MODERN PHYSICS

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CRYSTAL STRUCTURES

INTRODUCTION

Solids can be broadly classified into *Crystalline* and *Non-crystalline* or *Amorphous.*

- **In crystalline solids the atoms are arranged in a periodic manner in all three directions, where as in non crystalline the arrangement is random.**

- **Non crystalline substances are *isotropic* and they have no directional properties.**

- **Crystalline solids are *anisotropic* and they exhibit varying physical properties with directions.**

- **Crystalline solids have sharp melting poi[illegible] amorphous solids melts over a range of temperature.**

SPACE LATTICE

- A Space lattice is defined as an infinite array of points in three dimensions in which every point has surroundings identical to that of every other point in the array.

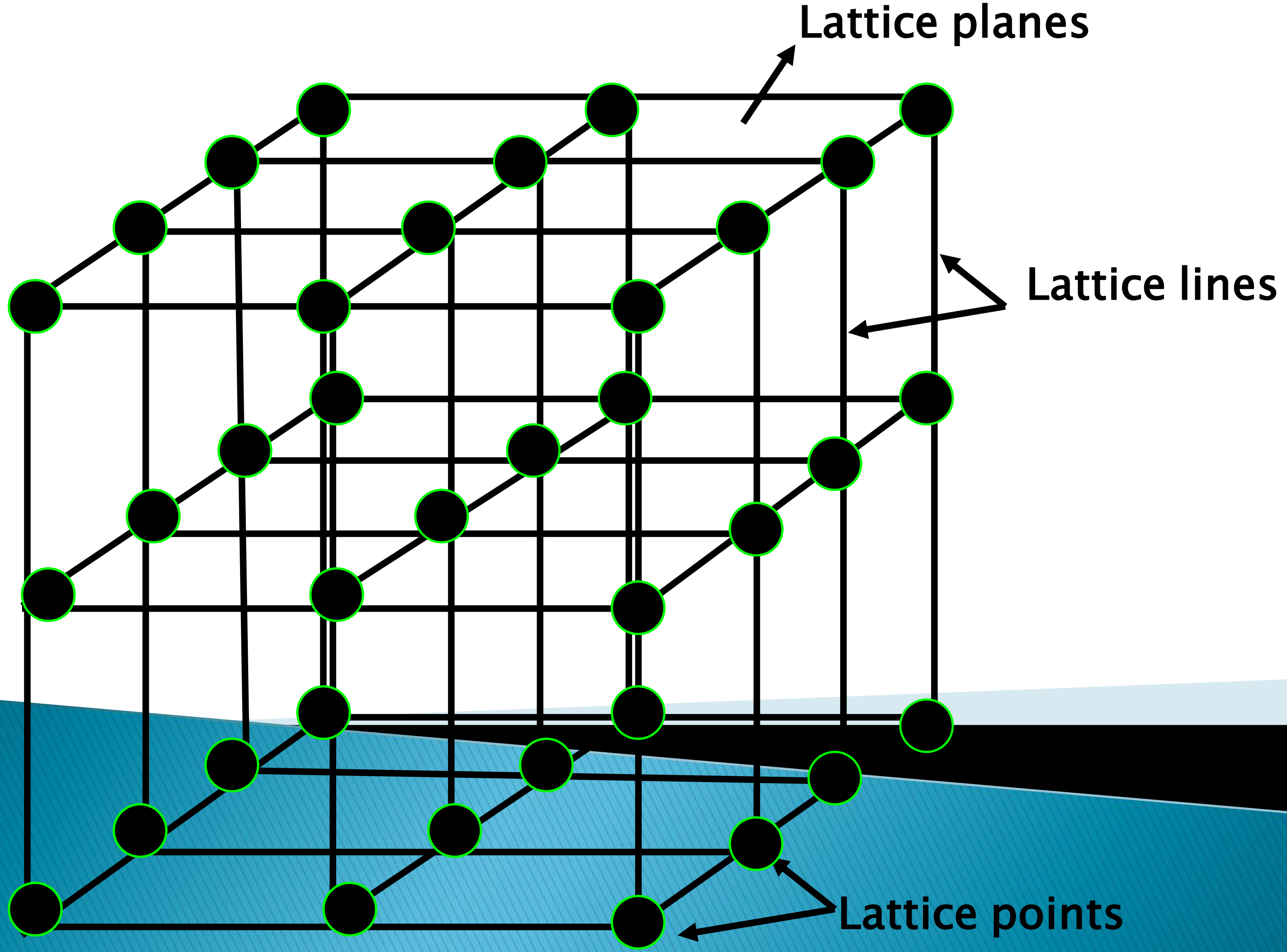
X X X X X

X X X X X

X X X X X

X X X X X

Three dimensional lattice



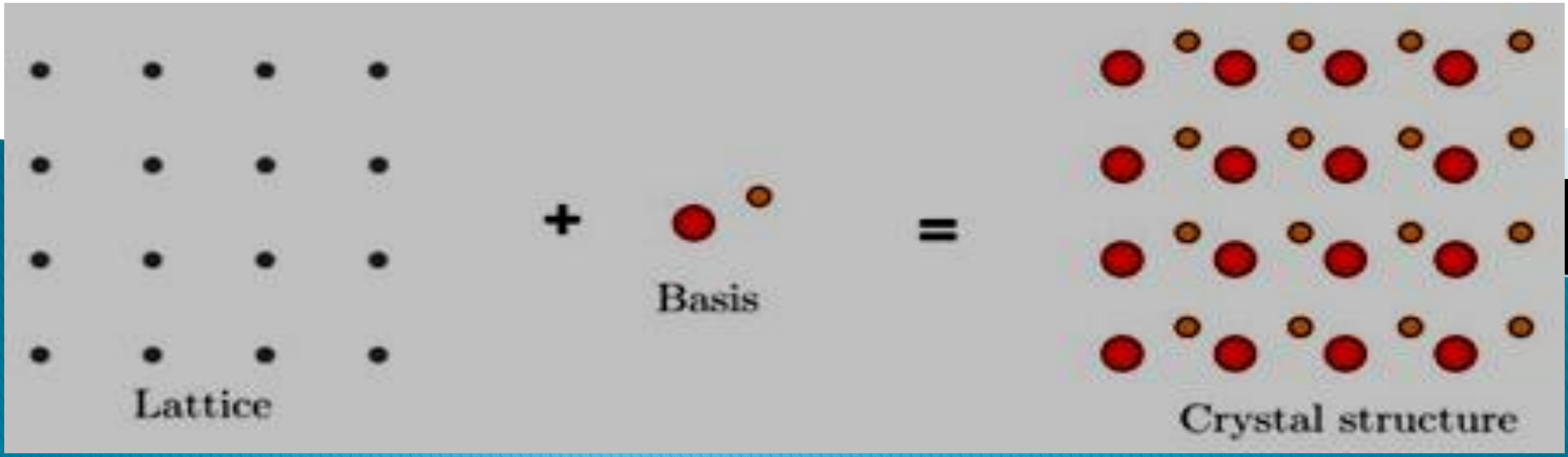
BASIS

If basis associated with every lattice point, crystal structure is generated.

The basis provides number of atoms per lattice point.

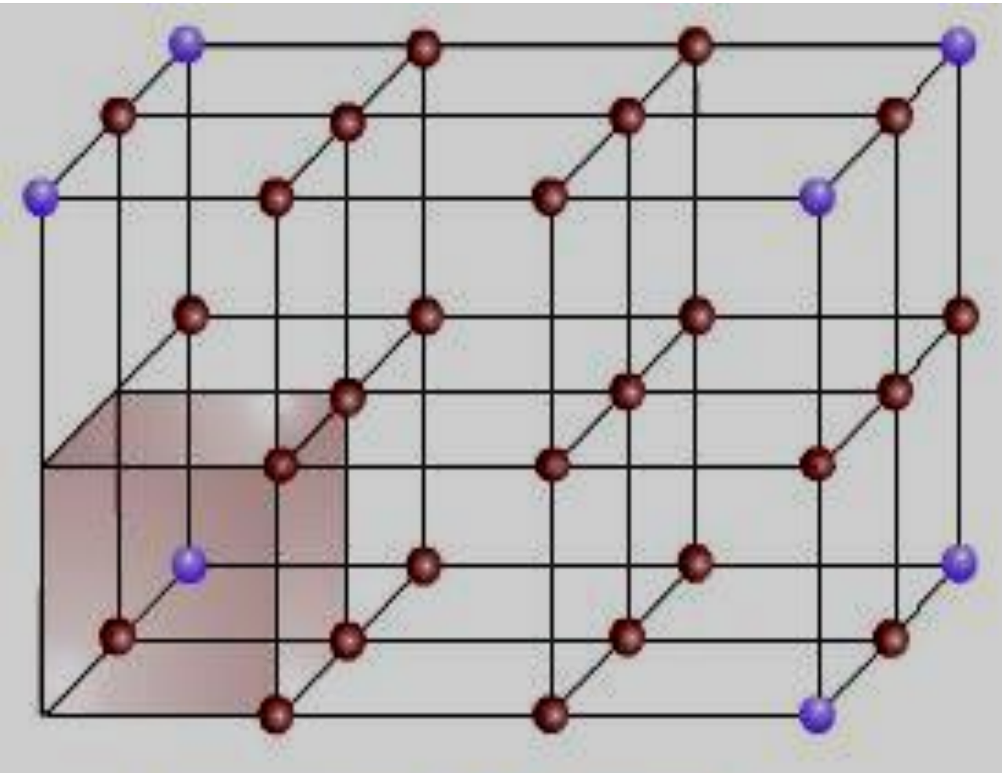
Example: In NaCl the basis is diatomic and in CaF_2 the basis is triatomic.

Lattice + basis = Crystal structure

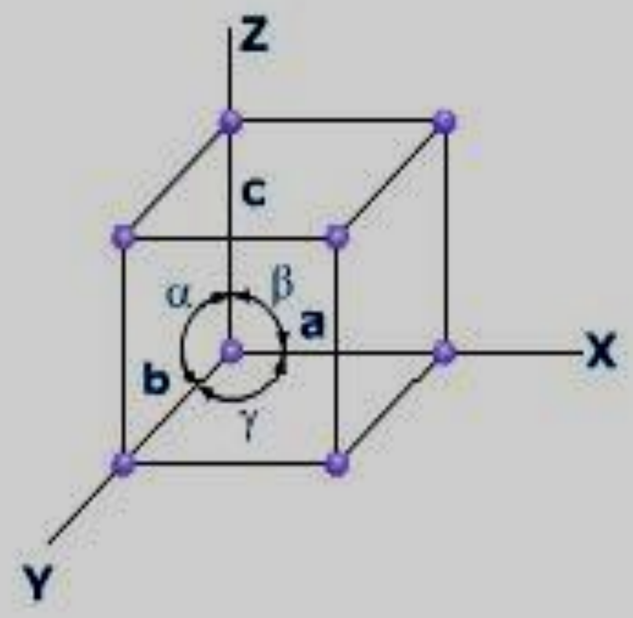


UNIT CELL

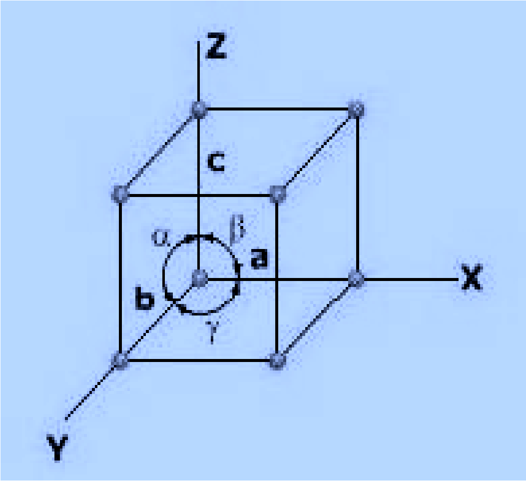
- A unit cell is the smallest geometric figure, the repetition of which gives the actual crystal structure.



Representation of space lattice and unit cell



Representation of dimensions of a unit cell



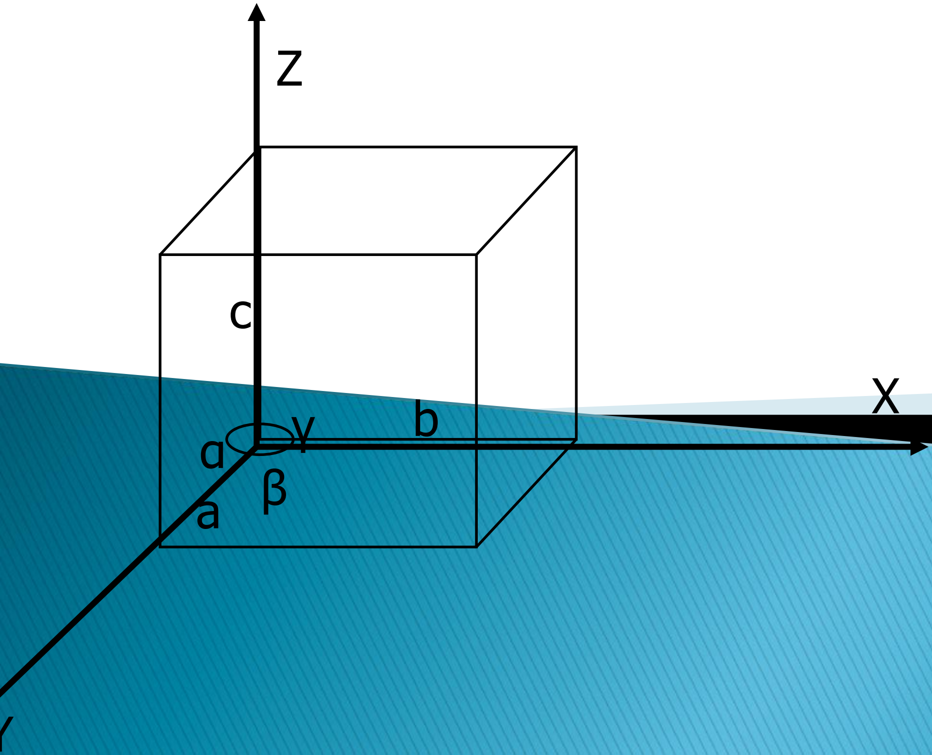
CRYSTALLOGRAPHIC AXES

The lines drawn parallel to the lines of intersection of any three faces of the unit cell which do not lie in the same plane are called *Crystallographic* axes.

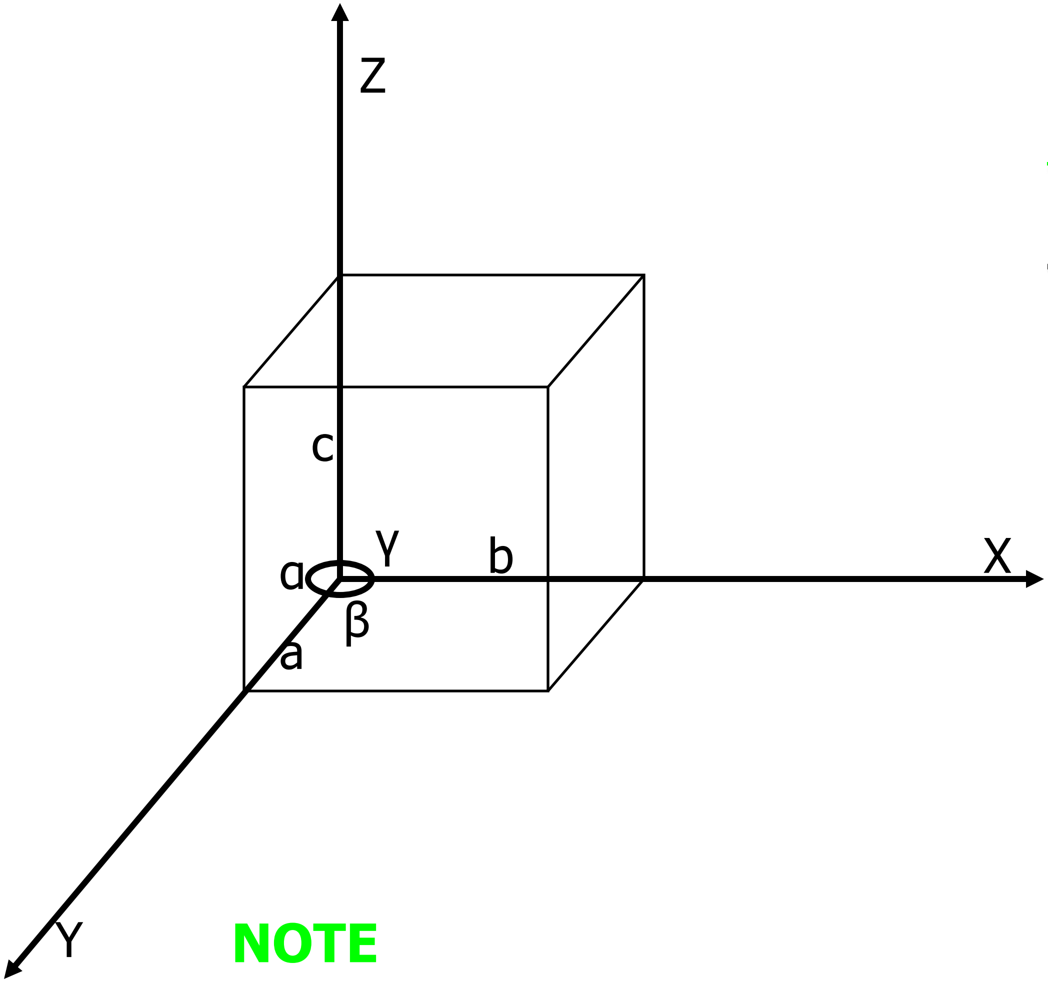
PRIMITIVES:

a, b and c are the dimensions of an unit cell and are known as ***Primitives.***

INTERFACIAL ANGLES:



The angles between three crystallographic axes are known as ***Interfacial angles*** α ,β **and** γ.



LATTICE PARAMETERS

The primitives and interfacial angles together called as lattice parameters.

NOTE

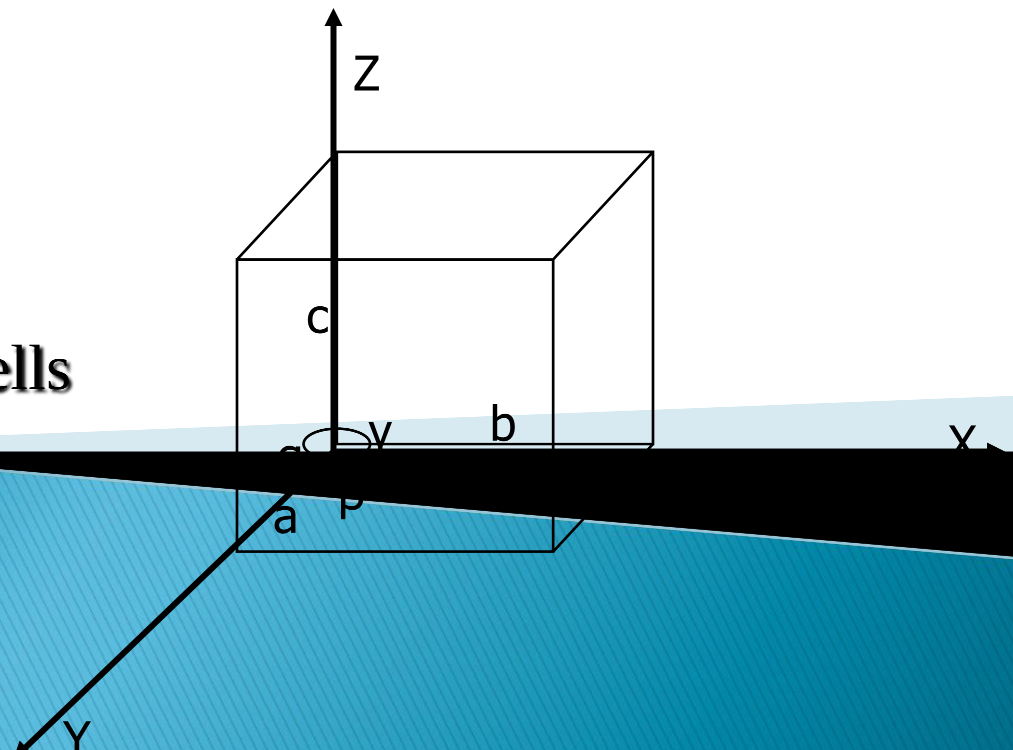
1. Primitives decides the **size** [redacted]

2. **Interfacial angles** decides the **shape** of the unit cell.

PRIMITIVE CELL

The unit cell which is formed by primitives is called **primitive cell.**

A primitive cell contain only one atom per unit cell.



NOTE:

All primitive cells are unit cells but not all unit cells are primitive cells.

Crystal System	Relation between primitives	Relation between Interfacial angles	Bravias lattices	No. of bravias lattices	Example
Cubic	a= b= c	$\alpha = \beta = \gamma = 90^o$	P, I, F	3	NaCl
Tetragonal	a= b≠ c	$\alpha = \beta = \gamma = 90^o$	P,I	2	TiO_2
Orthorhombic	a≠ b≠ c	$\alpha = \beta = \gamma = 90^o$	P,I,F,C	4	KNo_3
Monoclinic	a≠ b≠ c	$\alpha = \beta = 90, \gamma \neq 90^o$	P,C	2	$CaSo_4 2H_2o$
Triclinic	a≠ b≠ c	$\alpha \neq \beta \neq \gamma \neq 90^o$	P	1	$K_2Cr_2O_7$
Trigonal	a= b= c	$\alpha = \beta = \gamma \neq 90^o$	P	1	calcite
Hexagonal	a= b≠ c	$\alpha = \beta = 90^o, \gamma = 120^o$	P	1	SiO_2
				Total=14	

