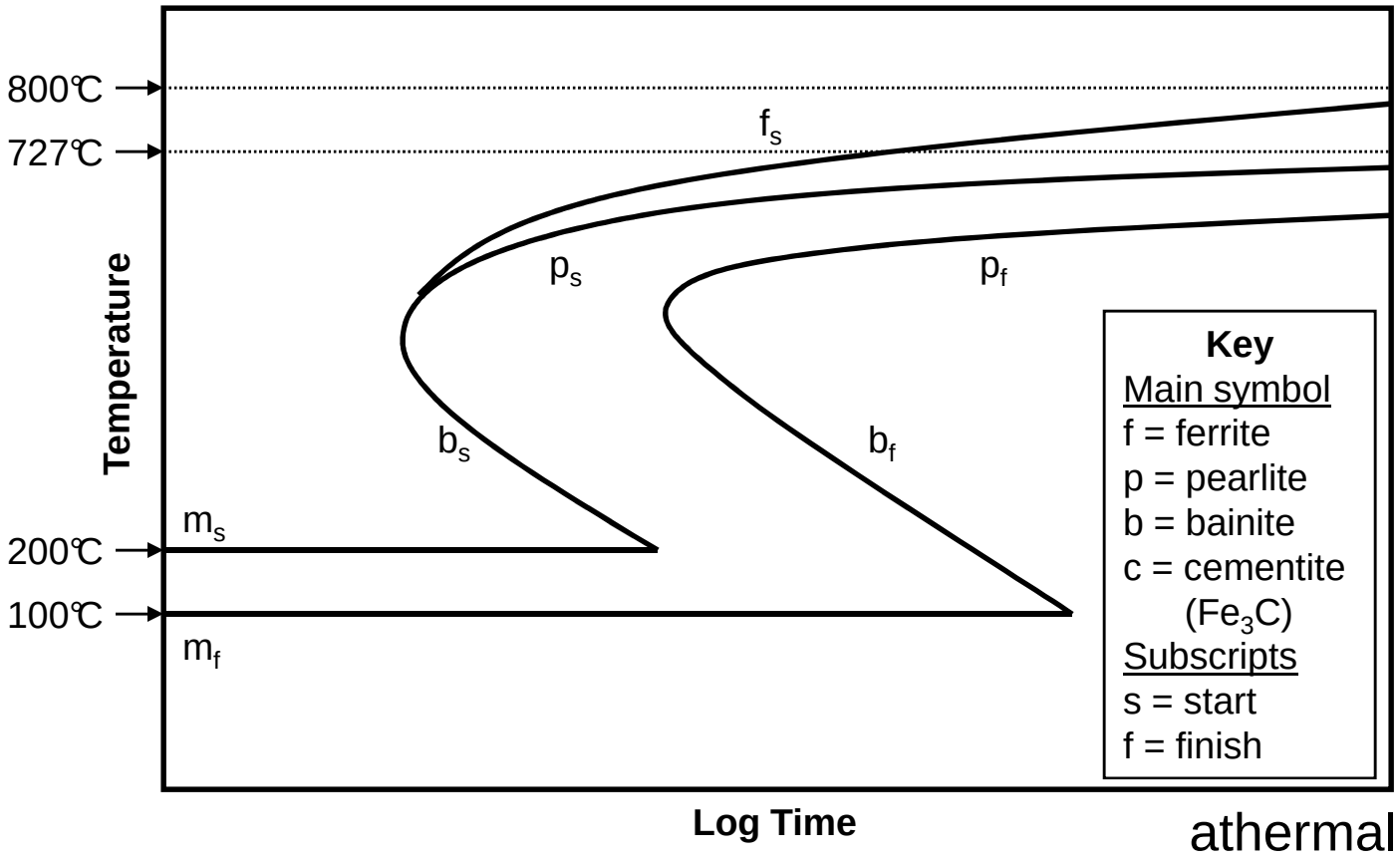
<u>Total amounts in 100 g sample</u>
Total (Pb) = 73 + 22 = 85 g
Total βSn = 15 g
(same as directly from the lever law)

Fe-Fe_3C Phase Diagram



Time-Temperature-Transformation (TTT) Diagram

Decomposition of Austenite at fixed temperature



Pearlite: High Temp slow nucleation

Coarse pearlite

Fine pearlite

Bainite: Diffusion slow for pearlite

Martensite athermal (diffusionless)

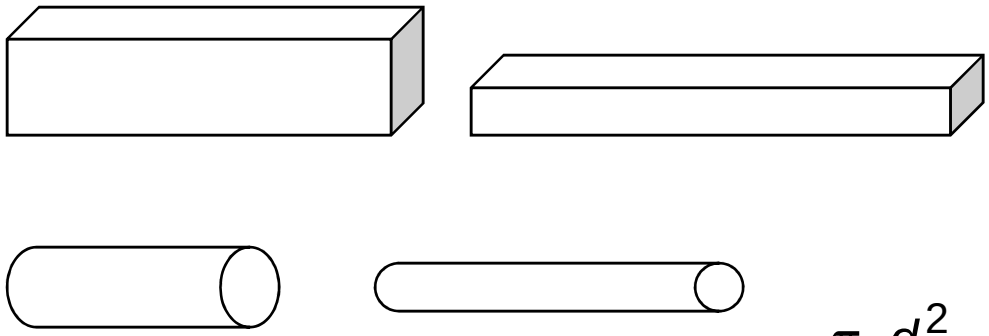
Quench / Hardenability / Tempering

- Quench - rapidly cool
  - in steel: cool fast enough to M_s to prevent pearlite / bainite formation
- Hardenability
  - ease of forming martensite in steels
  - alloying elements inhibit pearlite / bainite formation, promote martensite formation
- Tempering of steels
  - reheating martensite to form transition carbides
  - improve toughness

Cold Working

- Plastic deformation creates dislocations, which increases strength / decreases ductility
- Reduction in Area used to quantify degree of cold working

