

MSE160 Notes

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1 Introduction

1.1 Types of Material

- There are three classes of material (though not all materials fall under these categories):
 - Metals
 - Ceramics
 - Polymers
- **Metals** (e.g. Fe, Cr, Cu, Zn, Al) are held together with *metallitic* bonds and is described by **bond theory**.
- **Ceramics** (e.g. porcelain, concrete) are held together with *ionic* bonds and are *brittle*. A lot of them are metal oxides.

- **Polymer** (Teflon®, Gore-tex®, polyethylene) *tend* to be from *covalent bonds*

Warning: The word plastic actually describes a material property, and not a material type. There are plastics that are not polymers.

- Examples of materials that do not fall under this classification scheme include wood, skin, superconductors, and more.

1.2 Elastic Behaviour

- Hooke's law tells us that $F = -k\Delta x$, where Δx is the displacement from equilibrium.
- **Engineering stress** is defined as $\sigma = \frac{F}{A_0}$ where A_0 is the *initial* (unloaded) cross-sectional area.

Warning: Due to material properties, the cross sectional area of a spring can change as it elongates or compresses, so the engineering stress only refers to the initial cross sectional area. The *true stress* refers to the force divided by the real area.

- **Engineering strain** is defined as $\varepsilon = \frac{\Delta \ell}{\ell_0}$ and the two are related via the **Young's Modulus**:

$$\sigma = E\varepsilon \quad (1)$$

- There are two possible definitions for elastic deformation. When viewing it from a macroscopic perspective:

Definition: During elastic deformation, the sample dimensions return to their original dimensions upon unloading.

but it is also possible to view it from a microscopic perspective:

Definition: During elastic deformation, atoms return to their original positions upon unloading.

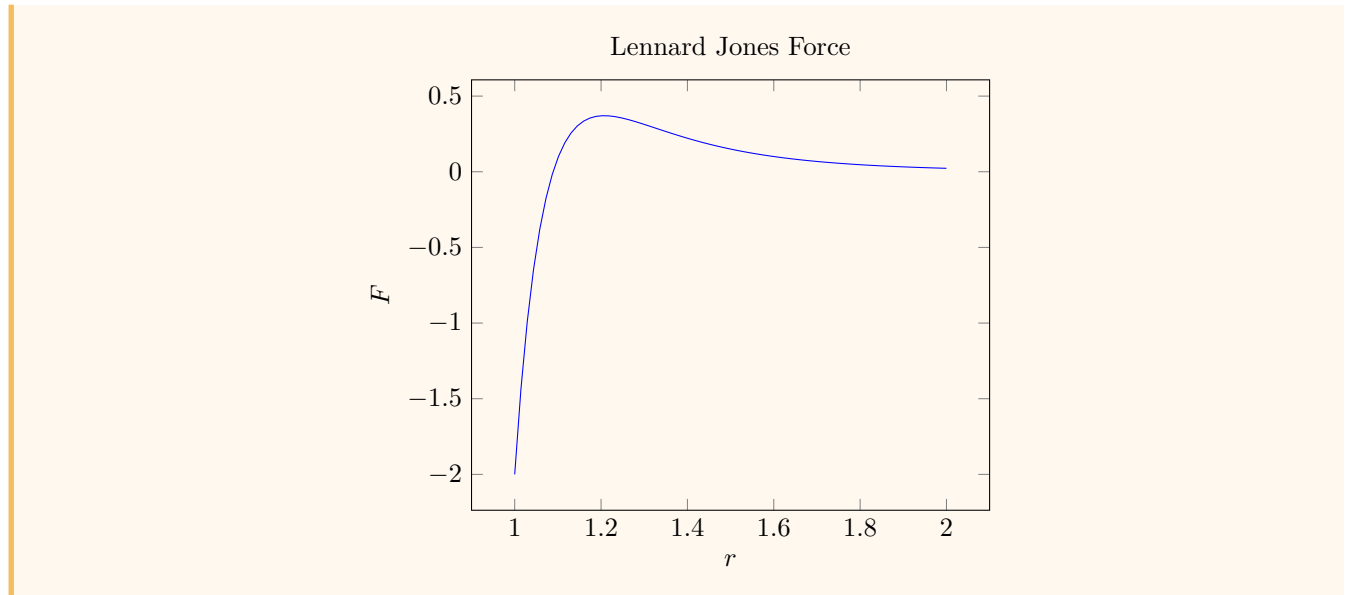
1.3 Simple Model for Bonding in solids

- A crude (but quite accurate) model is to assume nearby atoms in a solid are connected by springs. (This is actually Einstein's model of solid, except he modeled the interactions as quantum harmonic oscillators)

Idea: A more realistic model would be using the Lennard-Jones potential, which gives the force between two atoms as:

$$V = -\frac{a_1}{r^{13}} + \frac{a_2}{r^7} \quad (2)$$

and is graphically represented below (here, $a_1 = 5$ and $a_2 = 3$ for illustration purposes only)



When the two atoms are close to each other, the force scales roughly linearly with displacement, which is exactly the description of Hooke's Law.