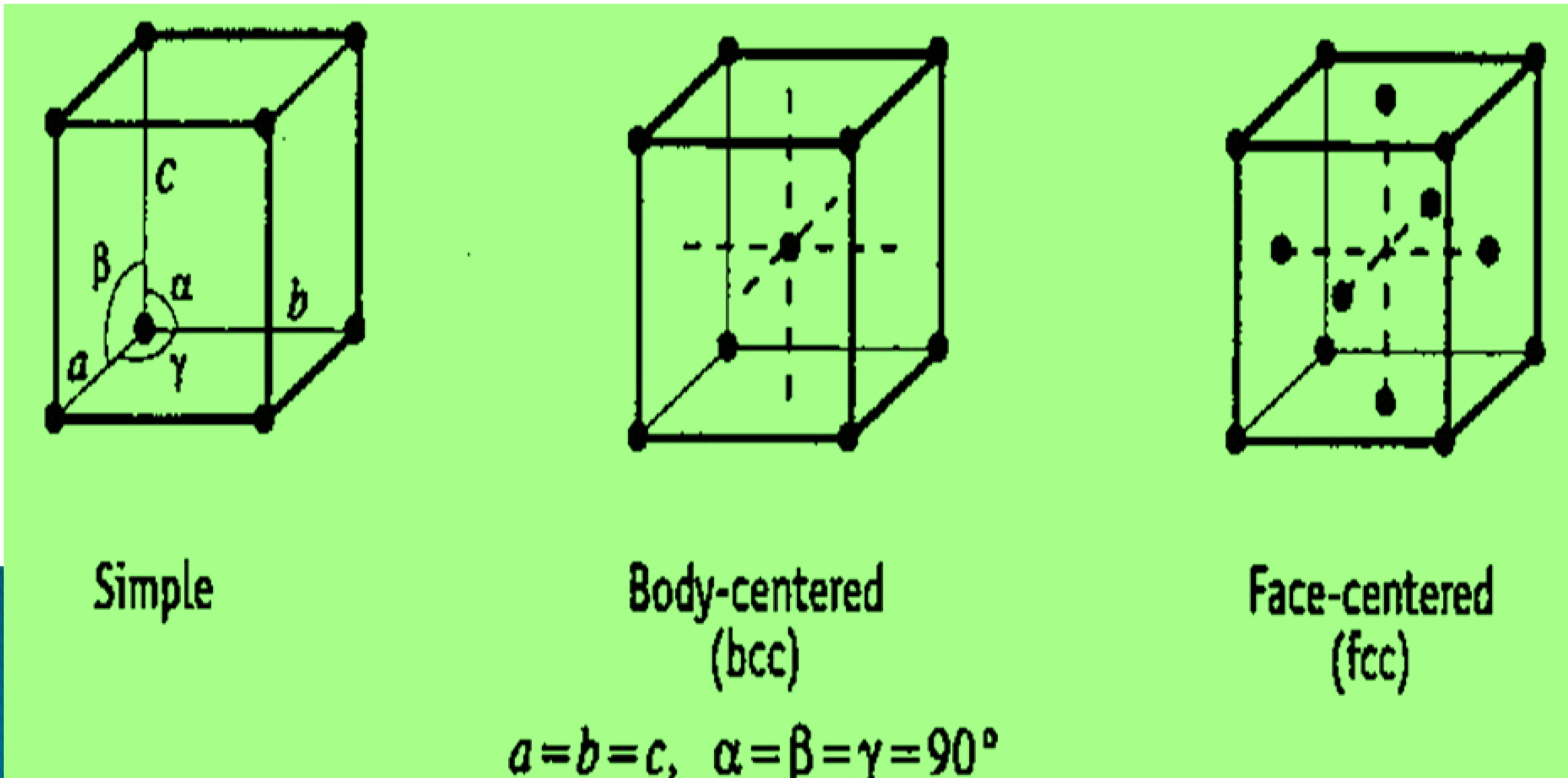
P – Primitive

C – Base Centered

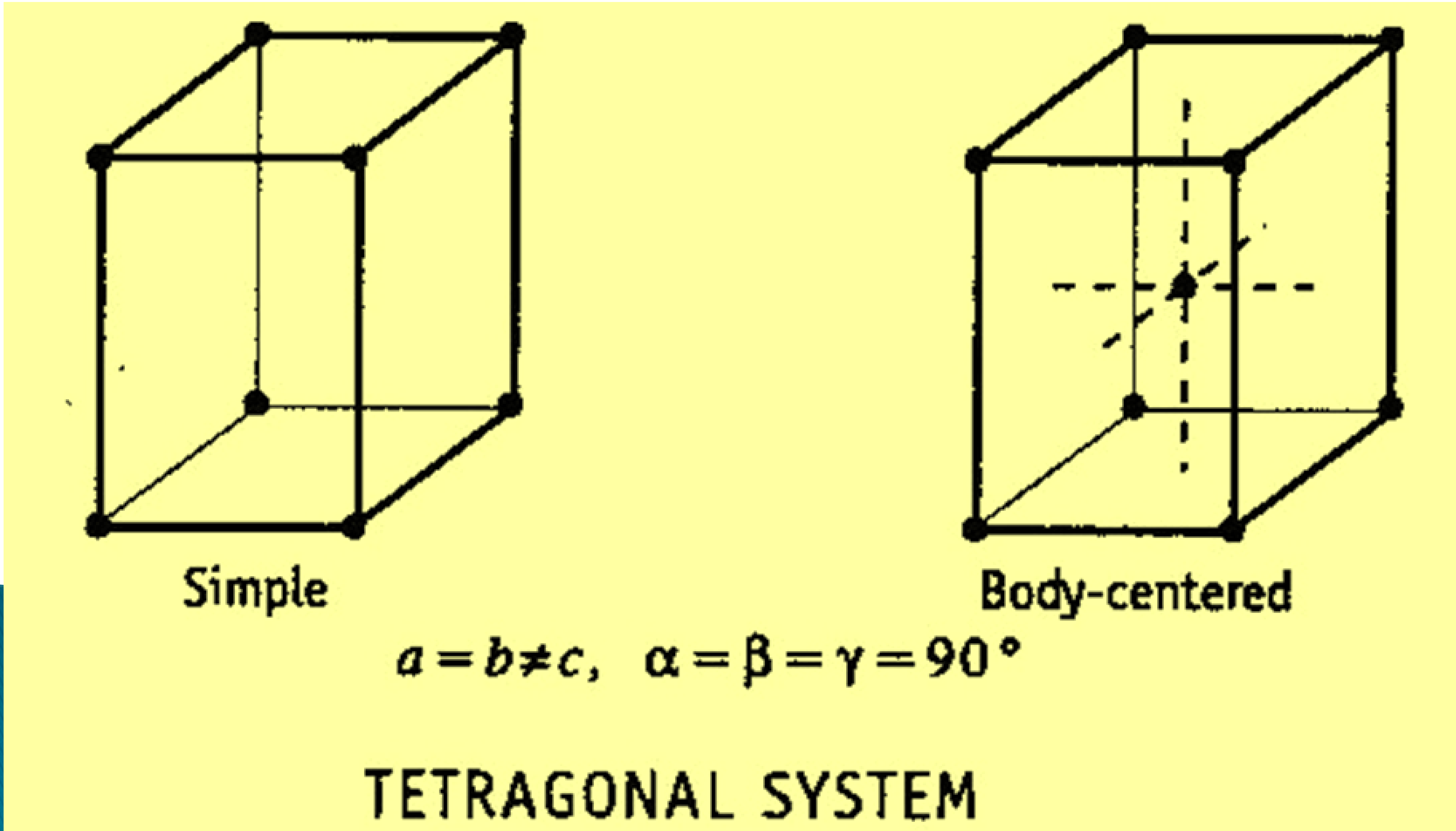
I – Body Centered

F – Face Centered

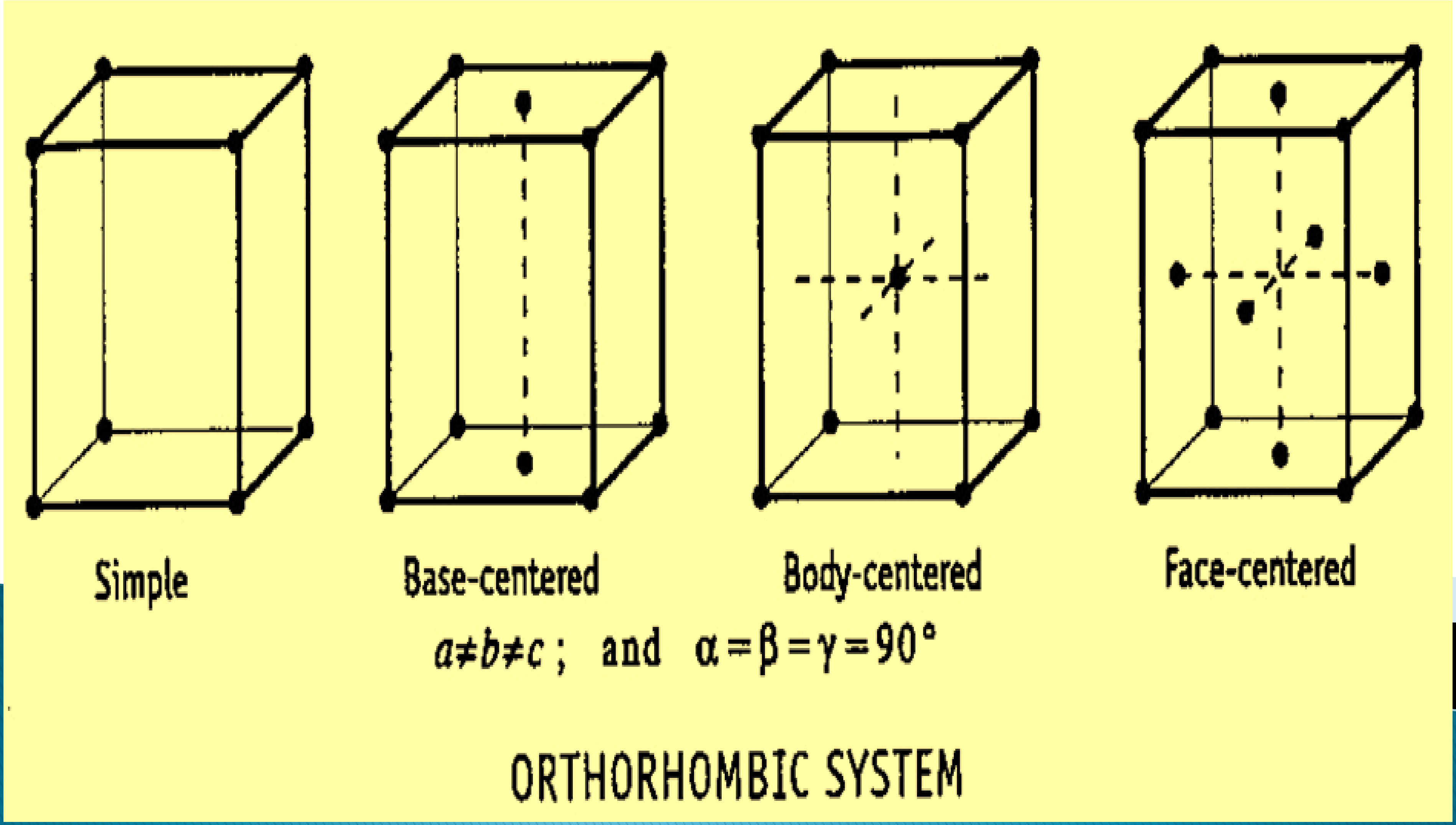
1.Cubic crystal system



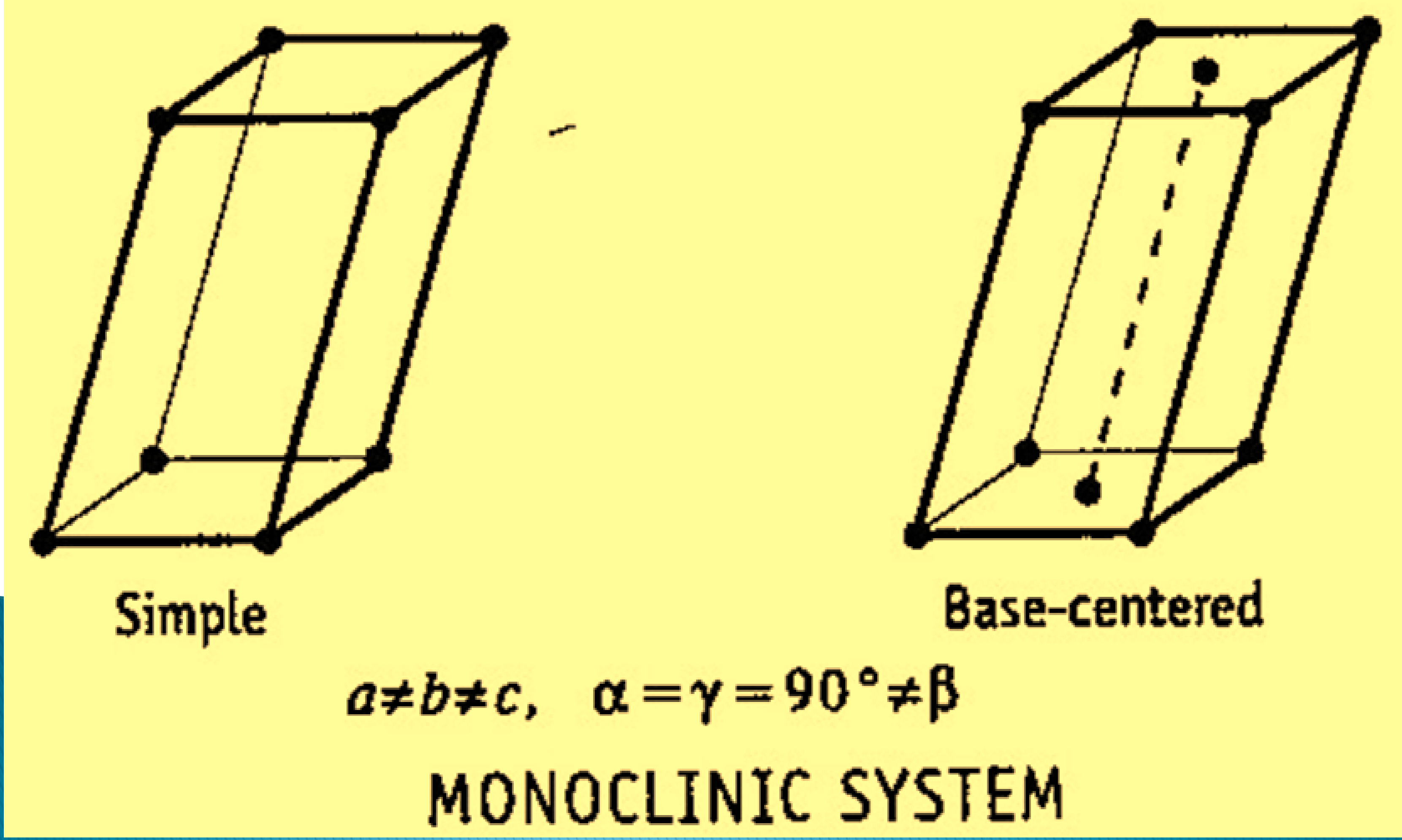
2.Tetragonal crystal system



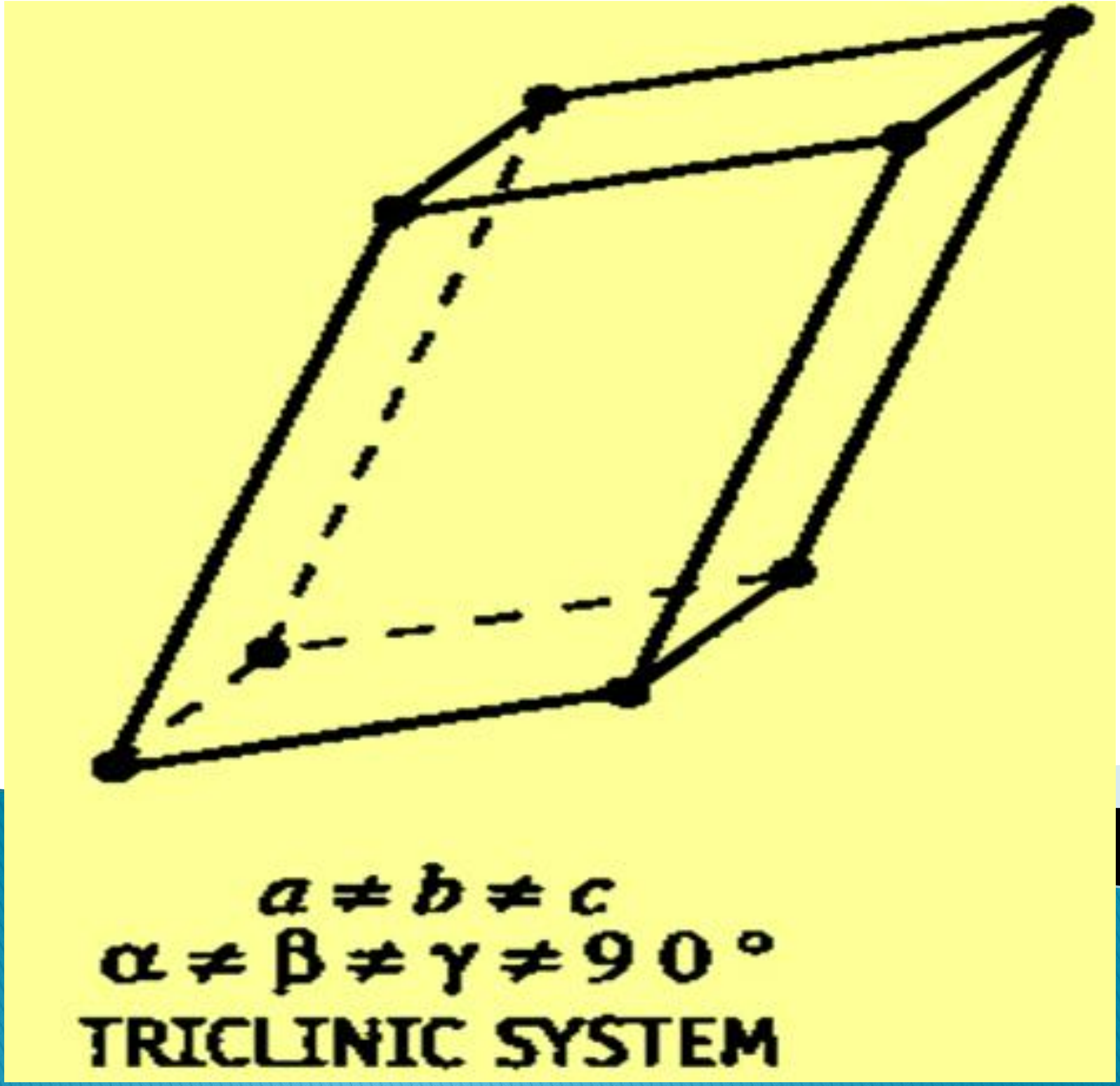
3.Ortho Rhombic crystal system



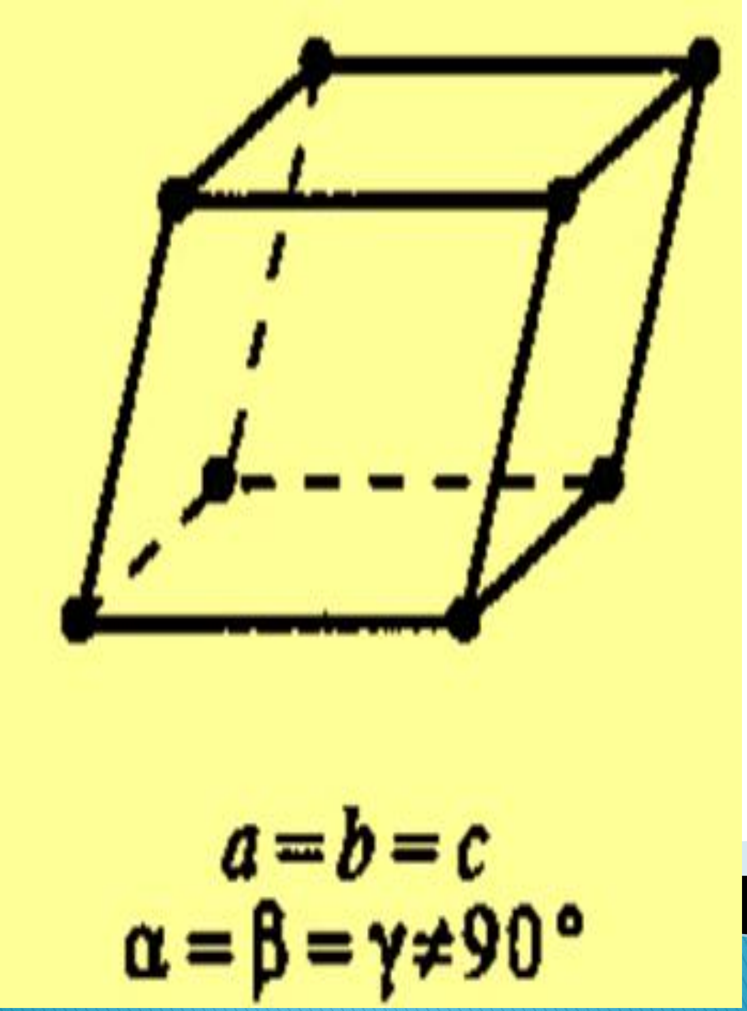
4.Monoclinic crystal system



5.Triclinic crystal system

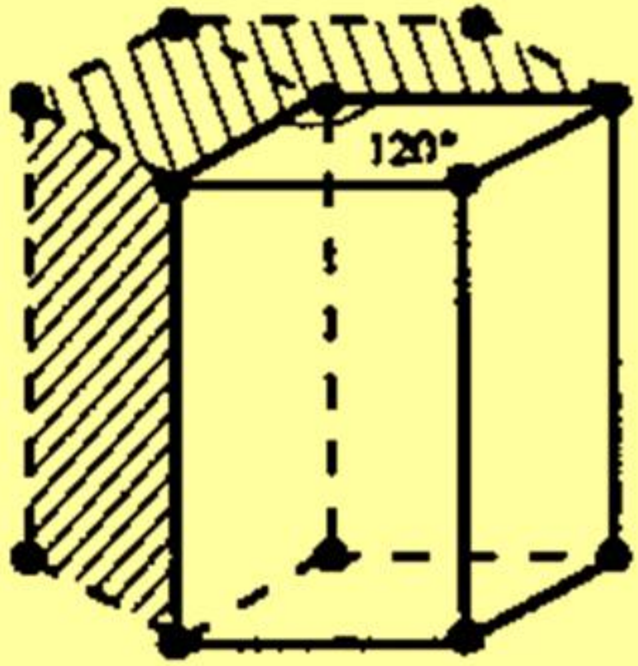


6.Trigonal crystal system



Rhombohedral or Trigonal System

Hexagonal crystal system



$a = b \neq c$

$\alpha = \beta = 90°, \ \gamma = 120°$

HEXAGONAL SYSTEM

Crystal Structures

Some Important Definitions:

1.NEAREST NEIGHBOUR DISTANCE:

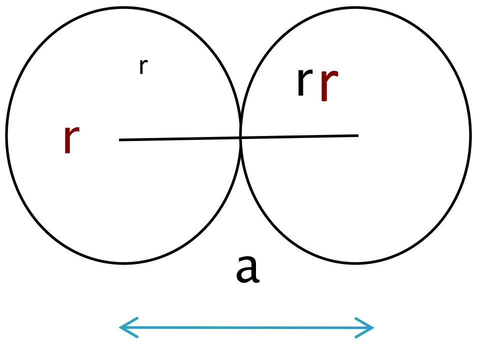
2. ATOMIC RADIUS

3.COORDINATION NUMBER:

4.PACKING FACTOR

1.Nearest neighbour distance:

The distance between the centers of two nearest neighboring atoms is called nearest neighbour distance.



2.Atomic Radius:

Half the distance between two nearest neighboring atoms in a crystal

3.Coordination Number:

Co-ordination number is defined as the number of equidistant nearest neighbors that an atom has in a given structure.

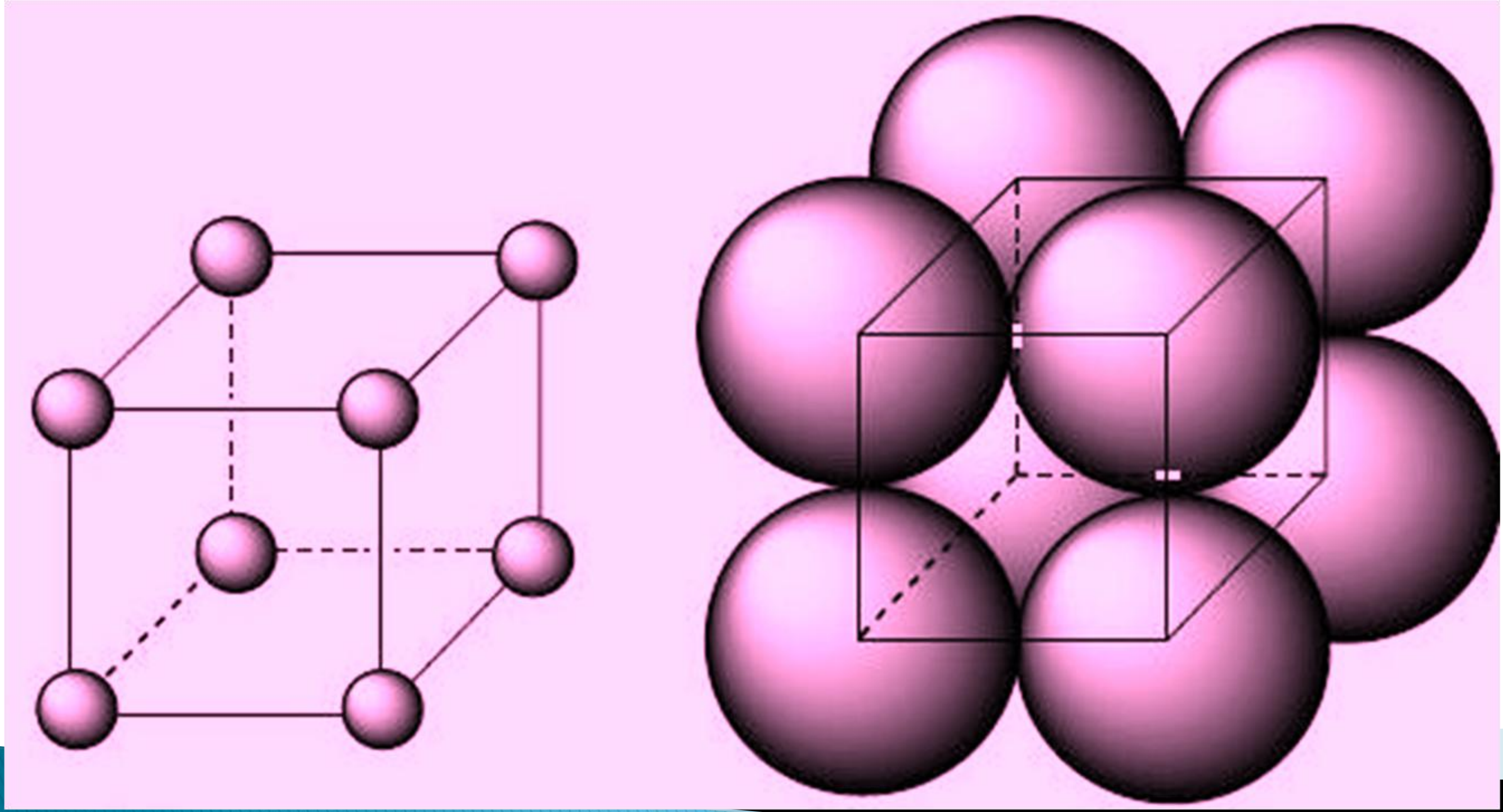
4.Packing Fraction or Atomic Packing Factor (P.F or A.P.F)

Atomic Packing factor is the ratio of volume occupied by the atoms in an unit cell to the total volume of the unit cell. It is also called packing fraction.

$$\text{Packing Factor or A.P.F} = \frac{\text{Vol. occupied by the atoms in an unit cell}}{\text{Total volume of a unit cell}}$$

$$\text{Packing Factor or A.P.F} = \frac{\text{Number of atoms in unit cell} \times \text{Volume of one atom}}{\text{Total volume of a unit cell}}$$

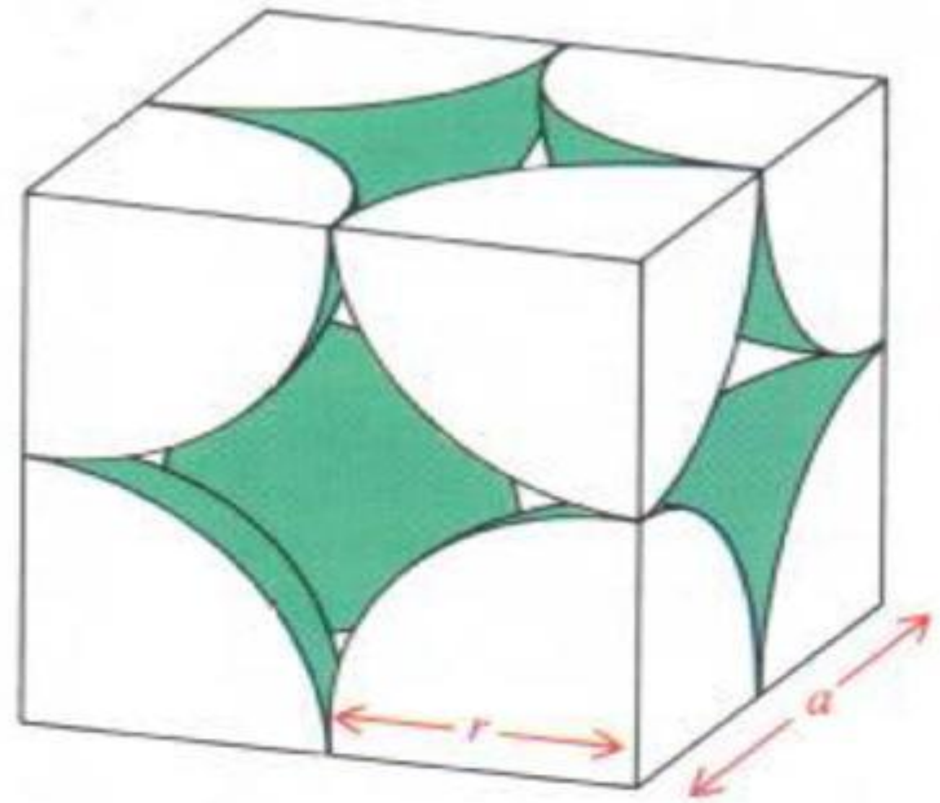
1.SIMPLE CUBIC STRUCTURE



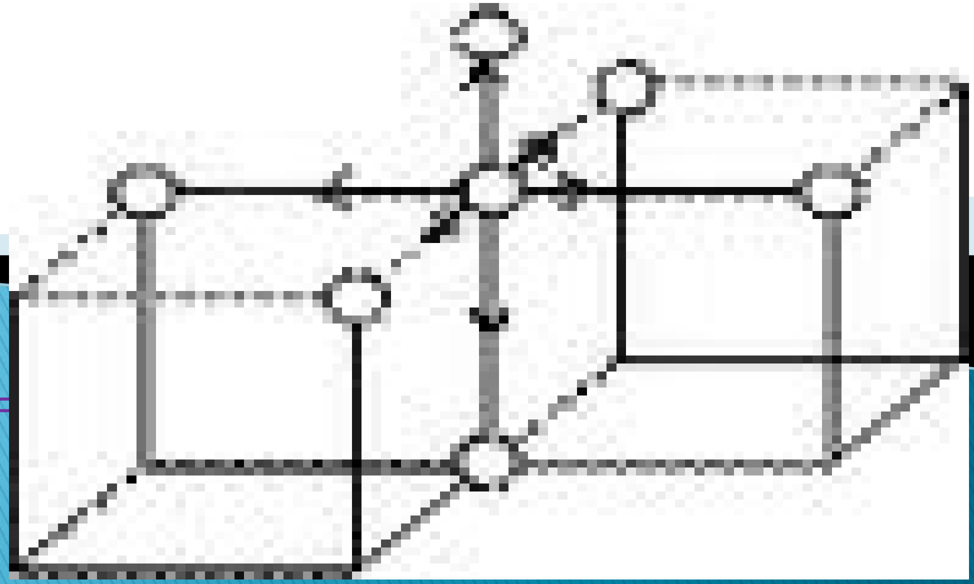
(i) The unit cell of this structure has atoms only at the corners of the cube.

(ii) Number of atoms per unit cell

(8 x 1/8) =1



(iii) Atomic radius r = a / 2



(iv) Co-ordination number = 6

(v) Packing factor

$$\text{Packing Factor or P.F} = \frac{\text{Number of atoms in unit cell} \times \text{Volume of one atom}}{\text{Total volume of a unit cell}}$$

$$= \frac{1 \times \frac{4}{3} \pi r^3}{a^3}$$

Where $a = 2r$

$$= \frac{1 \times \frac{4}{3} \pi r^3}{(2r)^3}$$

$$= 0.52$$

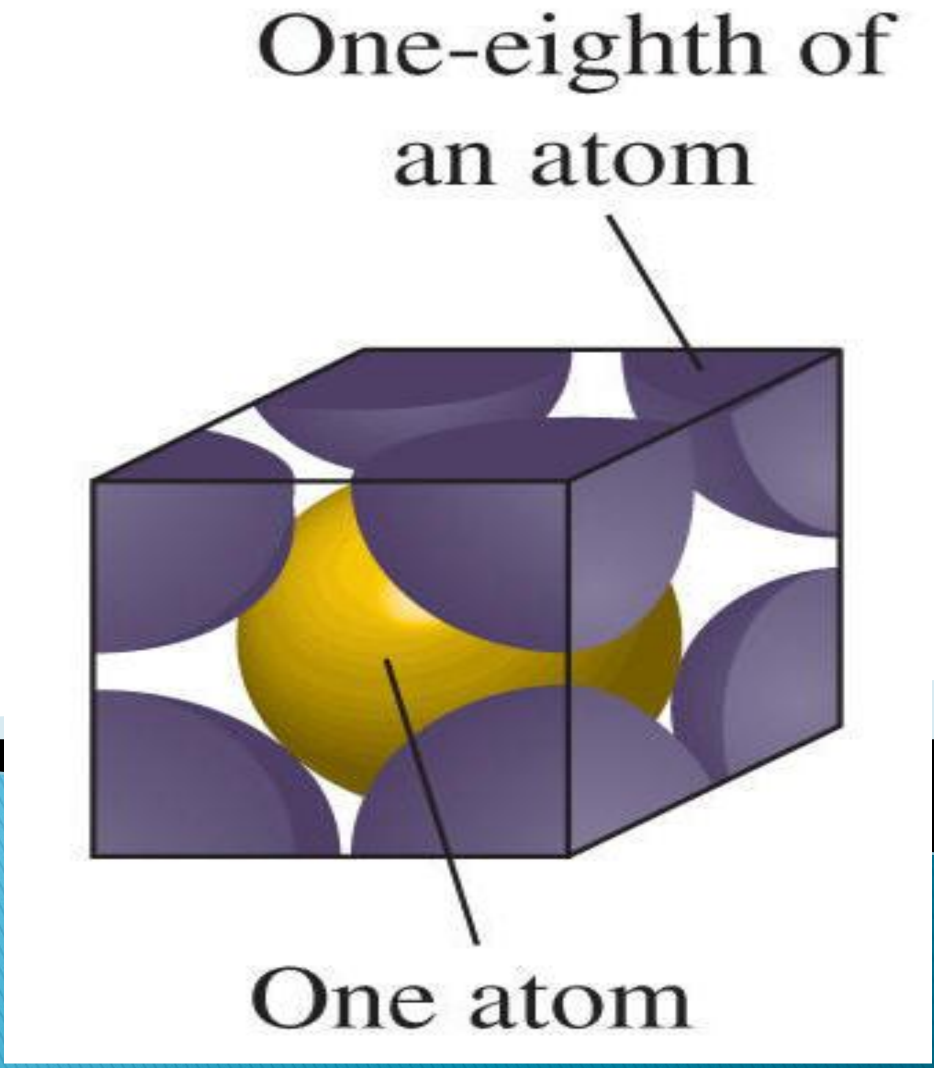
$$= (52\%)$$

2. BCC STRUCURE

(i) **Structure:** The unit cell of this structure has one atom at each corner and one atom at the center of the cube.

(ii) Number of atoms per unit cell

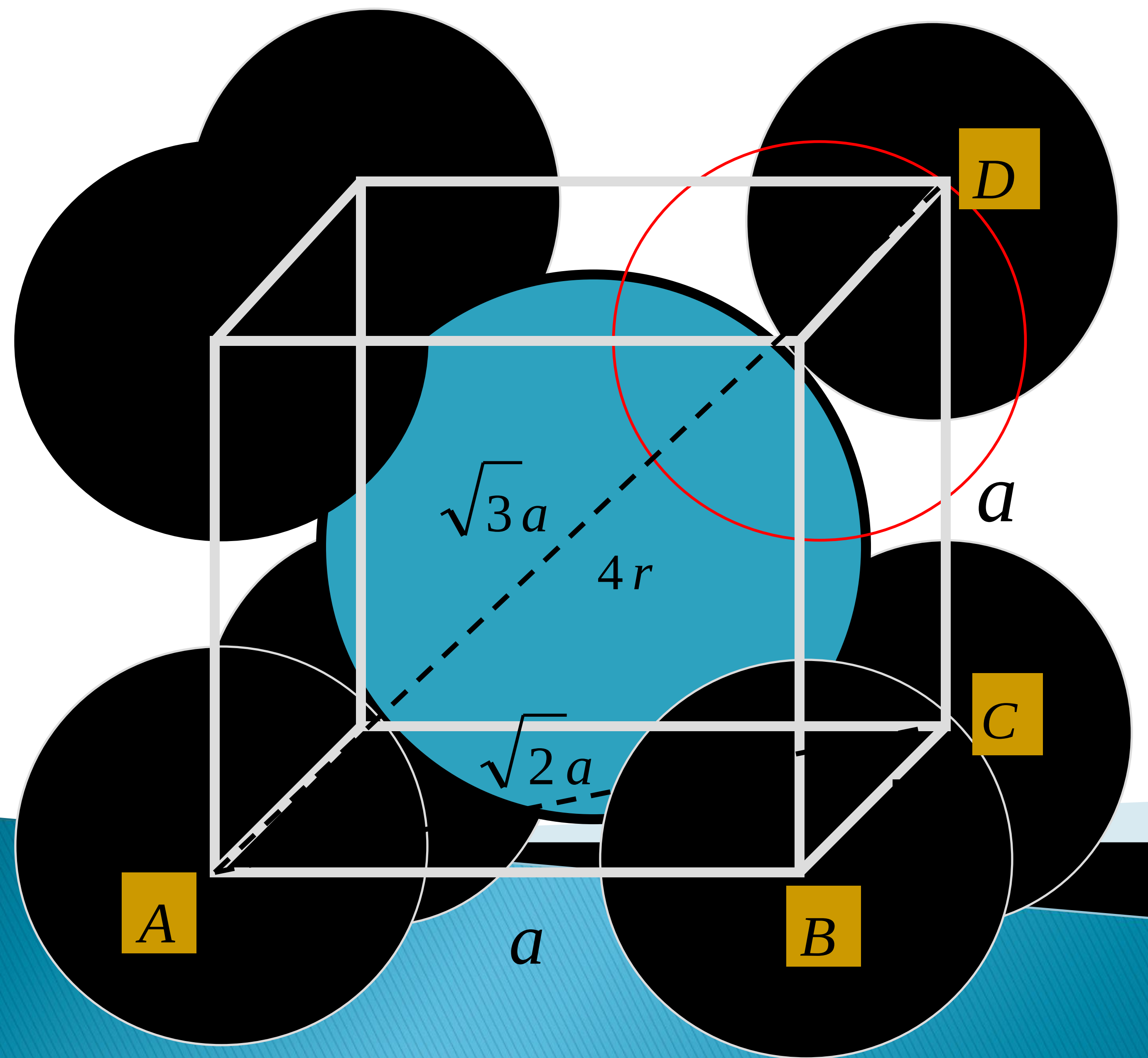
$(8 \times 1/8) + I = 2$



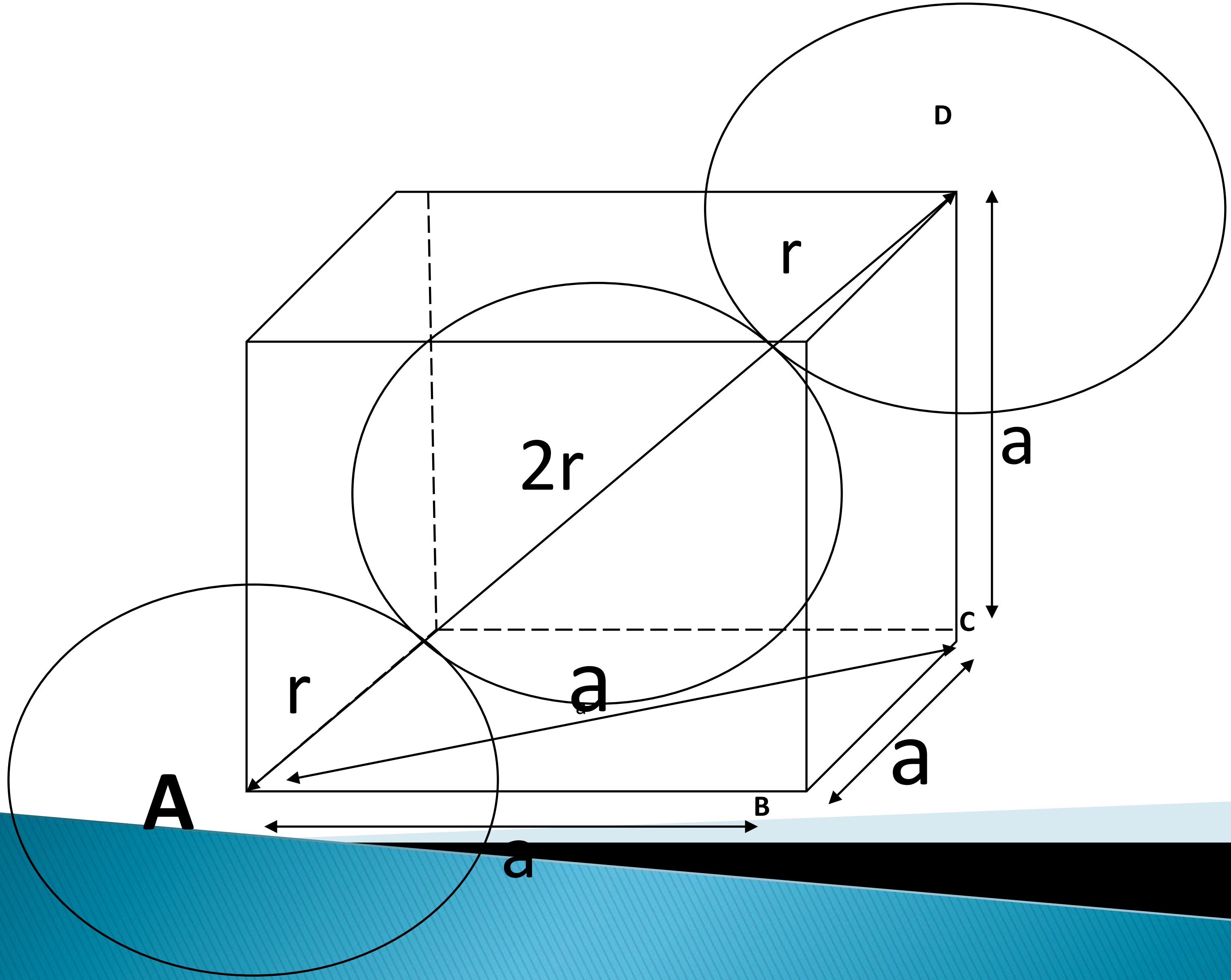
(iii) Atomic radius

$r = \sqrt{3}a / 4$

(iV) Co-ordination number = 8



D
$\sqrt{3}a$
$4r$
a
C
$\sqrt{2}a$
A
a
B



D
r
2r
a
C
r
a
a
A
B
a

(v). Atomic packing factor

$$\text{Packing Factor or P.F} = \frac{\text{Number of atoms in unit cell} \times \text{Volume of one atom}}{\text{Total volume of a unit cell}}$$

$$= \frac{2 \times \frac{4}{3}\pi r^3}{a^3}$$

where $r = \frac{\sqrt{3}}{4} a$

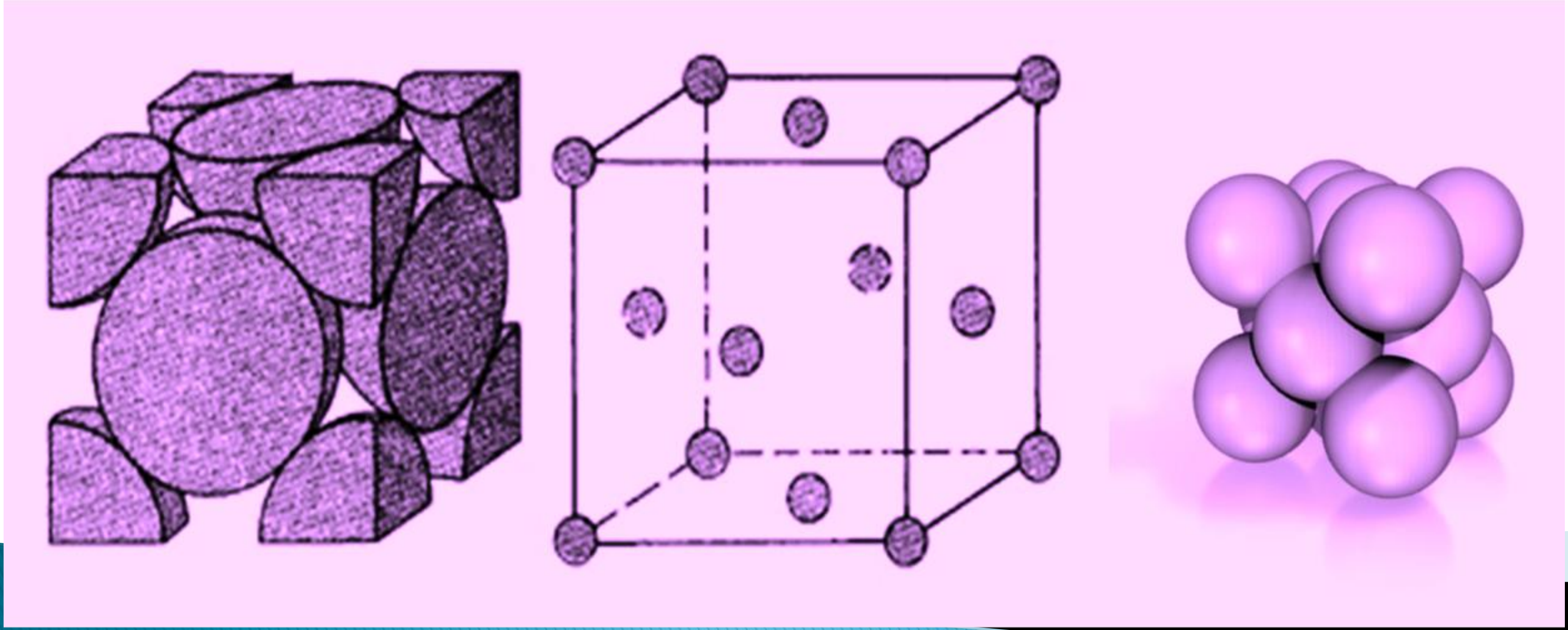
$$= \frac{2 \times \frac{4}{3}\pi \left(\frac{\sqrt{3}}{4} a\right)^3}{(a)^3}$$

$$= 0.68$$

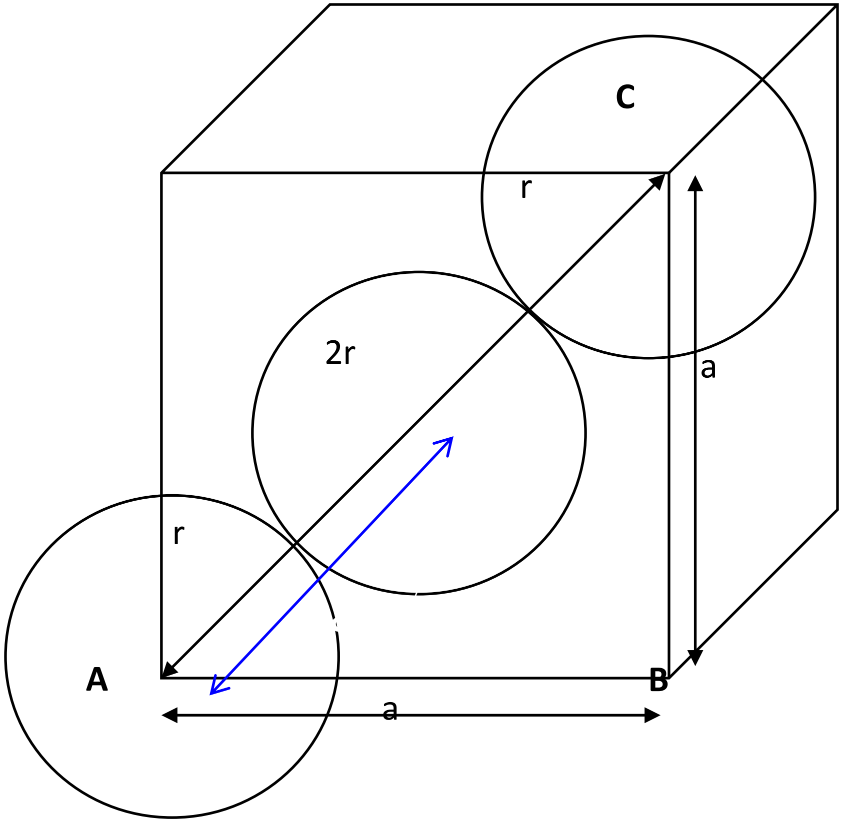
$$= (68\%)$$

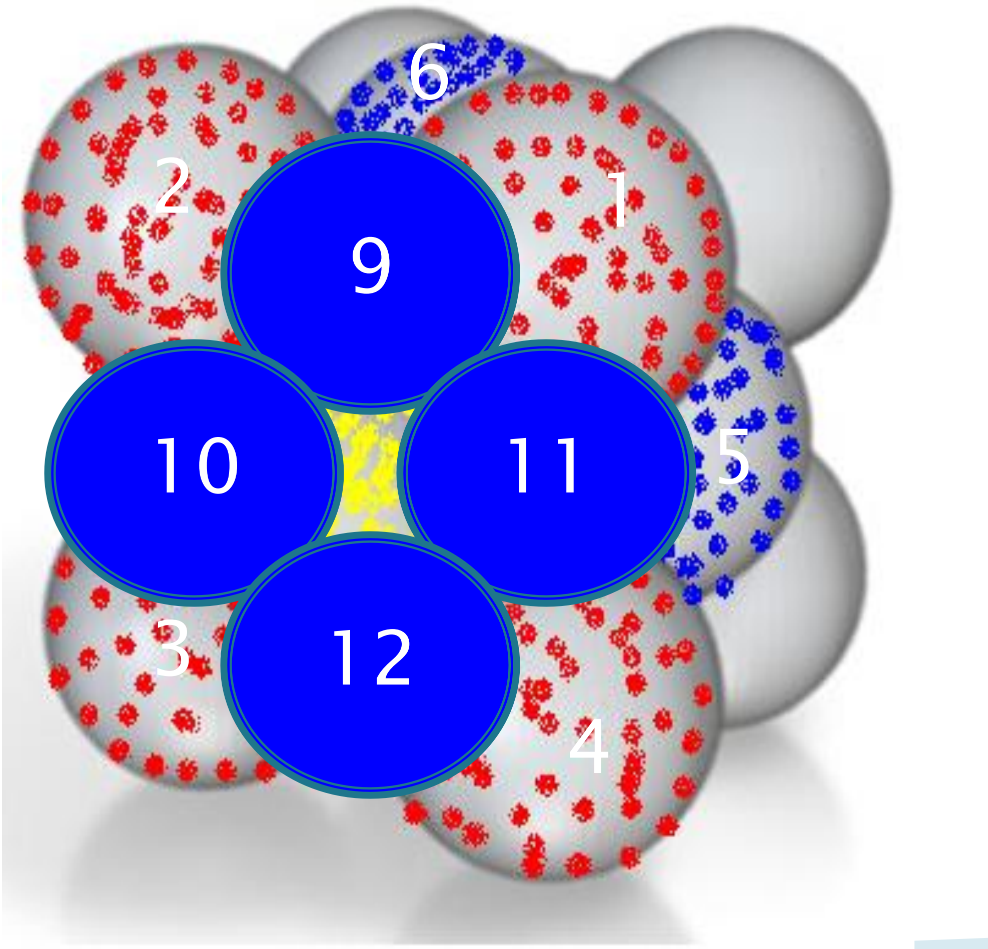
3.FCC CRYSTAL STRUCTURE

(i) Structure: This type of unit cell contains 8 corner atoms and 6 face centered atoms.