$$\%CW = \%RA = \frac{A_i - Af}{A_i} \cdot 100\%$$



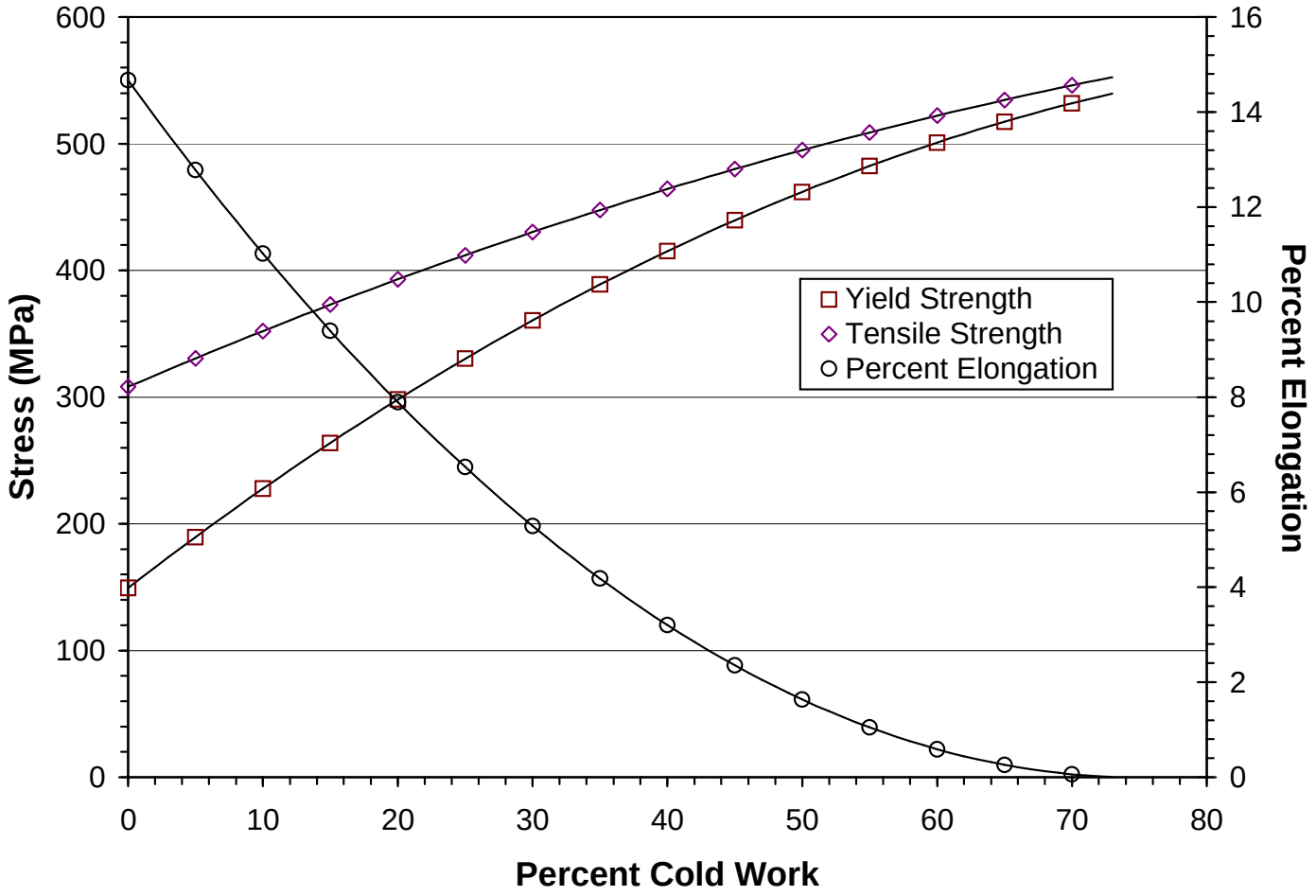
$$\%RA = \frac{w_i \cdot l_i - w_f \cdot l_f}{w_i \cdot l_i} \cdot 100\%$$

$$for\ w_f \cong w_i$$

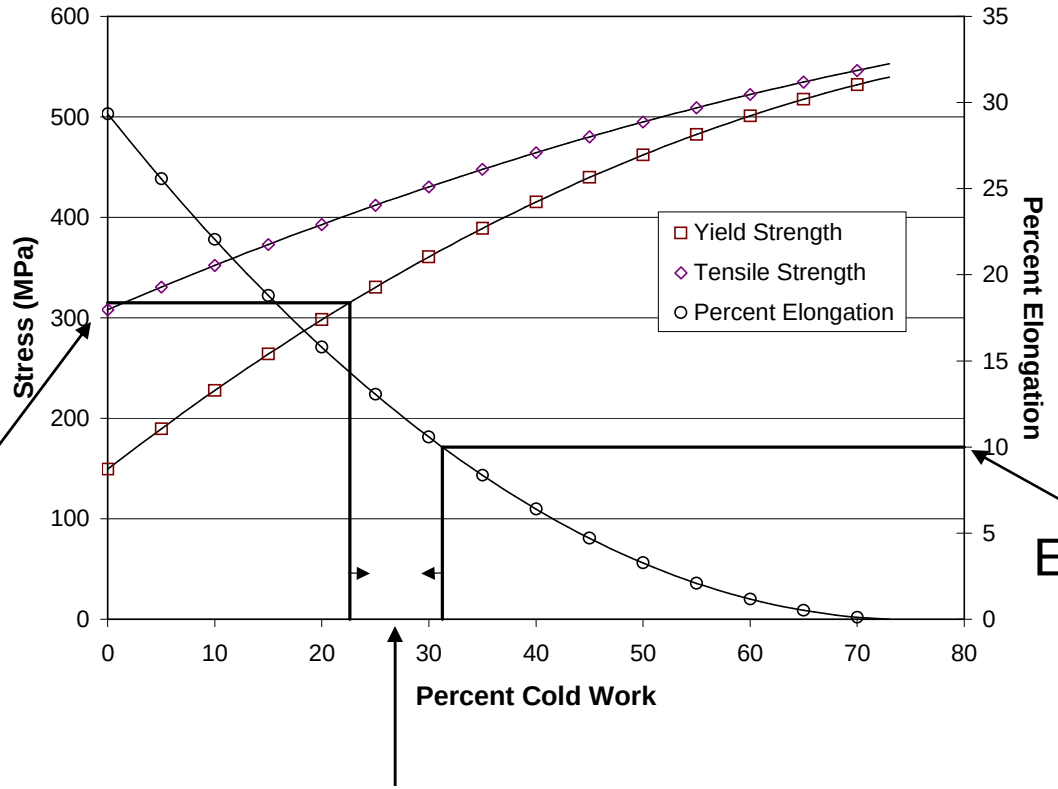
$$\%RA = \frac{l_i - l_f}{l_i} \cdot 100\%$$

$$\%RA = \frac{\frac{\pi \cdot d_i^2}{4} - \frac{\pi \cdot d_f^2}{4}}{\frac{\pi \cdot d_i^2}{4}} \cdot 100\% = \frac{d_i^2 - d_f^2}{d_i^2} \cdot 100\%$$