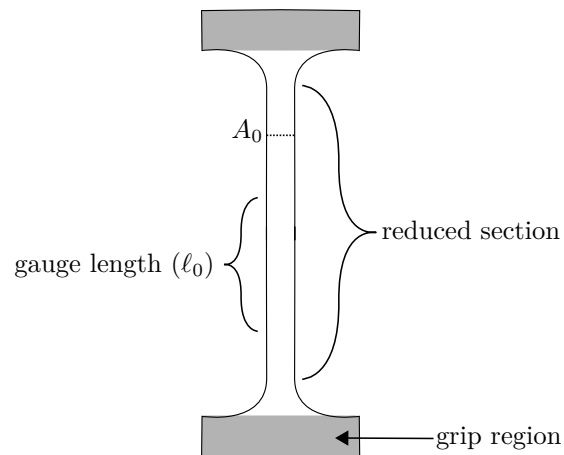
- Specifically, the Young's Modulus can be recovered by defining it as:

$$E \propto \left. \frac{dF}{dr} \right|_{r=r_0} \quad (3)$$

where r_0 is the equilibrium distance and is only dependent on the material. Permanently deforming a metal will not change its Young's Modulus.

1.4 Getting a stress-strain curve

- The tensile specimen is in a **dogbone** shape as illustrated below: and the test is performed by gripping the grip



regions and performing a uni-axial tension test.

1.5 Poisson's Ratio and Shear

- When a material deforms, it does not deform in only one direction. The **poisson's ratio** ν relates the strain in all three directions:

$$\nu = -\frac{\varepsilon_R}{\varepsilon_Z} = -\frac{\varepsilon_x}{\varepsilon_z} = -\frac{\varepsilon_y}{\varepsilon_z} \quad (4)$$

for a cylindrically symmetrical material.

- Shear stress is defined as

$$\tau = \frac{F}{A_0} \quad (5)$$

and shear strain is defined as:

$$\gamma = \frac{\Delta \ell}{\ell_0} \quad (6)$$

- Similarly, shear stress and strain is related via the shear modulus G :

$$\tau = G\gamma \quad (7)$$

- The Young's modulus and the shear modulus is related via the poisson ratio:

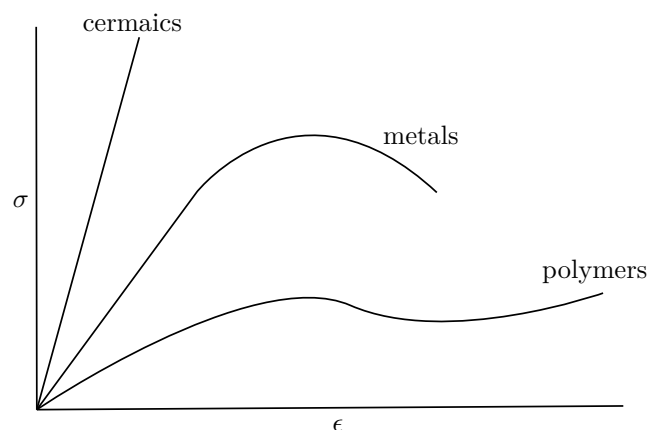
$$E = 2G(1 + \nu) \quad (8)$$

2 Inelastic Behaviour

- Permanent deformation can be defined in three ways:
 1. Upon unloading, sample does not return to original dimensions
 2. Strain does not return to zero
 3. Atoms move to new positions
 4. Occurs near the end of linear behaviour
- Plastic comes from the greek word *plastikos*, which means to shape or to sculpt. In this course, plastic does not refer to the material type but instead the permanent deformation.
- The **strength** of a material describes when the permanent deformation occurs.

Warning: Strength depends on context and is not always defined as above.

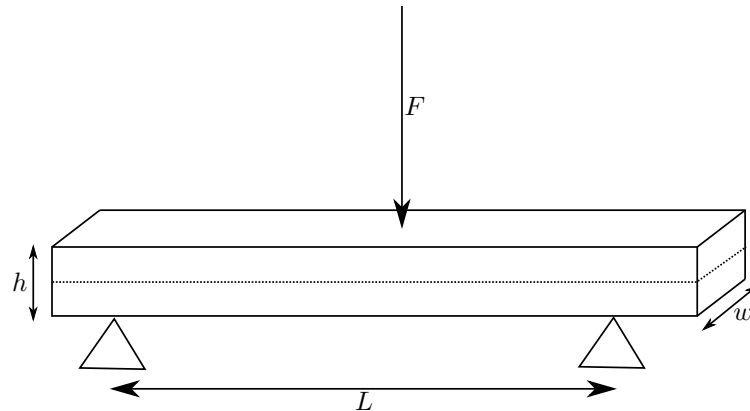
- The stress strain curve for different materials resemble different shapes.
 - Polymers have a distinct yielding region
 - Metals start a concave down behaviour as soon as elastic deformation ends
 - Ceramics have linear behaviour all the way until they fracture



- For polymers, the use of *Young's Modulus* is misleading since the elastic behaviour depends on several different types of bonds, while Young's Modulus is related to the behaviour of a single bond. As a result, the term **elastic modulus** is used to describe polymers and composite materials.

