FE Review
Materials Properties

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Electrical Properties

• Electrical resistance
  – resistance \( (R) = \text{resistivity } (\rho) \text{ length } (l) / \text{area } (A) \)
  – resistivity is a material property
  – conductivity \( (\sigma) = 1 / \text{resistivity } (\rho) \)

• 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

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

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

Tension: $\sigma > 0$

Compression: $\sigma < 0$
Strain

Strain \( \varepsilon = \frac{l - l_o}{l_o} = \frac{\Delta l}{l_o} \)

Shear strain \( \gamma = \frac{a}{h} = \tan \theta \)
Tensile Test

Control length (l)

\[ \text{Strain} = \varepsilon = \frac{l - l_0}{l_0} = \frac{\Delta l}{l_0} \]

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

Ultimate Tensile Strength

Yield Point

Elastic Limit

Proportionality Limit

Force decreases due to necking

Slope = E (Young’s Modulus)

Percent Elongation (total plastic deformation)
0.2% Offset Yield Strength

0.2% offset yield strength

Stress

0.2% strain

Strain
### True/Engineering Stress/Strain

<table>
<thead>
<tr>
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<th>Stress</th>
<th>Strain</th>
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<tr>
<td><strong>Engineering</strong></td>
<td>$\sigma_E = \frac{F}{A_o}$</td>
<td>$\varepsilon_E = \frac{l-l_o}{l_o} = \frac{\Delta l}{l_o}$</td>
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<td>(initial dimensions)</td>
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<tr>
<td><strong>True</strong></td>
<td>$\sigma_T = \frac{F}{A_i}$</td>
<td>$\varepsilon_T = \int \frac{l_i , dl}{l_o} = \ln \left( \frac{l_i}{l_o} \right)$</td>
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<td>(instantaneous dimensions)</td>
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<td><strong>Using and</strong></td>
<td></td>
<td>$\varepsilon_T = \ln (\varepsilon_E + 1)$</td>
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<tr>
<td>$A_i \cdot l_i = A_o \cdot l_o$</td>
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<tr>
<td>$\sigma_T = \sigma_E (1 + \varepsilon_E)$</td>
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</table>
True/Engineering Stress/Strain

Decrease in engineering stress due to decreased load required in the reduction cross-sectional area of the neck.

True stress does not decrease
Strain Hardening

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

Onset of plastic deformation after reloading
Bending Test

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

- Creep
  - Fixed load $F$
  - Time $t$

- Stress Relaxation
  - Fixed strain
  - Permanent deformation
  - Time $t$

- Fixed load $F$
Fatigue

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

\[ \sigma_{\text{max}} \]
\[ \sigma_{\text{min}} \]
\[ \sigma_{\text{ave}} \]
\[ \Delta \sigma \]

Fatigue Limit
(ferrous metals)

Number of Cycles to Failure
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)
  – \( 2H^+ + 2e^- = H_2 \)
  – \( 2H^+ + \frac{1}{2}O_2 + 2e^- = H_2O \)
  – \( H_2O + \frac{1}{2}O_2 + 2e^- = 2OH^- \)

• Overall Reactions
  – \( M + 2H^+ = M^{2+} + H_2 \)
  – \( M + 2H^+ + \frac{1}{2}O_2 = M^{2+} + H_2O \)
  – \( M + H_2O + \frac{1}{2}O_2 = M^{2+} + 2OH^- = M(OH)_2 \)
Electromotive Force

• Gibbs Free Energy ($\Delta G =-nFE$) (Electromotive Force)
  – $n =$ number of electrons, $F =$ Faraday’s Constant
  – favorable: energy decrease (-) = positive voltage

• $\text{Fe}^{2+} + 2e^- = \text{Fe}: \ E_{\text{red}} = +0.440 \text{ V}$
• $\text{Fe} = \text{Fe}^{2+} + 2e^- : E_{\text{ox}} = -0.440 \text{ V}$
• $\text{H}_2\text{O} = 2\text{H}^+ + \frac{1}{2}\text{O}_2 + 2e^- : E_{\text{red}} = +1.229 \text{ V}$
• $\text{Fe} + 2\text{H}^+ + \frac{1}{2}\text{O}_2 = \text{Fe}^{2+} + \text{H}_2\text{O}: E = 0.789 \text{ V}$
  – $E$ does not change with number of moles ($\Delta G$ does)
  – $E$ must be corrected for non-standard state
    • concentration of $\text{H}^+$ (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

Higher corrosion rate near oxygen access

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$_3$C 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

\[
D = D_0 \exp \left( -\frac{Q}{RT} \right) = D_0 \exp \left( -\frac{E_A}{kT} \right)
\]

- Gas constant
- Temperature
- Boltzmann’s constant
- Activation Energy
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 \[ J = -D \left( \frac{\Delta C}{\Delta x} \right) \]