Cold Worked Properties



Balancing Strength / Ductility



S_y > 310 MPa
requires
%CW > 22%

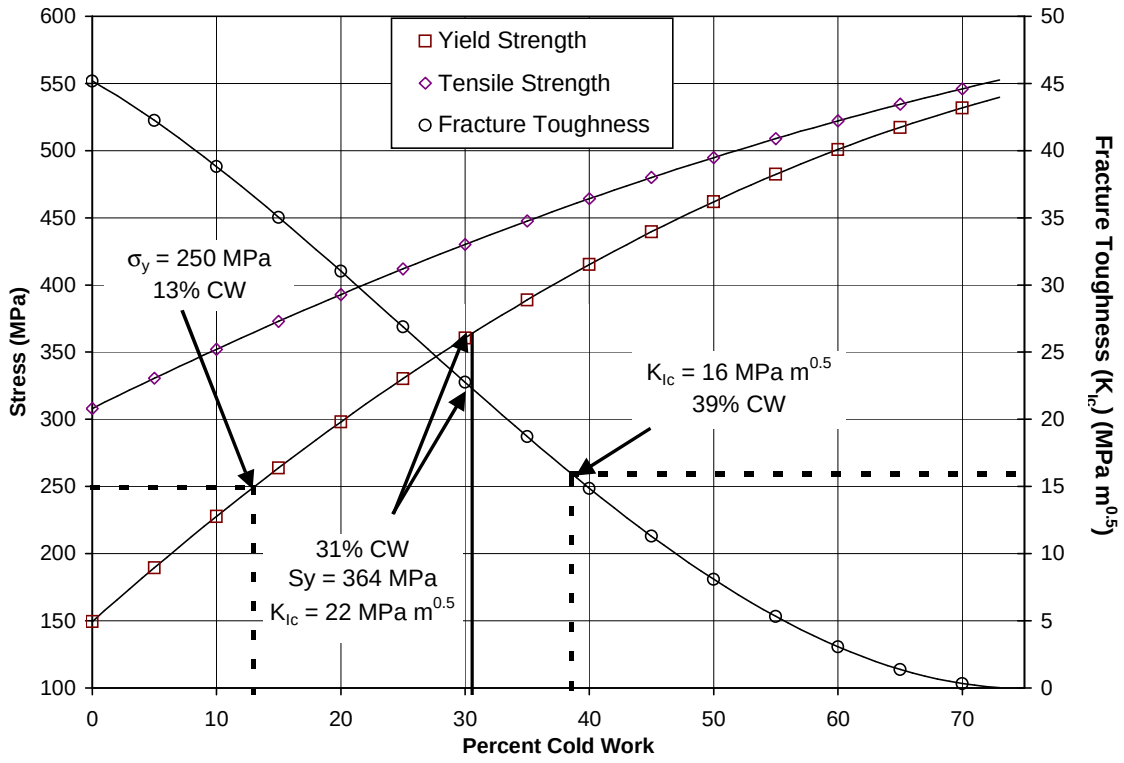
Elongation > 10%
requires
%CW < 31%

Both Properties
requires
22% < %CW < 31%

Balancing Strength / Toughness

S_y > 250 MPa
and
K_{Ic} > 16 MPa $m^{½}$
requires
13% < %CW < 39%

Example
for 31% CW
S_y = 364 MPa
K_{Ic} = 22 MPa $m^{½}$



Cold Work / Anneal / Hot Work

- Annealing can eliminate effect of cold work
  - recovery - stress relief, little change in properties
  - recrystallization - elimination of dislocations, decrease in strength, increase in ductility
  - grain growth - increase in grain size, decreases ***both*** strength and ductility
- Hot working
  - deforming at high enough temperature for immediate recrystallization
  - list cold-working and annealing at the same time
  - no increase in strength
  - used for large deformation
  - poor surface finish - oxidation
  - after hot working, cold working used to increase strength and improve surface finish

Organization from 1996-7 Review Manual (same topics in 2004 review manual)

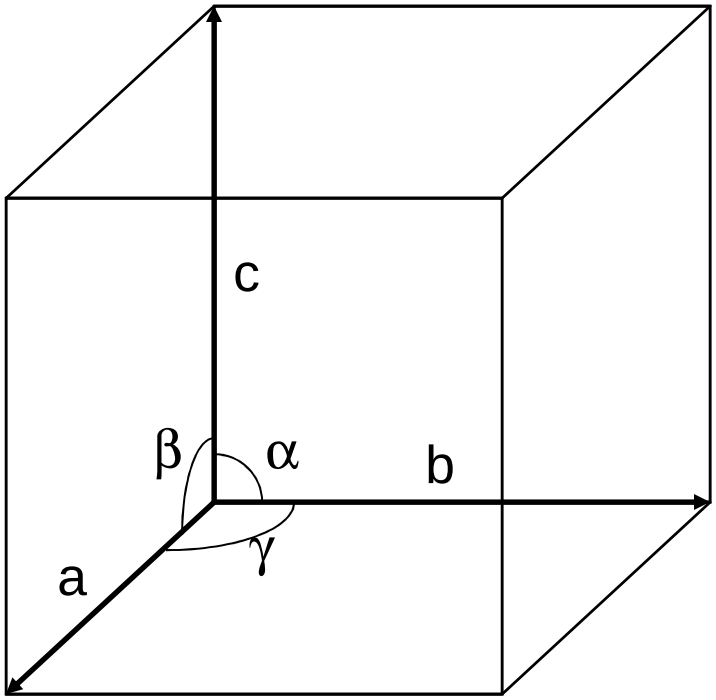
- Crystallography
- Materials Testing
- Metallurgy

Crystallography

- Crystal structure
  - atoms/unit cell
  - packing factor
  - coordination number
- Atomic bonding
- Radioactive decay

Bravais Lattice

Crystal System



Centering

(*x*,*y*,*z*): Fractional coordinates - proportion of axis length, not absolute distanct

P: Primitive: (*x*,*y*,*z*)

I: Body-centered: (*x*,*y*,*z*); (*x*+½,*y*+½,*z*+½)

C: Base-centered: (*x*,*y*,*z*); (*x*+½,*y*+½,*z*)

F: Face-centered: (*x*,*y*,*z*); (*x*+½,*y*+½,*z*)
(*x*+½,*y*,*z*+½); (*x*,*y*+½,*z*+½)

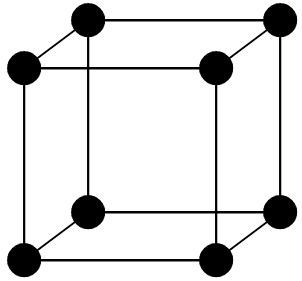
Centering must apply to all atoms in unit cell.

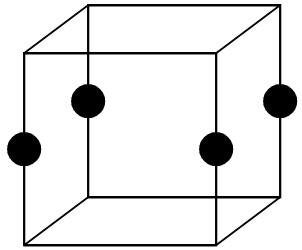
Bravais Lattices (14)

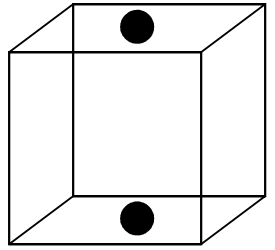
Crystal System	Parameters	Primitive (Simple)	Body-Centered	Face-Centered	Base-Centered
Cubic	$a=b=c$ $\alpha=\beta=\gamma=90°$	X	X	X	
Tetragonal	$a=b\neq c$ $\alpha=\beta=\gamma=90°$	X	X		
Orthorhombic	$a\neq b\neq c$ $\alpha=\beta=\gamma=90°$	X	X	X	X
Rhombohedral	$a=b=c$ $\alpha=\beta=\gamma\neq 90°$	X			
Hexagonal	$a=b\neq c$ $\alpha=\beta=90°, \gamma=120°$	X			
Monoclinic	$a\neq b\neq c$ $\alpha=\gamma=90°, \beta\neq 120°$	X			X
Triclinic	$a\neq b\neq c$ $\alpha\neq\beta\neq\gamma\neq 90°$	X			

Atoms Per Unit Cell

- Corners - shared by eight unit cells (x 1/8)
  - (0,0,0)=(1,0,0)=(0,1,0)=(0,0,1)=(1,1,0) =(1,0,1)=(0,1,1)=(1,1,1)
- Edges - shared by four unit cells (x 1/4)
  - (0,0,½)= (1,0,½)= (0,1,½)= (1,1,½)
- Faces - shared by two unit cells (x 1/2)
  - (½,½,0)= (½,½,1)