2.1 Ceramics

- Ceramics are not typically tested in tension because:
 1. It is difficult to grip because it crumbles easily
 2. It is difficult to shape it into a dogbone shape
 3. Machine alignment is difficult to achieve.
- Instead, we test them by **3-point bending**:



- The dotted line is the neutral axis and since it is weak in tension, the plate will break in the lower half at a stress value of:

$$\sigma = \frac{3FL}{2wh^2} \quad (9)$$

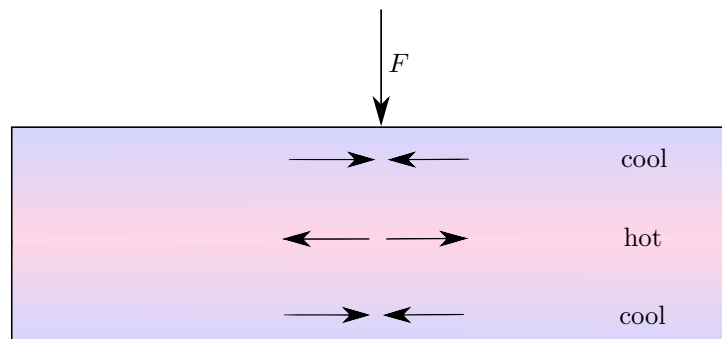
2.2 Tempered Glass

- **Tempered glass** has a very high strength and is relatively “safe” when it fractures (small pieces instead of large ones)

Idea: Initially, tempered glass is very hot in a large volume. However, as it rapidly cools, the surfaces cool faster than the center. Since glass is made of silica bonded to four oxygen, it forms a very complex network structure. Therefore, during this rapid cooling, it “fixes” in excess volume.

The regions in the middle that are cooling more slowly is trying to contract but is constrained by the outer surface that it goes into tension. The fast cooling regions on the other hand will be in tension.

- When the glass bends, the opposite side of the window can still be in considerable compression even though for a regular ceramic it should be in tension. This increases the strength.



- The stress distribution creates **residual stress** which results in stored strain energy. When the glass gets fractured, the stored strain energy gets transformed into **surface energy**.
- Since surface energy is proportional to surface area, this means that the fractured pieces are smaller.
- **Chemical processes** can also be used to create tempered glass, such as gorilla glass. Ions with a larger size diffuse into the surface and take up a larger space in the network resulting in an increase in volume at the surface.

3 Structure Property Relationship

- If we plot the relationship between the Young's Modulus and the density, we find that there are no materials with a high Young's Modulus and a low density and that most materials fall on a single line.
- The **materials performance index** MPI for a beam is defined as:

$$MPI = \frac{E^{1/2}}{\rho} \quad (10)$$

Proof. The deflection of a beam takes the form of:

$$\delta = \frac{FL^3}{CEA^2} \implies A = \left(\frac{FL^3}{CE\delta} \right)^{1/2} \quad (11)$$

and using the equation:

$$m = AL\rho \quad (12)$$

we are able to retrieve the equation above. \square

- If we were to plot the Young's Modulus against the density on a log-log scale and draw out the curve:

$$\log E = 2 \log \rho + \log MPI \quad (13)$$

then materials on the same line would have the same materials performance index. If we shift this line to the left, the performance index of the material improves.

- For a beam, performing this analysis will give us composites such as carbon fibre. Ceramics also belong in this category but because they are susceptible to catastrophic brittle fracture, we can ignore them.
- For a loaded plate, the MPI is:

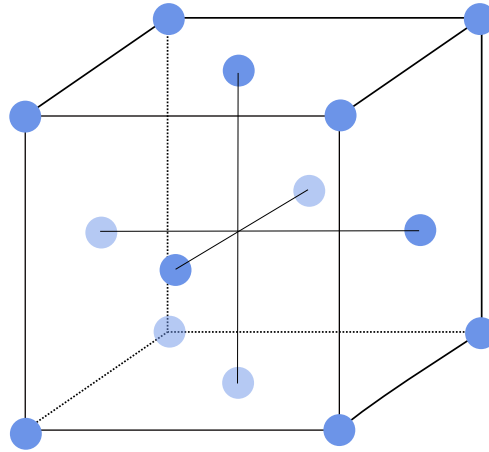
$$MPI = \frac{E^{1/3}}{\rho} \quad (14)$$

and the best in this category is wood.

- **Polycrystalline** refers to materials made of crystals, typically around the micron scale.
- Most metals and some ceramics are crystalline (e.g. sapphire), but not everything is. **Amorphous** materials are not organized, an example being window glass.
 - Long-range order refers to a organization at a distance well beyond the nearest neighbour
 - Short-range order refers to organization at only the first or second nearest neighbour.
- One such highly organized material has a **face-centered cubic** (FCC) structure. Many metals have this organization:
- Each of the eight corners have $\frac{1}{8}$ of an atom and each of the six faces have $\frac{1}{2}$ of an atom, which gives: $n_{\text{FCC}} = 4$ atoms in a unit cell.
- Given n , we can calculate the density of an FCC material such as aluminium, via:

$$\rho = \frac{nA}{a^3 N_A} \quad (15)$$

where a is the length of the unit cube known as the **lattice parameter**, A is the molar mass, and N_A is Avocado's number.