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

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

One component: H₂O
If formation of H₂ and O₂ were considered there would be two components (H and O)

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)

One component: H₂O
If formation of H₂ and O₂ were considered there would be two components (H and O)
Two-component @ constant pressure
Three-phase - horizontal line

Peritectic
L + solid (δ) → solid (γ)

Eutectic
L → 2 solids (γ + β)

Eutectoid
solid (γ) → 2 solids (α + β)

β (pure B, negligible solubility of A)
Lever Law

• Phase diagram gives compositions of phases
  – two-phase boundaries in 2-phase mixture
• Mass balance generates lever law

\begin{align*}
\text{Percentage solid} &= \frac{X_L - X_{\text{alloy}}}{X_L - X_S} \\
\text{Percentage liquid} &= \frac{X_{\text{alloy}} - X_S}{X_L - X_S}
\end{align*}
70 wt% Pb - 30 wt% Sn

First solid

At 183.1°C

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

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

Pb 12.8 wt% Sn

256°C
70 wt% Pb - 30 wt% Sn

First solid

At 182.9°C

\[
%\beta(97.8\% Sn) = \frac{30\% Sn(alloy) - 18.3\% Sn(Pb)}{97.8\% Sn(liq.) - 18.3\% Sn(Pb)} = 15\%
\]

Eutectic (Pb)+β

\[
%Pb - phase(18.3\% Sn) = \frac{97.8\% Sn(liq.) - 30\% Sn(alloy)}{97.8\% Sn(liq.) - 18.3\% Sn(Pb)} = 85\%
\]
Microconstituents

Primary Pb

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

Eutectic Microconstituent ((Pb)+βSn)

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

Phases in Eutectic Microconstituent

\[ \%_{\beta_{\text{in eut.}}}(97.8\%\text{Sn}) = \frac{61.8\%\text{Sn}(eut.) - 18.3\%\text{Sn}(Pb)}{97.8\%\text{Sn}(liq.) - 18.3\%\text{Sn}(Pb)} = 55\% \]

\[ \%_{\text{Pb}_{\text{in eut.}}}(18.3\%\text{Sn}) = \frac{97.8\%\text{Sn}(liq.) - 61.8\%\text{Sn}(eut.)}{97.8\%\text{Sn}(liq.) - 18.3\%\text{Sn}(Pb)} = 45\% \]
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)

Total amounts in 100 g sample
Total (Pb) = 73 + 22 = 85 g
Total βSn = 15 g
(same as directly from the lever law)
Fe-Fe$_3$C Phase Diagram

Austenite

Cementite

Ferrite

Cast Irons

Hypoeutectoid

Hypereutectoid

Steels

Pearlite (ferrite + cementite) 

%C = 0.77%
Time-Temperature-Transformation (TTT) Diagram

Decomposition of Austenite at fixed temperature

Pearlite: High Temp slow nucleation
Coarse pearlite
Fine pearlite

Martensite athermal (diffusionless)

Key
- Main symbol
  - f = ferrite
  - p = pearlite
  - b = bainite
  - c = cementite
  - (Fe₃C)
- Subscripts
  - s = start
  - f = finish

Temperature vs Log Time Diagram:
- 800°C
- 727°C
- 200°C
- 100°C

Frequencies and temperatures for each transformation:
- Decomposition of Austenite:
  - 800°C
  - 727°C
- 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 \( w_f \equiv w_i \)

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

\[ \%RA = \frac{\pi \cdot d_i^2}{4} - \frac{\pi \cdot d_f^2}{4} \cdot 100\% = \frac{d_i^2 - d_f^2}{d_i^2} \cdot 100\% \]
Cold Worked Properties

![Graph showing Cold Worked Properties]

- **Stress (MPa)**: 0, 10, 20, 30, 40, 50, 60, 70, 80, 100, 120, 140, 160, 200, 300, 400, 500, 600
- **Percent Elongation**: 0, 2, 4, 6, 8
- **Percent Cold Work**: 0, 10, 20, 30, 40, 50, 60, 70, 80
- **Yield Strength**
- **Tensile Strength**
- **Percent Elongation**

Legend:
- □ Yield Strength
- ◈ Tensile Strength
- ○ Percent Elongation
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 $K_{lc} > 16$ MPa m$^{1/2}$ requires $13% < \%CW < 39%$

Example for 31% CW
$S_y = 364$ MPa
$K_{lc} = 22$ MPa m$^{1/2}$
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 distance

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)

Centering must apply to all atoms in unit cell.
## Bravais Lattices (14)

<table>
<thead>
<tr>
<th>Crystal System</th>
<th>Parameters</th>
<th>Primitive (Simple)</th>
<th>Body-Centered</th>
<th>Face-Centered</th>
<th>Base-Centered</th>
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<tr>
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<td>$\alpha$,$\beta$$\neq\gamma\neq90^\circ$</td>
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</tbody>
</table>
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)
  - \((0,0,\frac{1}{2}) = (1,0,\frac{1}{2}) = (0,1,\frac{1}{2}) = (1,1,\frac{1}{2})\)

- **Faces** - shared by two unit cells (x 1/2)
  - \((\frac{1}{2},\frac{1}{2},0) = (\frac{1}{2},\frac{1}{2},1)\)
Common Metal Structures

- **Face-Centered Cubic (FCC)**
  - 8 corners $\times \frac{1}{8} + 6$ faces $\times \frac{1}{2}$
  - $1 + 3 = 4$ atoms/u.c.