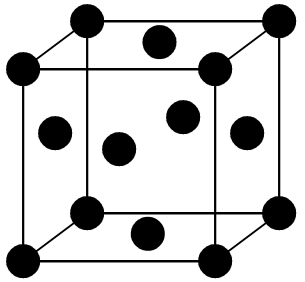


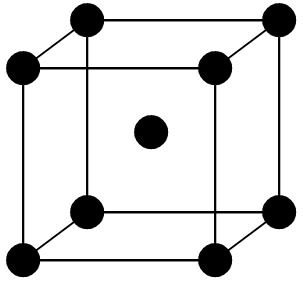


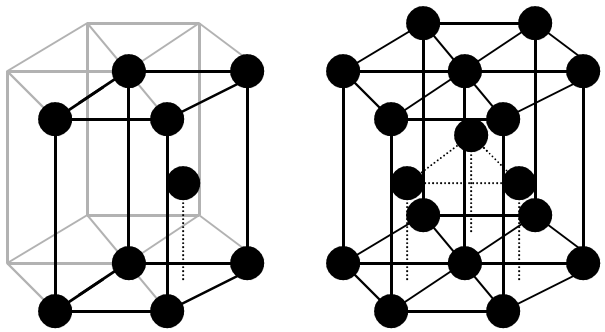


Common Metal Structures

- Face-Centered Cubic (FCC)
  - 8 corners x 1/8 + 6 faces x 1/2
  - 1 + 3 = 4 atoms/u.c.
- Body-Centered Cubic (BCC)
  - 8 corners x 1/8 + 1 center
  - 1 + 1 = 2 atoms/u.c.
- Hexagonal Close-Packed (HCP)
  - 8 corners x 1/8 + 1 middle
  - 1 + 1 = 2 atoms/u.c.
  - 12 hex. Corner x 1/6 +2 face x 1/2 + 3 middle = 6 atoms/u.c.





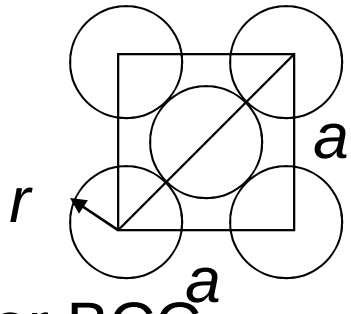


Packing Factor

- Fraction of space occupied by atoms

$$P.F. = \frac{\sum \frac{4}{3}\pi r_i^3}{a \cdot b \cdot c}$$

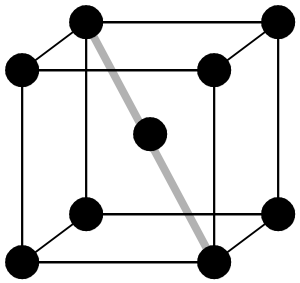
- For FCC



$$\text{face diagonal} = \sqrt{a^2 + a^2} = 4 \cdot r \Rightarrow a = \frac{4}{\sqrt{2}} r$$

$$P.F. = \frac{4 \cdot \left(\frac{4}{3}\pi r^3\right)}{a^3} = \frac{4 \cdot \left(\frac{4}{3}\pi r^3\right)}{\left(\frac{4}{\sqrt{2}}\right)^3} = \frac{\pi}{3\sqrt{2}} = 0.74$$

- For BCC



$$\text{body diagonal} = \sqrt{a^2 + a^2 + a^2} = 4 \cdot r \Rightarrow a = \frac{4}{\sqrt{3}} r$$

$$P.F. = \frac{2 \cdot \left(\frac{4}{3}\pi r^3\right)}{a^3} = \frac{2 \cdot \left(\frac{4}{3}\pi r^3\right)}{\left(\frac{4}{\sqrt{3}}\right)^3} = \frac{\pi\sqrt{3}}{8} = 0.68$$

Density

$$Density = \frac{\left(\frac{atom}{u.c.}\right)\cdot\left(\frac{mass}{mole}\right)}{\left(\frac{atom}{mole}\right)\cdot\left(\frac{volume}{u.c.}\right)} = \frac{mass}{volume}$$

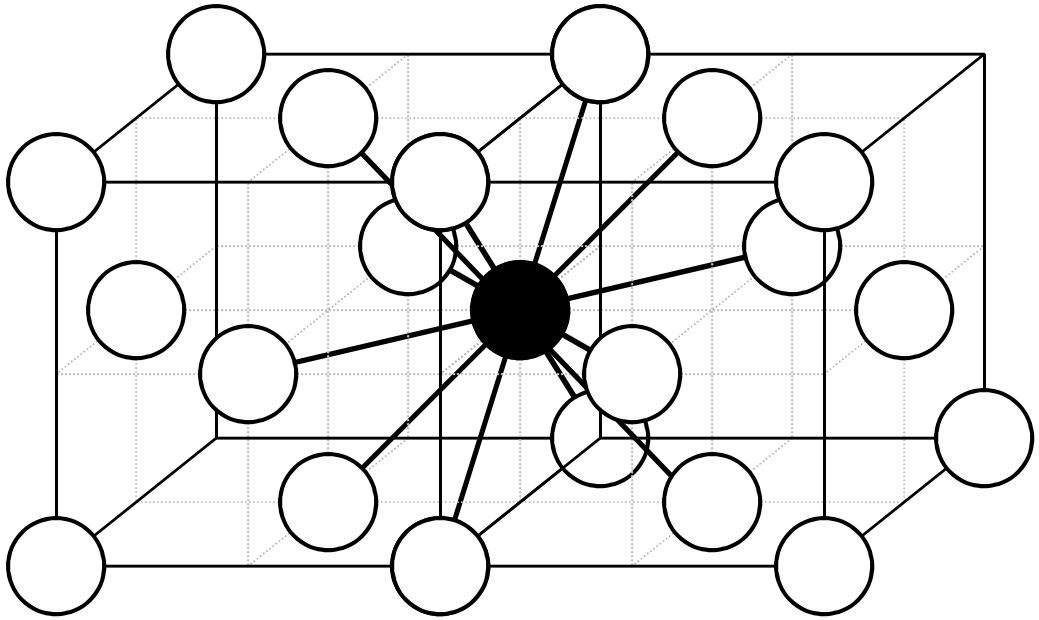
For nickel:

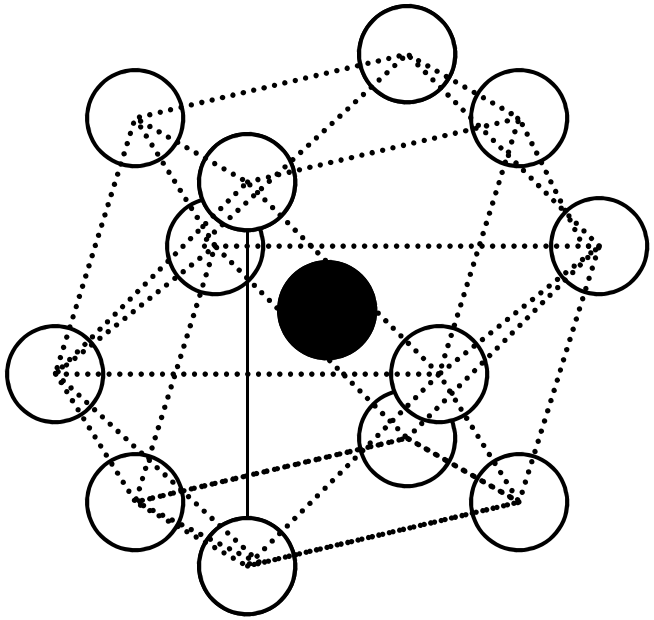
- Atomic weight = 58.71 g/mole
- Lattice parameter = 3.5239 Å=3.5239 x 10^{-8} cm
- Avogadro's No. = 6.02 x 10^{23} = 0.602 x 10^{24} = atoms/mole

$$Density = \frac{\left(\frac{4\,atom}{u.c.}\right)\cdot\left(58.71\frac{g}{mole}\right)}{\left(0.602\,x10^{24}\,\frac{atom}{mole}\right)\cdot\left(3.5239\,x10^{-8}\,cm\right)^3} = 8.915\,\frac{g}{cm^3}$$