- Based off of the hard sphere model, we treat atoms in ordered solids as hard spheres that make contact with their nearest neighbours. However, this is very hard to draw so we will go by the *reduced sphere* model by drawing atoms smaller.

Example 1: Suppose we wish to find the theoretical density of Aluminum, which is a FCC structure. We are given:

$$A = 26.892 \text{ g mol}^{-1}$$

$$R = 143 \text{ pm}$$

The lattice parameter is given by:

$$a = 2\sqrt{2}R \quad (16)$$

which gives us:

$$\rho = \frac{nA}{(2\sqrt{2}R)^3 N_A} = 2.71 \text{ g cm}^{-3} \quad (17)$$

- The **atomic packing factor** is given by:

$$\text{APF} = \frac{V_{\text{spheres}}}{V_{\text{unit cell}}} \quad (18)$$

Since the unit cell is a cube with volume a^3 , we have:

$$\text{APF} = \frac{4\pi R^3 n}{3a^3} \quad (19)$$

and for FCC:

$$\text{APF} = \frac{16\pi R^3}{3a^3} \quad (20)$$

We can also relate the R and a together via:

$$a = 2\sqrt{2}R \quad (21)$$

for FCC packing, which yields:

$$\text{APF}_{\text{FCC}} = \frac{\pi}{3\sqrt{2}} \approx 0.74 \quad (22)$$

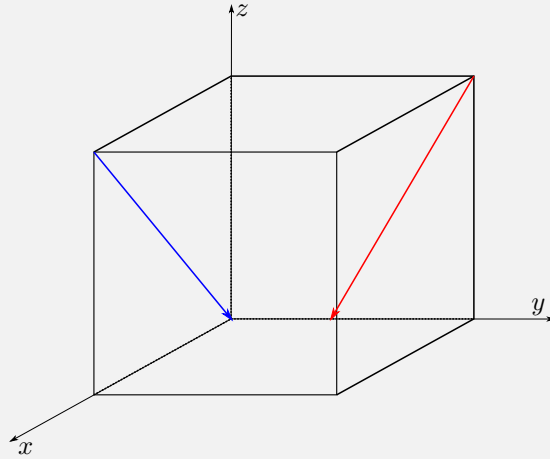
which is the highest possible value. The maximum fraction that a volume can be filled up is 74%.

4 Crystallographic Planes and Directions

- We develop a set of notation to describe directions. It comes with a set of rules:
 - Translate vector, if it simplifies things.

- Determine projection onto x , y , z .
- Reduce to lowest integers.
- Enclose in square brackets (negative signs are moved above, no commas)

Example 2: We can find the crystallographic directions of both the blue and the red vectors in the figure below.



For the blue vector, we first let the tail be the origin. The vector travels 1 in the negative x direction, 0 in the y direction, and -1 in the negative z direction, which gives $[\bar{1} 0 \bar{1}]$.

For the red vector, it travels in the negative y direction for 0.5 and in the negative z direction for 1 so we get, after getting rid of fractions: $[0 \bar{1} \bar{2}]$.

- To denote a family of directions, we can use bracket notation. All face diagonals can be written as:

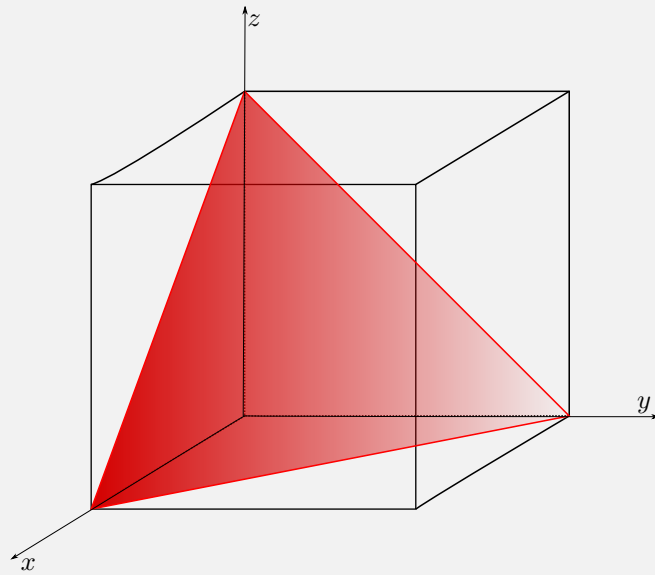
$$\langle 011 \rangle \quad (23)$$

which includes:

$$[011], [0\bar{1}1], [01\bar{1}], [101], \dots \quad (24)$$

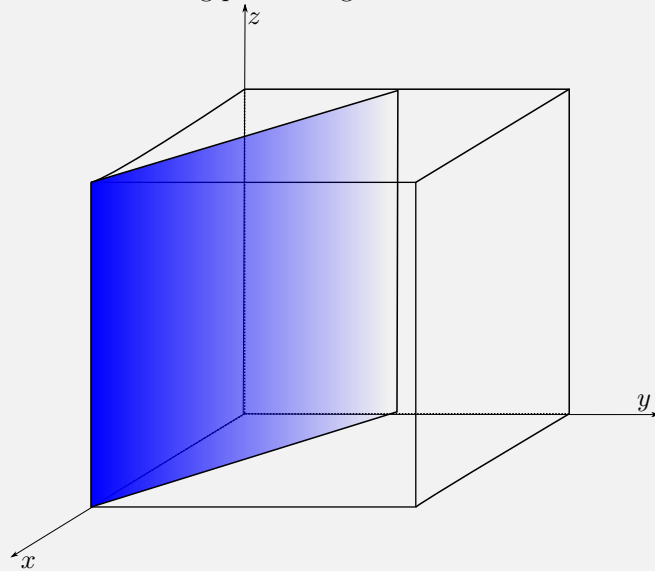
- To determine crystallographic planes, we use **crystallographic planes**. It uses the following set of rules:
 - Translate plane so origin is not on the plane (defining new origin).
 - Determine distance to intercept plane by travelling along each axis, from the origin.
 - Take the reciprocal of the distance.
 - Enclose in parentheses (use h , k , ℓ). Negatives go above, no commas.

Example 3: We can represent the following plane using Miller indices:



We can start from the origin and travel a length of 1 in both the positive x , y , and z direction. Taking the reciprocal, we still have 1, 1, 1, so the final miller index is $(1\ 1\ 1)$.

Example 4: We can represent the following plane using Miller indices:



We can start from the origin and travel a length of 1 in the x direction, $1/2$ in the y direction, and ∞ in the z direction. Taking the reciprocal we get $(1\ 2\ 0)$.

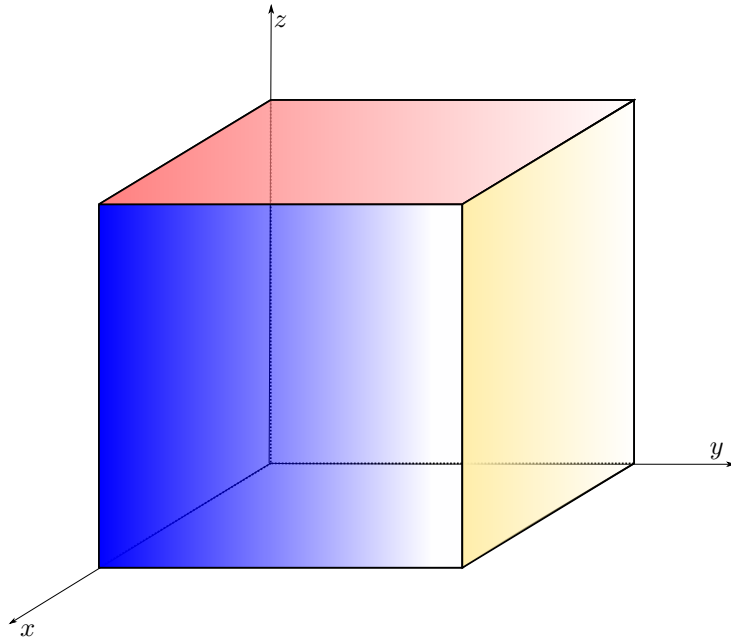
- We can represent **families of planes** using curly braces. For example, faces of a cube can be represented by:

$$\{001\} \quad (25)$$

which represent the following planes:

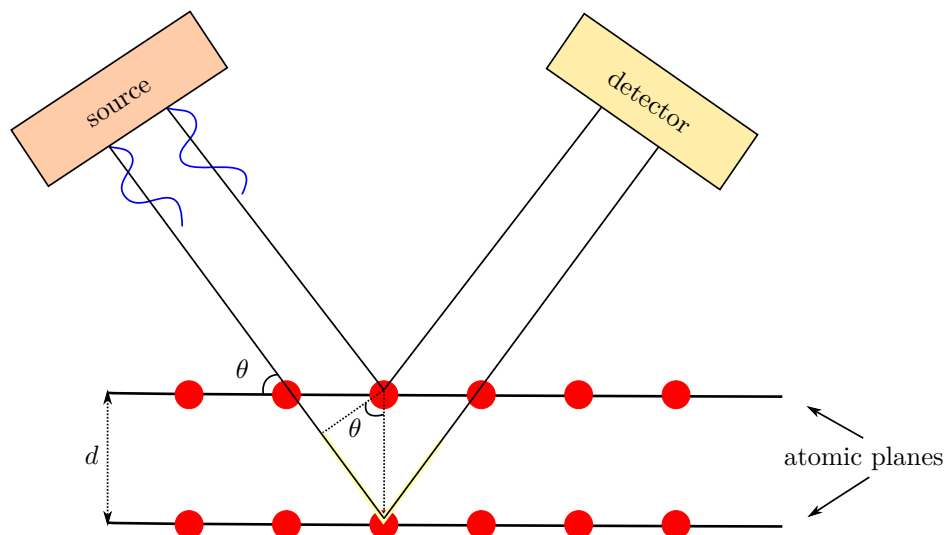
$$(100), (010), (001) \quad (26)$$

corresponding to the below blue, yellow, and red plane respectively:



5 X Ray Diffraction

- Suppose there is an x-ray source that reflects off a sample and hits a detector at a certain angle θ . If we plot the intensity as a function of θ , we see that it peaks at very specific values.