(ii) Number of atoms : (8 x 1/8) + 1/2 X 6 = 4





(ii) Atomic radius r = a / 2√2 (iv) Co-ordination number = 12

(v).Atomic packing factor

$$\text{Packing Factor or P.F} = \frac{\text{Number of atoms in unit cell} \times \text{Volume of one atom}}{\text{Total volume of a unit cell}}$$

$$= \frac{4 \times \frac{4}{3}\pi r^3}{a^3}$$

where

$$r = \frac{a}{2\sqrt{2}}$$

$$= \frac{4 \times \frac{4}{3}\pi \left(\frac{a}{2\sqrt{2}}\right)^3}{(a)^3}$$

$$= 0.74$$

$$= (74\%)$$

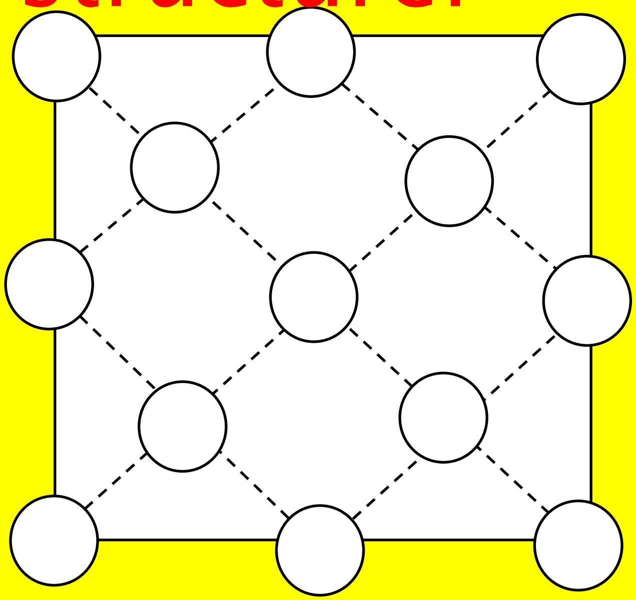
Diamond structure:

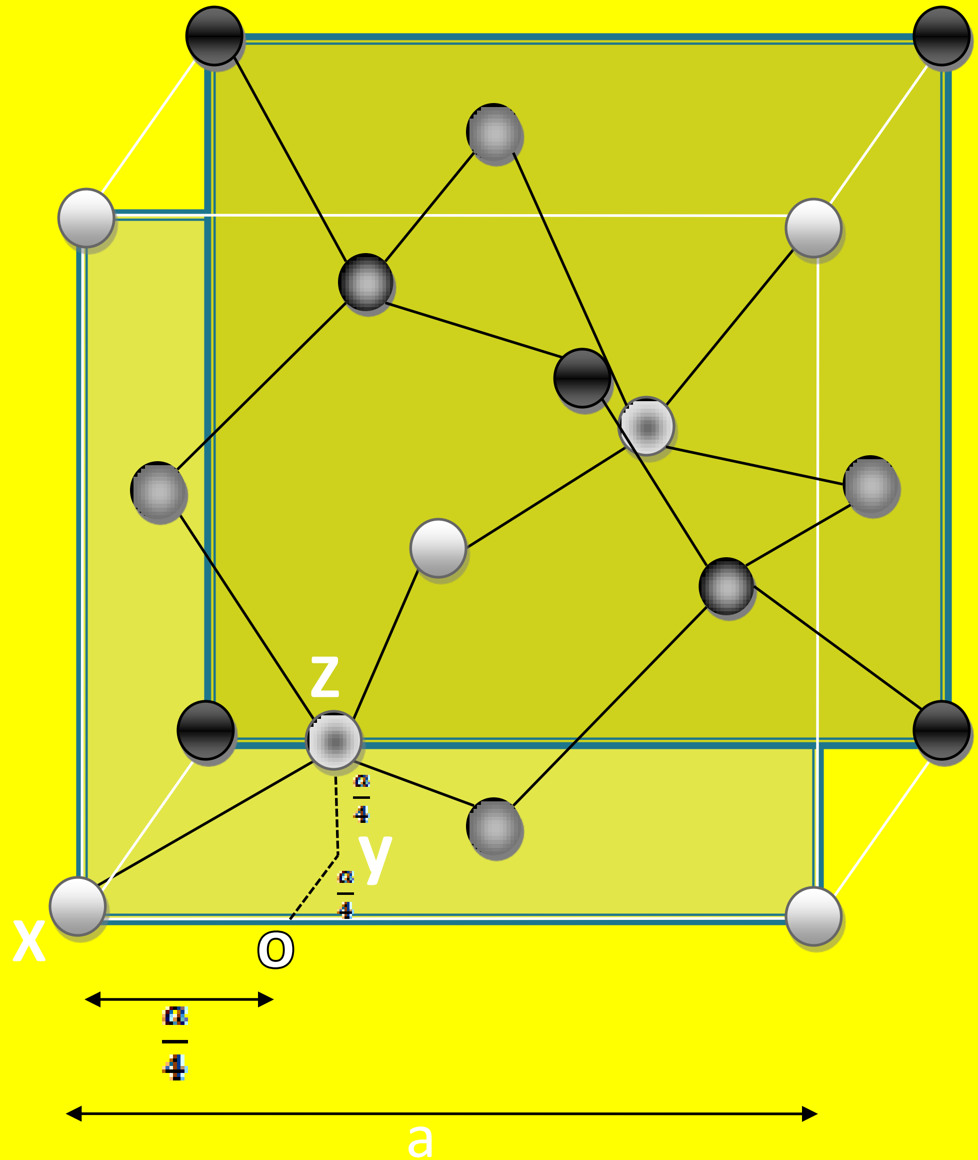
(i) Structure: Diamond is a combination of two interpenetrating FCC – sub lattices.

One starts from X (0,0,0)

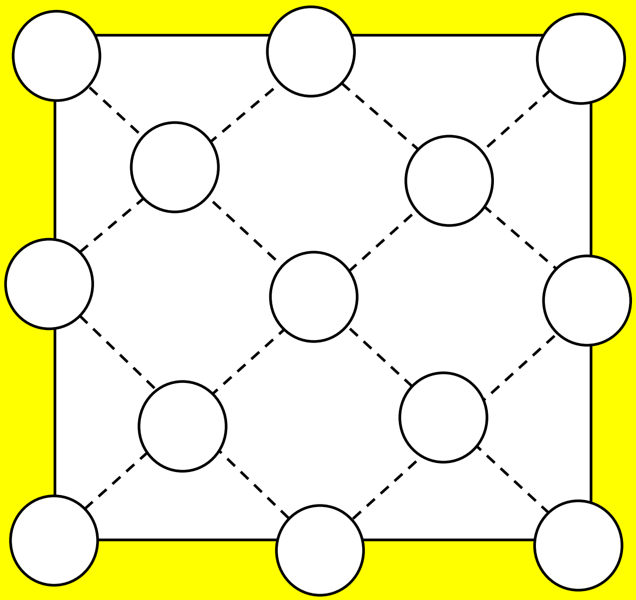
and the other starts from Z (a/4 ,a/4, a/4)

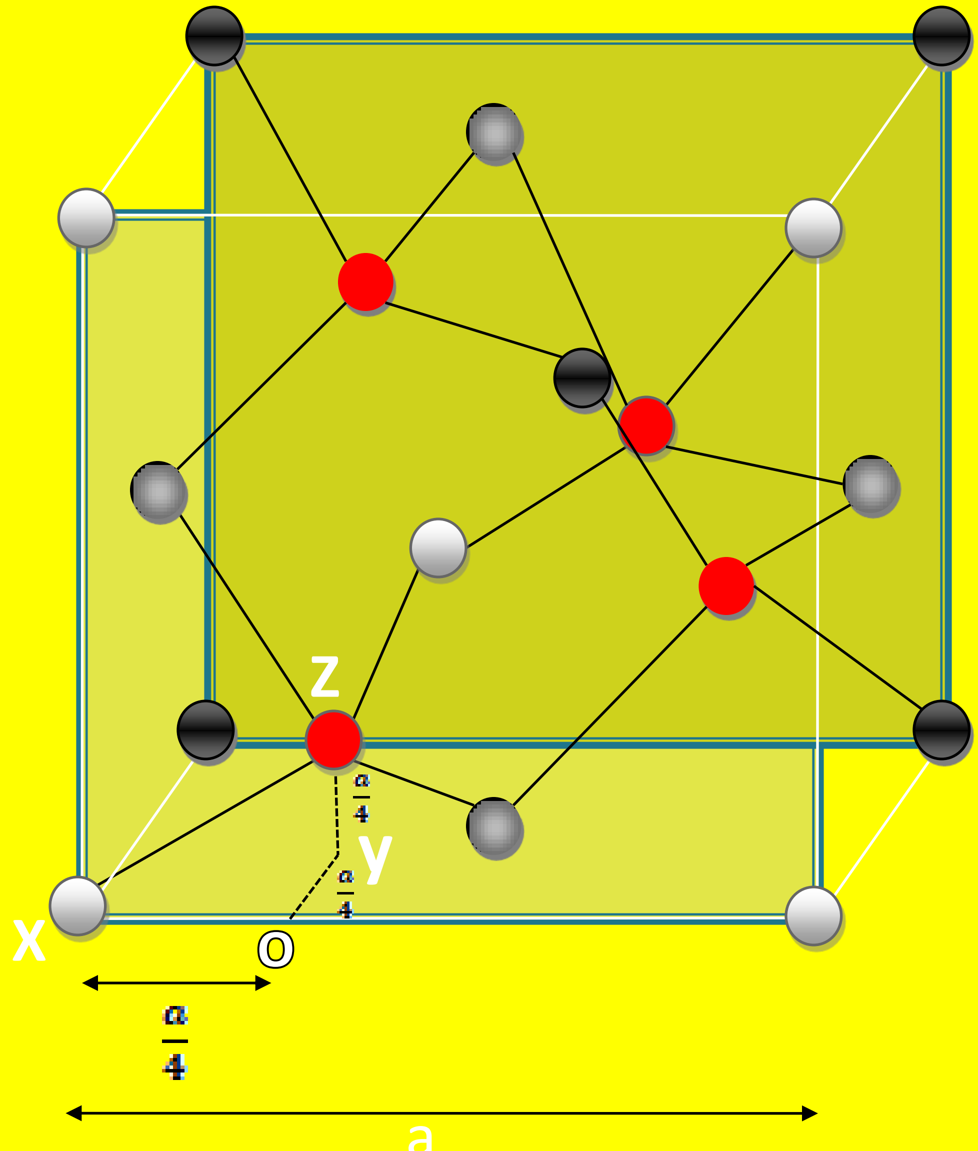
How to draw this difficult structure?





X (0,0,0) Z ($\frac{a}{4}$, $\frac{a}{4}$, $\frac{a}{4}$)

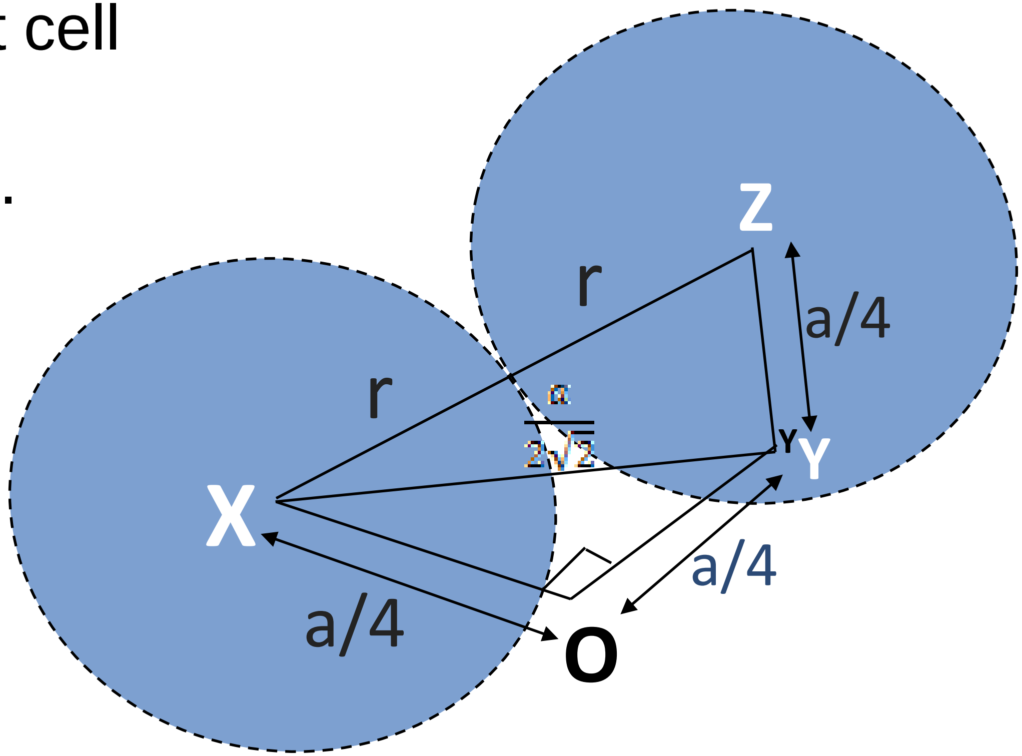




$X\ (0,0,0) \qquad Z\ (\frac{a}{4}, \frac{a}{4}, \frac{a}{4})$

(ii)Number of atoms per unit cell

(8 x 1/8) + (1/2 X 6) + 4 = 8.



(iii) Atomic radius r = √3a / 8.

(iv) Co-ordination number = 4.

(v). Atomic packing factor

$$\text{Packing Factor or P.F} = \frac{\text{Number of atoms in unit cell} \times \text{Volume of one atom}}{\text{Total volume of a unit cell}}$$

$$= \frac{8 \times \frac{4}{3} \pi r^3}{a^3}$$

Where

$$r = \frac{\sqrt{3}}{8} a$$

$$= \frac{8 \times \frac{4}{3} \pi \left(\frac{\sqrt{3}}{8} a\right)^3}{(a)^3}$$

$$= 0.34$$

$$= (34\%)$$

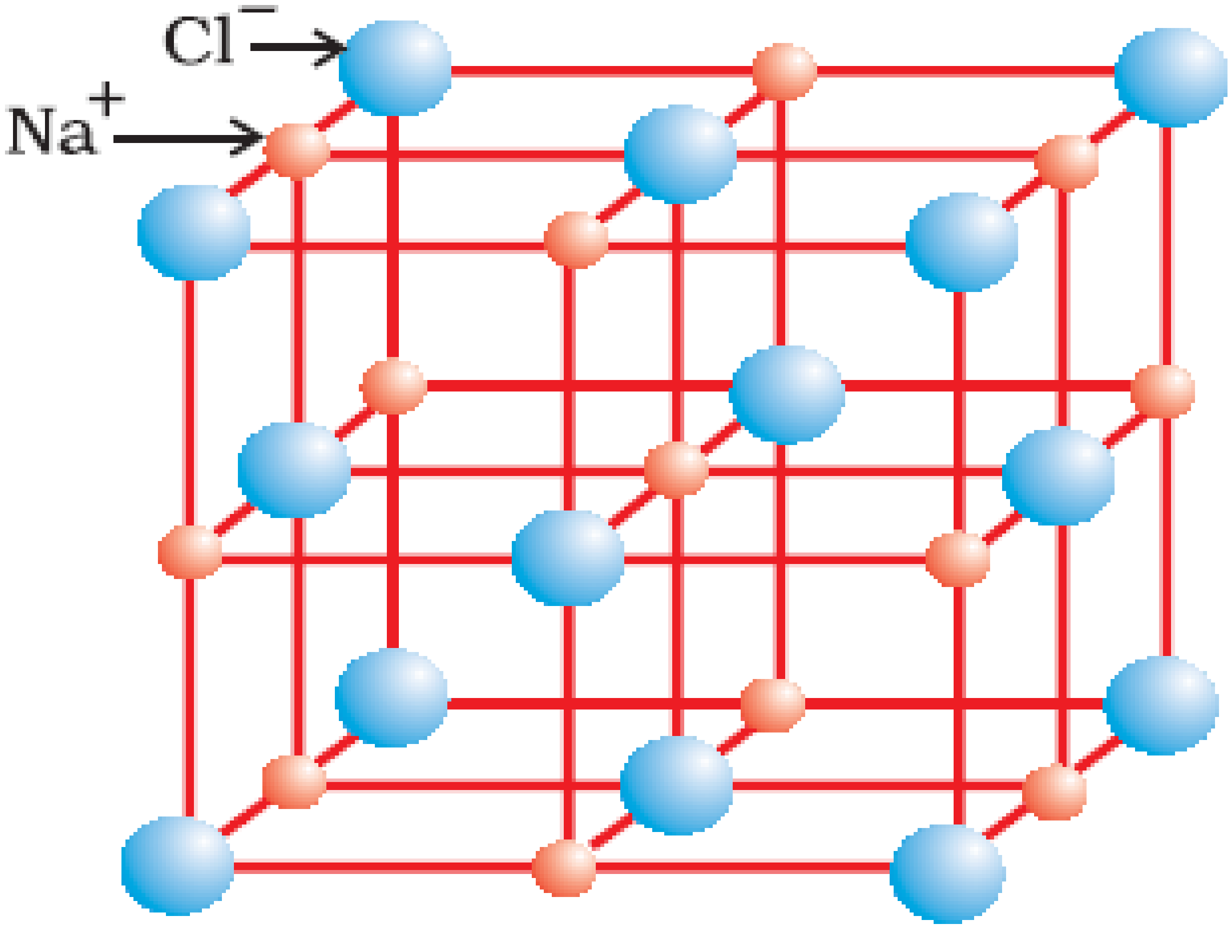
SODIUM CHLORIDE STRUCTURE

- Nacl Crystal is an ionic crystal. It consists of two FCC sub lattices.

- One of the chlorine ion having its origin at the (0, 0, 0) point and other of the sodium ion having its origin at (a/2,0,0).

- Each ion in a NaCl lattice has six nearest neighboring ions at a distance a/2, i,e its Co-ordination number is 6.

Sodium Chloride structure



Rock salt structure

- Each unit cell of a sodium chloride having four sodium ions and four chlorine ions. Thus there are four molecules in each unit cell.

Positions :

Cl : (0,0,0) (1/2,1/2,0) (1/2,0,1/2) (0,1/2,1/2)

Na : (1/2,1/2,1/2),(0,0,1/2) (0,1/2,0)(1/2,0,0)

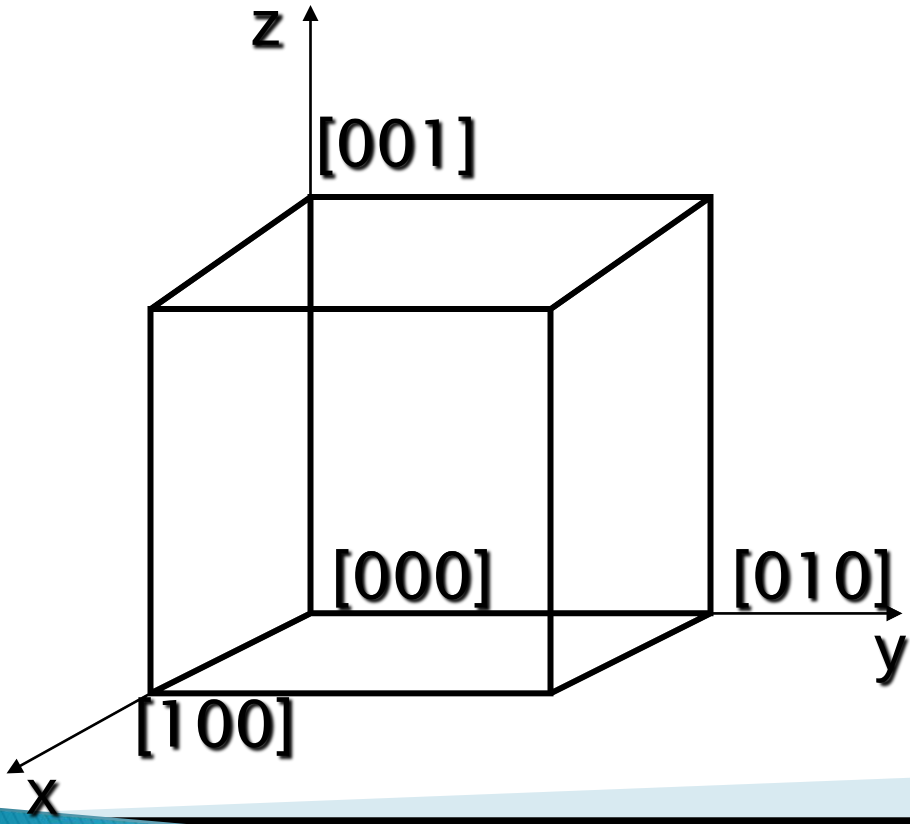
SOME IMPORTANT DIRECTIONS IN CUBIC CRYSTAL

- Square brackets [ ] are used to indicate the directions
- The digits in a square bracket indicate the indices of that direction.
- A negative index is indicated by a 'bar' over the digit .

Ex: for positive x-axes→[100]

for negative x-axes→[100]

–



Fundamental directions in crystals

CRYSTAL PLANES & MILLER INDICES

Reciprocals of intercepts made by the plane which are simplified into the smallest possible numbers or integers and represented by (h k l) are known as Miller Indices.

(or)

The Miller indices are the three smallest integers which have the same ratio as the reciprocals of the intercepts having on the three axes.

These indices are used to indicate the different sets of parallel planes in a crystal.

PROCEDURE FOR FINDING MILLER INDICES

- Find the intercepts of desired plane on the three Co-ordinate axes.

  Ex: (pa, qb, rc)

  where a, b, c are the primitives.

- Divide the intercepts by the primitive vectors.

  (pa/a, qb/b, rc/c) =(p, q, r)

- Take the reciprocals of these numbers which is equal to 1/p:1/q:1/r.

- Convert these reciprocals into whole numbers by multiplying each with their L.C.M , to get the smallest whole number.

- These smallest whole numbers are Miller indices (h k l) of the crystal.

Important features of miller indices

When a plane is parallel to any axis, the intercept of the plane on that axis is infinity. Hence its miller index for that axis is zero.

When the intercept of a plane on any axis is negative, a bar is put on the corresponding miller index.

All equally spaced parallel planes have the same index number (h k l).

If a plane passes through origin, it is defined in terms of a parallel plane having non-zero intercept.

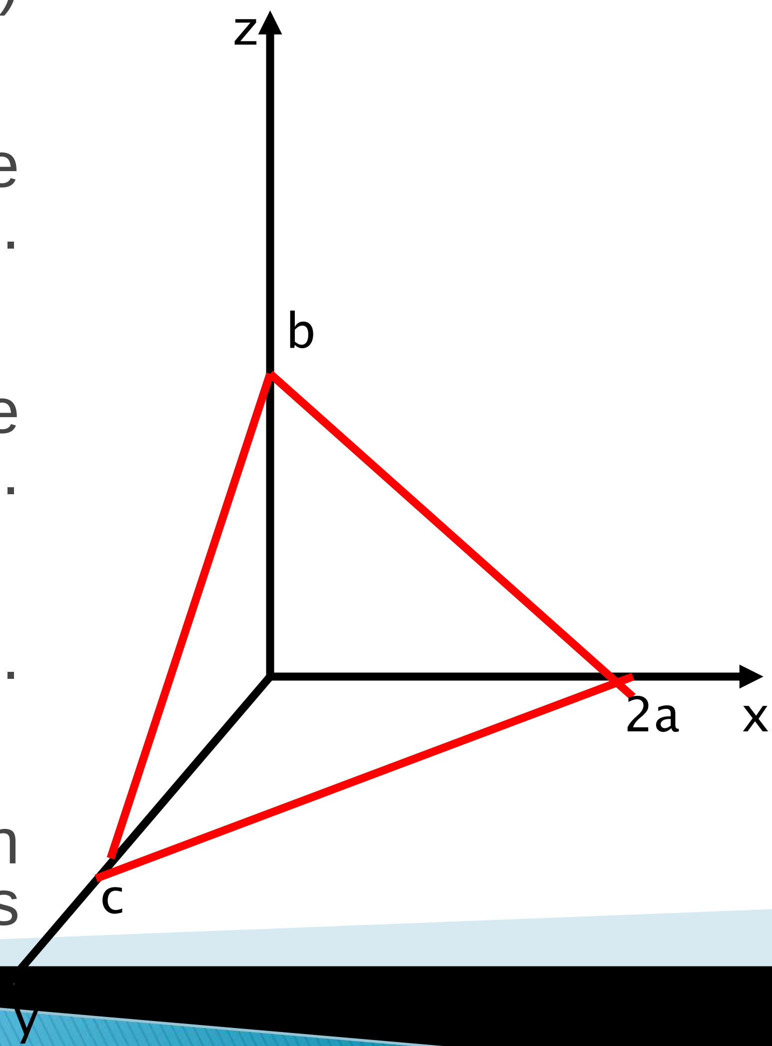
Intercepts of the plane (2a, b, c)

After dividing the intercepts by the primitive vectors then (2,2,1).

The reciprocal of these values are given by (1/2,1/2,1).

LCM is equal to 2.

Multiplying the reciprocals with LCM we get Miller indices (1 1 2)



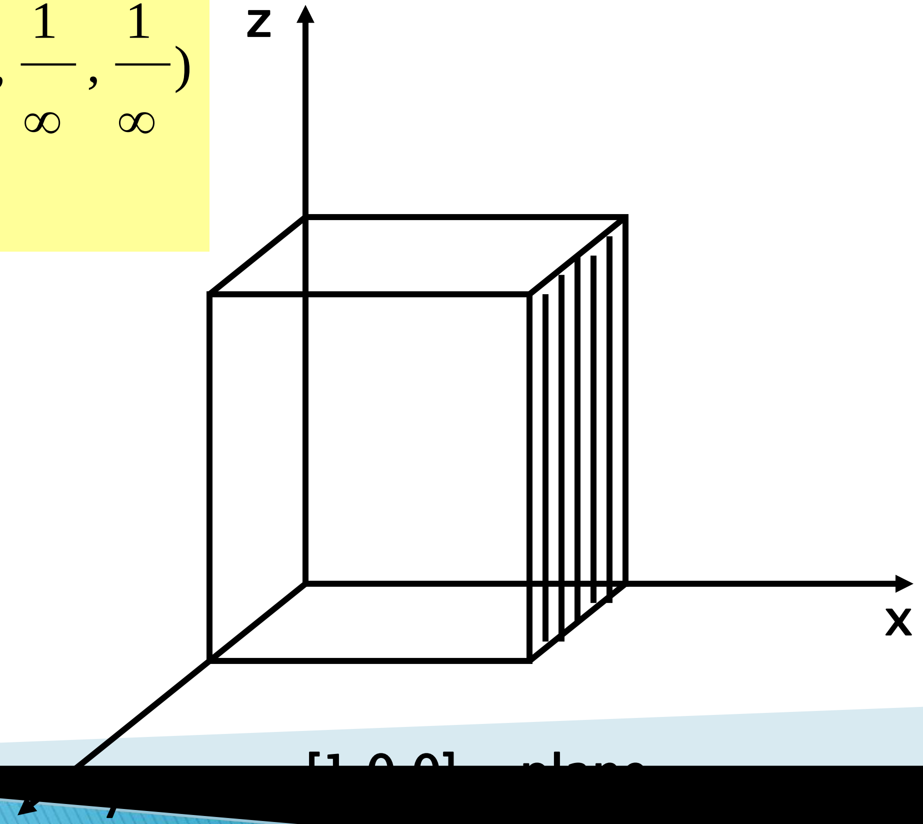
NOTE: NEVER USE ' ,' BETWEEN (h k l) PARAMETERS

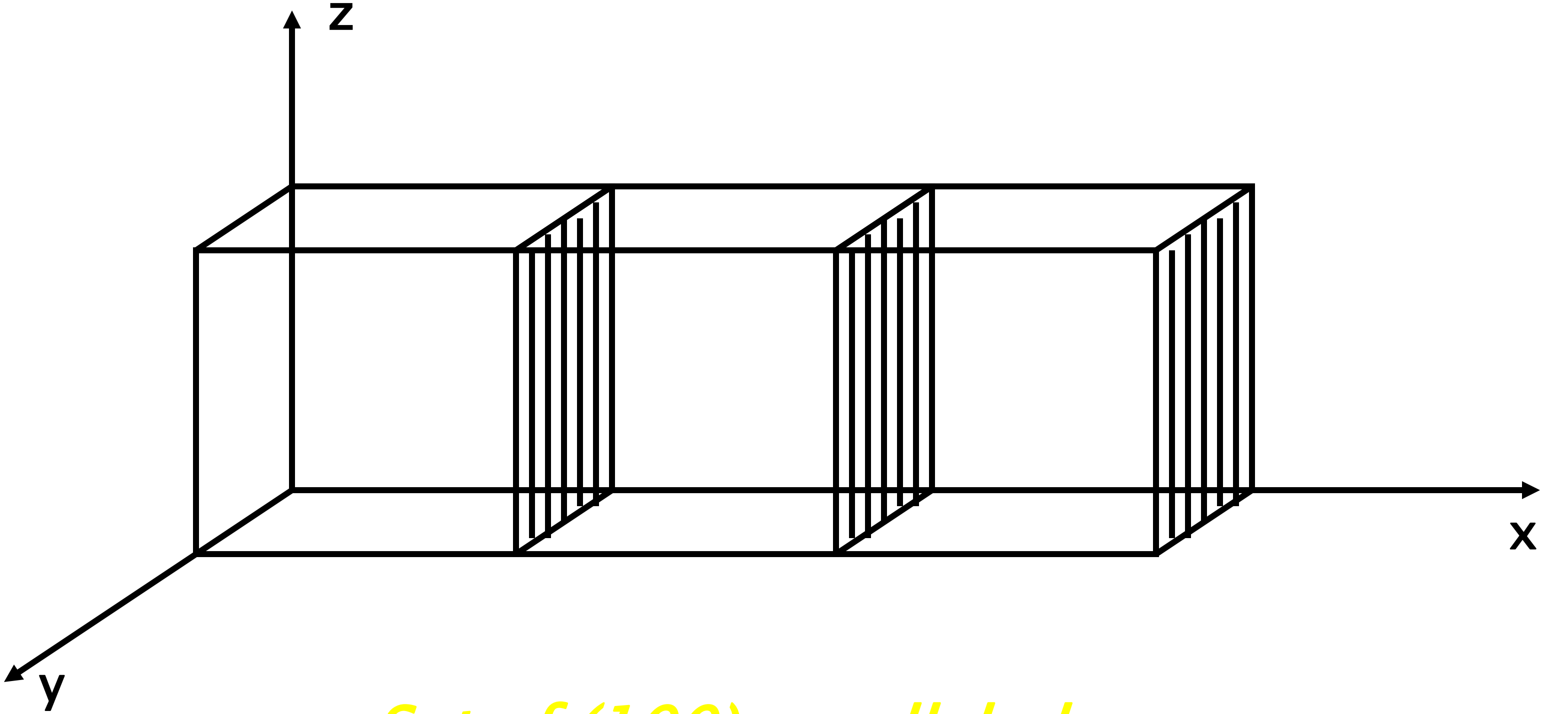
Construction of [100] plane

Intercepts of the Plane are $= (1, \infty, \infty)$

Reciprocals of intercepts are $= (\frac{1}{1}, \frac{1}{\infty}, \frac{1}{\infty})$

Miller indices : (100)





Set of (100) parallel planes

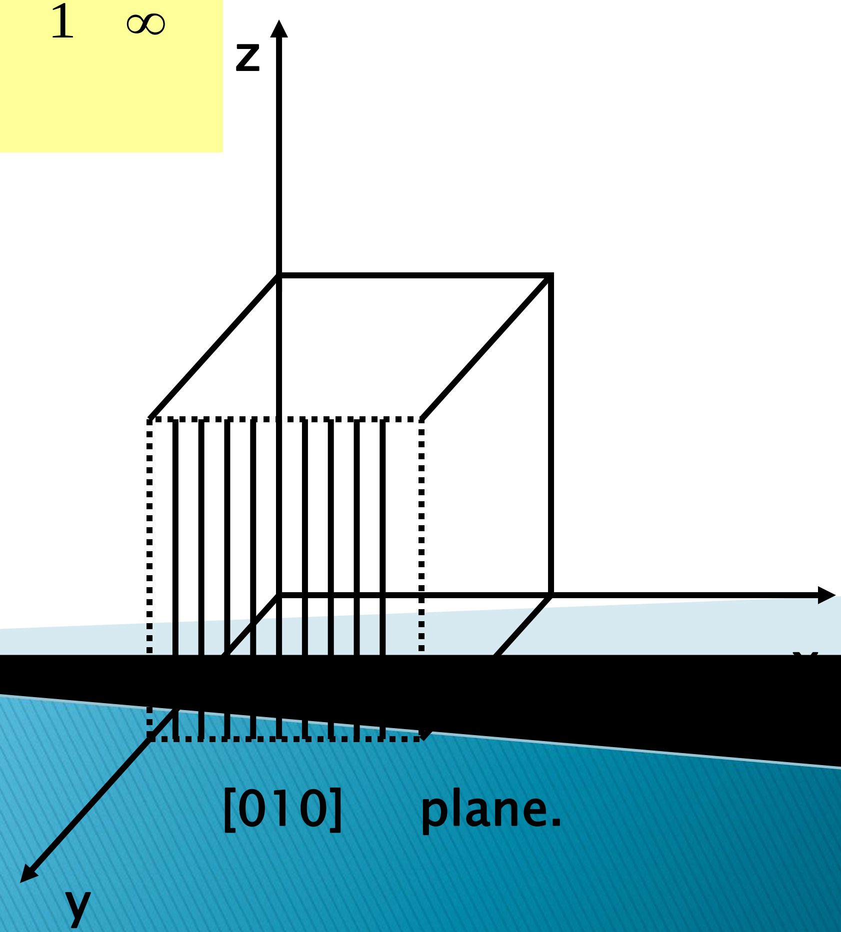
ALL PARALLEL PLANES HAVING THE SAME MILLER INDICES

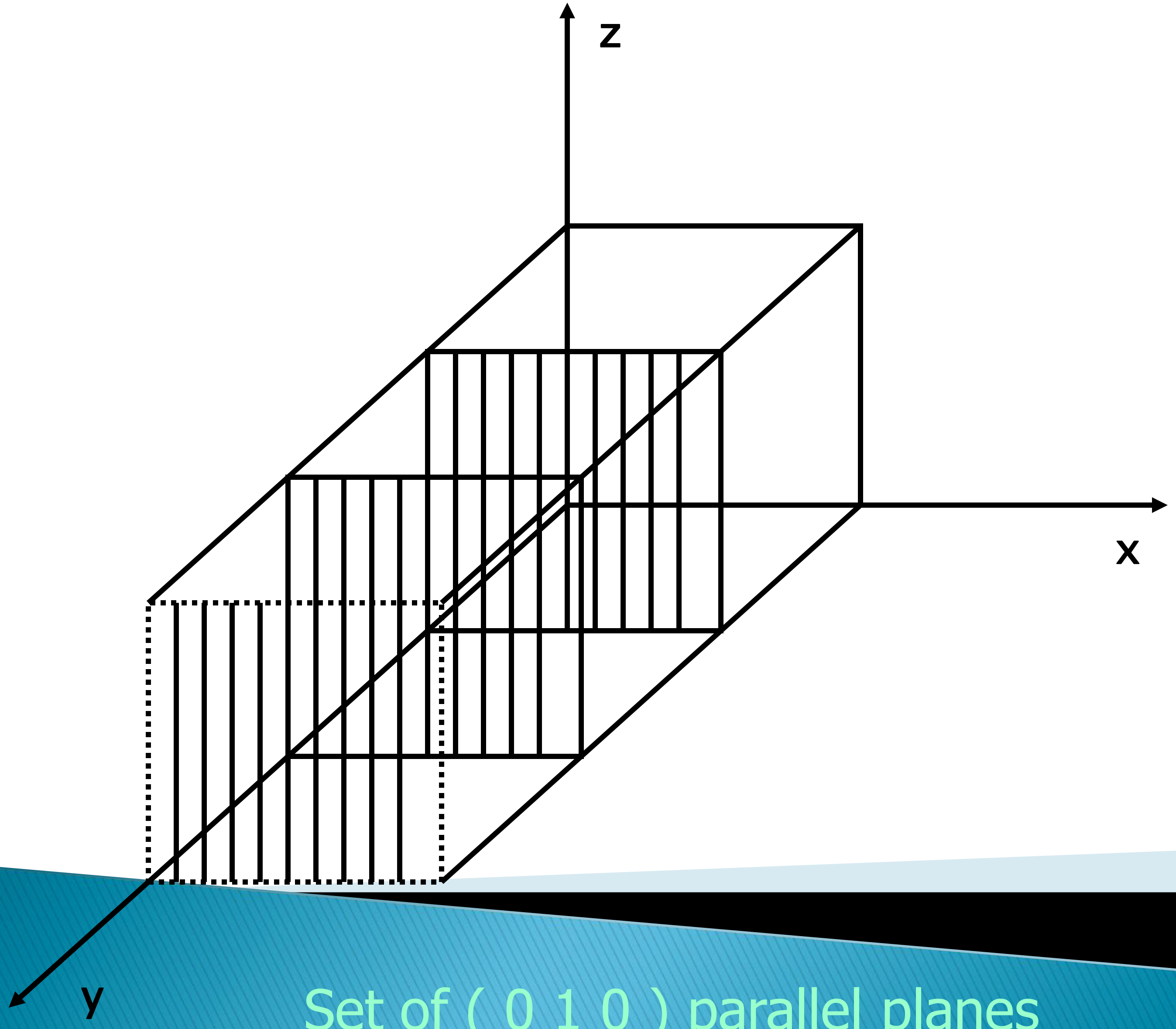
Construction of (010) plane

Intercepts of the Plane are $= (\infty, 1, \infty)$

R`eciprocals of intercepts are $= \left(\frac{1}{\infty}, \frac{1}{1}, \frac{1}{\infty}\right)$

Miller indices : (010)