Close Packed (CN=12)

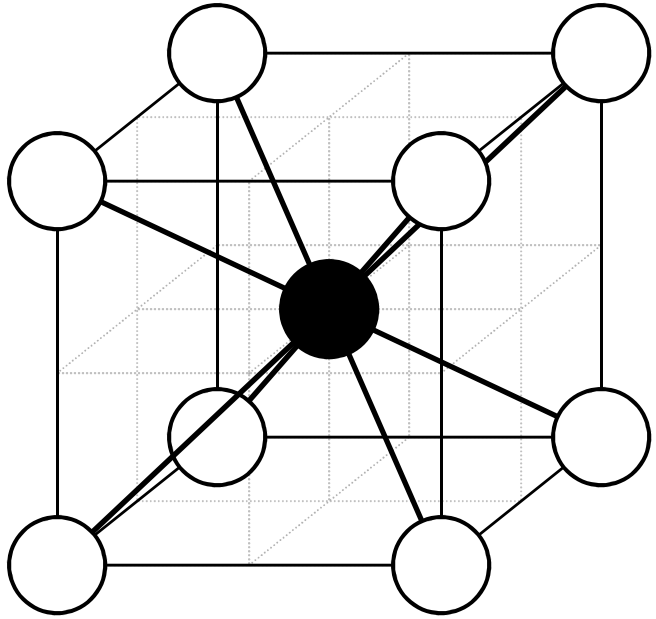
Highest packing density for same sized spheres
FCC and HCP structures





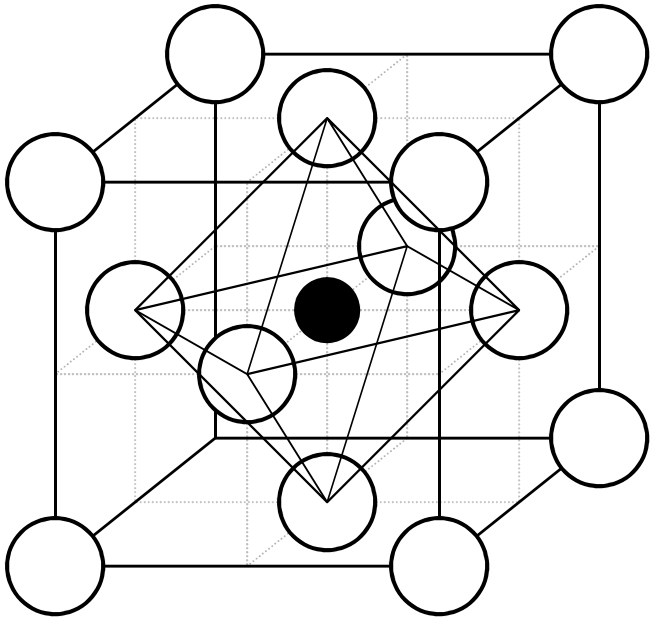
Cube Center (CN=8)

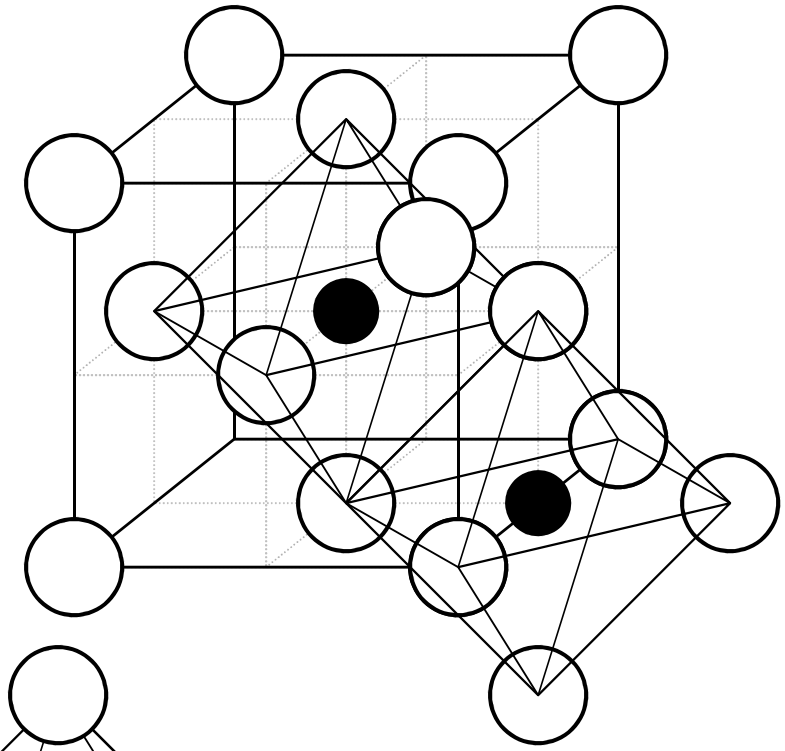
Same atoms: BCC
Different atoms: CsCl

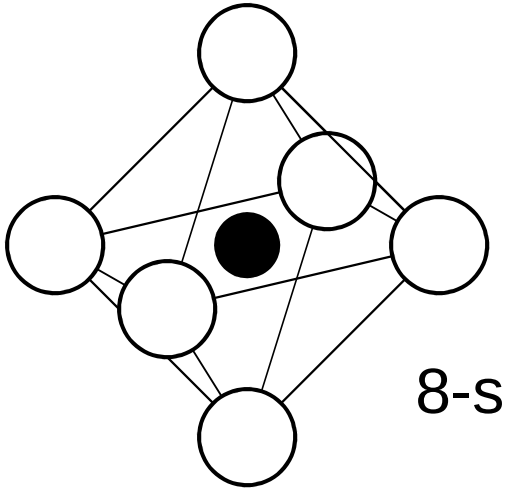


Octahedral Site (CN=6)

In FCC:
- Center (½,½,½)
- Edges (0,0,½),(0,½,0),(½,0,0)
- 4 per unit cell
- All filled - NaCl structure