- This is a result of constructive interference where the peaks of both wavelengths add up at the detector.
- This will only occur if the extra distance (shown in yellow) is an integer multiple of the wavelength λ . Mathematically:

$$2d \sin \theta = n\lambda \quad (27)$$

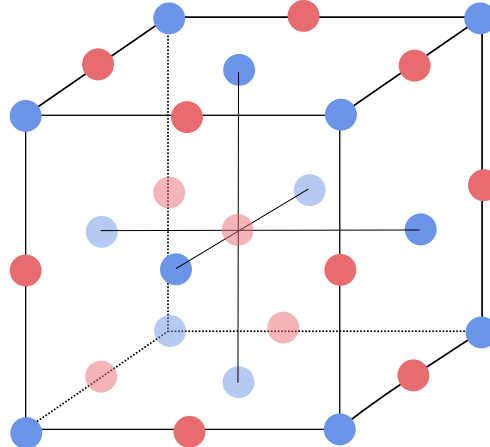
known as **Bragg's Law**, where n is an integer.

6 More Structures

- We begin our discussion of various more complicated crystal structures.

6.1 Rock Salts

- A common crystal structure are **rock salts**, such as NaCl, MgO, FeO, ...
- The rock salt structure is visualized below, with blue representing anions (negative) and red representing cations.



Notice that the number of cations and anions are equal in a unit cube. It consists of three layers, with cations and anions alternating across each layer such that all adjacent neighbours have a parity charge. As a result, we have $n = 4$.

- We can define the **coordination number** as the number of atoms directly adjacent to a particular atom. For rock salts, the coordination number is 6.
- The theoretical density can be calculated as:

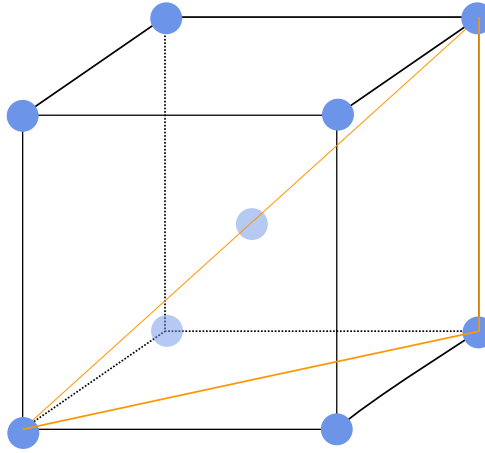
$$\rho = \frac{n_c A_c + n_A A_A}{V_c N_A} \quad (28)$$

where for a rock salt, $a = 2R_A + 2R_c$.

Warning: Anions do *not* touch along face diagonals for a rock salt. Instead, they touch their adjacent neighbours only.

6.2 Body Centered Cubic

- Another common structure are **body centered cubic** (BCC) crystals.

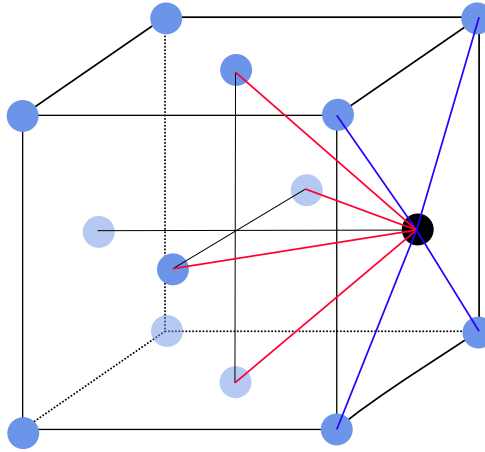


They consist of atoms at the corners of the cube with another atom at the very beginning. As a result, we have $n = 2$.

- To calculate the lattice parameter, we can apply Pythagorean's theorem:

$$a^2 + a^2 + a^2 = (4R)^2 \implies a = \frac{4}{\sqrt{3}}R \quad (29)$$

- The coordinate number of a BCC structure is 8 since each atom is directly adjacent to eight other atoms.
- The coordinate number of a FCC structure is 12. This is harder to see but can be illustrated below:



Suppose we look at the black atom located on the rightmost plane. It is $a/\sqrt{2}$ away from the other four atoms on its face, but it's also $a/\sqrt{2}$ away from four other atoms (shown in red). Since the unit cell pattern repeats forever, by symmetry, there must be four more atoms it touches on the other side (if pattern continues).