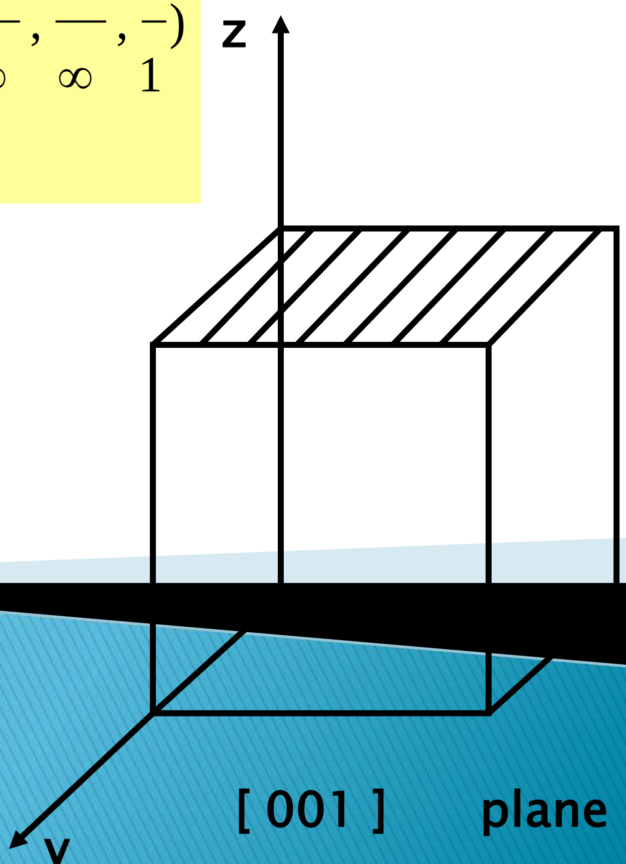
Set of (0 1 0) parallel planes

Construction of (001) plane

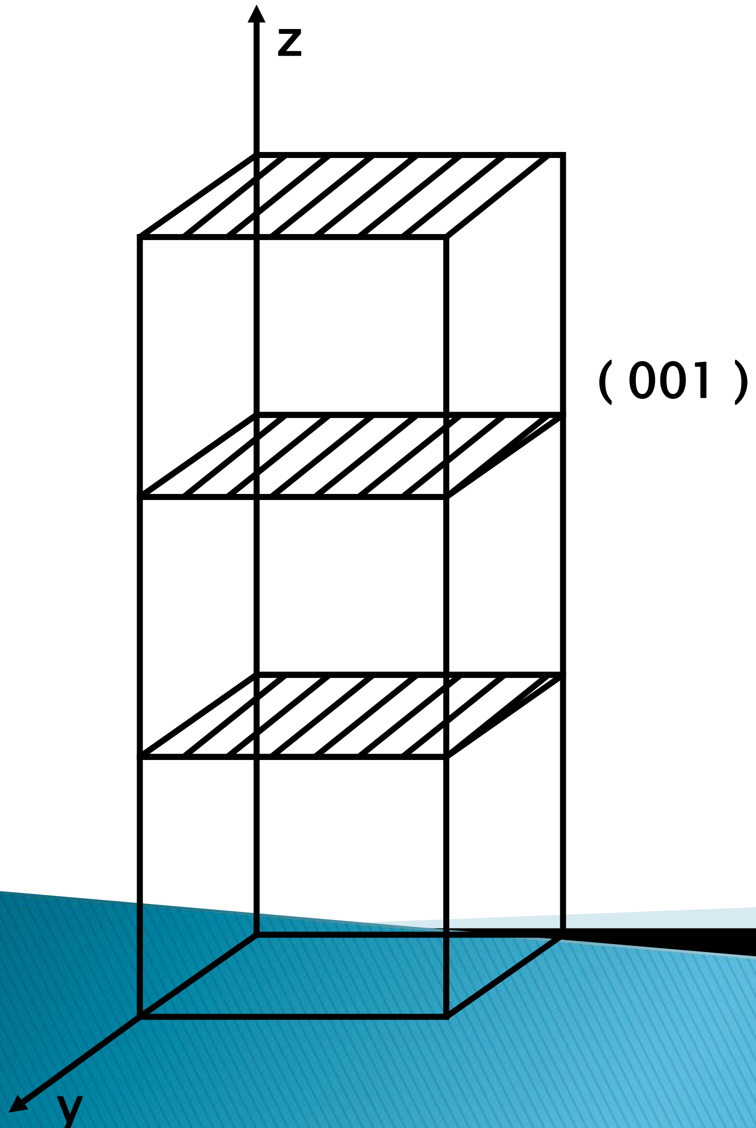
Intercepts of the Plane are $= (\infty, \infty, 1)$

R`eciprocals of intercepts are $= (\frac{1}{\infty}, \frac{1}{\infty}, \frac{1}{1})$

Miller indices : (001)



Set of (0 0 1) parallel planes

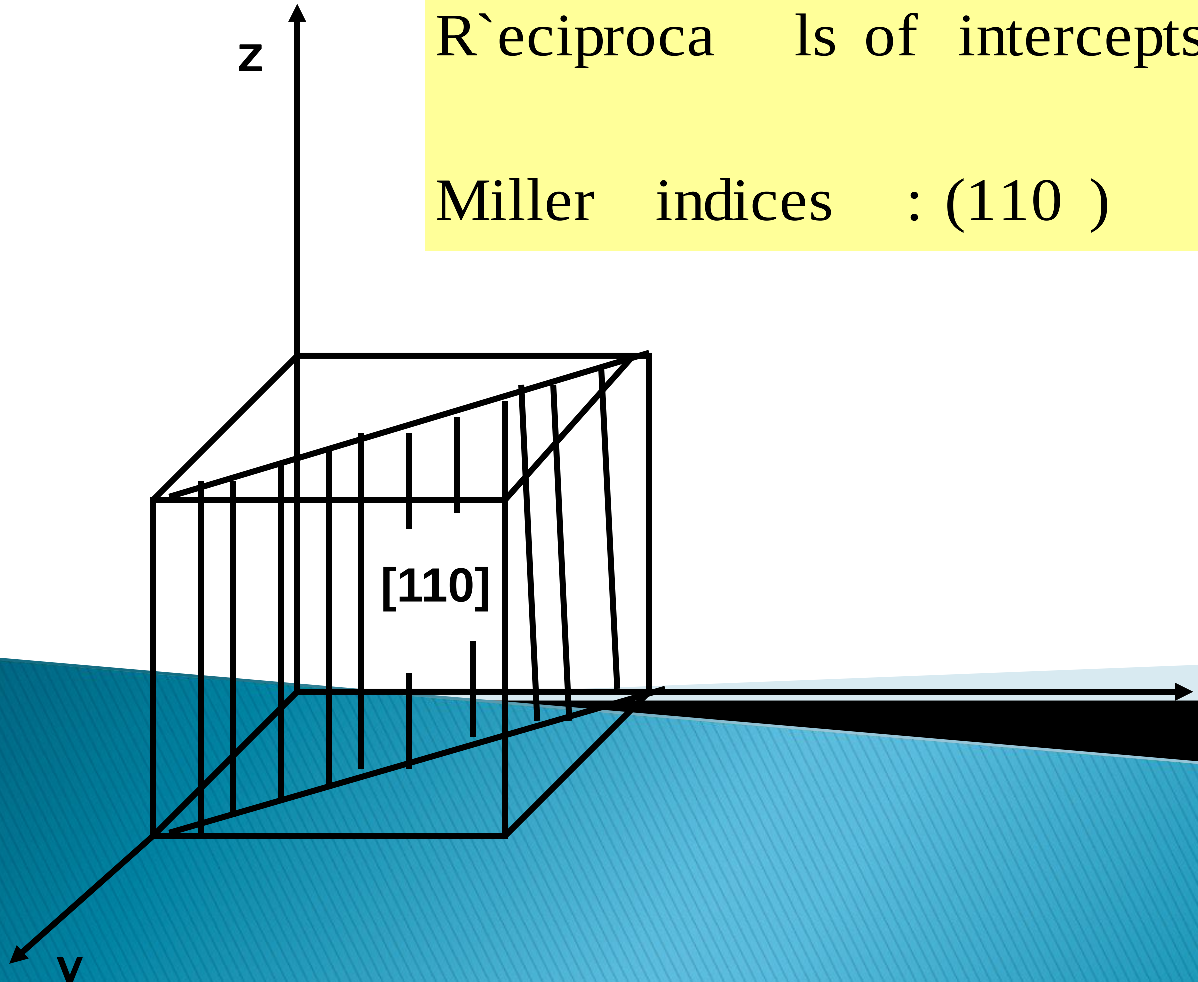


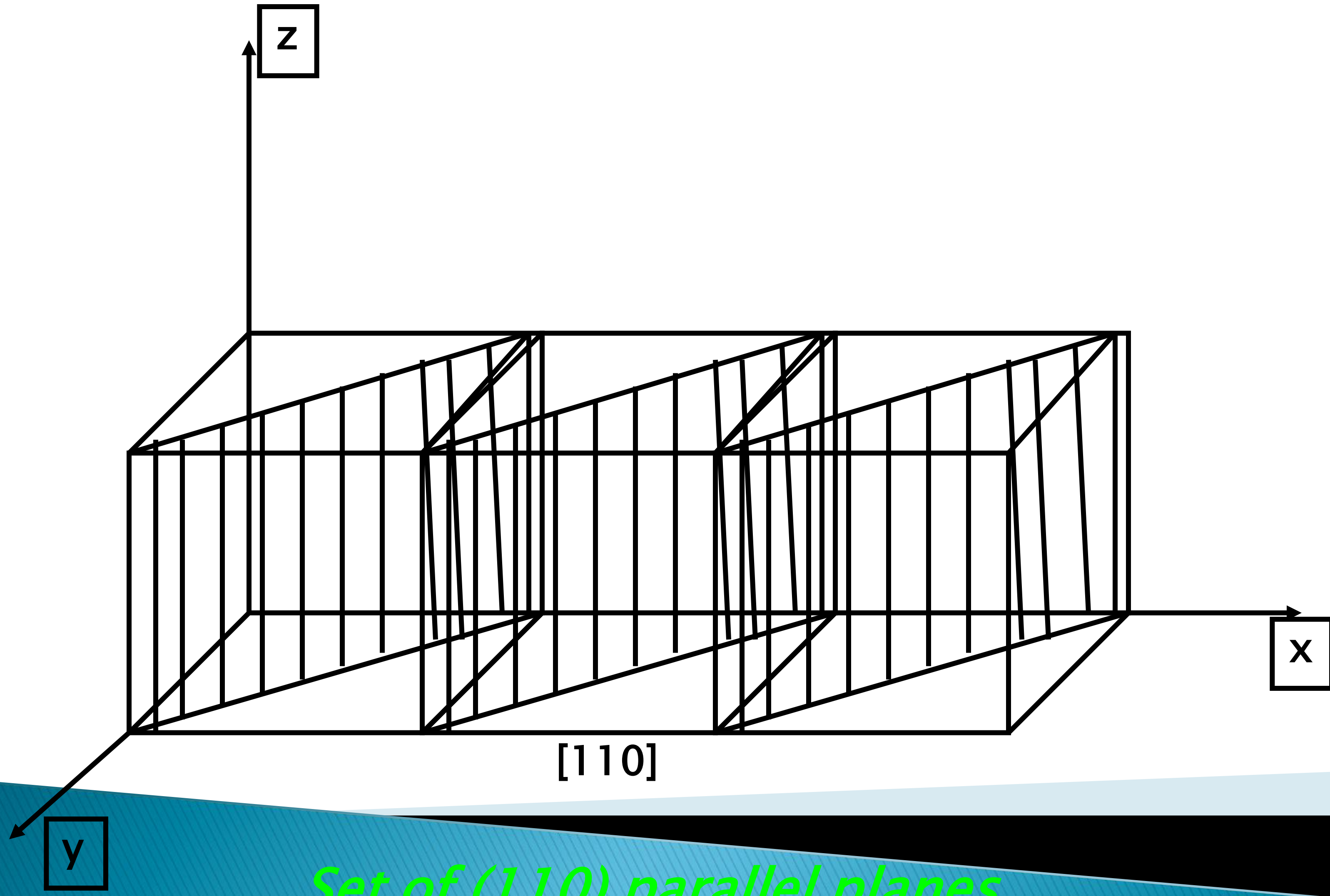
Construction of (110) plane

Intercepts of the Plane are = $(1,1,\infty)$

R`eciprocals of intercepts are = $(\frac{1}{1},\frac{1}{1},\frac{1}{\infty})$

Miller indices : (110)





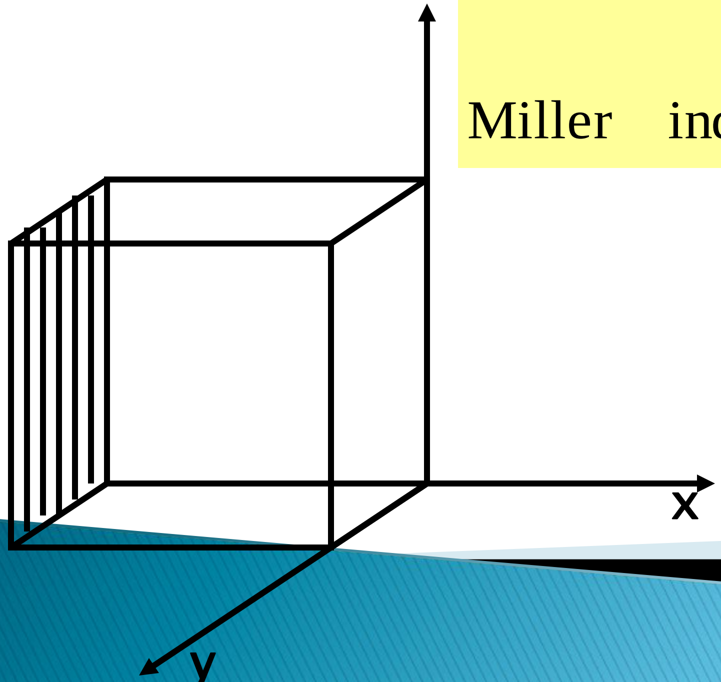
Set of (110) parallel planes

Construction of $(\bar{1}\,0\,0)$ planes

Intercepts of the Plane are $= (\bar{1}, \infty, \infty)$

Reciprocals of intercepts are $= (\frac{1}{\bar{1}}, \frac{1}{\infty}, \frac{1}{\infty})$

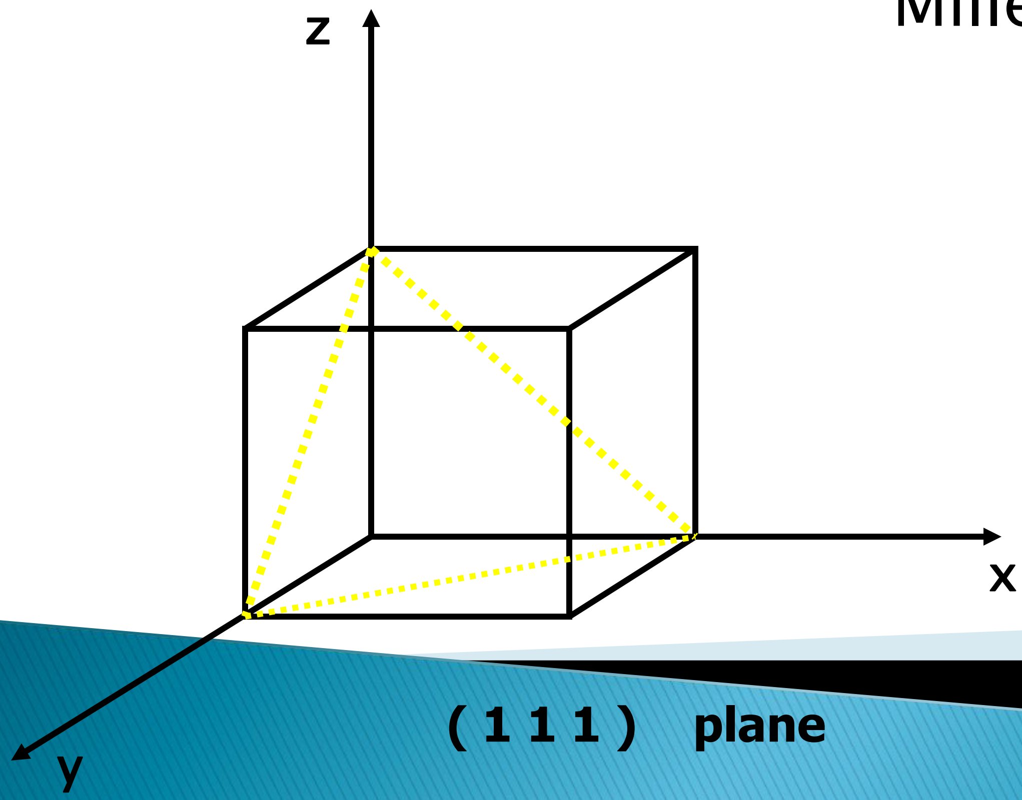
Miller indices : $(\bar{1}00)$



Intercepts of the planes are (1,1,1)

Reciprocals of intercepts are (1/1,1/1,1/1)

Miller indices:(1 1 1)



(1 1 1) plane

How to draw the planes by using Miller Indices?

Step1: Write the miller indices

Step2: Take the reciprocals of miller indices

Step3: Multiply the numbers with their primitives.

Step4: Draw the three axes with a cube and put a points on these axes.

Step5: Join all these points and shade that region which is our required [illegible]

Example: Draw (100) plane

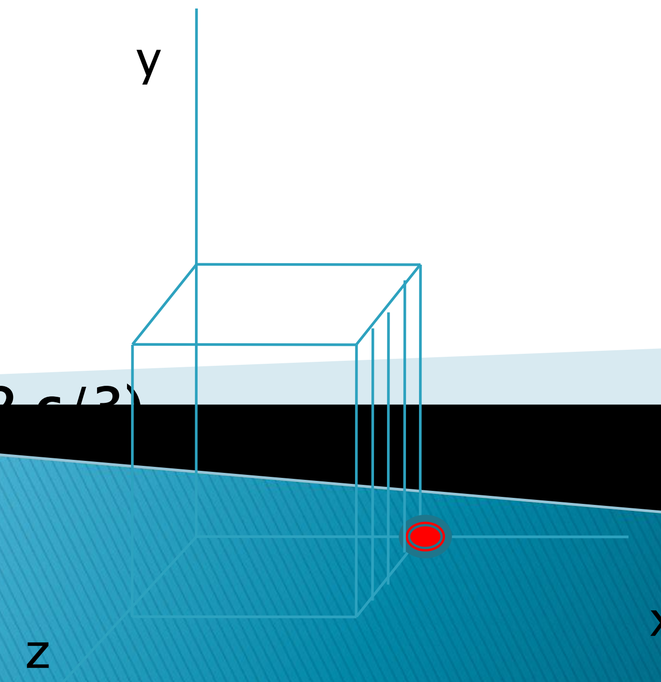
Step1: (100)

Step2: $(1/1\ 1/0\ 1/0) = (1\ \infty\ \infty)$

Step3: $(1\times a\ \infty\times b\ \infty\times c)$

Step4: $(a\ \infty\ \infty)$

Step5: Draw the axes with cube and represent the point at a and ∞ means which is parallel to those axes

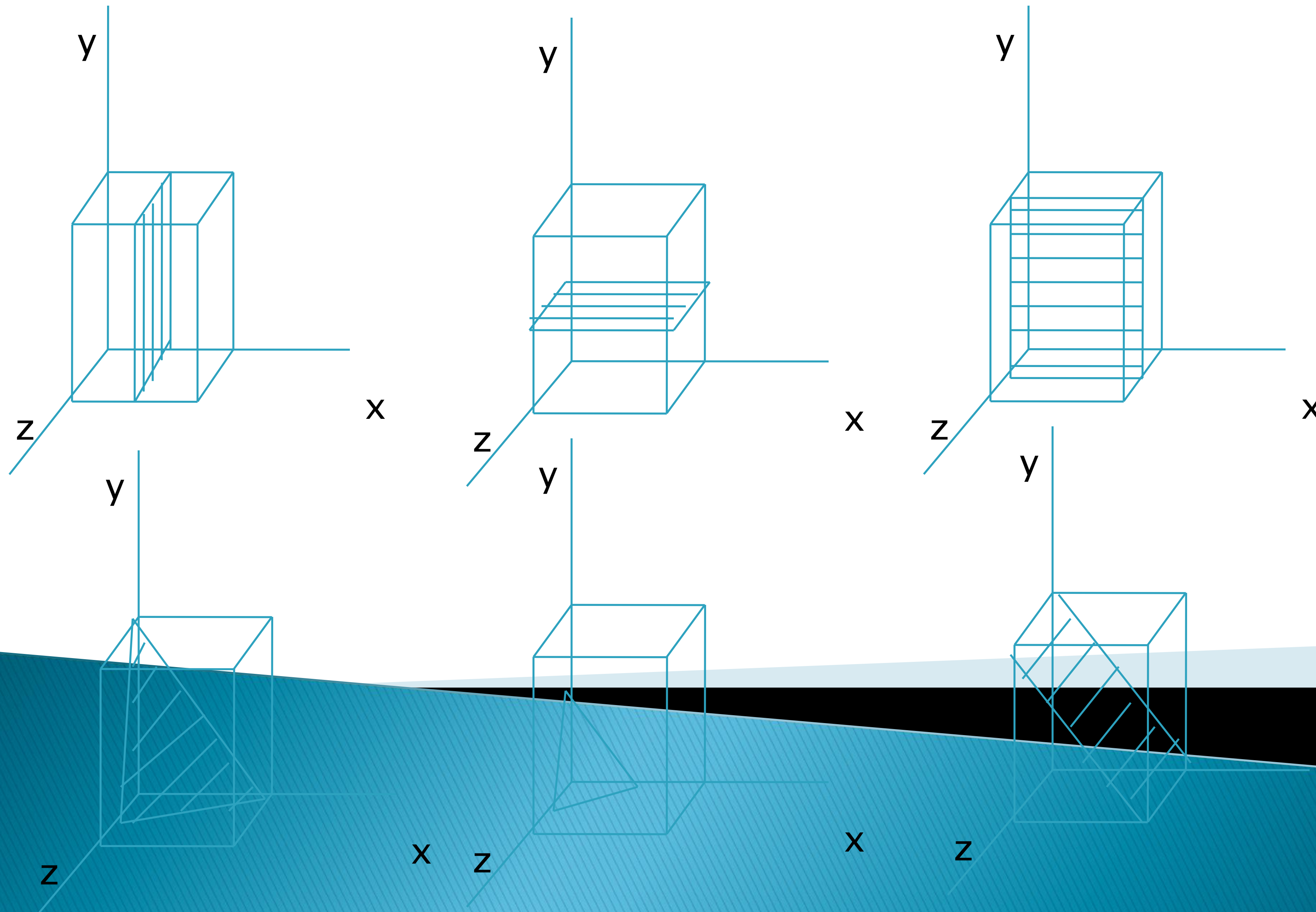


Step2: If step 2 contains fractions for example $(1\ 1/2\ 1/3)$

Step3: multiply with primitives then $(a\ b/2\ c/3)$

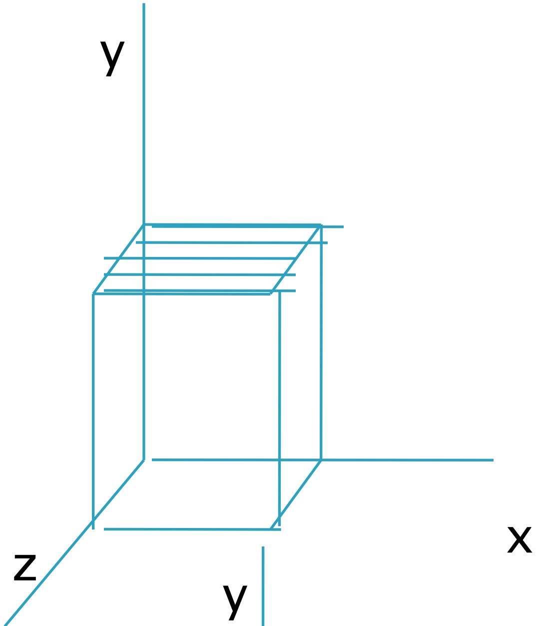
EXERCISE

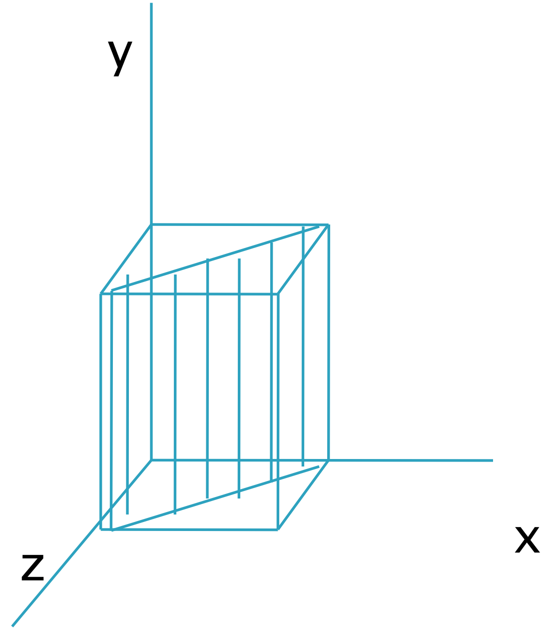
Find miller indices of following planes

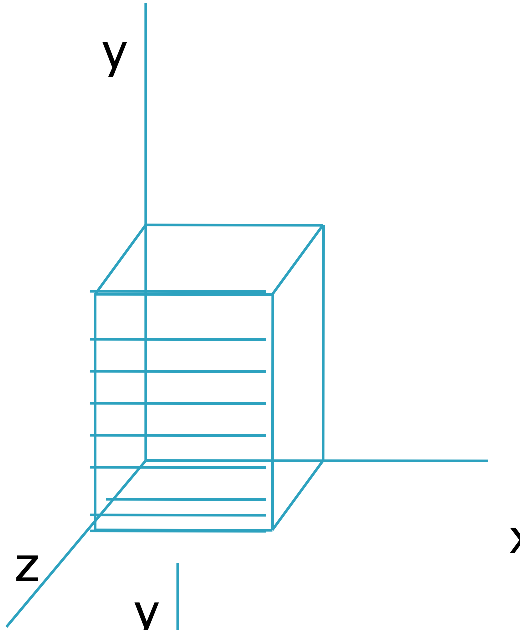


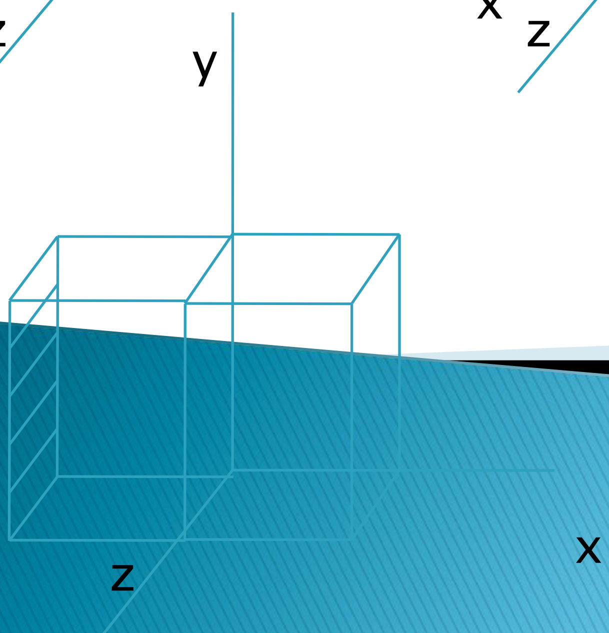
EXERCISE

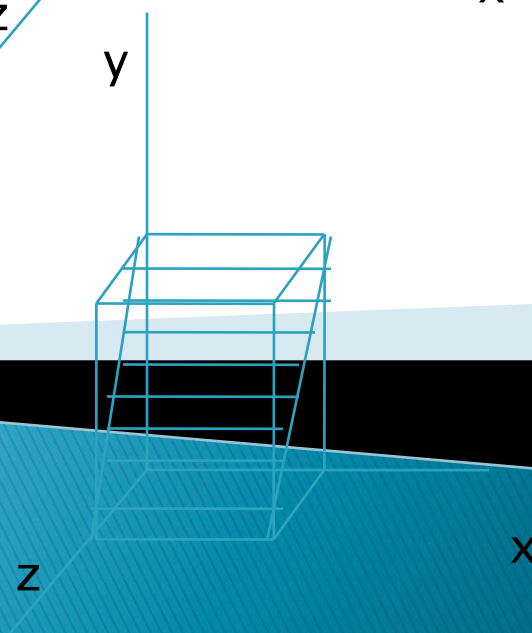
Find miller indices of following planes





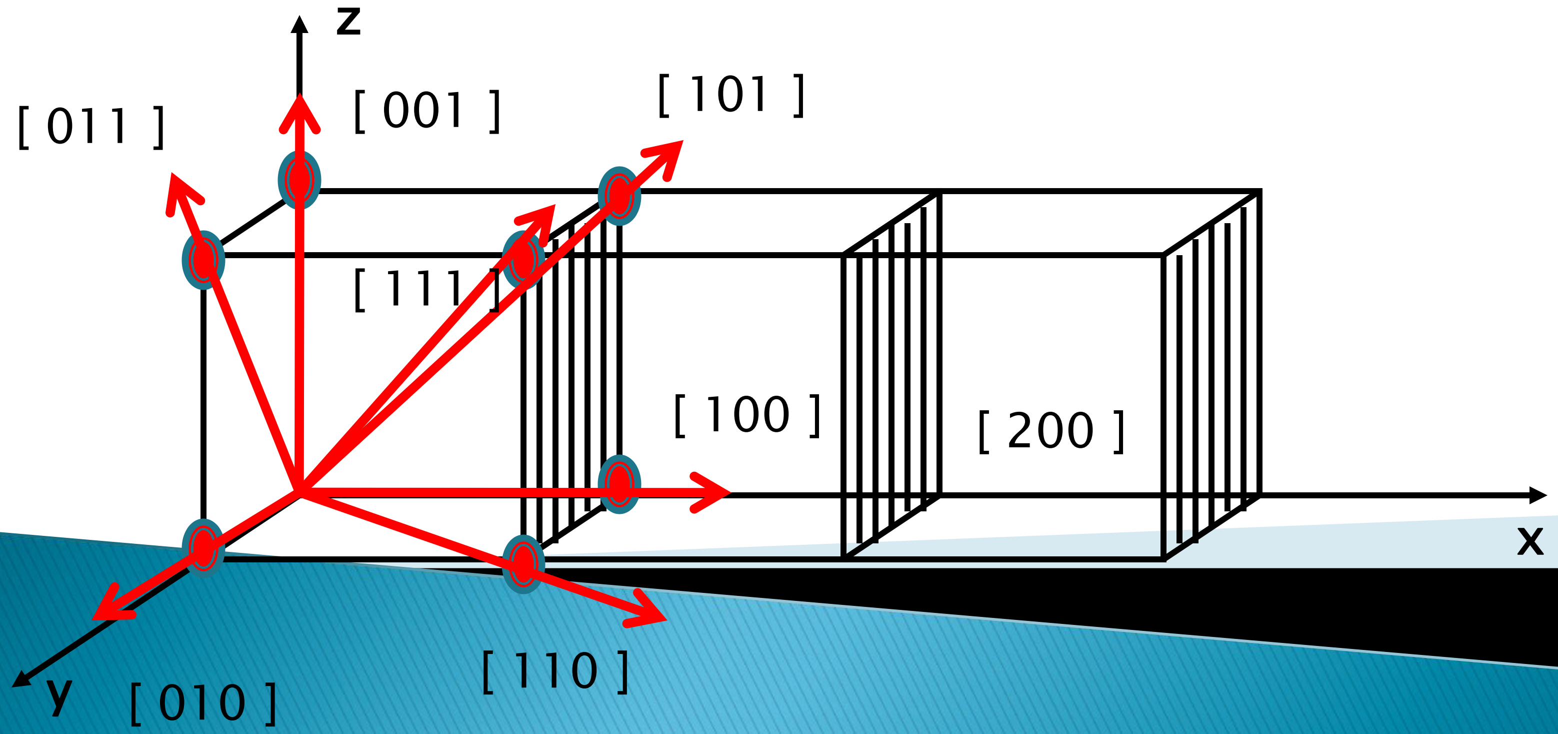






Crystal Directions

The general representation of crystal directions are [h k l]



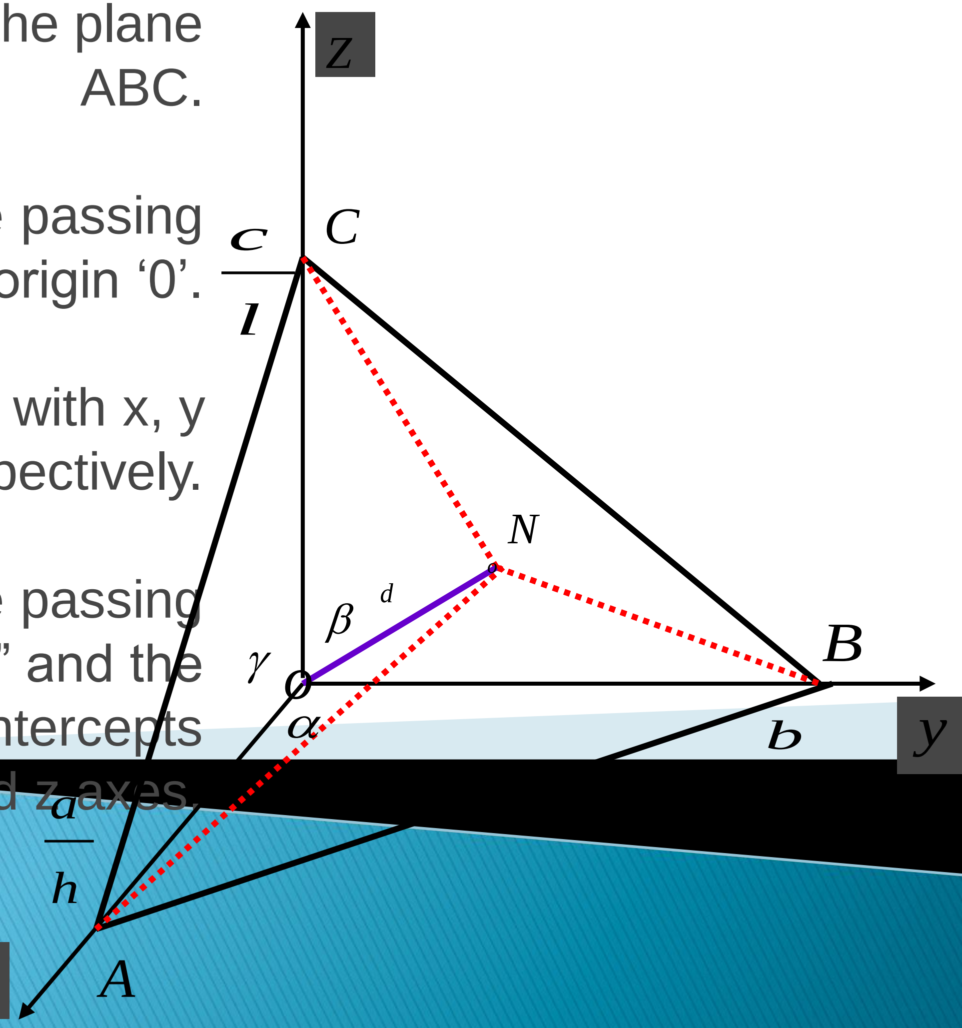
INTER PLANNER SPACING OF ORTHOGONAL CRYSTAL SYSTEM:

Let (h k l) be the miller indices of the plane ABC.

Let ON=d be a normal to the plane passing through the origin ‘0’.

Let this ON make angles α, β and γ with x, y and z axes respectively.

Imagine the reference plane passing through the Origin “o” and the next plane cutting the intercepts a/h, b/k and c/l on x, y and z axes.



OA = a/h, OB = b/k, OC = c/l

A normal ON is drawn to the plane ABC from the origin “o”. the length “d” of this normal from the origin to the plane will be the inter planar separation.

fromΔ ONA

fromΔ ONB

fromΔ ONC

Where cosα, cosβ ,cosγ are directional cosines of α,β,γ angles.

of directional cos

$$\cos^2\alpha + \cos^2\beta + \cos^2\gamma = 1$$

$$\left[\frac{d}{\left(\frac{a}{h}\right)}\right]^2 + \left[\frac{d}{\left(\frac{b}{k}\right)}\right]^2 + \left[\frac{d}{\left(\frac{c}{l}\right)}\right]^2 = 1$$

$$d^2\left\{\frac{h^2}{a^2} + \frac{k^2}{b^2} + \frac{l^2}{c^2}\right\} = 1$$

$$d = \frac{1}{\sqrt{\frac{h^2}{a^2} + \frac{k^2}{b^2} + \frac{l^2}{c^2}}}$$

In cubic system as we know that a = b = c, so the expression becomes

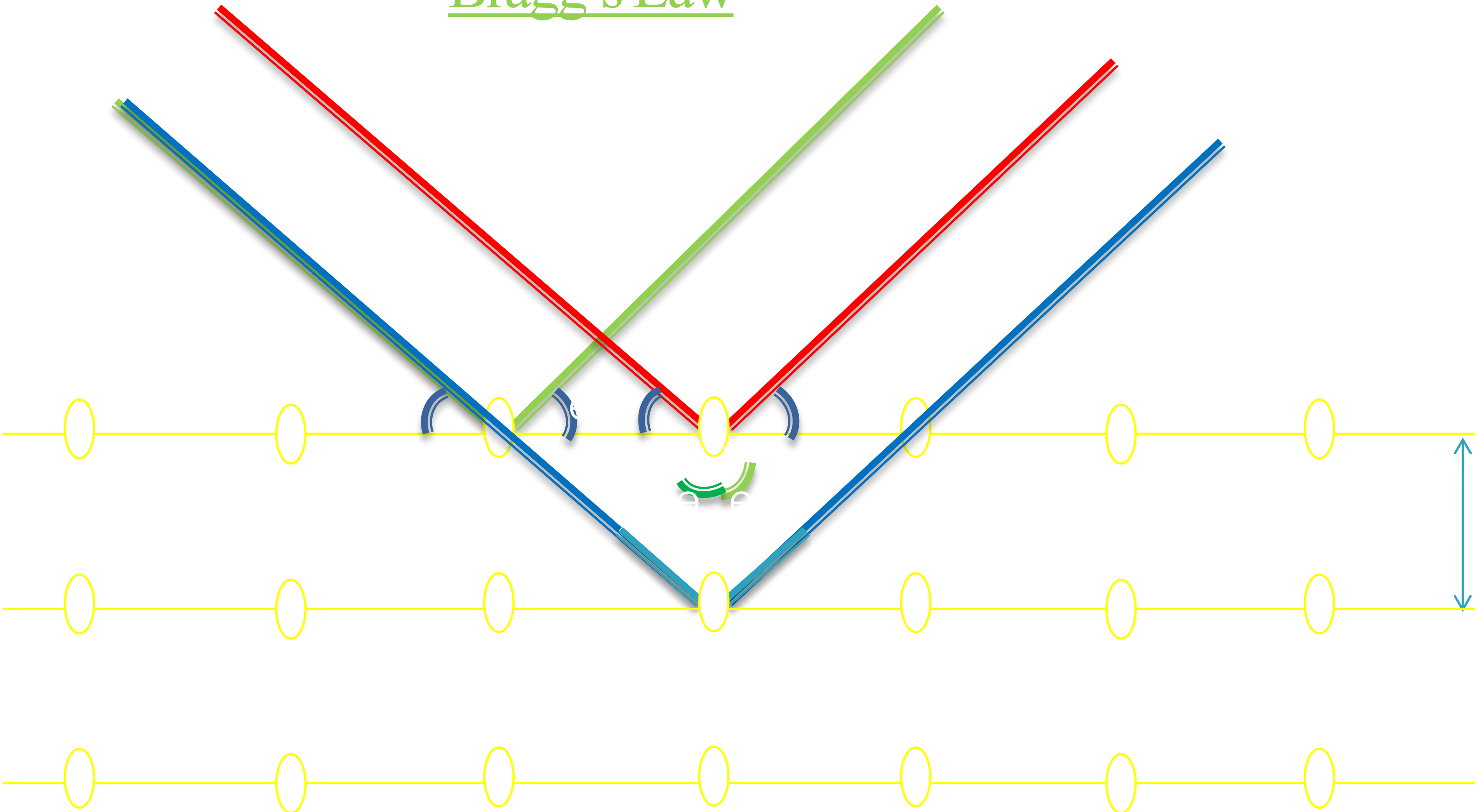
$$d = \frac{a}{\sqrt{h^2 + k^2 + l^2}}$$

X- RAY DIFFRACTION

&

DEFECTS IN CRYSTALS

Bragg's Law



$\Delta = n\lambda$

From Δ ACD, ...