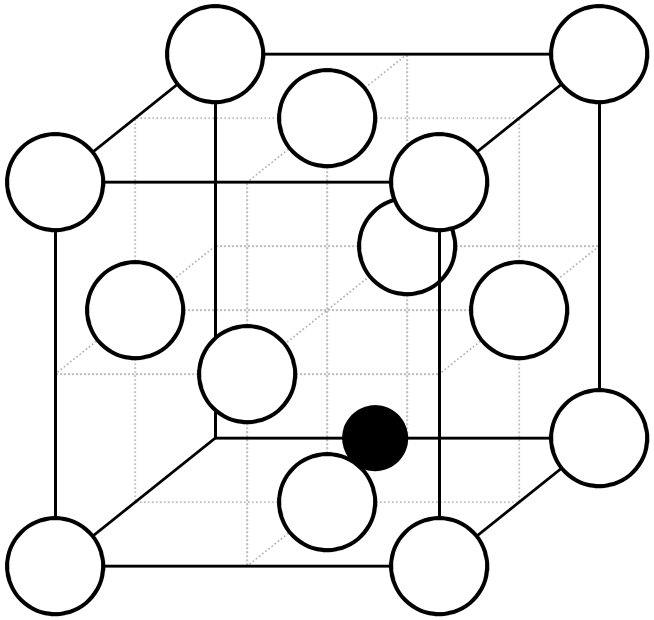


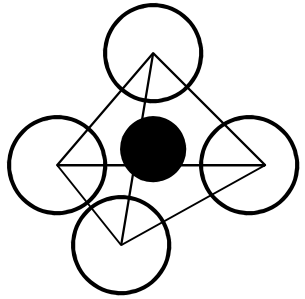
8-sided shape

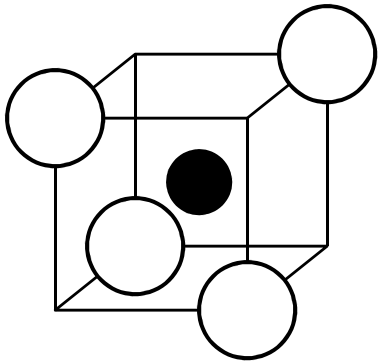
Tetrahedral Site (CN=4)

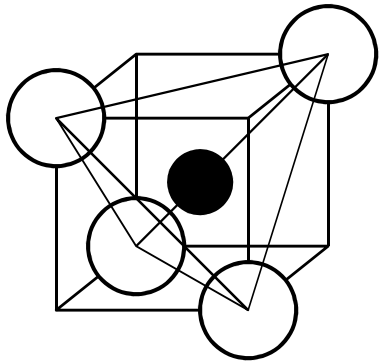
In FCC:

- Divide cell into 8 boxes - center of small box
- (¼,¼,¼),(¾,¼,¼),(¼,¾,¼),(¾,¾,¼)
(¼,¼, ¾)(¾,¼, ¾),(¼,¾, ¾)(¾,¾, ¾)
-8 per unit cell
-All filled - CaF_2 structure; half-filled - ZnS