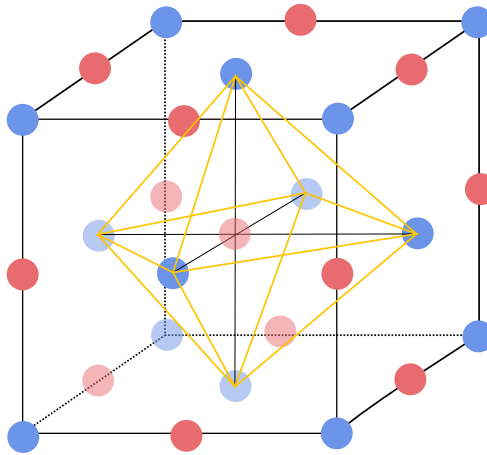
- The atomic packing factor for BCC is given by:

$$APF_{\text{BCC}} = \frac{n \frac{4}{3}\pi R^3}{a^3} \approx 0.68 \quad (30)$$

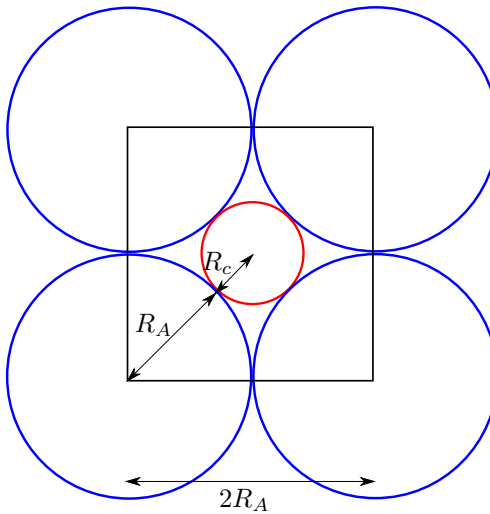
which is below the 0.74 atomic packing factor for FCC.

6.3 Interstitial Sites

- An interstitial site is a position between the atoms that can be occupied by other atoms.
- An octahedral interstitial site exists within rock salt crystals, illustrated below:



The yellow outline forms an octahedron with eight faces, and the red ion is placed in the octahedral site. We can calculate exactly the maximum size of R_c with respect to R_A by consider a two dimensional plane:



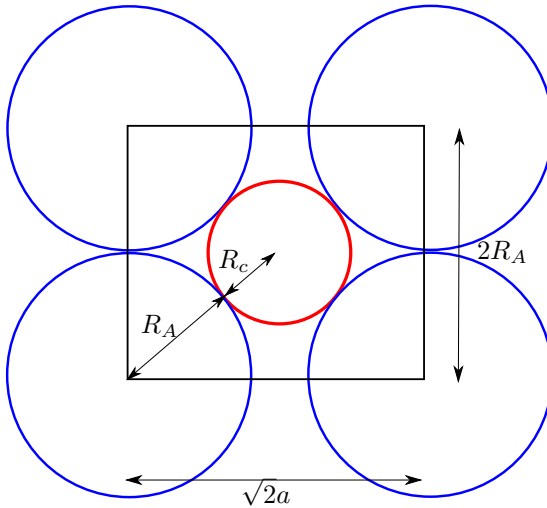
We see that:

$$R_A = (R_A + R_c) \sin(45^\circ) \quad (31)$$

and we get the ratio to be:

$$\frac{R_c}{R_a} = \frac{1 - \sin(45^\circ)}{\sin(45^\circ)} \approx 0.414 \quad (32)$$

- We can perform a similar calculation for a body centered cubic by slicing a plane across the diagonal:



and we get a similar result:

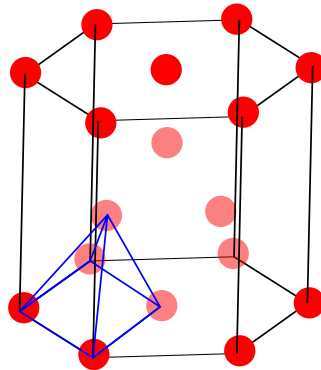
$$\frac{R_c}{R_A} = \frac{1 - \sin \theta}{\sin \theta} \quad (33)$$

Here, $\theta = \tan^{-1} \left(\frac{1}{\sqrt{2}} \right) = 35.3^\circ$ which gives:

$$\frac{R_c}{R_A} \approx 0.732 \quad (34)$$

6.4 Hexagonal Close Packed

- Another common packing structure is **hexagonal closed packed** (HCP). It has the same atomic packing factor as FCC:



It consists of atoms stacked in an *ABA* pattern in hexagons. If we continue the pattern for several unit cells and connect the centers of the atoms in each layer, it will form a hexagonal honeycomb shape.

- The height of this unit cell is $c = 1.633a$ where $a = 2R$ is the side length. The volume of the prism is given by:

$$V = \frac{3\sqrt{3}}{2} a^2 c \quad (35)$$

- Similar to an FCC structure, each atom in HCP has a coordinate number of 12.
- These similarities between FCC and HCP are not a coincidence. It's possible to stack face centered cubic unit cells such that it forms a HCP structure.