From above equations Δ = d Si...

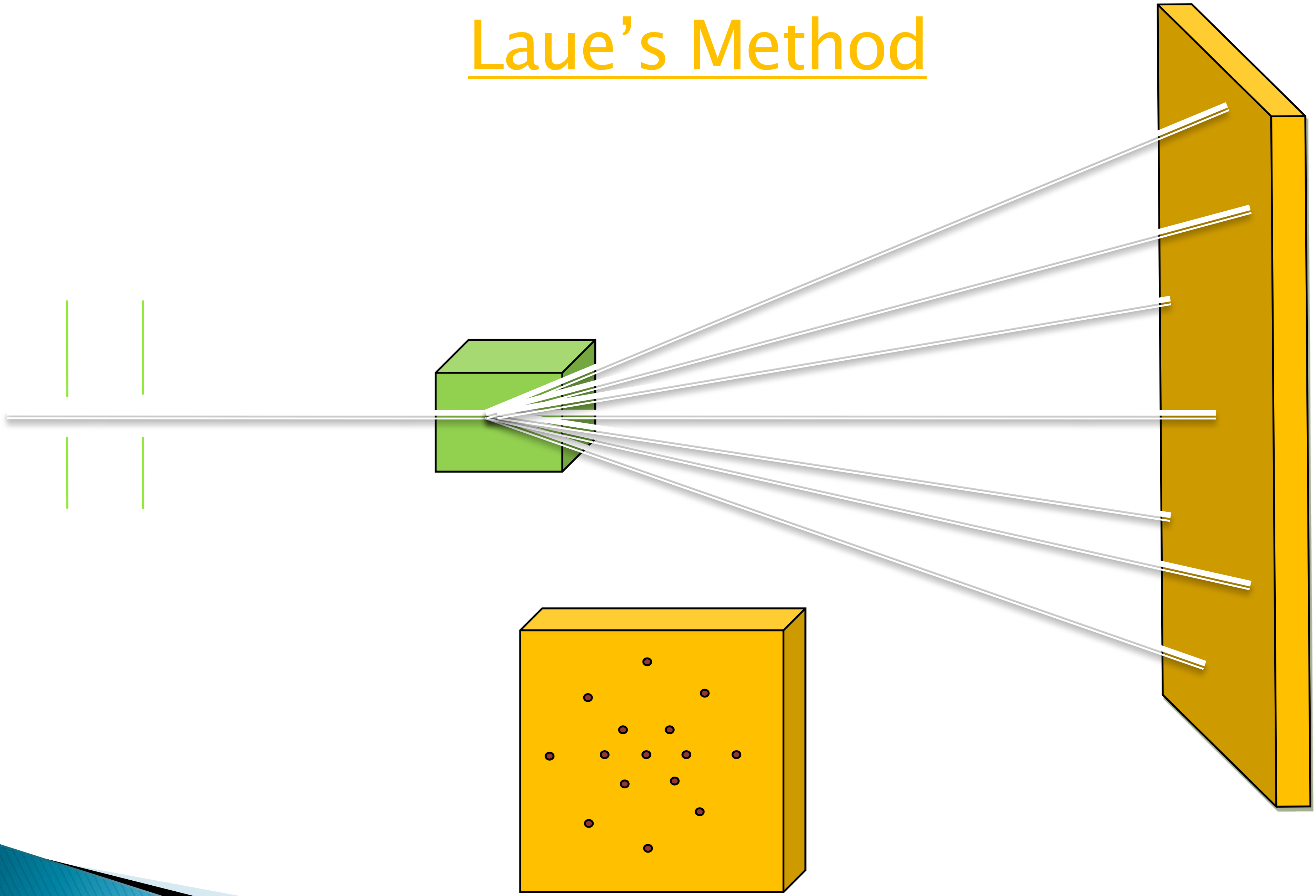
$$n\lambda = 2\ d\ \sin\theta$$

X - Ray Diffraction methods

1. Laue method

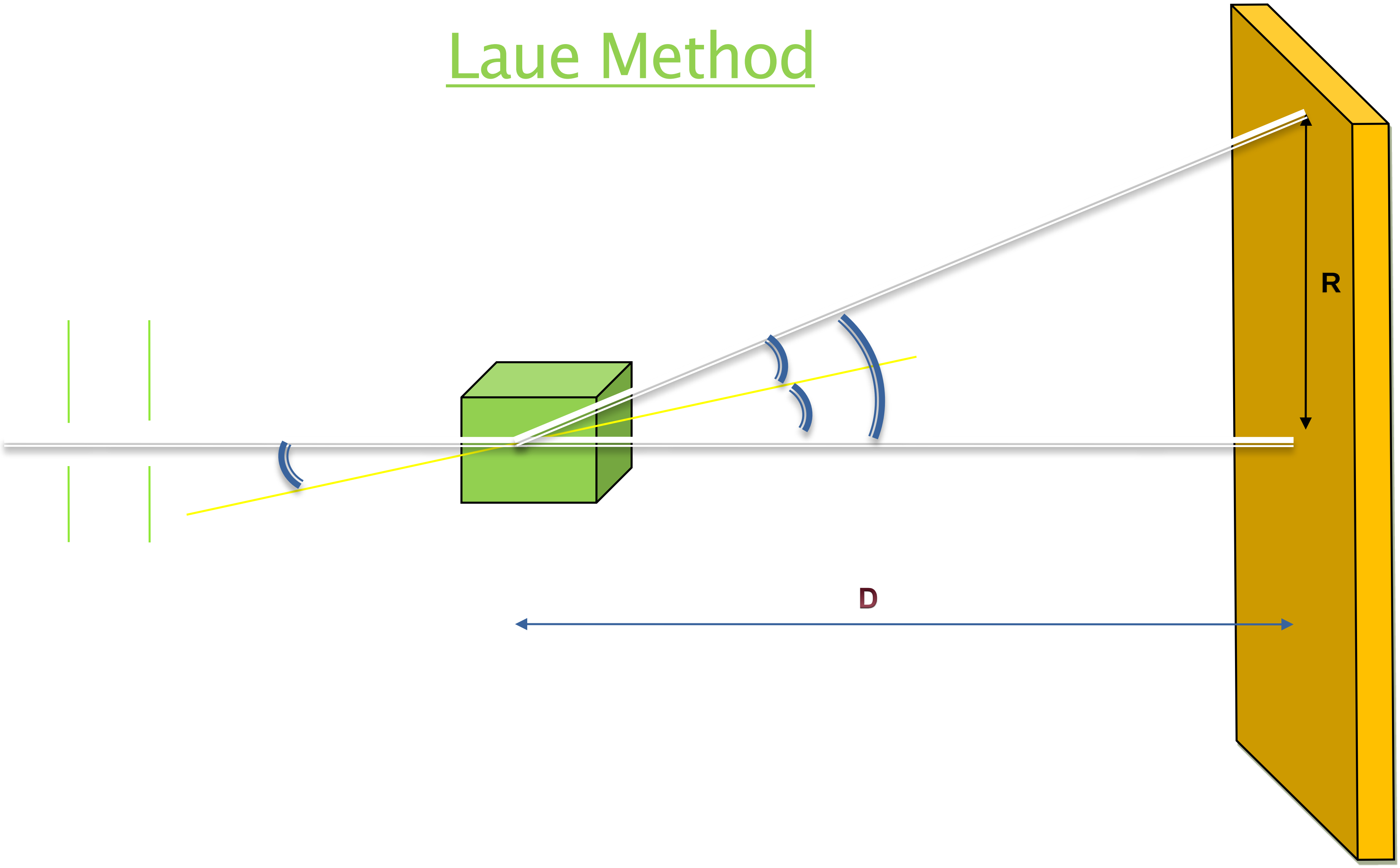
2. Powder method

Laue's Method



Pattern

Laue Method



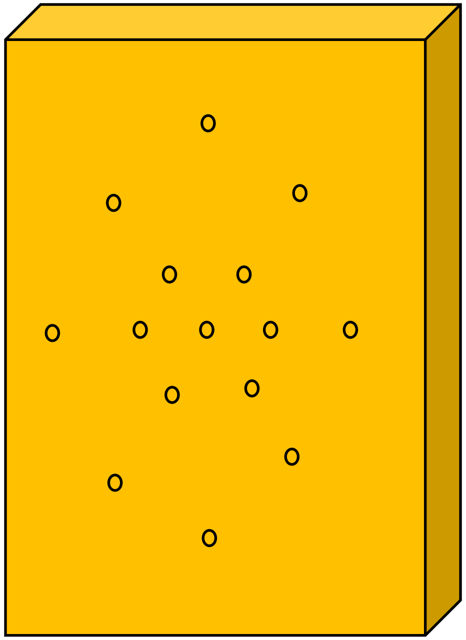
From figure

$$\tan 2\theta = R / D$$

$$2\theta = R / D \quad \text{(Since } \theta \text{ is small)}$$

$$\theta = R / 2D$$

Knowing "ϴ" and observing "Laue pattern" we can analyze the crystal structure of the specimen.



Laue's Pattern

Merits:

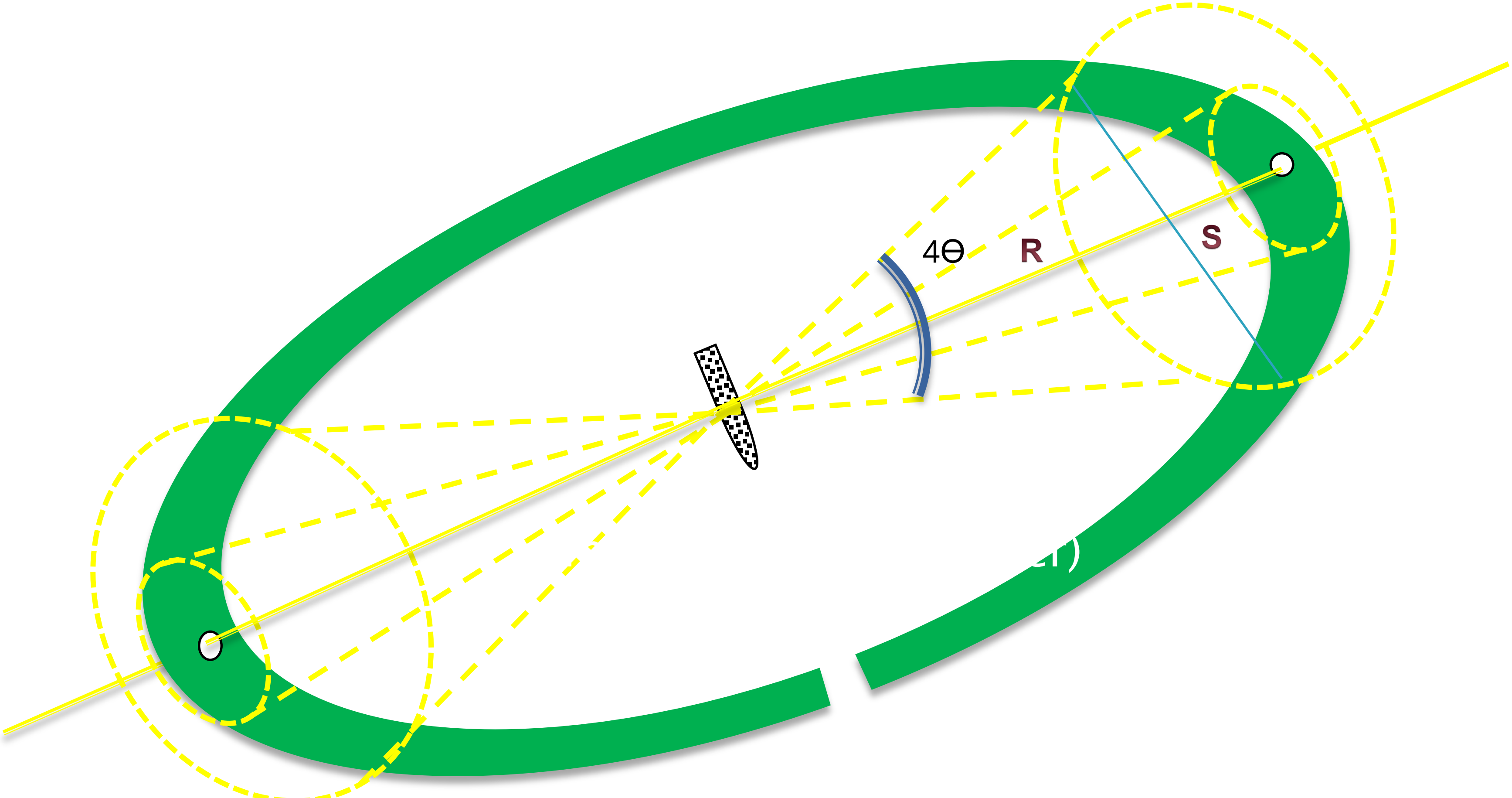
1. It is useful to determine the orientation of the internal arrangement of the atoms in a crystal.
2. It is used to study the crystal Symmetry.

Demerits:

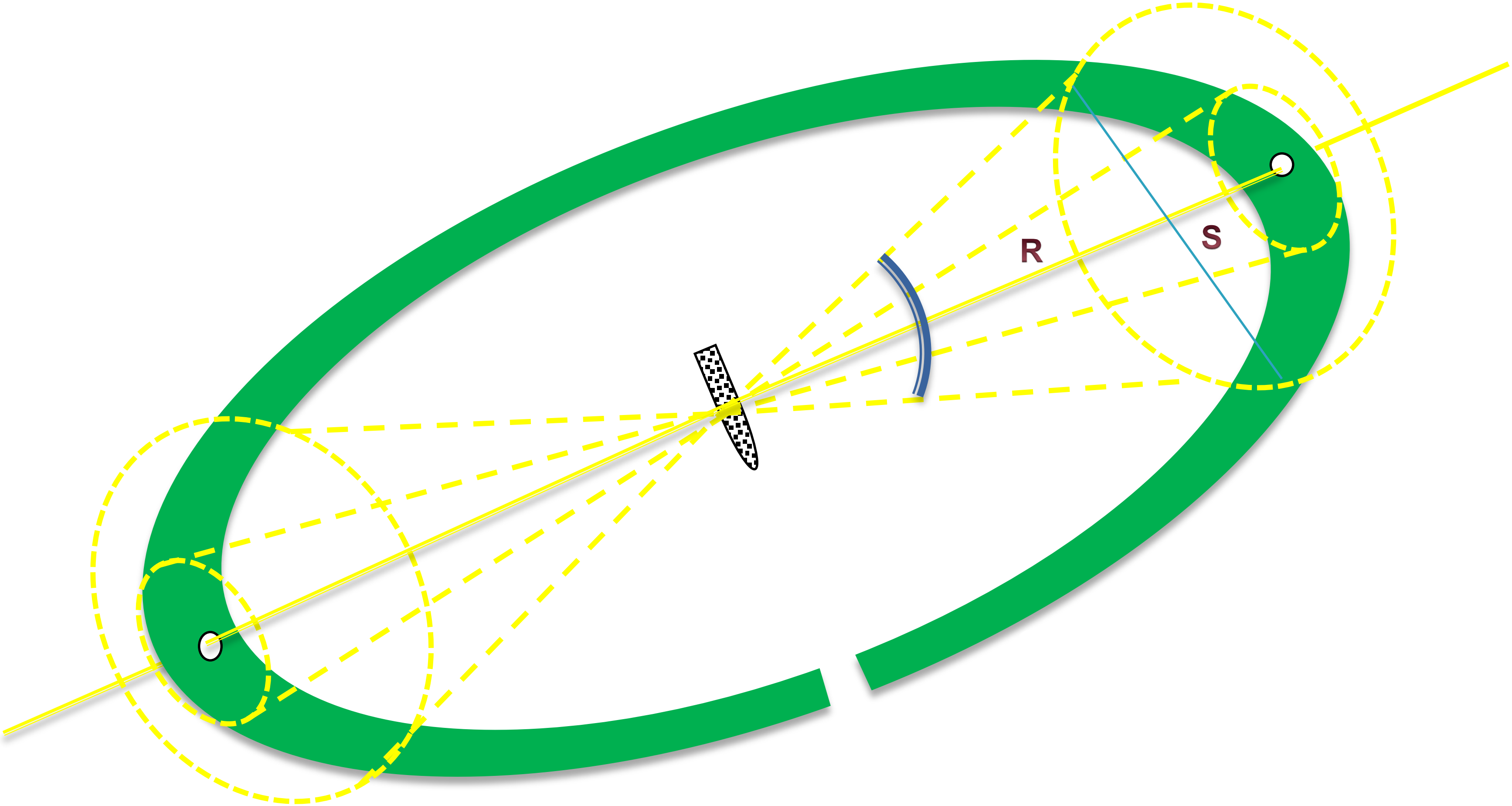
It is not suitable to determine the crystal structure and properties of the crystal.

2. Powder Method
or
(Debye- Scherer method)

Each Cone is formed due to same set of parallel planes

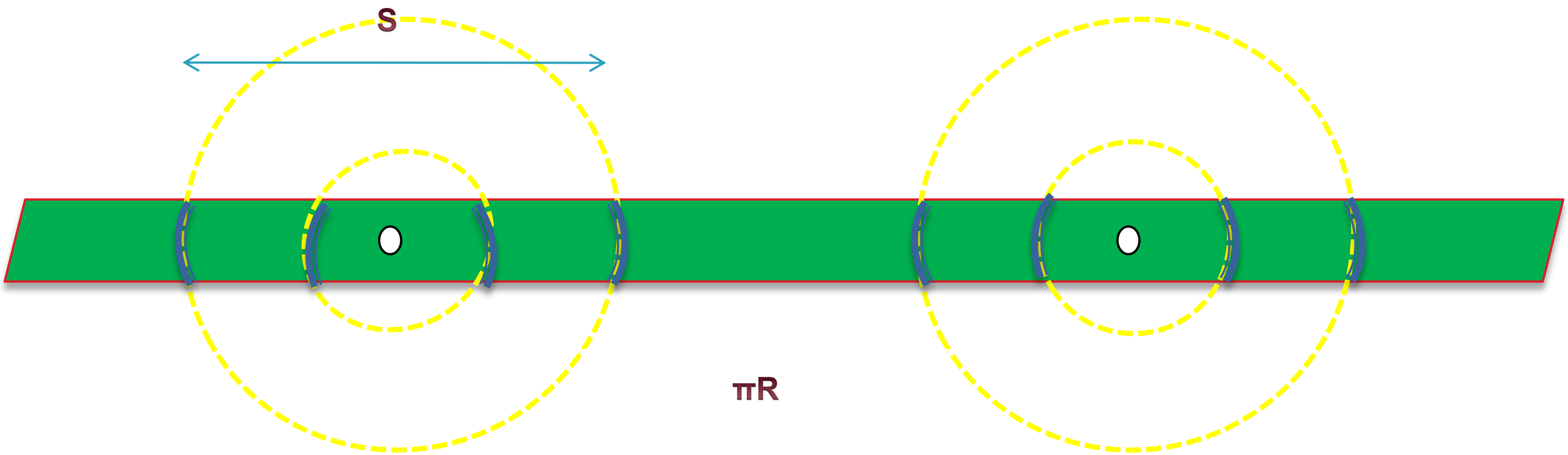


Each Cone is formed due
to same set of parallel



)

Mono
Rays



From figure

$$4\theta = S / R$$

$$\theta = S / 4R$$

By knowing θ values of different cones, the inter planar spacing(d) can be calculated. (∵$\mathbf{n\lambda = 2d\sin\theta}$)

Knowing inter planar spacing of different planes and match any set containing three values(d_1, d_2, d_3) with standard values of (d_{100}:d_{110}:d_{111}), try this for different combinations one can find type of lattice (SC,BCC,FCC).

- Knowing 'θ' --------------→ d can be calculated. (∵**$n\lambda = 2d_{100}\sin\theta$**)

- Knowing 'd' of different planes -----→ (d_{100}:d_{110}:d_{111}) One can find type of lattice (SC,BCC,FCC)

- Knowing type of lattice ------→ One can know number of atoms 'n'.

- Knowing no. of atoms ,molecular weight M , density ρ ----→ One can find lattice parameter 'a'

USES: It is used to determine

1. Size of the unit cell 'a
2. Interplanar spacing 'd'
3. Type of the lattice
4. Presence of impurities, distortions.

DEFECTS IN CRYSTALS

Introduction

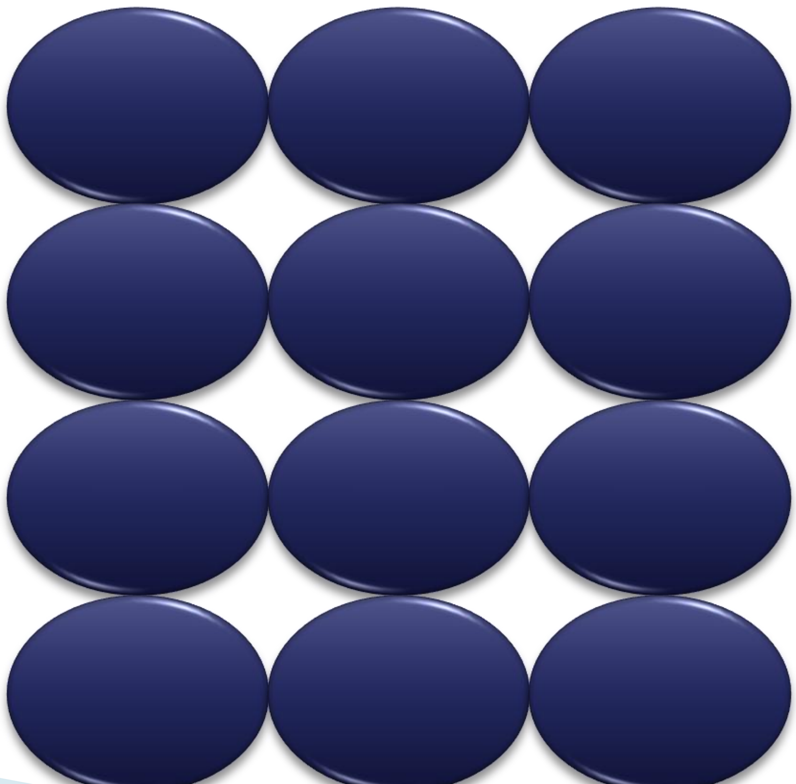
- In an ideal crystal, the atomic arrangement is perfectly regular and continuous but real crystals never perfect.
- They always contain a considerable density defects and imperfections that affect their physical, chemical ,mechanical and electronic properties.
- Crystalline imperfections can be classified on the basis of their geometry under four main divisions namely

Defects

- **1. Point defects (0-dimensional)**
  - **(i) INIONIC DEFECTS :**
    1. Vacancies
    2. Interstitial impurity
    3. Compositional defects.
       - a. Substitutional
       - b. interstitial
    4. Electronic defects
  - **(ii) IONIC DEFECTS:**
    1. Schottky
    2. Frenkel
- **2. Line defects (1-dimensional)**
  1. Edge dislocation
  2. Screw dislocation
- **3. Surface defects (2-dimensional)**
  1. Grain boundaries
  2. Tilt boundaries
  3. Twin boundaries
  4. Stacking faults
- **4. Volume defects (3-dimensional)**
  1. Cracks
  2. Voids or air bubbles

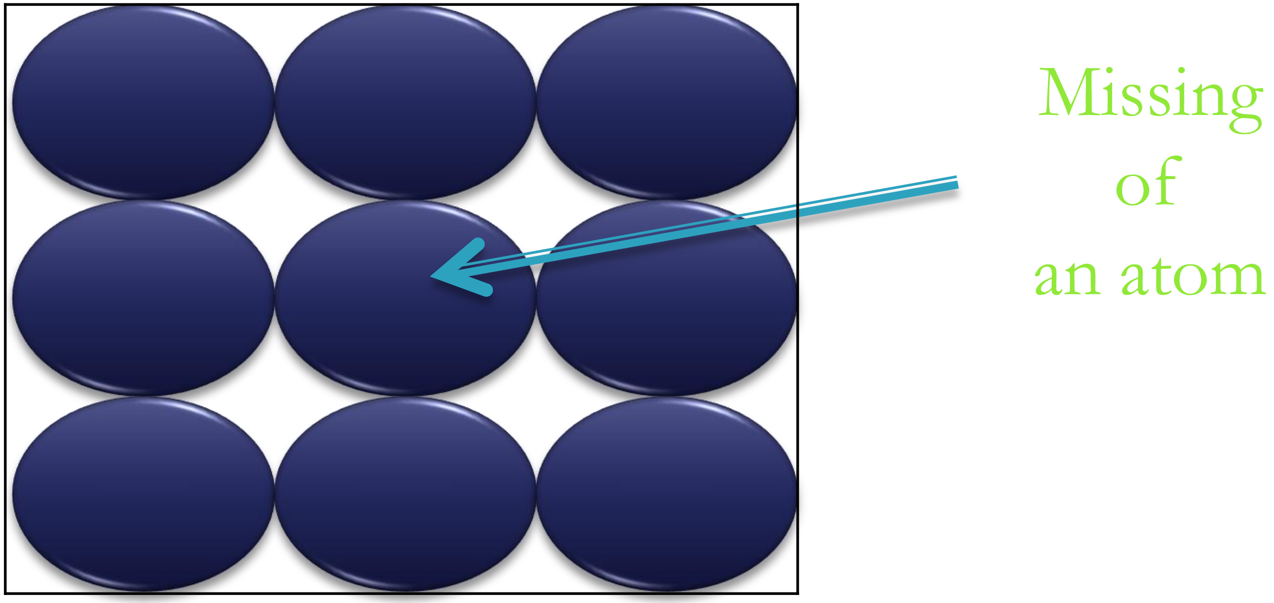
1.Point Defects

Point imperfections are also called zero dimensional imperfections.
One or two atomic diameters is the typical size of a point imperfection.



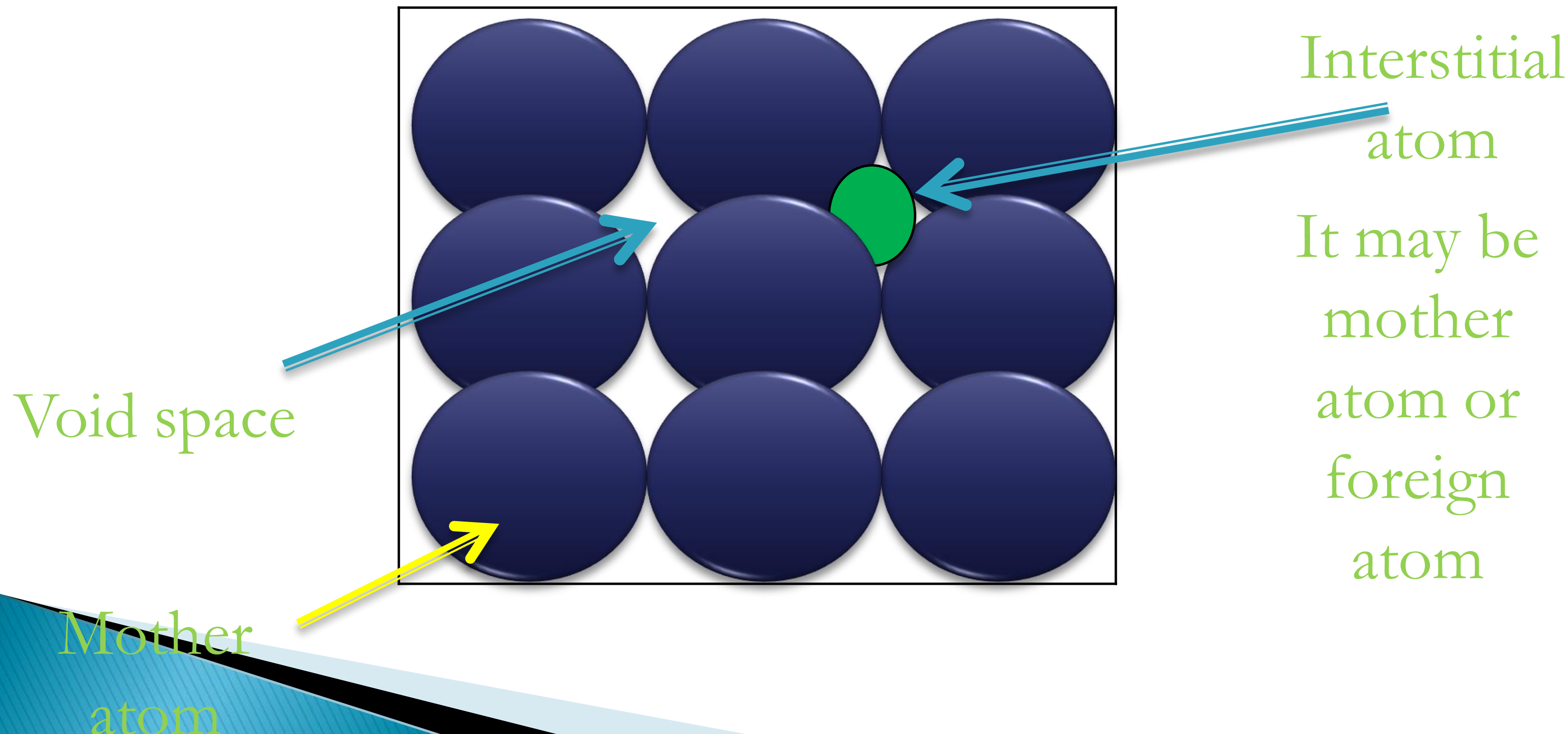
1. Vacancy Defect :

It is formed by missing of an atom in the atomic sight.



2. Interstitial impurity defect:

It is formed by occupying void space by interstitial atom.



3. Compositial defects:

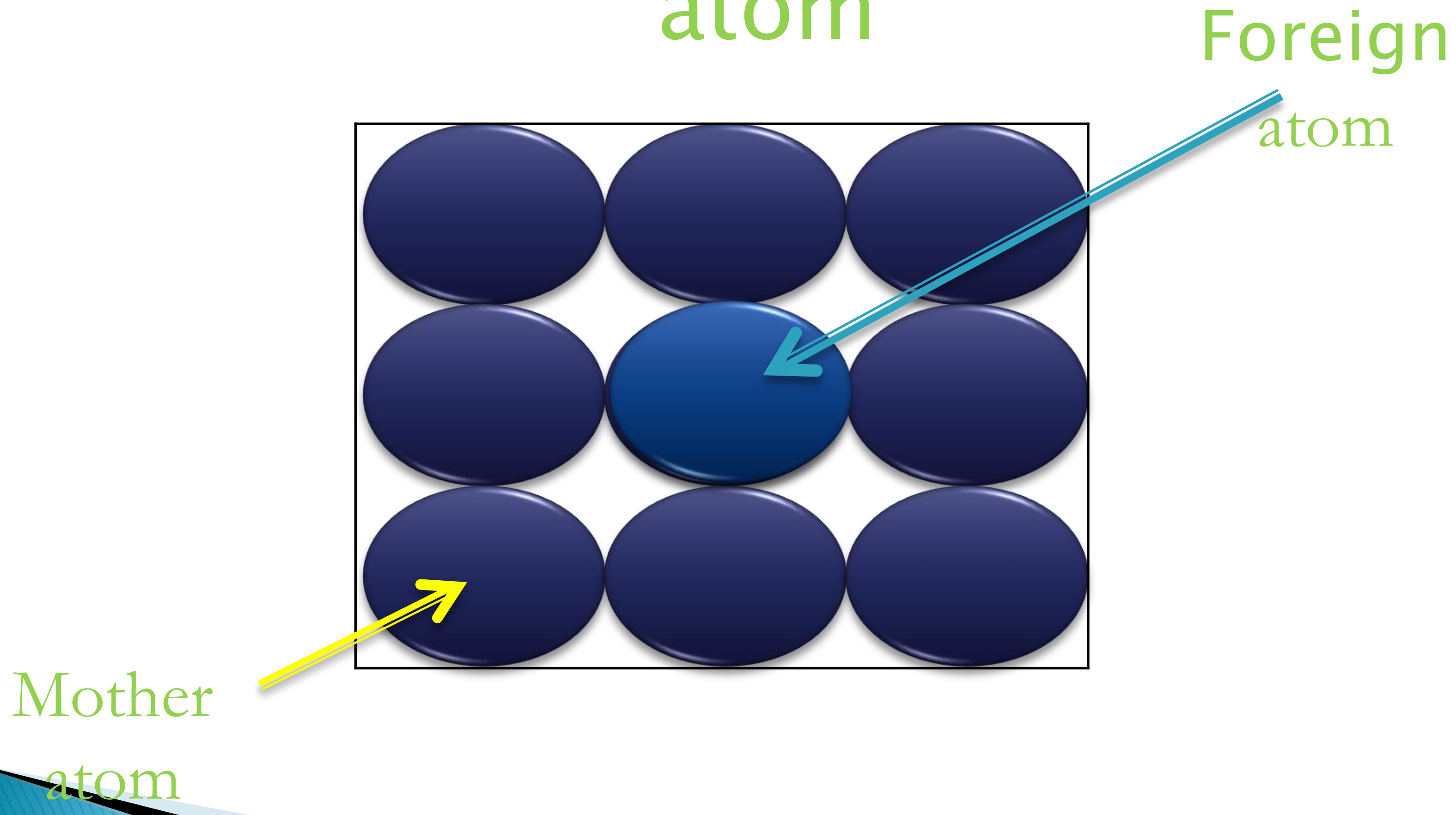
Basically these are two types

a) Substitutional Impurity

b) Interstitial Impurity

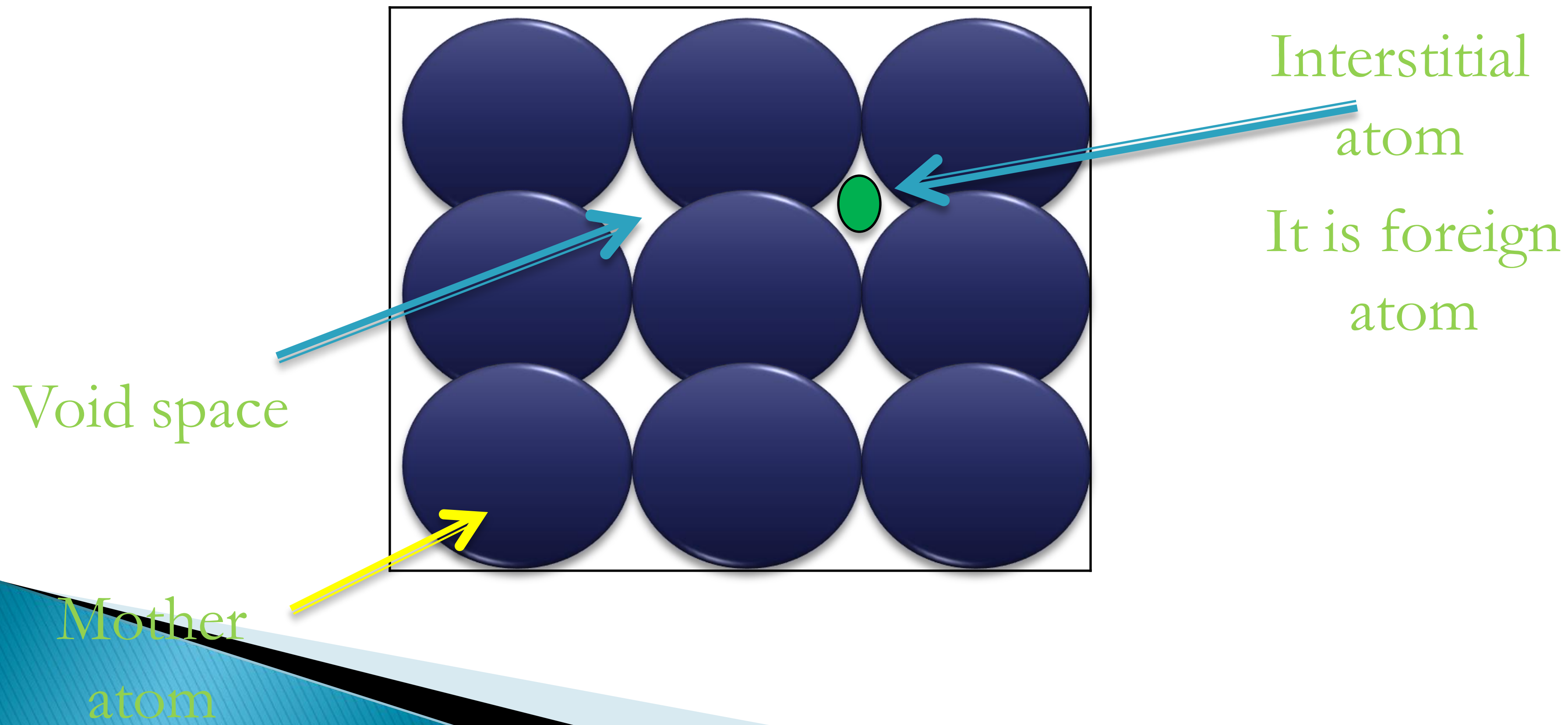
a) <u>Substitutional Impurity:</u>

It is formed by occupying mother atom by foreign atom



b) Interstitial impurity defect:

It is formed by occupying void space by interstitial atom without disturbing the atomic site.