- **Body-Centered Cubic (BCC)**
  - 8 corners $\times \frac{1}{8} + 1$ center
  - $1 + 1 = 2$ atoms/u.c.

- **Hexagonal Close-Packed (HCP)**
  - 8 corners $\times \frac{1}{8} + 1$ middle
  - $1 + 1 = 2$ atoms/u.c.
  - 12 hex. Corner $\times \frac{1}{6} + 2$ face $\times \frac{1}{2} + 3$ middle = 6 atoms/u.c.
Packing Factor

- Fraction of space occupied by atoms
- For FCC

\[
P.F. = \sum \frac{4}{3} \pi r_i^3
\]

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

- For BCC

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

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

\[
Density = \frac{\frac{\text{atom}}{\text{u.c.}} \cdot \frac{\text{mass}}{\text{mole}}}{\frac{\text{atom}}{\text{mole}} \cdot \frac{\text{volume}}{\text{u.c.}}} = \frac{\text{mass}}{\text{volume}}
\]

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

\[
Density = \frac{\left(\frac{4 \text{ atom}}{\text{u.c.}}\right) \cdot \left(\frac{58.71}{\text{g/mole}}\right)}{\left(0.602 \times 10^{24} \frac{\text{atom}}{\text{mole}}\right) \cdot \left(3.5239 \times 10^{-8} \text{ cm}^3\right)^3} = 8.915 \frac{\text{g}}{\text{cm}^3}
\]
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 \((\frac{1}{2},\frac{1}{2},\frac{1}{2})\)
- Edges \((0,0,\frac{1}{2}),(0,\frac{1}{2},0),\frac{1}{2},0,0)\)
- 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
- $(1/4,1/4,1/4), (3/4,1/4,1/4), (1/4,3/4,1/4), (3/4,3/4,1/4)
- 8 per unit cell
- All filled - CaF$_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)

- Critical Radius for CN 8 = 0.732
- Critical Radius for CN 6 = 0.414
- Critical Radius for CN 4 = 0.225
Close Packed Plane

HCP: ABABABABABABABABABABABABABABABABAB
FCC: ABCABCABCABCABCABCABC
Same packing density (0.74)
Same coordination (CN=12)
Miller Indices

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</table>

- 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≠a)
Miller Indices - Directions

\[ \begin{array}{c c c}
  x & y & z \\
  1/2 & -1 & -1/3 \\
\end{array} \]

\[ \begin{array}{c c c}
  x & y & z \\
  1/4 & 1 & 1/2 \\
\end{array} \]

\[ \begin{array}{c c c}
  x & y & z \\
  3 & 6 & 2 \\
\end{array} \] (x 6)

\[ \begin{array}{c c c}
  x & y & z \\
  1/4 & 1/2 \\
\end{array} \] (x 4)

\[ \begin{array}{c c c}
  x & y & z \\
  1/3 & 1/2 \\
\end{array} \]
Miller Indices - Planes

\[
\begin{array}{ccc}
\text{x} & \text{y} & \text{z} \\
\text{intercept} & \frac{1}{4} & \infty & -\frac{1}{2} \\
\text{reciprocal} & 4 & 0 & -2 \\
\end{array}
\]

\((4 \ 0 \ \bar{2})\)
Miller Indices - Planes

intercept

\[
\begin{array}{ccc}
\frac{1}{4} & -\frac{1}{3} & -\frac{1}{2} \\
\end{array}
\]

reciprocal:

\[
\begin{array}{ccc}
4 & -3 & -2 \\
\end{array}
\]

\[(4 \bar{3} \bar{2})\]
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
  \[ N = N_0 \exp\left(-\frac{t}{\tau}\right) \]
  \[ \tau = -\frac{t_\frac{1}{2}}{\ln(2)} \]

\[ N = \frac{1}{2} N_0 = N_0 \exp \Rightarrow \frac{t_\frac{1}{2}}{\tau} = -\ln\left(\frac{1}{2} \frac{N_0}{N_0}\right) = \ln(2) \Rightarrow \tau = -\frac{t_\frac{1}{2}}{\ln(2)} \]

\[ N = N_0 \exp\left(-\frac{t \cdot \ln(2)}{t_\frac{1}{2}}\right) = N_0 \exp\left(-\frac{0.693 \cdot t}{t_\frac{1}{2}}\right) \]