6.5 Examples

- Aluminum is a fascinating example of a FCC structure. It starts off as a thin flat piece of aluminum and through a series of plastic deformations, it's able to elongate.

This shows that FCC and HCP lead to materials that can experience greater plastic deformations. This is because the layers can shift and “snap” into place.

- Recall that iron has a BCC structure. The spacing of atoms along the diagonal and the edges are not the same. As a result, we can expect the Young’s Modulus in these two directions to also differ and this is verifiable.
- We can also look at the differences between the behaviour of a metal versus the behaviour of a ceramic.
 - In metals, planes are able to slide past each other. The result is plastic deformation.
 - In ceramics, we cannot have a lot of plastic deformation using the rock salt crystal structure. If planes do attempt to slide, like charges would overlap and would create fracture.

7 Technical Mechanical Behaviour

- The ultimate tensile strength, denoted as UTS or σ_{UTS} is the highest stress that a material can occur in a material.
- The *proportional limit* describes the point on the tensile stress-strain curve where elastic deformations no longer occur.
- Along with the yield strength, it is difficult to define this objectively. Instead, we use the following convention:

Definition: The yield strength is the stress value at which if the material is unloaded at that point, the strain will be $\epsilon = 0.002 = 0.2\%$.

- Uniform deformation occurs when the thickness of the material is uniform. Non-uniform deformation occurs when an increase in strain results in a decrease in stress. This is known as **necking**.
- Crystalline imperfections are called **dislocations**. The dislocation density can be reduced by heating (annealing), and plastic deformation can increase the density.
- Dislocations are known as **linear imperfection** as they can form a “tunnel” like bonding environment where there is a dislocation line.
- Plastic deformation is the result of the step by step movement of linear imperfections:
 1. As a force is applied, the bonds to the right of the dislocation stretch and eventually break
 2. A new set of bonds re-forms
 3. This breaking and re-forming happens again
 4. And again, and so forth.

Warning: Remember that this mechanism is *not* the breaking of all bonds at the same time on a plane of atoms.

- It is possible to classify imperfections:
 - 0-dimensional: point defect
 - 1-dimensional: linear imperfections (dislocations)
 - 2-dimensional: interfacial imperfections (grain boundaries, free surfaces)
 - 3-dimensional: volume defects (pores, 2nd phases)

7.1 Point Defects

- An example of a 0-dimensional imperfection is an **interstitial impurity**, for example putting in the much smaller carbon atoms in a lattice with iron atoms.
- A substitutional impurity is when an atom gets replaced by another atom, and satisfies the following conditions:
 - Same crystal structure

- Similar size (usually 10%)
- Similar electronegativity (prevent unwanted reactions)
- These impurities can disrupt the intermolecular interactions, causing other atoms to move slightly from their original equilibrium location. This is known as **lattice strain**.
- A **vacancy** is when an atom is missing altogether. The number of vacancies is given as:

$$N_v = N \exp\left(-\frac{Q_v}{kT}\right) \quad (36)$$

where Q_v is the energy to form vacancies, k is the Boltzmann constant, T is the temperature, and N_v is the number of vacancies.

- We can obtain interesting behaviour if we introduce two impurities (i.e. a dislocation and a interstitial impurity). We can often find that impurities diffuse towards dislocations (state with less energy). This is known as a **pin dislocation**
- Impurities can also inhibit dislocation movements.
- Adding impurities creates defects, but defects aren't bad. Most of the time, they are able to inhibit dislocation movements, which actually increases the strength of the material!

7.2 One-dimensional Dislocations

- There exists strain fields that surround dislocations (areas of tension and compression). They can repel or under special circumstances, cancel out, leaving a small region of a perfect crystal structure.
- Since plastic deformation is able to increase the dislocation density, it makes it harder for lattices to slide past each other. As an industry practice, this is known as **cold work** and plastic deformation is known as **forging**
- **cold forging** and **hot forging** is used to classify the different types of forging, as it can involve very high temperatures sometimes.
- Because the metal accumulates plastic strain during the strengthening process we also use the term strain hardening.

7.3 Two-dimensional Dislocations

- Atoms at a free surface have fewer nearer neighbours cause be a smaller amount of unsatisfied bonds. This causes atoms at the surface to be at a higher energy state. For water, this behaviour at the surface is known as the **surface tension**.
- However, we are interested in what happens at an internal surface. Suppose we have two separate crystals (or grains) initially growing independently. However, when these two grains come into contact, it creates a *two-dimensional dislocation*.
- The dislocation at the grain boundary will have to:
 - Change direction
 - Planar Mismatch
 - Lattice Strain

As a result, grain boundaries inhibits dislocation movement and strengthens metals by decreasing grain size.

7.4 Three-Dimensional Dislocations

- Pores can be thought of “bubbles” in a material. They can be visible to the naked eye or may be finer.
- A second phase is when we insert a different material with a different crystal structure to strengthen materials (i.e. Fe_3C)
- Similarly to before, it is difficult to navigate across these phases.