4.Electronic defects :

It is formed by the errors in charge distribution in solids

Ex: Zinc Oxide

$Zn^{+2}\ O^{-2}$	$Zn^{+1}\ O^{-3}$
$Zn^{+2}\ O^{-2}$	
$Zn^{+3}\ O^{-1}$	$Zn^{+2}\ O^{-2}$
$Zn^{+2}\ O^{-2}$	

This is due to presence of a vacancy or an interstitial impurity or due to high temperature.

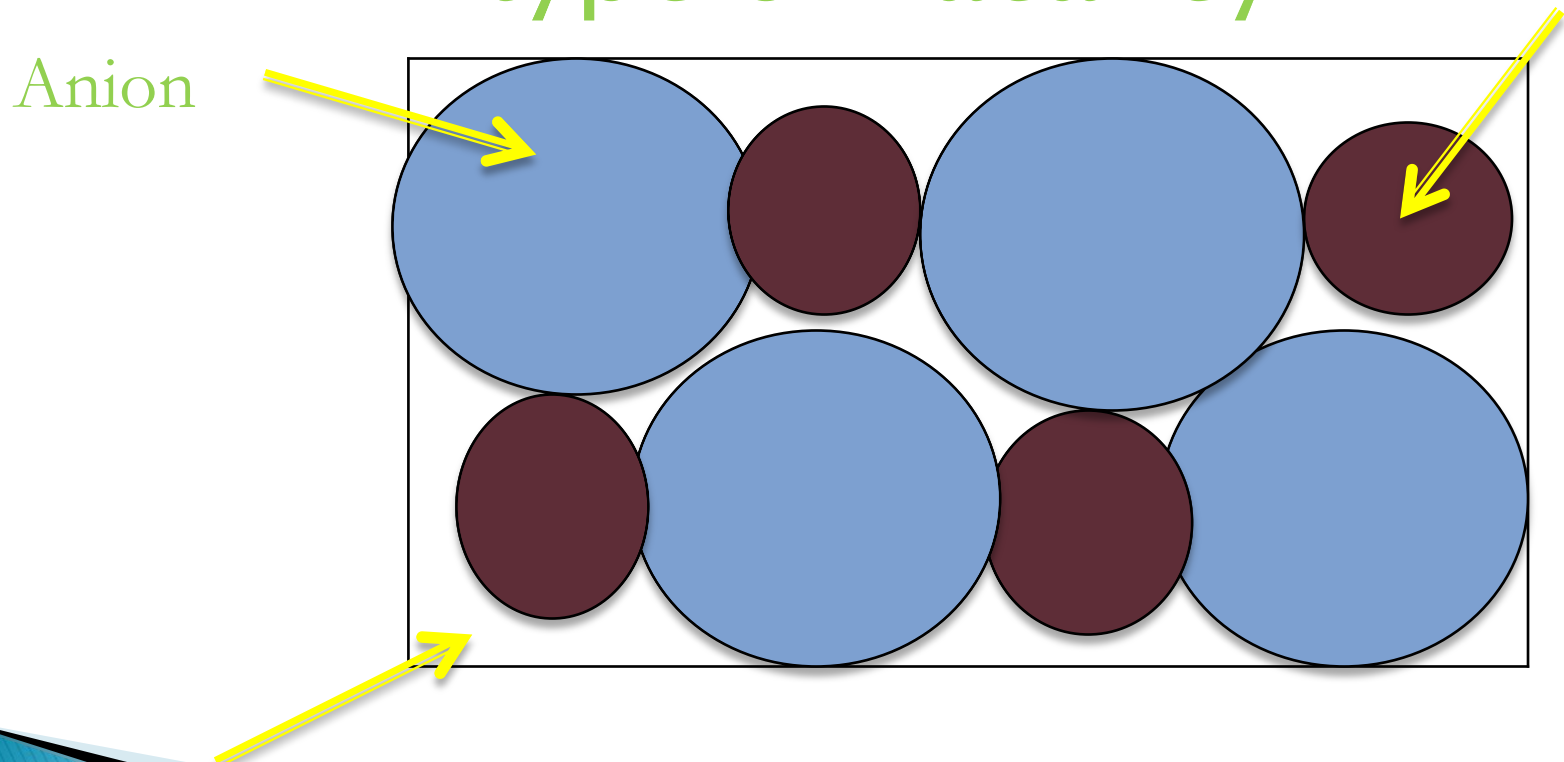
(ii) IONIC DEFECTS:

1. **Schottky Defect**

2. **Frenkel Defect**

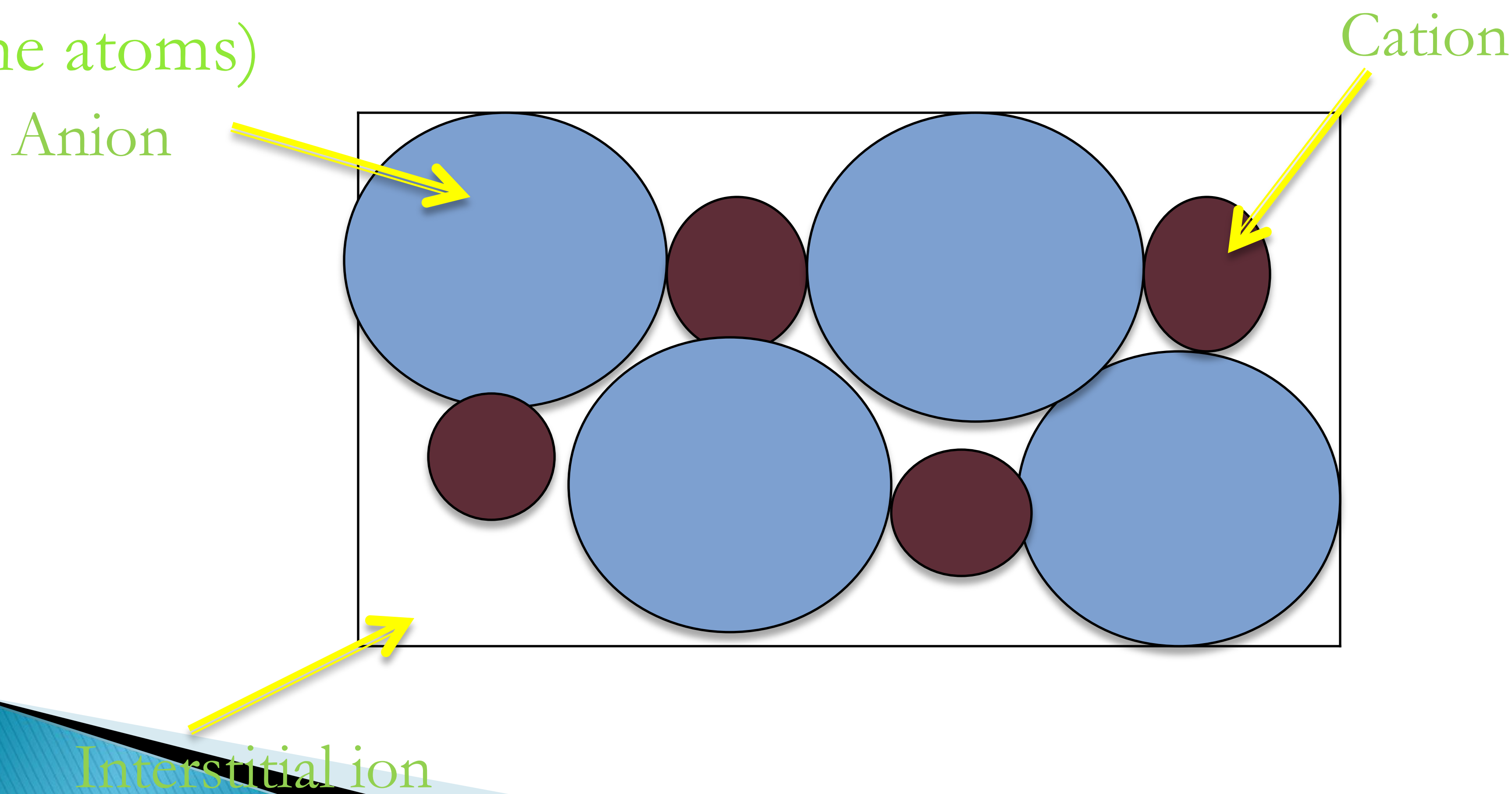
1. Schottky Defect

It is formed by missing of one anion and one cation. It is a type of vacancy.



2.Frenkel Defect

It is formed by occupying the void space by interstitial ion (usually cations are smaller than anions. So cations can occupy empty space between the atoms)



2. Line defects
(1- dimensional defects)

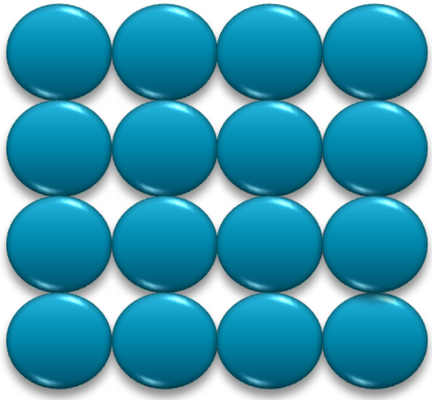
These are also called as dislocations.

These are of two types

1. Edge dislocations

2. Screw locations

1. Edge dislocations



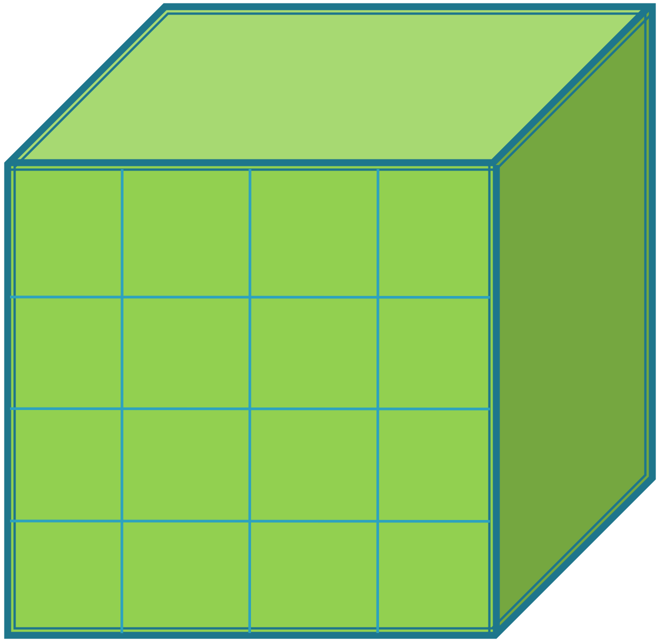
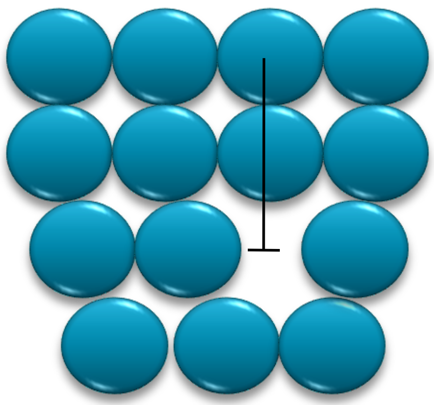


Fig (a): Perfect Crystal: In a perfect crystal, atoms are arranged in both vertical and horizontal planes parallel to the side faces.

1. Edge dislocations



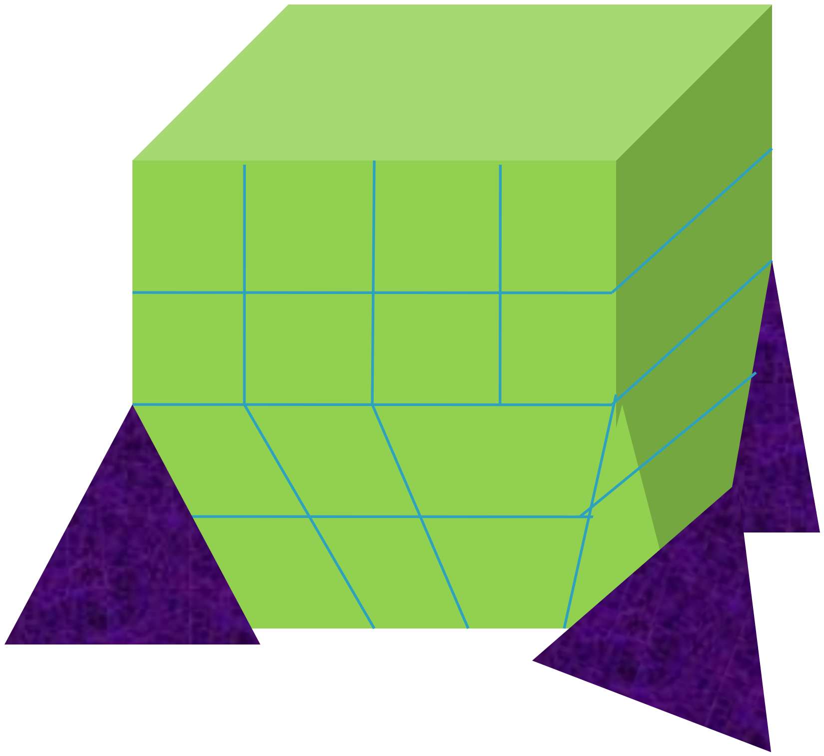


Fig (b): Crystal with Edge dislocation: If one of these vertical planes does not extended to full length but ends in between, within the crystal as shown in figure, it is called **"edge dislocation"**.

⊥ → Symbol indicates the dislocation starts from top to bottom (Positive dislocation)

⊤ → Symbol indicates the dislocation starts from bottom to top (Negative dislocation)

2. Screw locations

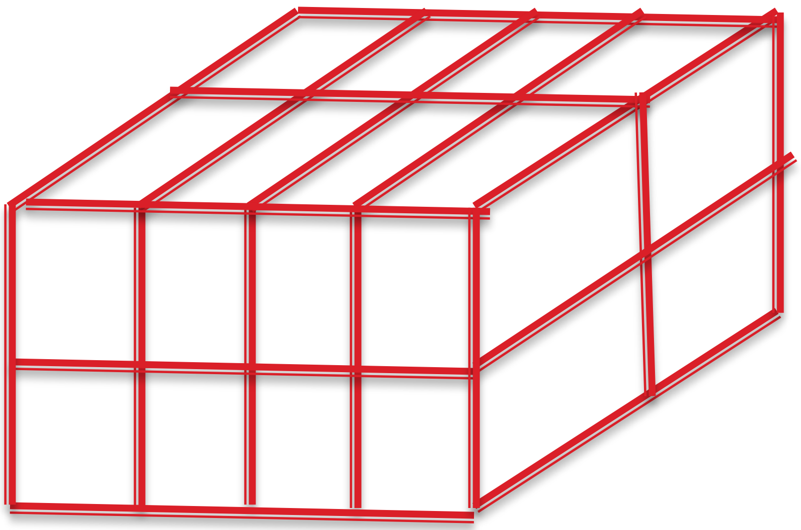


Fig (a): Perfect Crystal

2. Screw locations

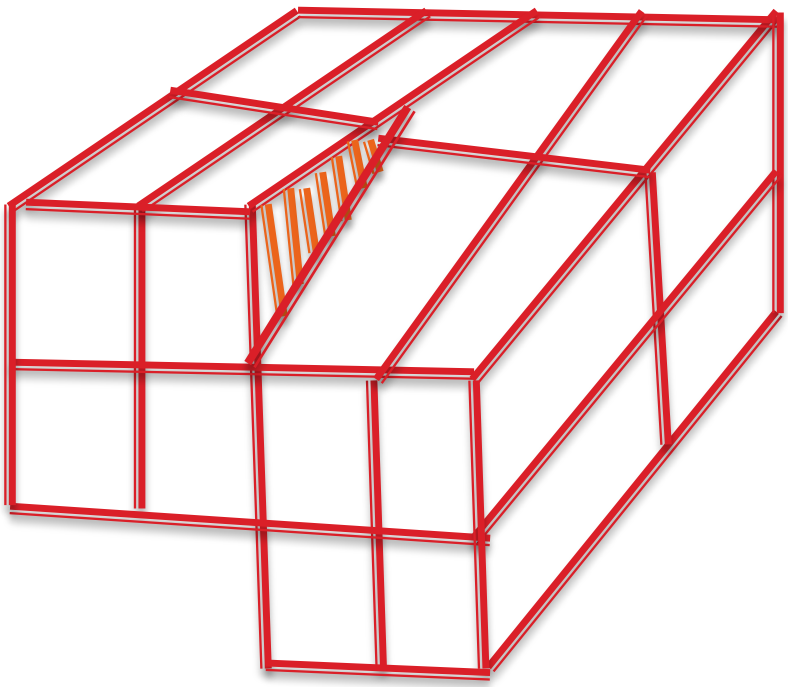


Fig (b): Crystal with Edge dislocation

If some part of the crystal is displaced spirally from the rest of the crystal then the dislocation is called screw dislocation.

If the dislocation is clockwise then the dislocation is called Right hand side dislocation.

If the dislocation is anti clockwise then the dislocation is called Left hand side dislocation.

Burger vector

- The magnitude and the direction of the dislocation is defined by a vector called the 'Burgers vector'.

- Consider two crystals one perfect and another with edge dislocation.

Fig 1: Perfect crystal

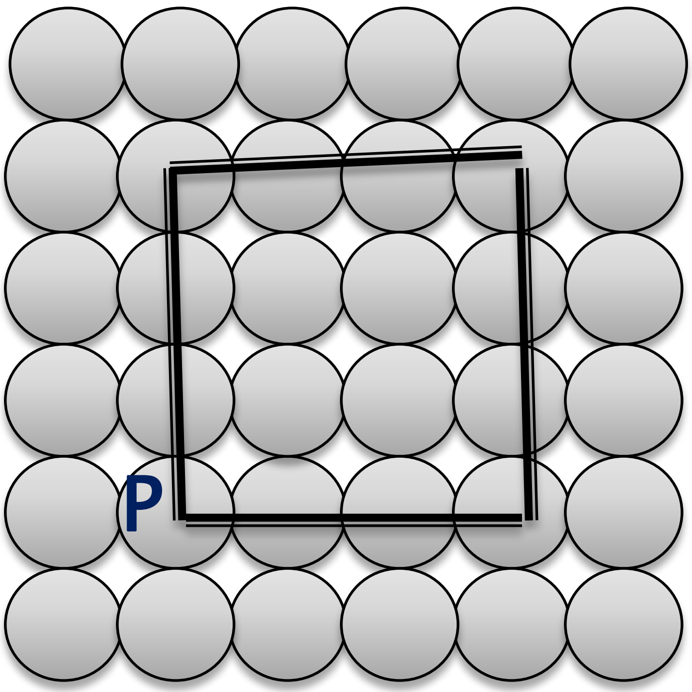
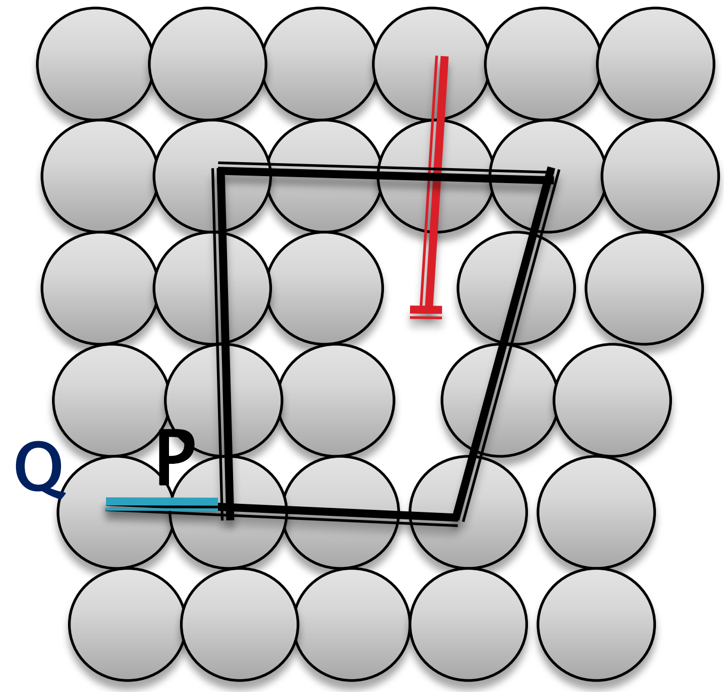


Fig 2: Crystal with Edge dislocation



$\vec{QP} = \vec{b}$ = Burger Vector

From fig. 1.

Starting from the point P, we go up by x steps, then move towards right by y steps, and move down by x steps and finally move towards left by y steps to reach the starting point P, the burgers circuit gets closed.

From fig 2.

We end up at Q instead of the starting point P.

Now we have to move an extra step QP to return to 'P' in order to close the burgers circuit.

The magnitude and the direction of the step defines the Burgers vector (BV)

Burger Vector = QP = b

The Burgers vector is perpendicular to the edge dislocation line.

Burgur vector – in Screw locations

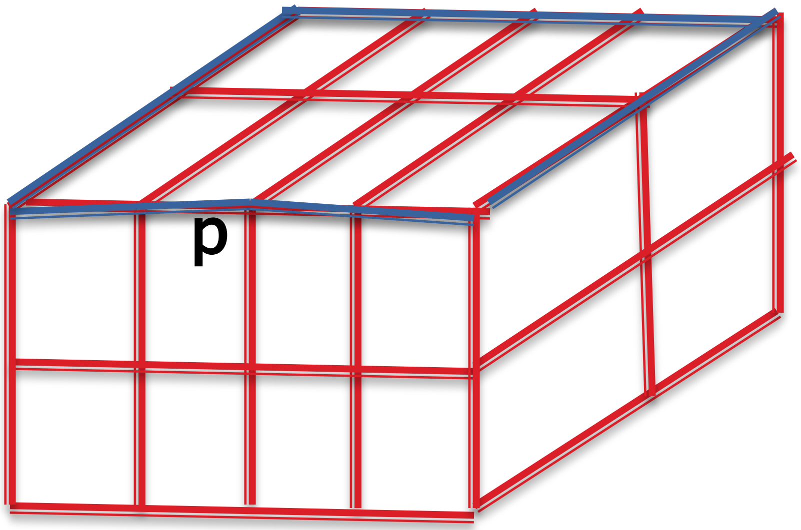
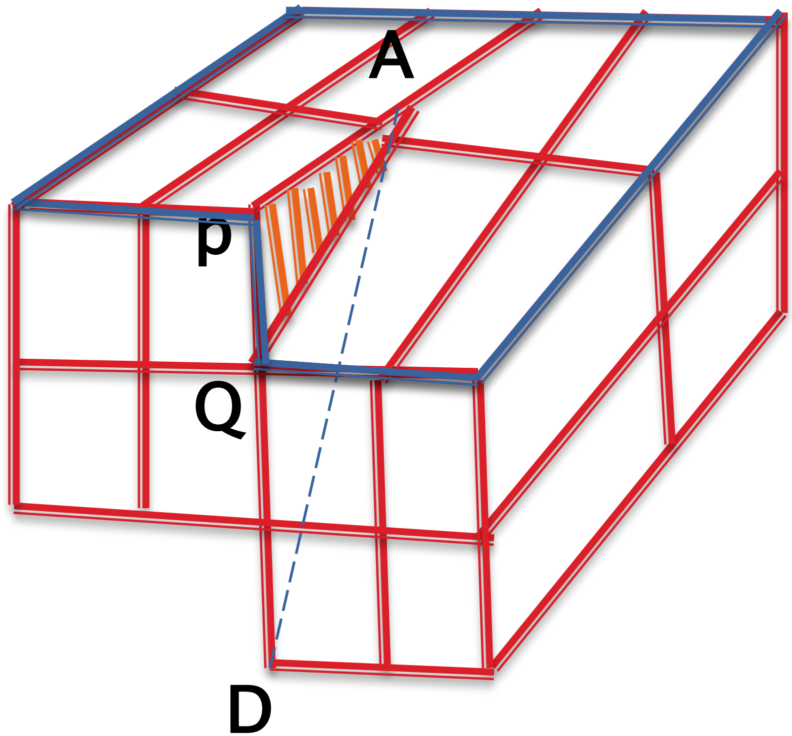


Fig (a): Perfect Crystal



The Burgers vector parallel to the screw dislocation line.

LASERS

A laser is a device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation.

The term “LASER" originated as an acronym for "light amplification by stimulated emission of radiation".

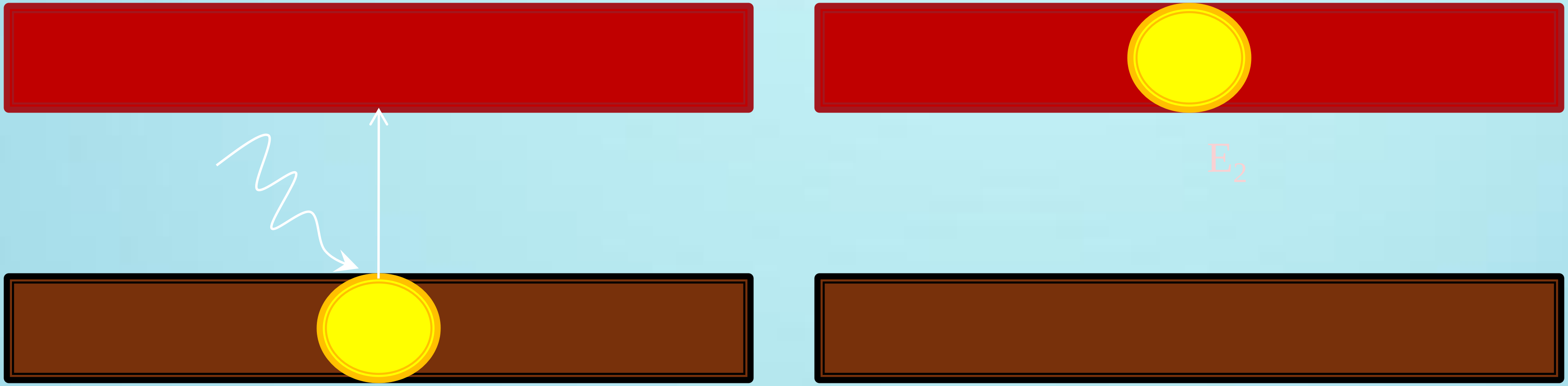
Stimulated emission was first used by Townes and Schawlov in USA & Bosov & Prokhrov in USSR.

Maiman demonstrated the first Laser in 1960.

Mechanism of Light Emission

For atomic systems in thermal equilibrium with their surrounding, the emission of light is the result of:

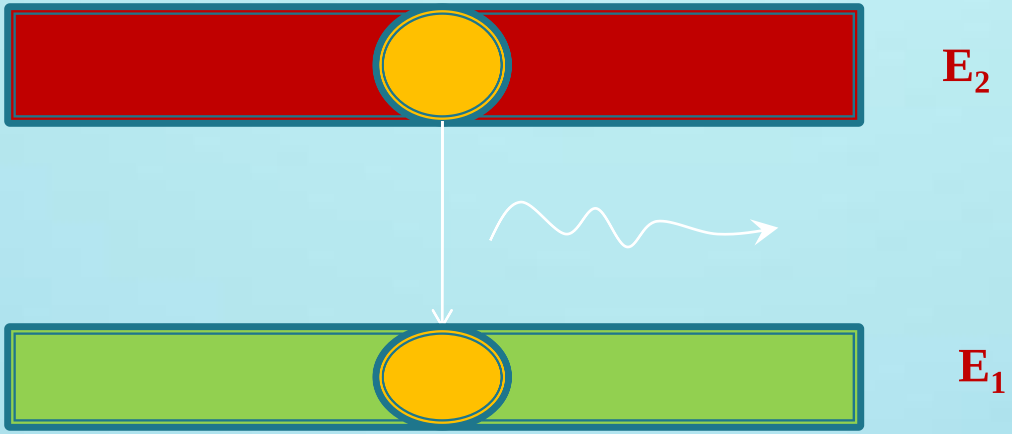
Absorption: If a photon of energy $h\nu_{12}(E_2-E_1)$ collides with an atom present in the ground state of energy E_1, then the atom completely absorbs the incident photon and makes transition to excited state E_2.



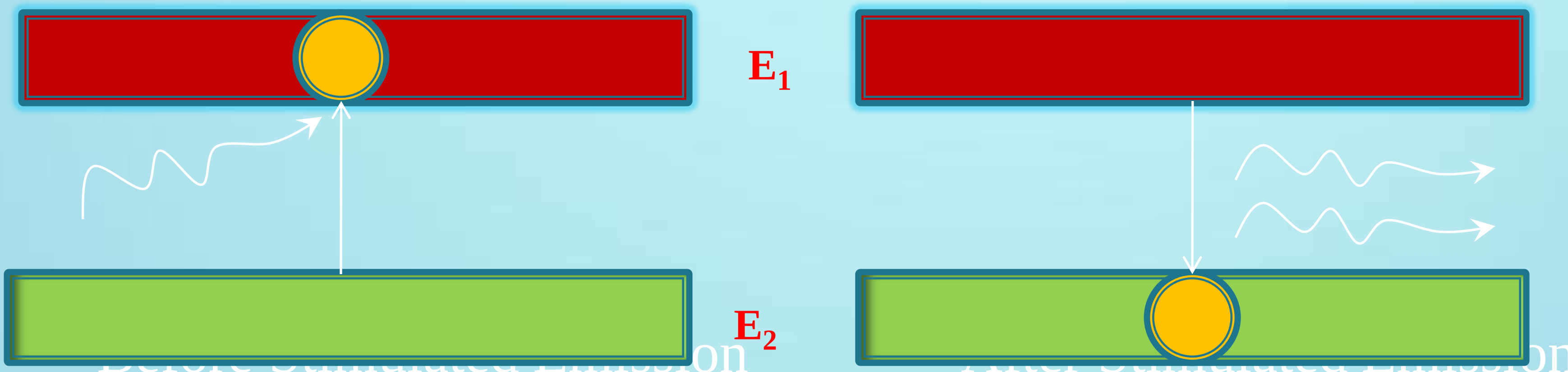
Before Absorption **After Absorption**

Spontaneous emission: An atom initially present in the excited state makes transition voluntarily on its own ,without any aid of external stimulus or an agency ,to the ground state and emits a photon of energy $h\nu=E_2-E_1$. The period of stay of the atom (electron) in the excited state is called its life time.

This process of emission of light is called spontaneous emission.



Stimulated Emission: A photon having energy $h\nu_{12}$ $(E_2\text{-}E_1)$ impinges on an atom present in the excited state and the atom is stimulated to make transition to the ground state. This gives off a photon of energy $h\nu_{12}$. The emitted photon is in phase with the incident photon. These are coherent. This type of emission is known as stimulated emission.



Difference between Spontaneous and Stimulated Emission of radiation

Spontaneous Emission of Radiation	Stimulated Emission of Radiation
It is a Polychromatic radiation.	It is a Monochromatic radiation.
It has less intensity.	It has High intensity.
It has less directionality and more angular spread during propagation.	It has high directionality and so less angular spread during propagation.
It is Spatially and temporally incoherent radiation.	It is Specially and temporally coherent radiation.
In this emission ,light is not amplified.	In this emission , light is amplified.
Spontaneous emission takes place when excited atoms make a transition to lower energy level voluntarily without any external stimulation.	Stimulated emission takes place when a photon of energy equal to $h\nu_{12}$ $(=E_2-E_1)$ stimulates an excited atom ,to make transition to lower energy level.
In a single downward transition, Spontaneous emission results in the emission of one photon.	In a single downward transition , Stimulated emission results in the emission of two photons.
Ex: Light from an ordinary electric bulb, Light from an LED.	Ex: Light from a Laser source.

Characteristics of Laser light

The most important characteristics of a Laser beam are,

1. **High Monochromaticity**
2. **High degree of coherence**
3. **High directionality**
4. **High brightness**

1.Monochromaticity:

- Laser light is monochromatic or very pure in color.
- A Laser beam is in single wavelength i.e., the line width of a laser beam is extremely narrow.
- In conventional light sources, the wavelength spread is usually 1 in 10^6
- In case of laser light, the spread will be 1 in 10^{15}

  This means that if the frequency of radiation is 10^{15} Hz, then the width of the line will be 1 Hz

2.Directionality:

Laser beam emits light only in one direction.

It travels very long distances without divergence. And so, Laser communication is carried on between the earth and the moon.

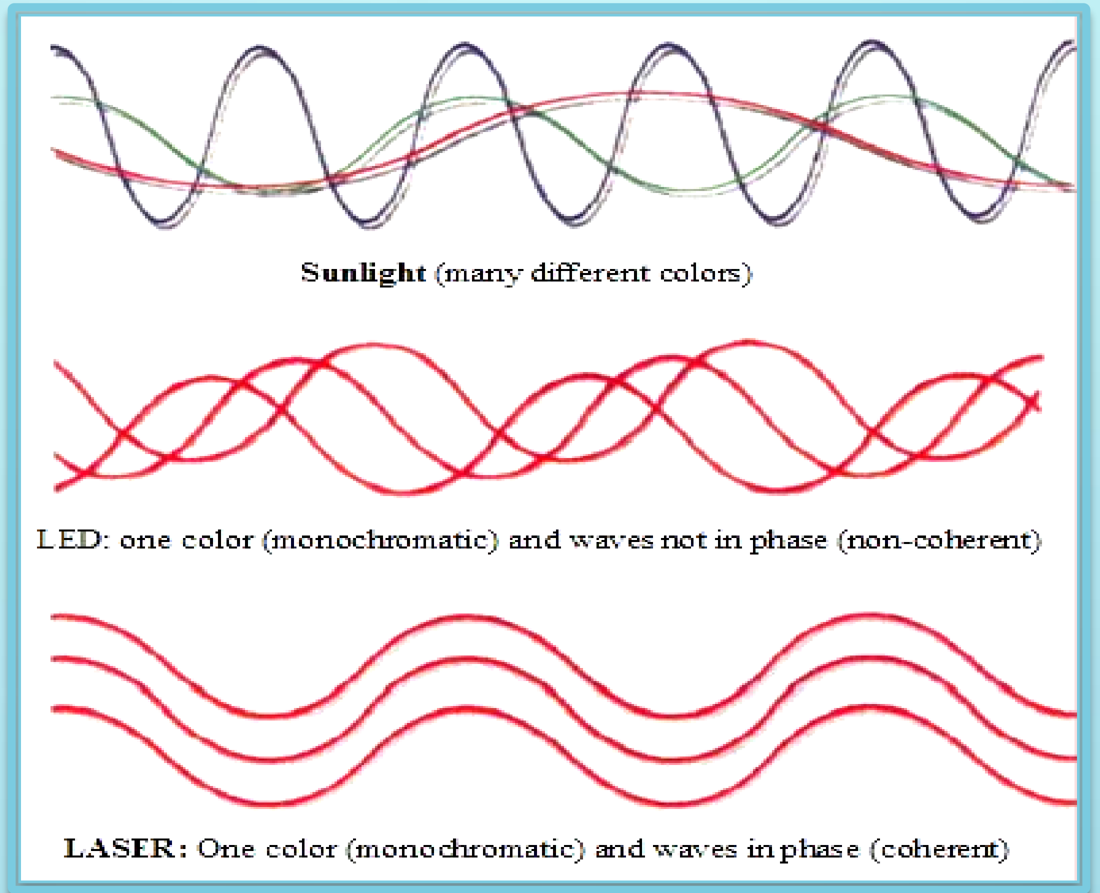
The directionality of a Laser beam is expressed in terms of divergence.

Suppose r_1 and r_2 are the radii of a laser beam at distances D_1 and D_2 from a laser, then the divergence, $\Delta\theta = (r_1 - r_2)/ D_2 - D_1$

The divergence for a laser beam is 0.01 milliradian where as incase of search light it is 0.5 radian.