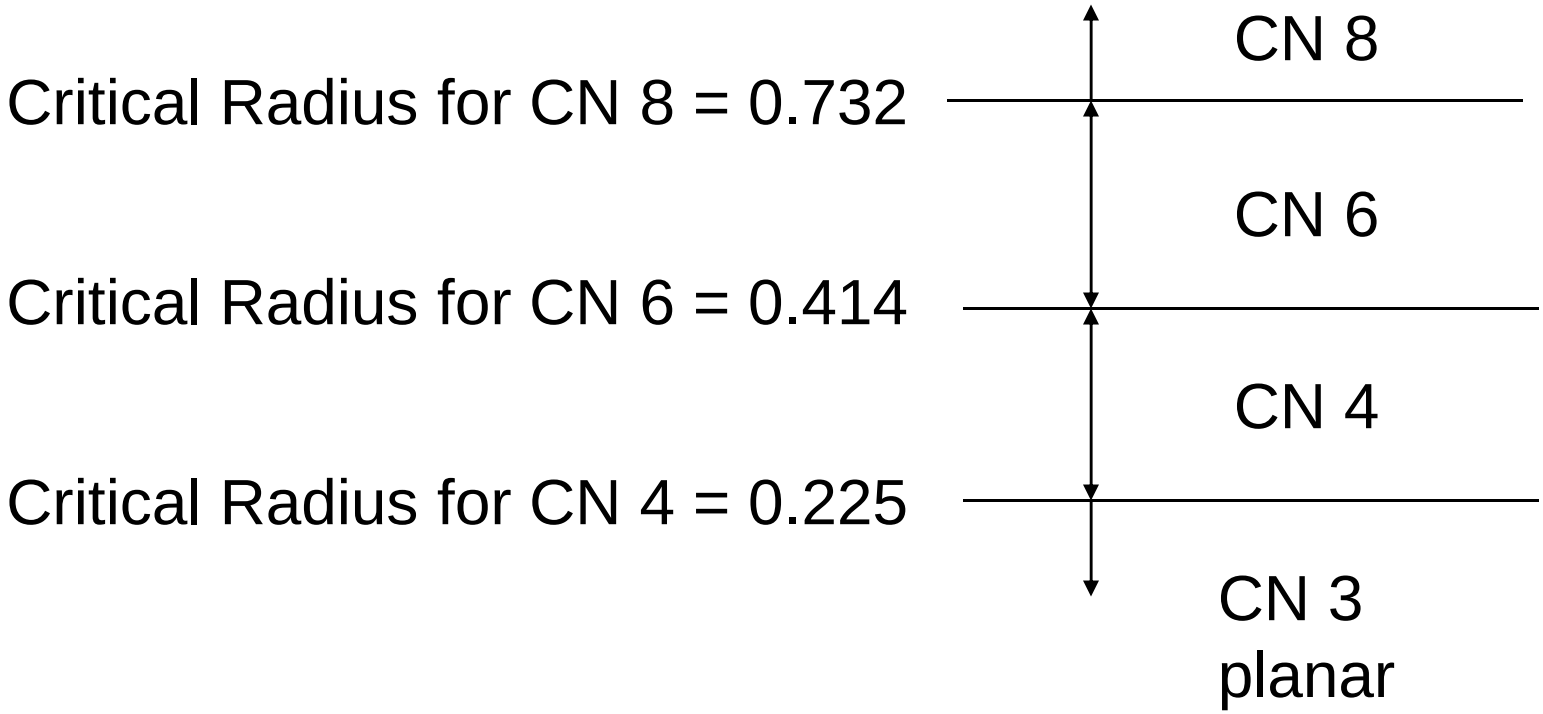




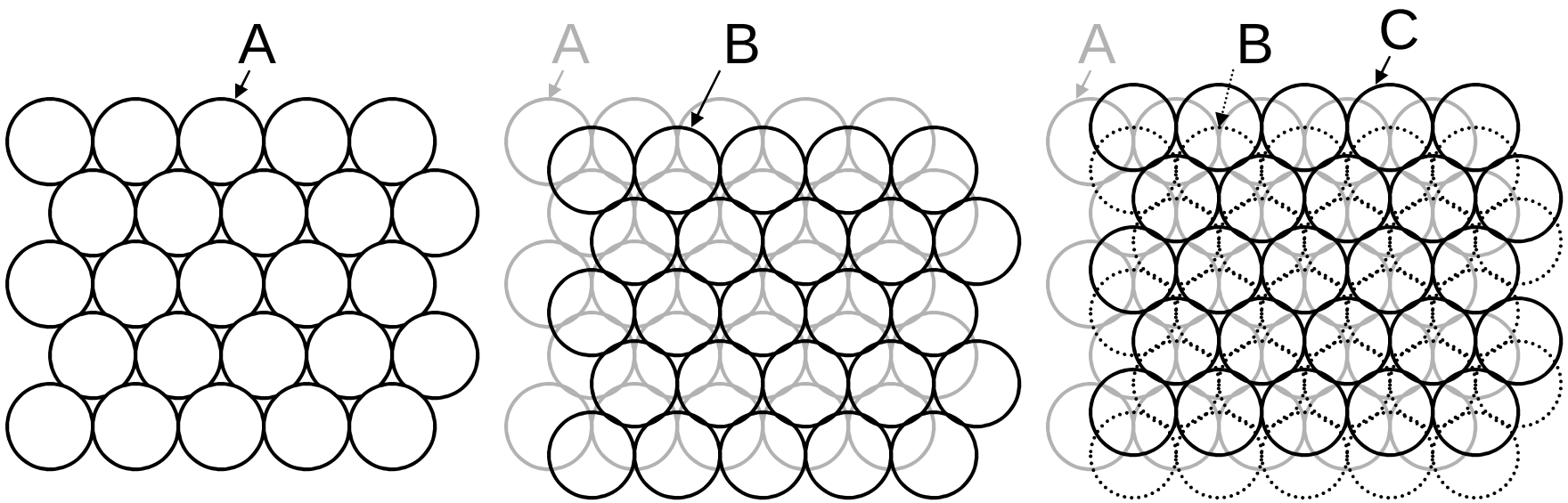
4-sided shape

Radius Ratio Rules

Critical radius is size of atom which just fits in site
Define minimum for bonding (*i.e*. atoms must touch to bond)



Close Packed Plane



HCP: ABABABABABABABAB
FCC: ABCABCABCABCABC
Same packing density (0.74)
Same coordination (CN=12)

Miller Indices

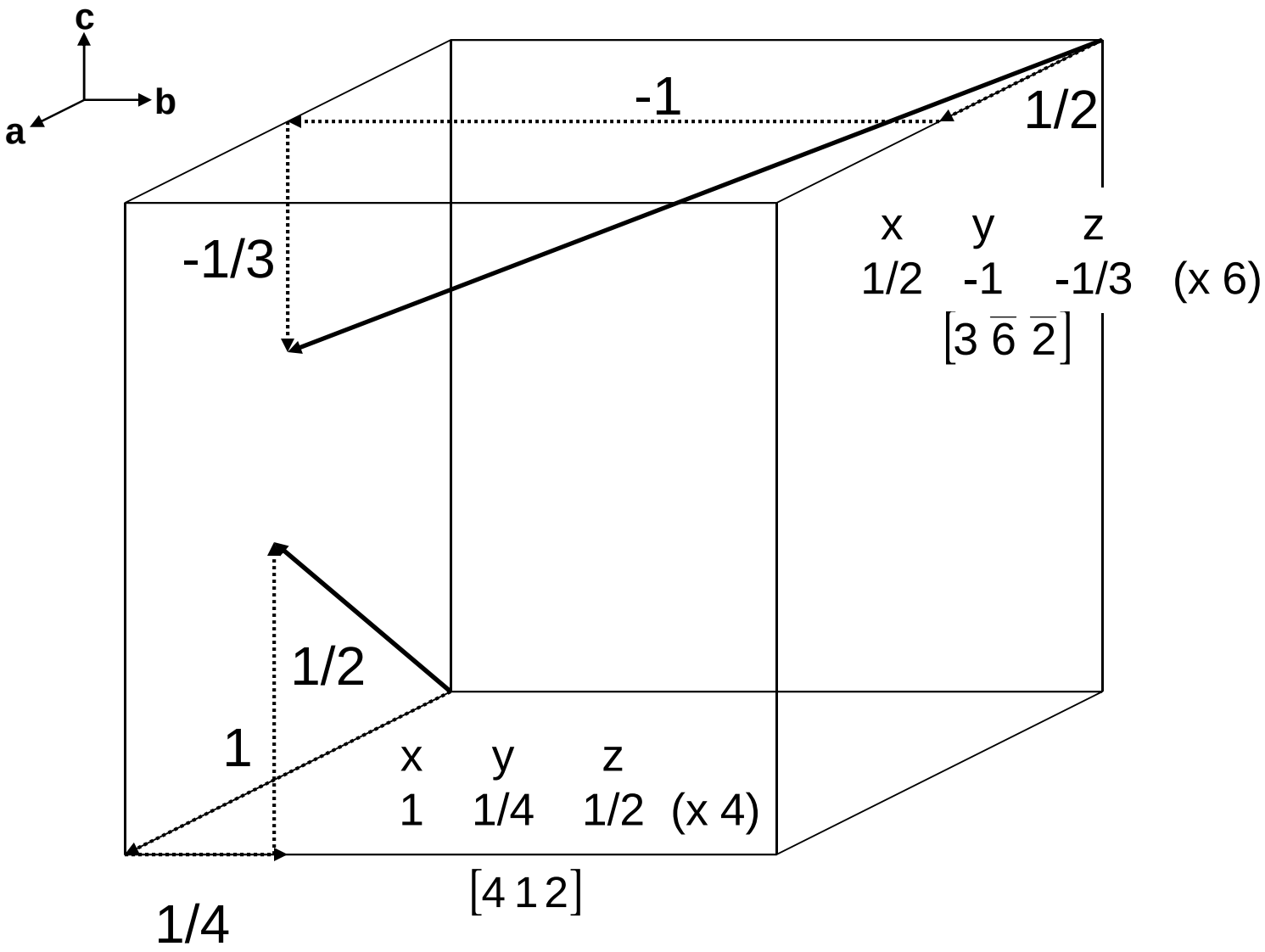
Planes	(hkl)	specific
	{hkl}	family
Directions	[hkl]	specific
	<hkl>	family