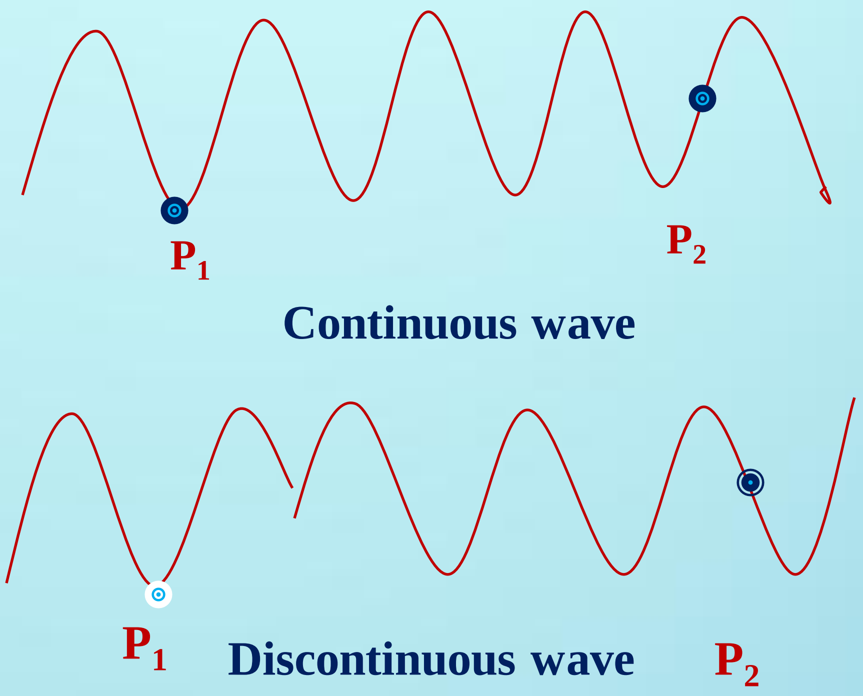
3. Coherence:

- Two sources of light are said to be coherent if they have zero or a constant phase difference between them.
- Laser beam is both Spatially and temporally coherent.



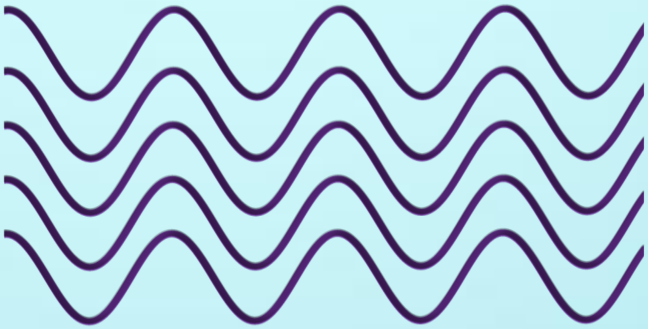
Temporal coherence:

- Temporal coherence refers to the correlation between the light fields at different times at a point on the wave.
- Temporal coherence refers to the fact that the wave is polarized and retains the same frequency and phase over the entire length of the beam. Hence, lasers have a long coherence length
- If there is no change in phase over a time ‘t’ at a point on the wave, then it is said to be temporally coherent during that time.
- since the two points P_1 and P_2 are on the same wave train which is continuous, they have correlation.

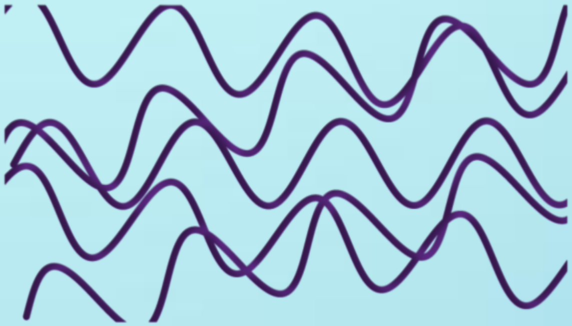


Spatial Coherence:

- If a wave maintains a constant phase difference or is in phase at two different points on the wave over a time ‘t’, then the wave is said to be in spatial coherence.
- Spatial coherence refers to the laser beam output being narrow and resistant to diffraction, essentially retaining its narrow shape.
- This allows lasers to be focused in small spots as well as reach large distances.



Spatially coherent waves



Spatially incoherent waves

4.Brightness:

The Laser beam is highly bright (intense) as compared to the conventional light because more light is concentrated in a small region.

It is observed that the intensity of 1mV laser light is 10,000 times brighter than the light from the sun at the earth's surface.

The number of photons coming out from a laser per second per unit area is about 10^{22} to 10^{34} where as the number of photons coming out per second per unit area of a black body at 1000K having a wavelength of 6000 is 10^{16}

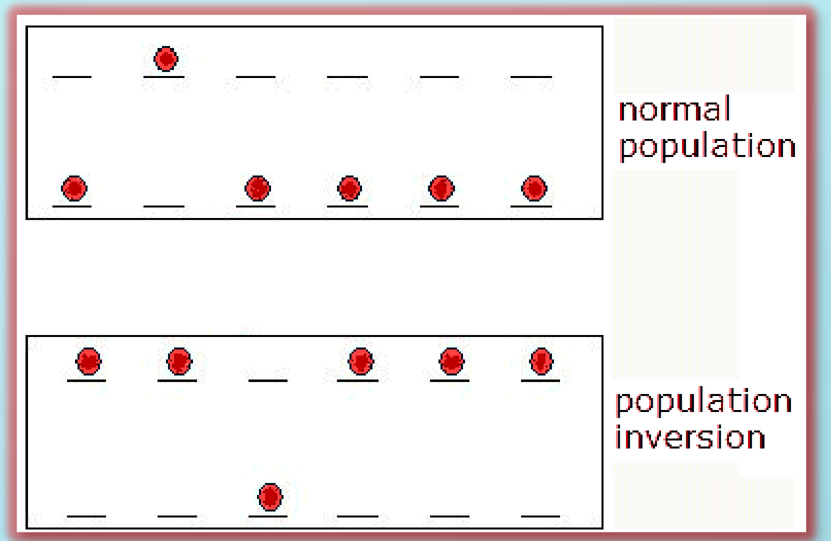
Laser light is coherent and so at a time many photons are in phase and they superimpose to produce a wave of larger amplitude.

The intensity is proportional to the square of the amplitude and hence the intensity of the resultant laser beam is very high.

Population Inversion

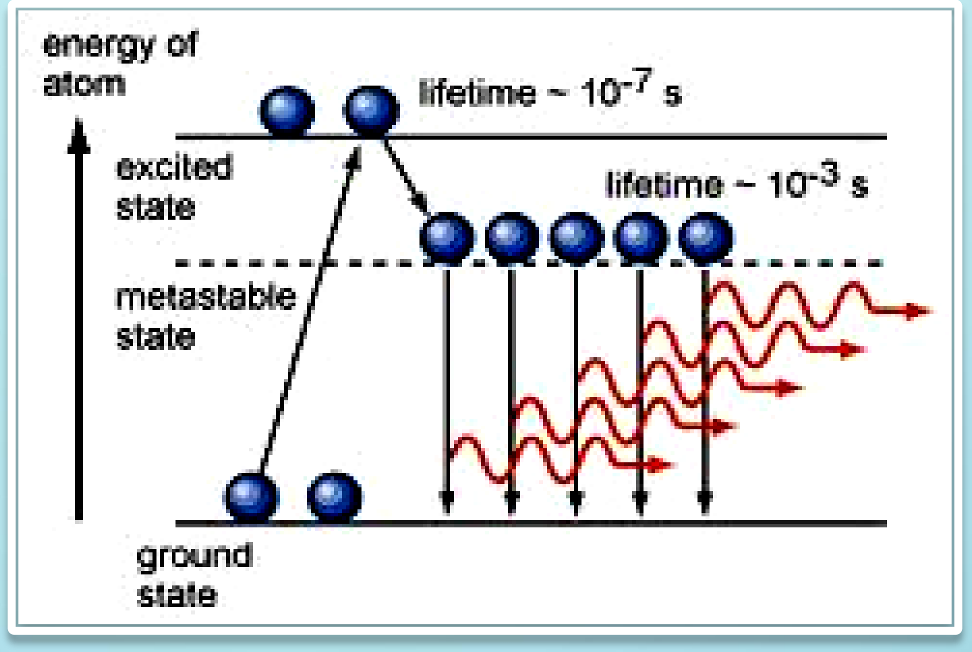
- Usually in a system, the number of atoms (N_1) present in the ground state (E_1) is larger than the number of atoms (N_2) present in the higher energy state. The process of making $N_2 > N_1$ is called population inversion.
- Conditions for population inversion are:
  - The system should posses at least a pair of energy levels ($E_2 > E_1$), separated by an energy equal to the energy of a photon ($h\nu$).
  - There should be a continuous supply of energy to the system such that the atoms must be raised continuously to the excited state.

Population inversion can be achieved by a number of ways. Some of them are,
(i) Optical pumping
(ii) Electrical discharge
(iii) Inelastic collision of atoms
(iv) Chemical reaction and
(v) Direct conversion



Meta Stable state

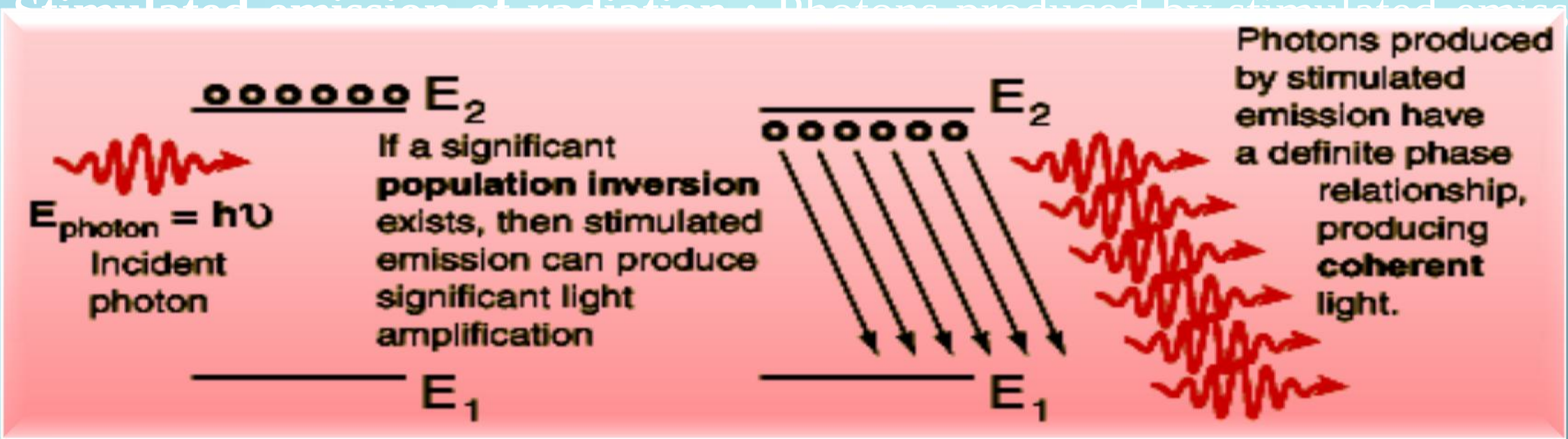
- An excited state with relatively more life time(10^{-3} sec) is called a Meta stable state.
- The necessary condition for population inversion is the presence of a meta stable state.



Lasing Action

The steps involved in Lasing action are,

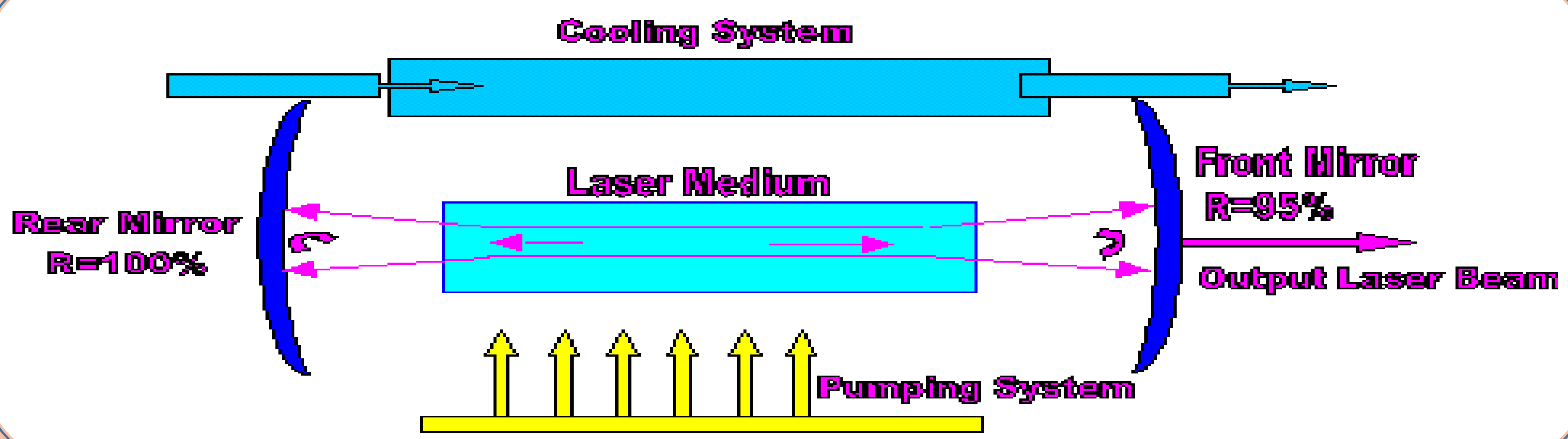
1. **Pumping:** The process of sending atoms from lower energy state to higher energy state is called Pumping. Different pumping mechanisms are adopted depending on the type of the laser. For Ruby laser, Optical pumping is adopted. For He-Ne laser, the pumping mechanism is Electric discharge. In Semi-conductor laser, it is Direct conversion and in the case of CO_2 laser, the mechanism is Chemical reaction.
2. **Population inversion :** Population inversion can be achieved with the presence of a meta stable state.
3. **Stimulated emission of radiation :** Photons produced by stimulated emission



Laser System

A Laser system consists of three basic parts.

1. An **Active medium,** with a suitable set of energy levels to support laser action. For example, in Ruby laser, Cr^{3+} ions are the active laser particles.
2. **Energy source,** (Source of Pumping) in order to establish population inversion.
3. An **Optical Cavity** or Resonator to introduce optical feedback and so maintain the gain of the system overcoming all losses. Depending on the type of the system, optical feedback is provided with the help of dielectric mirrors or polished and coated ends of a crystal rod or cleaved crystal face.



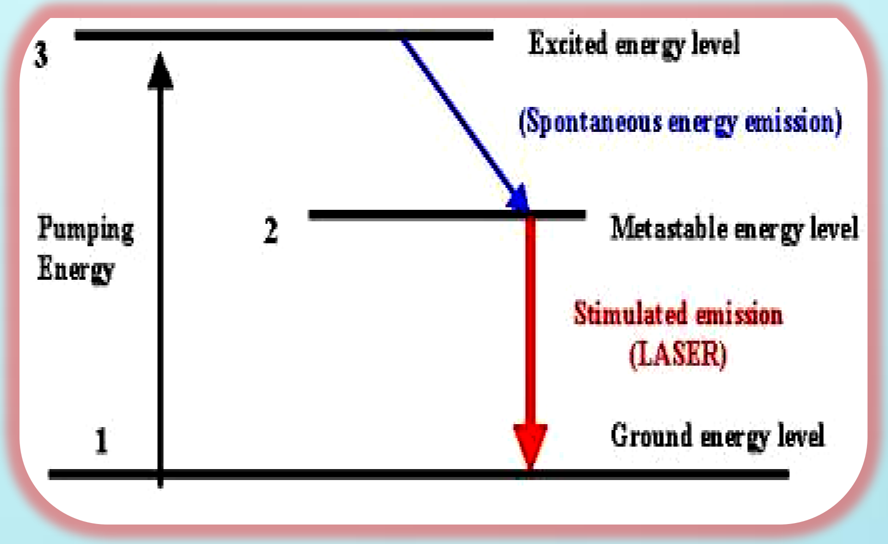
Ruby Laser

- Ruby Laser is the first type of laser, demonstrated in the year 1960 by T.H.Maiman.
- Ruby Laser is a solid state laser.
- It is a pulsed three level pumping scheme.

Active medium: The active medium in Ruby rod ($Al_2O_3+Cr_2O_3$) is Cr^{3+}ions.

- Some of the Aluminum atoms are replaced by 0.05% of Chromium atoms.
- Lasing action takes place in Chromium energy levels.

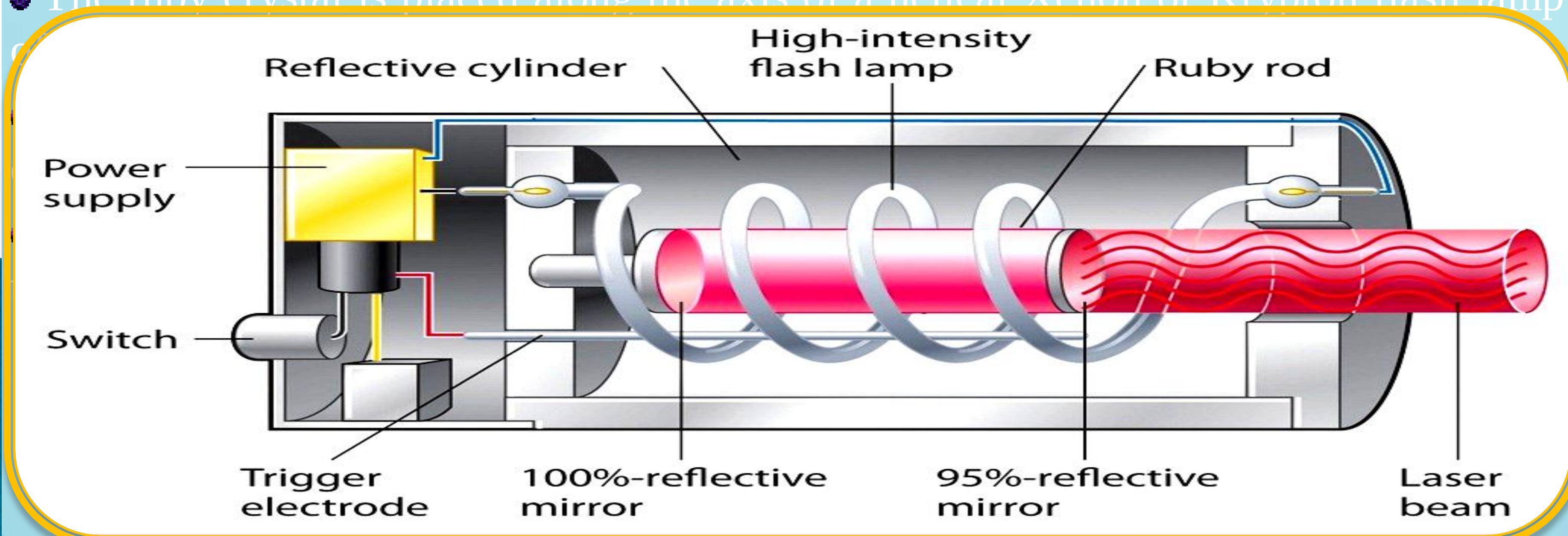
Energy Source: The pumping of ions is through optical pumping, using Xenon flash lamp.



Energy states of a Three level Active medium

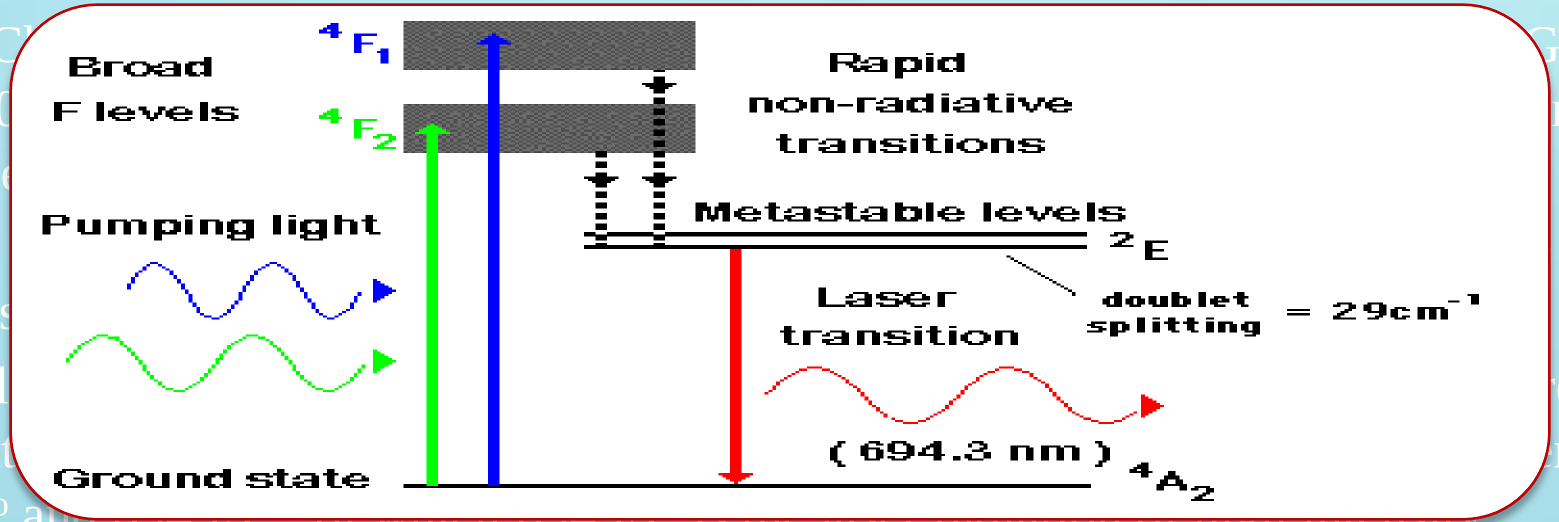
Construction:

- Ruby Laser consists of a cylindrical shaped Ruby crystal rod. One of the end faces is highly silvered and the other face is partially silvered so that it transmits 10-25% of the incident light and reflects the rest.
- The ruby crystal is placed along the axis of a helical Xenon or Krypton flash lamp



Working:

- The Chromium ions are responsible for the stimulated emission of radiation, whereas Aluminum and Oxygen ions are passive, sustaining the lasing action.
- The C… Green) and 400… nergy levels r…
- After … state ^2E, cons…
- Popul… result, stimulat… ngths 6929A° and 6943A°, of which 6943A° is the laser radiation of high intensity.



Applications

Ruby laser is used in Distance measurement using ‘pulse echo’ technique.

Ruby laser is used to create holograms of large objects such as aircraft tires to look for weaknesses in the lining.

Used in atmospheric ranging, scattering studies and LIDAR measurements.

Used for trimming resistors and integrated circuit masks.

Ruby lasers were used mainly in research One of the main industrial uses is drilling holes through diamond.

Used in military as target designators and range finders.

Used in research applications such as Plasma production and fluorescence spectroscopy.

Ruby lasers were used extensively in tattoo and hair removal.

Drawbacks

As Ruby laser is a three level pumping scheme, it generally requires very high pumping power.

Efficiency is very less, as only green and blue components of the incident light are absorbed and the remaining components are left unused.

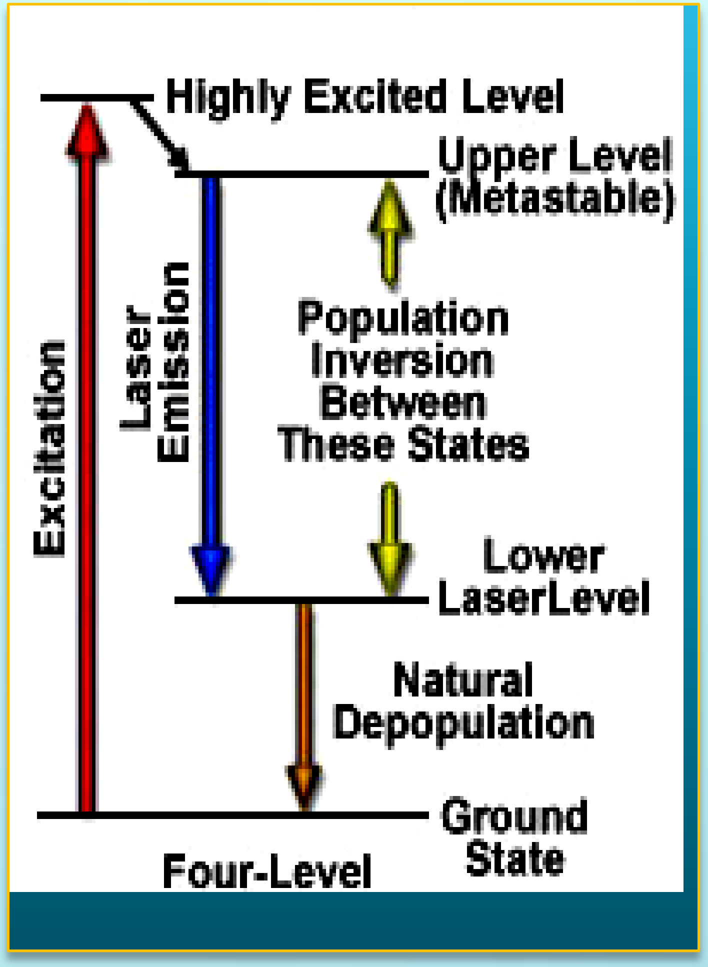
The laser output is not continuous. It is in a pulsed mode.

Helium-Neon(He-ne)laser

- The best-known and most widely used He-Ne laser operates at a wavelength of 632.8 nm in the red part of the visible spectrum.
- It was developed at Bell Telephone Laboratories in 1962.
- Helium-Neon is a gas laser.
- It is a continuous four level laser.

Active medium: Helium and Neon gases in the ratio of 10:1respectively. Ne atoms are responsible for lasing action.

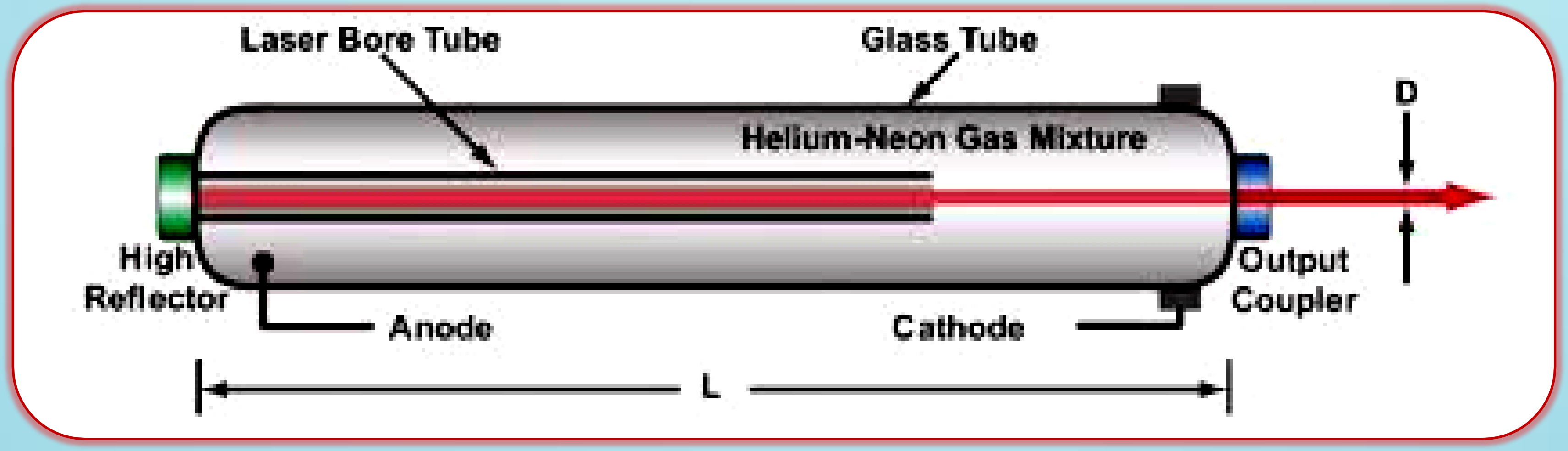
Energy Source: Two electrodes are fixed near the ends of the tube to pass electric discharge through the gas.



Energy states of a Four level Active medium

Construction:

- He-Ne laser consists of a long, narrow cylindrical tube made up of fused quartz, of diameter around 2 to 8 mm and length around 10 to 100 cm.
- The tube is filled with helium and neon gases in the ratio of 10:1. The pressure of the mixture of gases inside the tube is nearly 1 mm of Hg.
- Two electrodes are fixed near the ends of the tube to pass electric discharge through the gas.
- Two optically plane mirrors are fixed at the two ends of the tube.
- One of the mirrors is fully silvered so that nearly 100% reflection takes place and the other is partially silvered, so that 1% of the light incident on it will be transmitted.



Working:

- Lasing action is due to the neon atoms. Helium is used for selective pumping of neon atoms to upper energy levels.

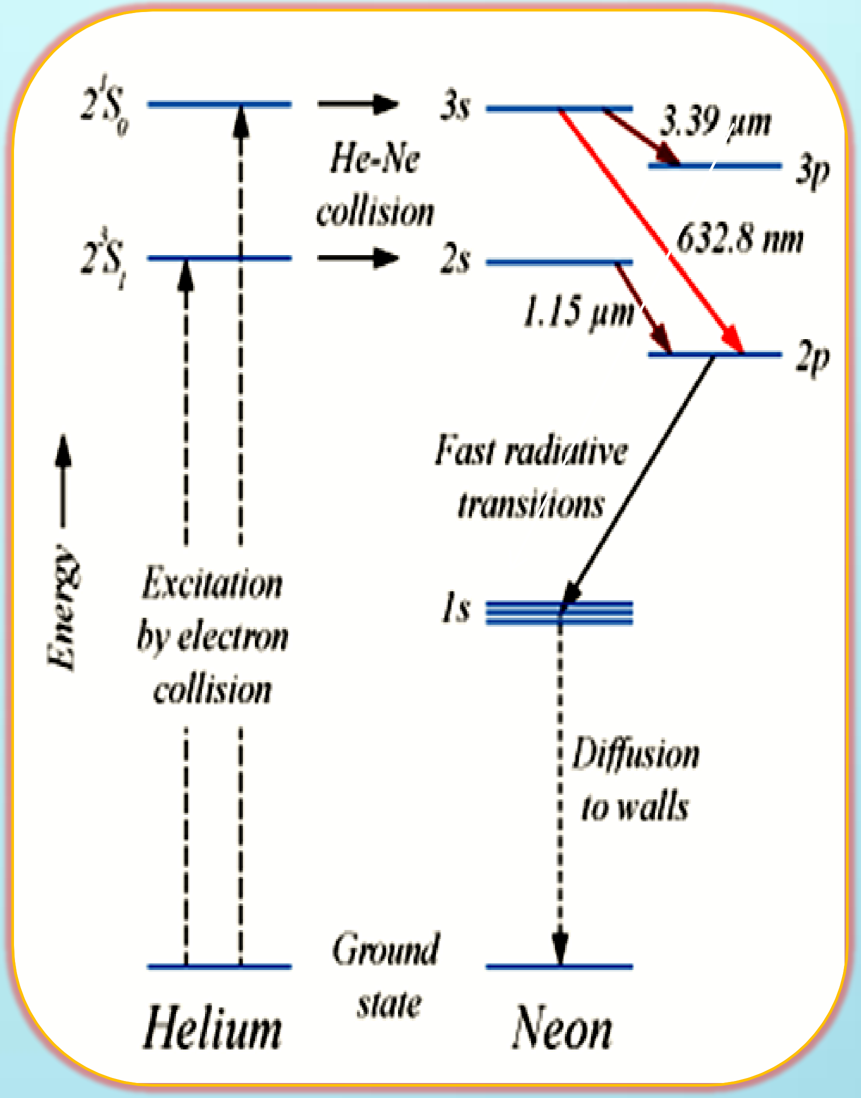
- When a discharge is passed through the gaseous mixture, electrons are accelerated down the tube. These accelerated electrons collide with the ground state helium atoms and excite them to two meta stable states 2^1s and 2^3s.

- The helium atoms in the meta stable state 2^1s collide with the neon atoms in the ground state and excite them to 3s level.

- Similarly, the helium atoms in the meta stable state 2^3s collide with the neon atoms in the ground state and excite them to 2s energy level

- During collisions, the helium atoms transfer their energy to neon atoms and come back to ground state.

- Since 3s and 2s levels of neon atoms are meta stable states, population inversion takes place at these levels. Any of the spontaneously emitted photon will trigger the laser action
- The excited neon atoms transit to ground state in three different ways, leading to three lasers of different wavelengths. They are,
- ✓ Transition from 3s to 3p level, giving rise to a radiation of 3.39μm, which lies in the infrared region.



Energy band diagram of He-Ne laser

- ✓ Transition from 3s to 2p level, giving rise to visible radiation of wavelength 6328A^o, that lies in red region.

- ✓ Transition from 2s to 2p level giving rise to a wavelength of 1.15μm, which lies in the infrared region.

- The atoms in the 3p and 2p levels undergo spontaneous emission to 1s level by fast decay, giving rise to photons by spontaneous emission.

- The atoms in the 1s level return back to the ground state, by non-radiative diffusion and collisions with the walls of the discharge tube.

- After arriving to ground state, the neon atoms raise back to 3s and 2s levels by excited helium atoms, for getting a continuous output.

Applications

He-Ne laser is widely used in laboratories for all interferometric experiments.

He-Ne lasers are used in super market checkout counters to read bar codes.

He-Ne laser scanners are used for optical character recognition.

The He-Ne lasers are used by newspapers for reproducing transmitted photographs.

He-Ne laser is widely used in metrology in surveying and as an alignment tool.

It is used in Guns for targeting.

They are used in 3D recording of objects called holography.

Disadvantages

It is a relatively low power device which means that its output power is low.

He-Ne laser is a low gain system or device.

To obtain single wavelength laser light, the other two wavelengths of laser need suppression, which is done by many techniques and devices. So it requires extra technical skill and cost.

High voltage requirement can be considered its disadvantage

Escaping of gas from laser plasma tube is also its disadvantage

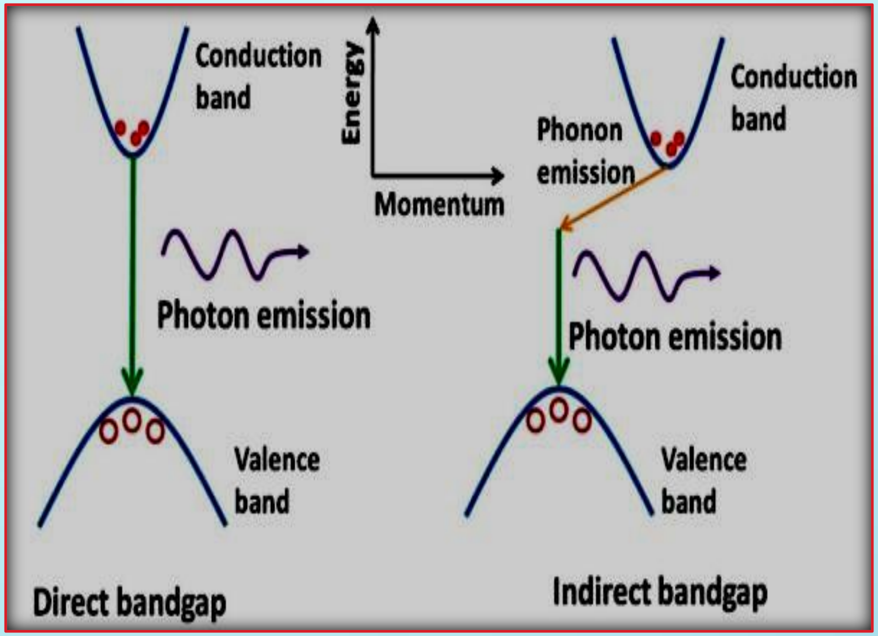
Semi-Conductor Laser

Semiconductor laser is of two types:

- **Homo junction Laser:** A p-n junction formed by a single crystalline material such that the basic material is same on both the sides.
- **Hetero junction Laser:** The material on one side of the junction differs from that on the other side.

Principle:

- Among the Direct band gap and the Indirect band gap semiconductor, a Direct band gap semiconductor is used to make light emitting diodes and lasers.
- In Direct band gap semiconductor, there is a large possibility for the direct recombination of electron and hole, and the electron emitting a photon.



Direct and Indirect band gap Semiconductors

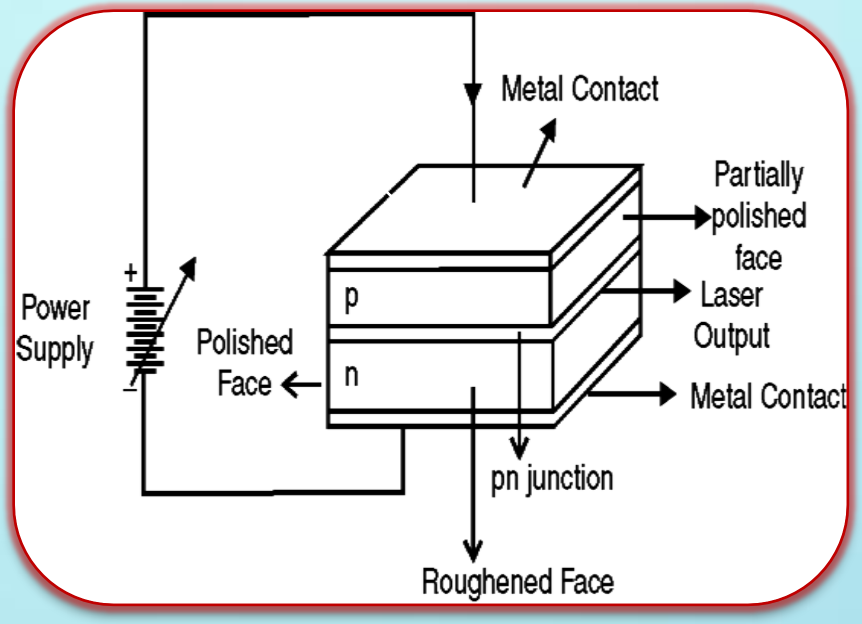
Construction:

Active medium:

- A p-n junction diode made from crystalline Gallium Arsenide is the active medium.
- The p-region and n-region in the diode are obtained by heavily doping Germanium and Tellurium respectively in GaAs.
- At the junction, the sides through which emitted light is coming out, are well polished and are parallel to each other.