- No commas
- No fractions
- Negative indicated by bar over number

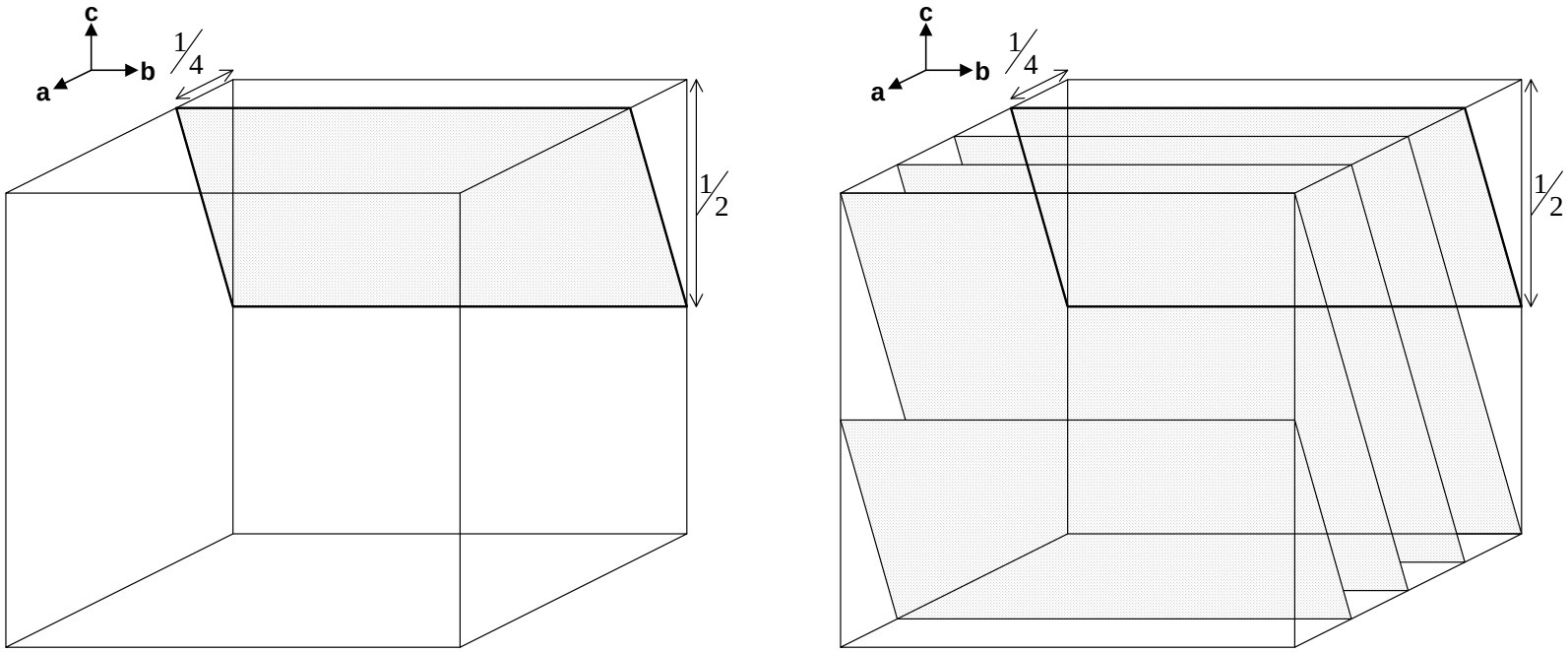
A family of planes includes all planes which are equivalent by symmetry - depends on crystal system.

- For cubic: (110),(011) and (101) are all {110}
- For tetragonal: (011) and (101) are {101}
  but (110) is not ($c \neq a$)

Miller Indices - Directions



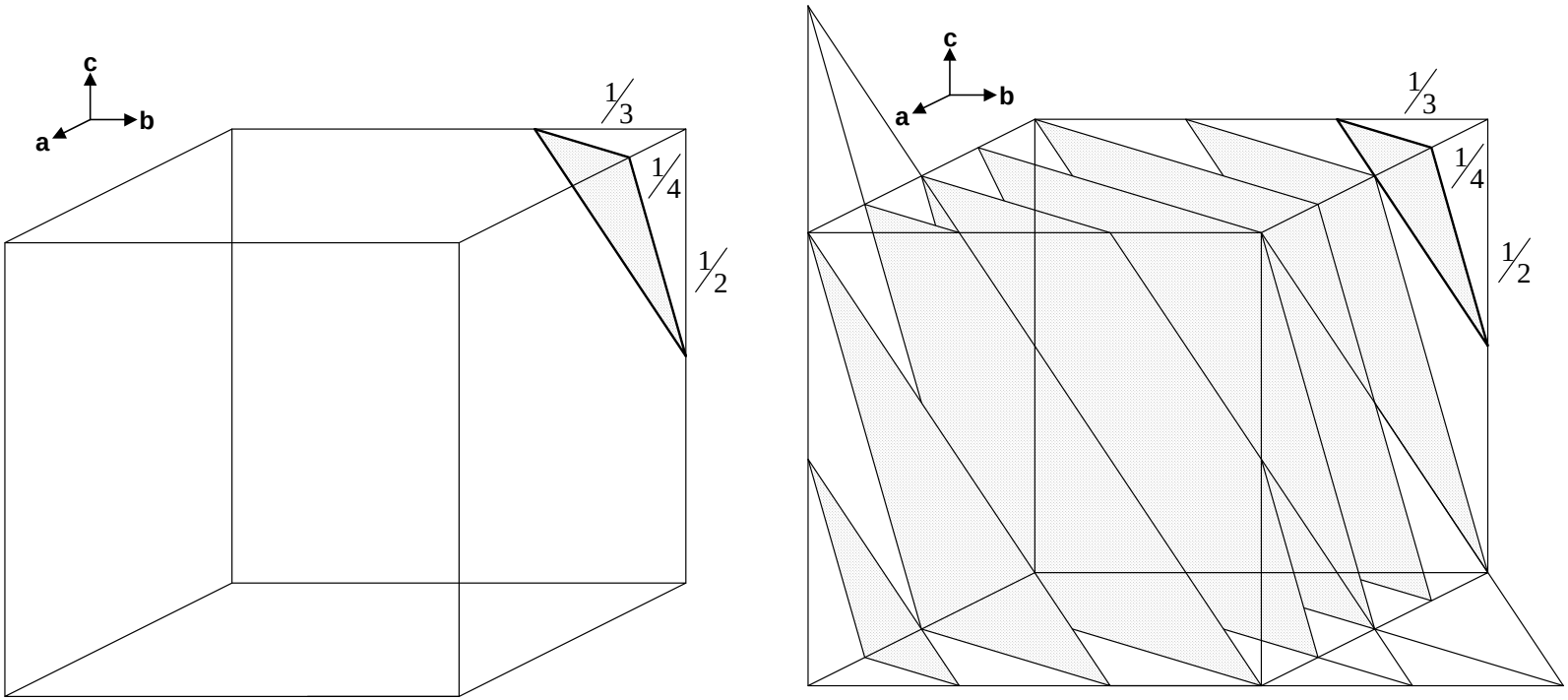
Miller Indices - Planes



	x	y	z
intercept	1/4	∝	-1/2
reciprocal	4	0	-2

$(4\,0\,\bar{2})$

Miller Indices - Planes



	x	y	z
intercept	1/4	-1/3	-1/2
reciprocal	4	-3	-2

$(4\ \bar{3}\ \bar{2})$

Atomic Bonding

- Covalent
  - sharing electrons
  - strong
  - directional
- Ionic
  - trading of electrons
  - electrostatic attraction or ions
  - strong
  - non-directional
- Metallic
  - metal ions in sea or electrons
  - moderately strong
  - non-directional
- Secondary
  - Van der Waals
  - H-bonding
  - electrostatic attraction of electric dipole (local charge distribution
  - weak

Radioactive Decay

- Loss of electrons/protons/neutrons
  - alpha - 2 protons / two neutrons (*i.e* He nucleus)
  - beta - electrons
  - gamma - energy
- Exponential decay

$$N = N_o \, exp\left(-\frac{t}{\tau} \right)$$

time

time constant

$$N = \frac{1}{2} N_o = N_o \, exp \Rightarrow \frac{t_{\frac{1}{2}}}{\tau} = -ln\left(\frac{\frac{1}{2} N_o}{N_o} \right) = ln(2) \Rightarrow \tau = -\frac{t_{\frac{1}{2}}}{ln(2)}$$

amount

$$N = N_o \, exp\left(-\frac{t \cdot ln(2)}{t_{\frac{1}{2}}} \right) = N_o \, exp\left(-\frac{0.693 \cdot t}{t_{\frac{1}{2}}} \right)$$

original amount

half life