Energy Source:

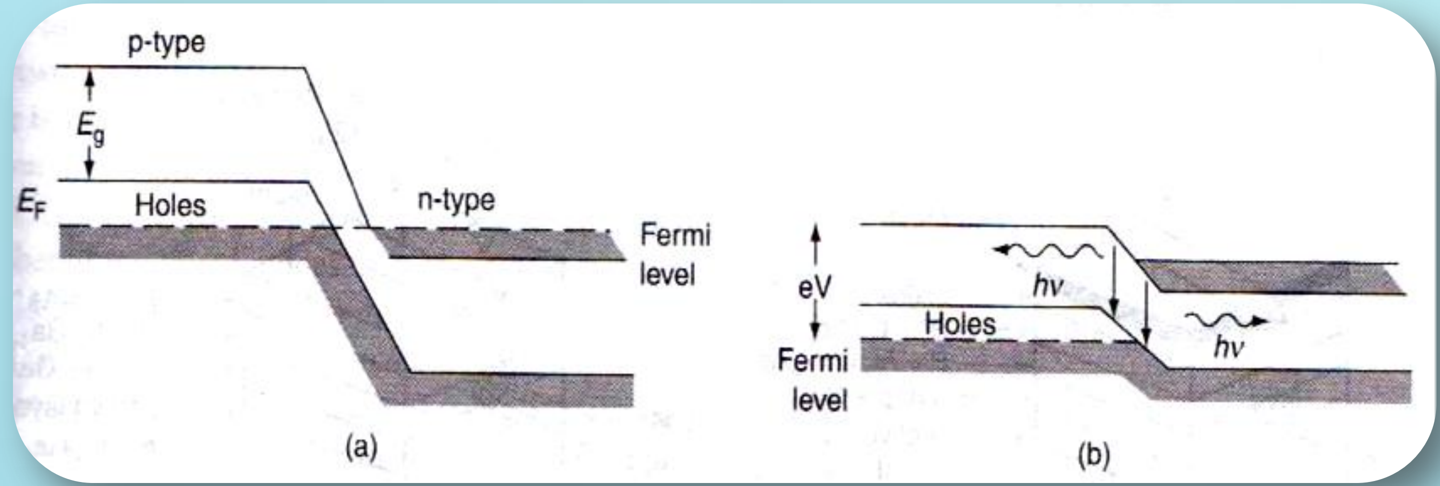
Electric current which is applied to the crystal platelet through a strip electrode fixed to its upper surface, is the energy source.



Ga As diode laser

Working:

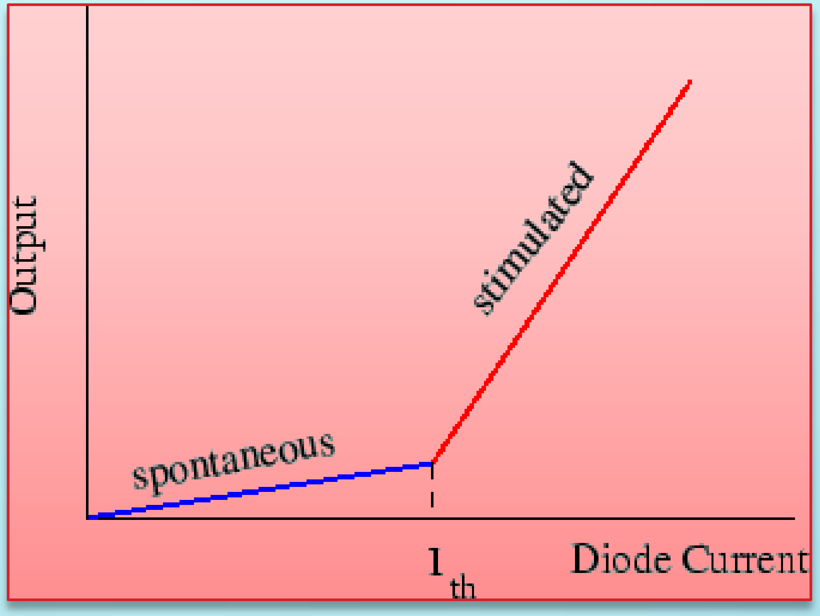
- Population inversion is achieved by injecting electrons across the junction from the n-region to the p-region by means of a forward bias voltage.
- When a large amount of current of the order 10^4 amp/cm^2 is passed through the junction to provide excitation, the direct recombination of electrons and holes take place resulting in the emission of photons. These photons further increase the rate of recombination .Thus, more number of photons are emitted.
- The wavelength of the emitted radiation depends upon the concentration of the donor and acceptor atoms in Ga As.
- In reverse bias, no carrier injection takes place and consequently no light is emitted.



Energy band diagram of heavily doped p-n junction (a) in equilibrium (b) Forward bias

Explanation:

- At thermal equilibrium, the Fermi level should be uniform throughout the junction. So the Fermi level in the n-side lies within the conduction band and in the p-side, it lies within the valence band.
- When the junction is forward biased, the energy levels shift and the electrons and holes are injected across the depletion layer, existing at the junction.
- At low threshold current, recombination of electrons and holes give spontaneous emission.
- Initially the spontaneously emitted photon starts the stimulated emission, at a current beyond the threshold value, and thus the number of photons increases with time.



Calculation of wavelength of the emitted radiation:

- Suppose the band gap of Ga As is 1.44eV

Therefore, $E_g = h\nu = hC/\lambda$

(or) $\lambda = hC/E_g = \frac{6.626\times10^{-34}\times3\times10^{8}}{1.44\times1.6\times10^{-19}}$

$= 8623\times10^{-10}$ m

$= 8628$ A°

- This wavelength corresponds to the near infrared region.
- Taking the wavelength in µm and E_g in eV … relati… to … V)

Drawbacks of homo-junction lasers:

- The threshold current density is very large (400 A/ mm^2)
- Only pulsed mode output is obtained.
- Laser output has large beam divergence.
- Laser output has poor coherence and poor stability.
- Electromagnetic field confinement is poor.

Advantages of hetero-junction lasers over Homo-junction lasers:

- The threshold current density is very low, (10 A/ mm^2) at room temperature.
- The laser output is continuous.
- High output power (10 mW) can be achieved even with low operating current (< 500 mA)
- Very narrow beam with high coherence and monochromaticity is achieved.
- The laser output is highly stable with longer life.

Hence hetero-junction laser diodes are used as optical sources in optical fibre communication.

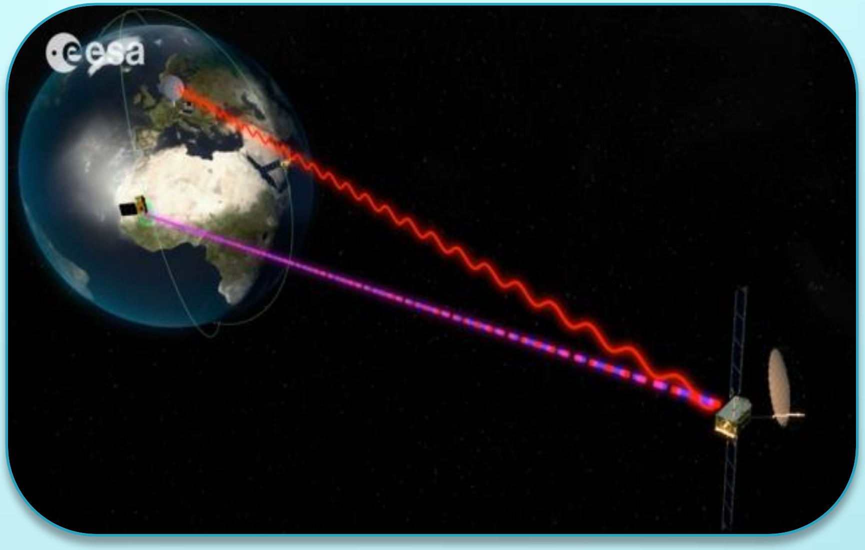
Applications of Lasers

Lasers in Communication:

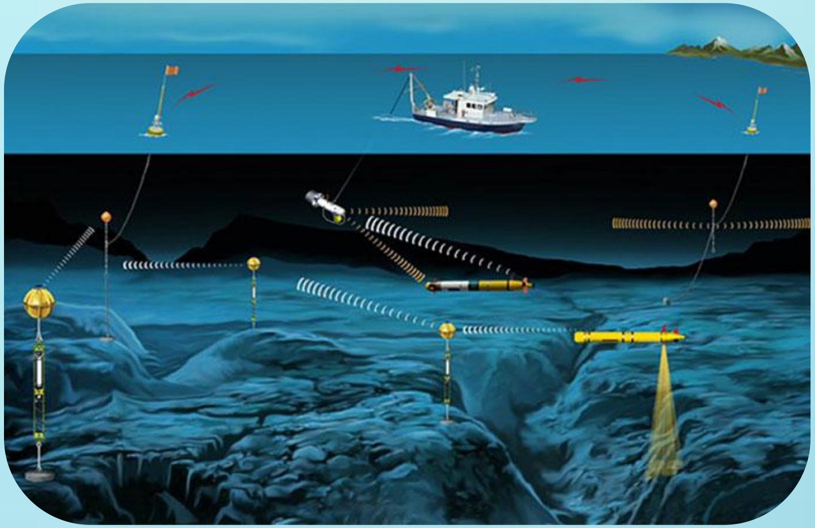
- Lasers are used in Optical fibre communication as light source to transmit audio, video signals and data to long distances without attenuation and distortion.

- Laser beam can be used for the communication between the earth and the moon or to other satellites.

- Laser beam can be used for under water communication, as laser radiation is not absorbed by water.



Lasers in Satellite communication



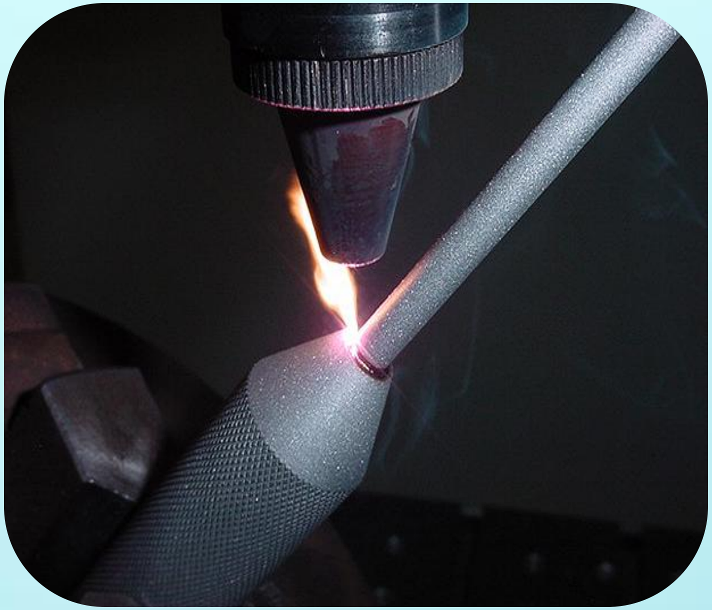
Lasers in under water communication

Lasers in Industry:

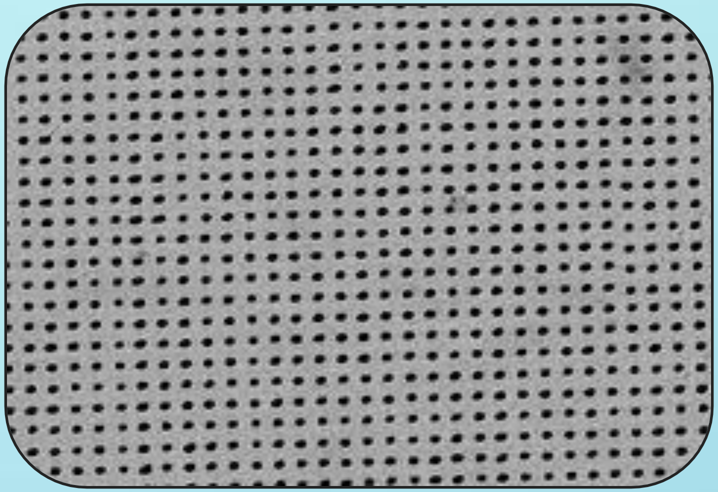
- Lasers are used for welding. Dissimilar metals can be welded using lasers.

- Holes with controlled precision can be drilled in steel, ceramics, diamond and alloys, using lasers.

- Lasers are widely used in electronic industry in trimming the components of ICs.



Lasers used in welding



Drilling Steel foil for high density filters

- Lasers are used in cutting metal sheets, diamond and cloths. In the mass production of stitched clothes, lasers are used to cut the cloth in a desired dimension, all at once.
- Lasers are used for surface treatment. Laser beam is used in selective heat treatment for tempering the desired parts in automobile industry.

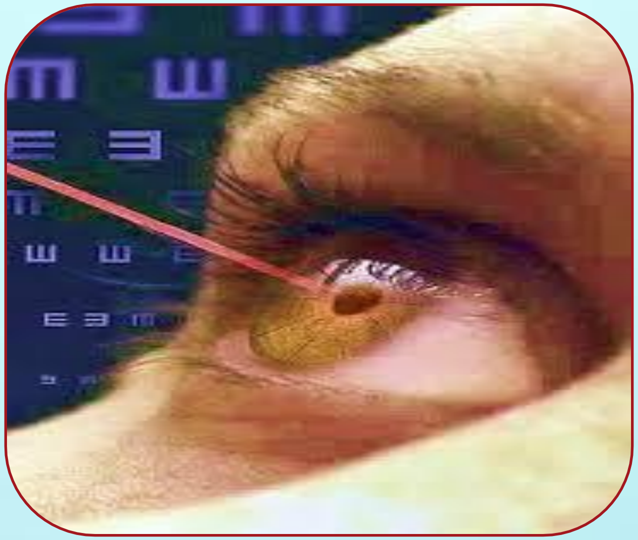
Cutting wood using laser

Laser surface treatment to change the micro structure of metals through controlled heating and cooling.

The world's first all-diamond ring, cut with Laser

Lasers in medicine:

- Lasers are used in eye surgery, especially to attach the detached retina.
- Lasers are used for treatments such as plastic surgery, skin injuries and to remove moles, tattoos and tumours developed in skin tissue.
- Lasers are used in stomatology-the study of mouth and its disease.



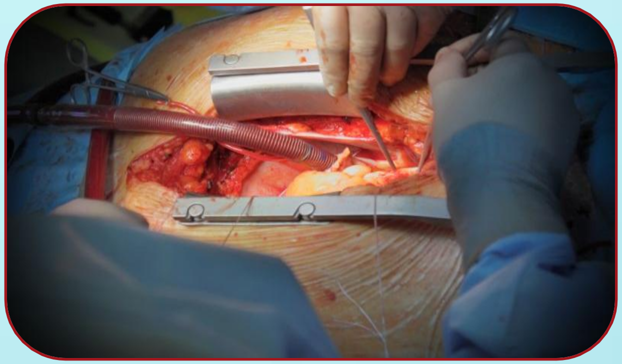
Lasers in Eye surgery

Lasers used in stomatology

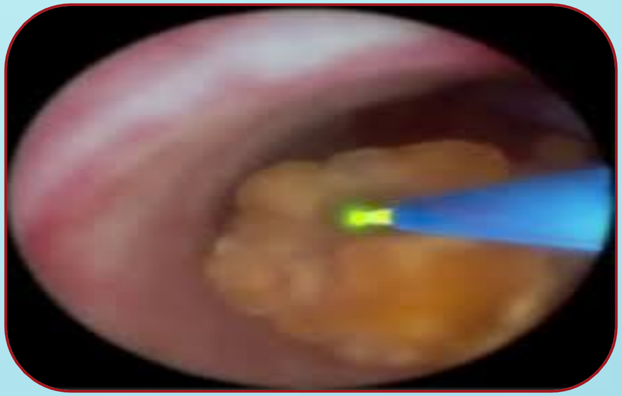
Lasers in tattoo removal

- Laser radiation is sent through optical fibre to open the blocked artery region.
- Lasers are used to destroy kidney stones and gall stones.
- Lasers are used in cancer diagnosis and therapy.
- Lasers are used in blood loss less surgery.
- Lasers are used to control hemorrhage.
- Using CO_2 laser, liver and lung treatment can be carried out.
- Lasers are used in endoscopes, to detect hidden parts.
- Laser Doppler velocimetry is used to measure the velocity of blood in blood vessels.

Red Argon laser used in throat cancer treatment



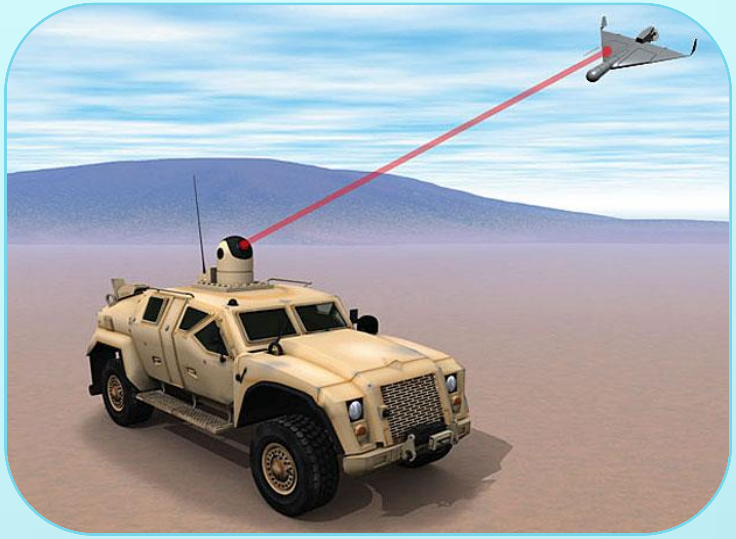
Lasers used to open artery block



Lasers used to destroy kidney stones

Lasers in Military:

- Focusing of high energetic laser beam for few seconds, destroys aircrafts, missiles, etc. These rays are called death rays.
- The vital part of the enemy’s body can be evaporated by focusing a highly convergent laser beam from a laser gun.
- LIDAR (Light Detecting And Ranging) is used to estimate the size and shape of distant objects or war weapons.



Laser armed Humvees shooting a Drone (flying Robot)

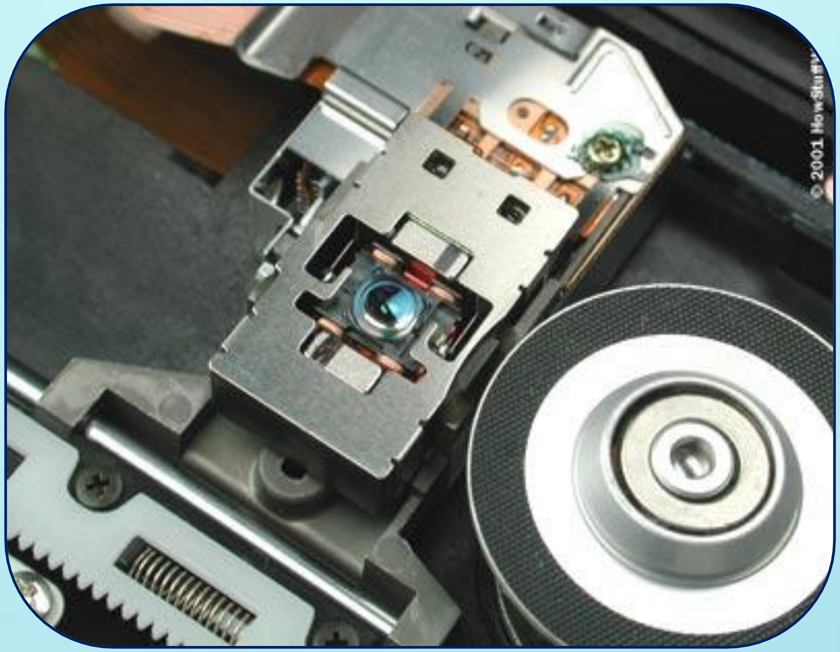
Lasers beams of RMR LIDAR at ALOMAR Observatory

Soldiers using laser gun

Lasers in Computers:

- By using Lasers, a large amount of information or data can be stored in CD-ROM or their storage capacity can be increased.
- Lasers are used in computer printers.

Laser Beam Printer (LBP) by Epson

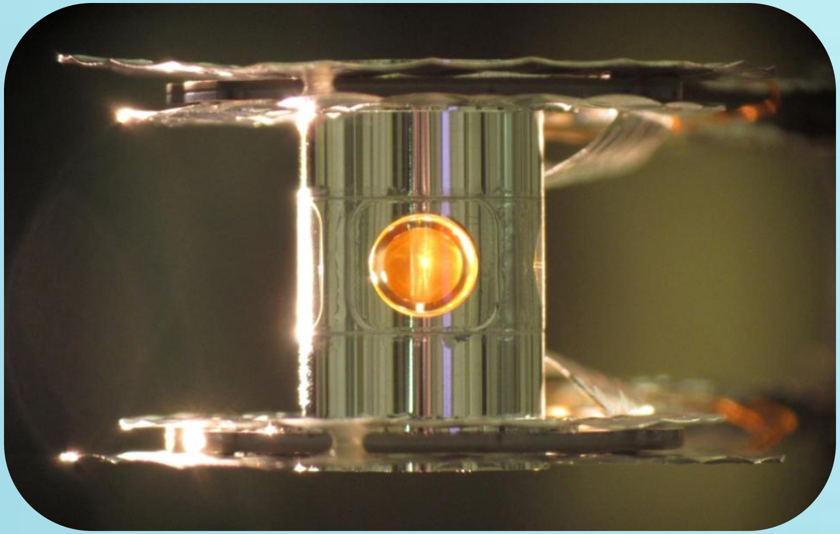


Laser assembly inside a CD burner

Lasers in thermo nuclear fusion:

- A nuclear fusion reaction can be initiated by concentrating a large amount of laser energy in a small volume.
- For example, in the fusion of deuterium and tritium, irradiation with a high energy laser beam, develops a temperature of 10^{17} ^oC , which is sufficient to initiate nuclear fusion reaction.

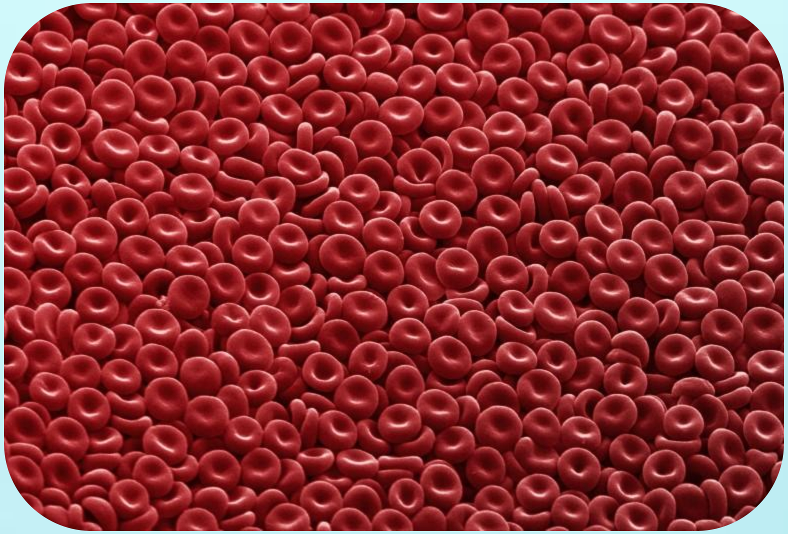
Lasers used in nuclear fusion reactors



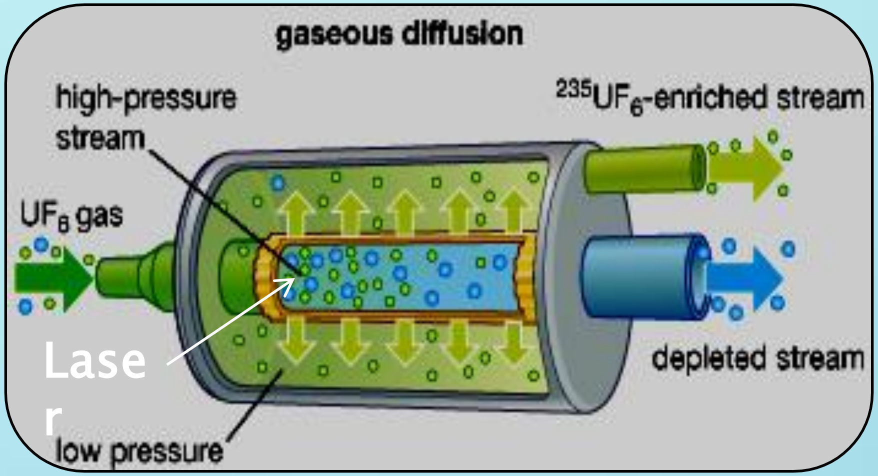
Fusion of deuterium and tritium using 192 lasers

Lasers in Scientific research:

- Laser beam can initiate chemical reactions, study the nature of chemical bonds and also can break molecules.
- Lasers are used to estimate the size and shape of biological cells such as erythrocytes.
- Lasers are used to find the size of dust particles.
- Lasers are used in counting the atoms in isotope separation.

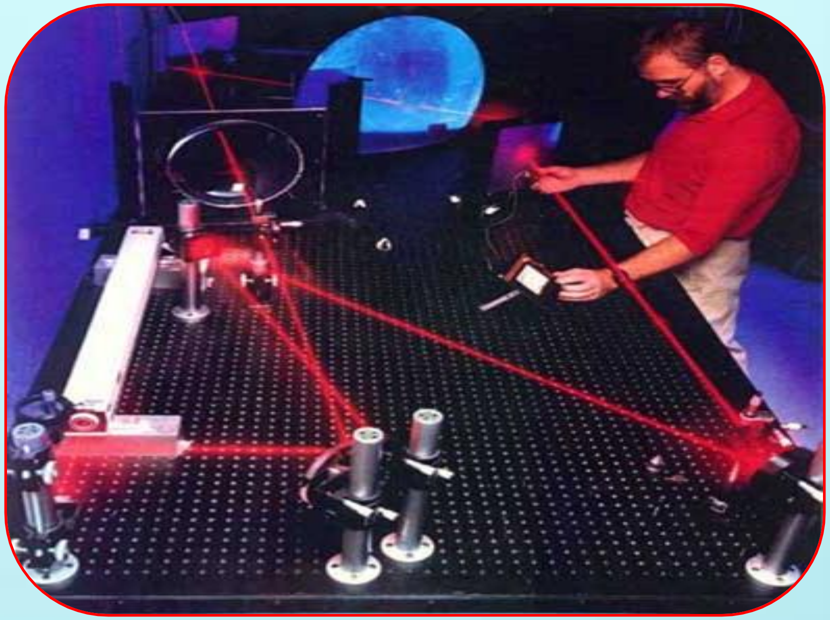


Laser Scanning Microscope micrograph of human RBCs



Laser used in isotope separation

- Lasers are used in holography, for recording and reconstructing of a hologram.
- Lasers are used to measure the constantly changing distance between the moon and the earth, by astronomers.
- Lasers are used in plastic industries to unite monomers to form polymers.
- Lasers are used to develop hidden finger prints and to clean delicate pieces of art.



Lasers used in Holography

Finger print scanning using Laser

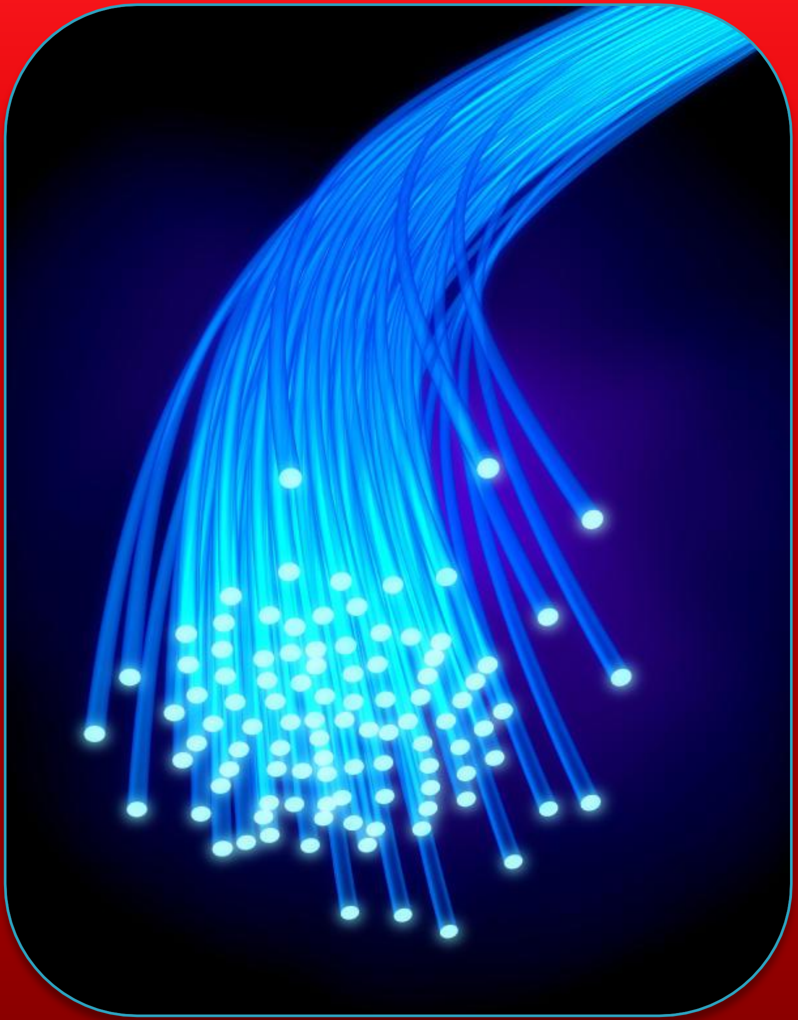
FIBRE OPTICS

Introduction to Fibre Optics

- Optical Fibre is a flexible, transparent fiber made of extruded glass (silica) or plastic, slightly thicker than a human hair.

- It can function as a waveguide, or "light pipe", to transmit light between the two ends of the fiber.

- Power over Fiber (POF) optic cables can also work to deliver an electric current for low-power electric devices.



Fiber optic bundle

- Optical fibers are widely used in fiber-optic communications, where they permit transmission over longer distances and at higher bandwidths(data rates) than wire cables.

- Fibers are used instead of metal wires because signals travel along them with less loss and are also immune to electromagnetic interference.

- Fibers are also used for illumination, and are wrapped in bundles so that they may be used to carry images.

Fibre Optic table lamp

Structure of an Optical Fibre

Structure of an optical fiber consists of three parts.

The core, the cladding and the coating (or buffer or outer jacket).

The core:

- The core is a cylindrical rod of dielectric material.
- Light propagates mainly along the core of the fiber.
- The core is generally made of glass.
- The core is described as having an index of refraction n_1.

The Cladding:

- The core is surrounded by a layer of material called the cladding, which is generally made of glass or plastic.
- The cladding layer is made of a dielectric material with an index of refraction n_2.
- The index of refraction of the cladding material is less than that of the core material.

- The cladding performs the following functions:

1. Reduces loss of light from the core into the surrounding air.
2. Reduces scattering loss at the surface of the core.
3. Protects the fiber from absorbing surface contaminants.
4. Adds mechanical strength.

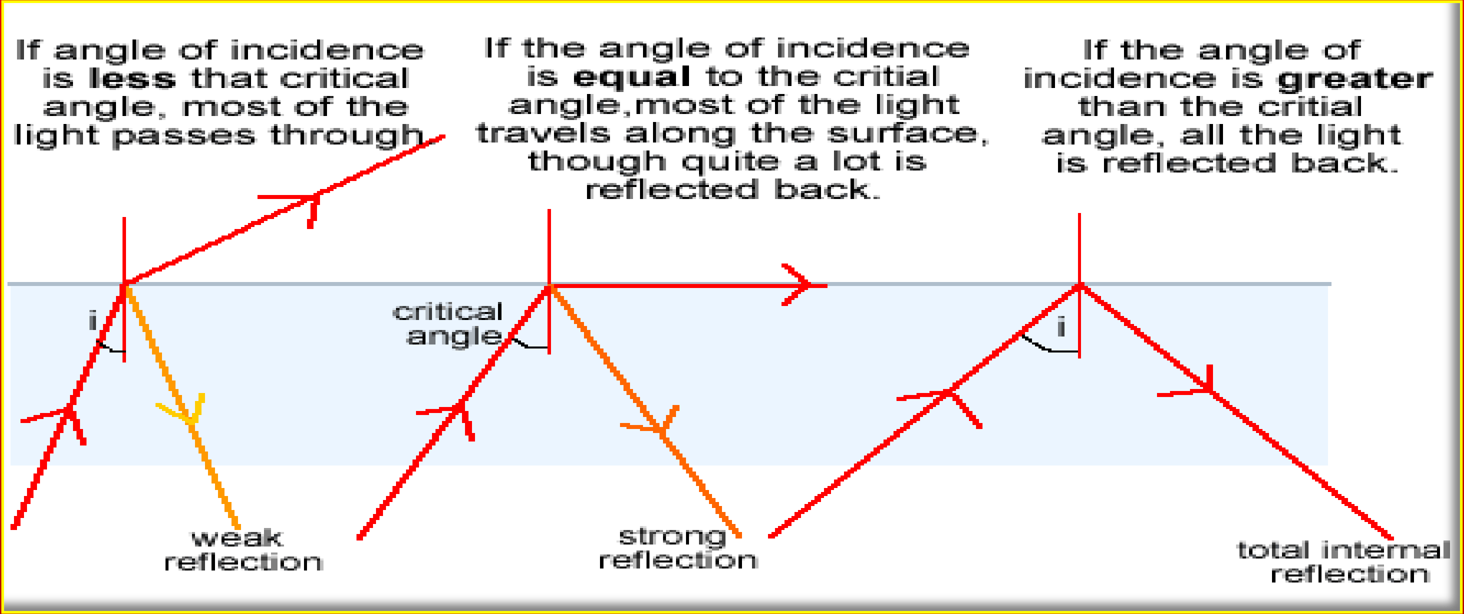
Buffer:

- The coating or buffer is a layer of material used to protect an optical fiber from physical damage.
- The material used for a buffer is a type of plastic.
- The buffer is elastic in nature and prevents abrasions.

Optical Fibre Structure

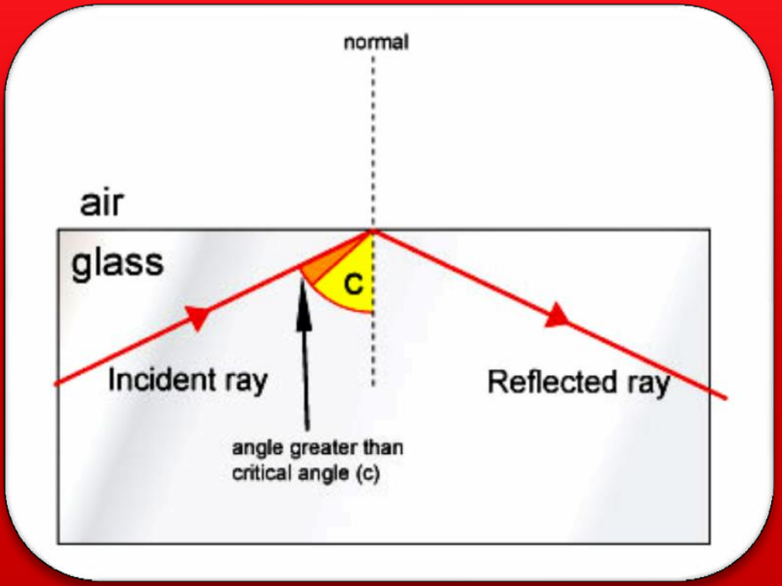
Principle of Optical Fibre

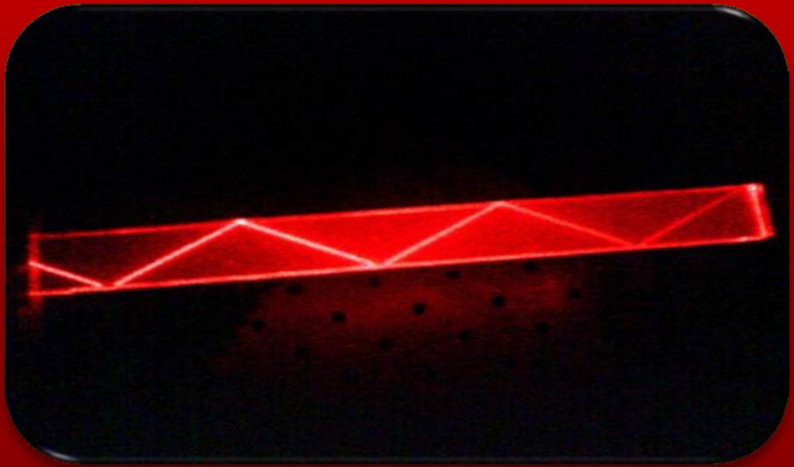
- Optical fibre carries light from one end of the fibre to the other by **total internal reflection.**
- When a ray of light passes from an optically denser medium into an optically rarer medium, the refracted ray bends away from the normal.
- **critical angle (θ_c):** When the angle of incidence is increased angle of refraction also increases and a stage is reached when the refracted ray just grazes the surface of separation of core and cladding. At this position the angle of refraction is 90 degrees. This angle of incidence is called the critical angle (θ_c) of the denser medium with respect to the rarer medium.



- If the angle of incidence is further increased, then the ray is totally reflected. This is called total internal reflection.

Total internal reflection: When a light ray, travelling from an optically denser medium into an optically rarer medium, is incident at an angle greater than the critical angle, then the ray is totally reflected back into the same medium by obeying the laws of reflection. This phenomenon is known as totally internal reflection.





Internally reflected light ray

Condition for Total Internal Reflection

Let the reflective indices of core and cladding materials be n_1 and n_2 respectively.

According to the law of refraction,

$n_1 \sin\theta_1 = n_2 \sin\theta_2$

Here, θ_1=, θ_c and θ_2= 90

$n_1 \sin\theta_c = n_2 \sin 90$

$\sin\theta_c = {}^{n}{}_{2}/n_1$

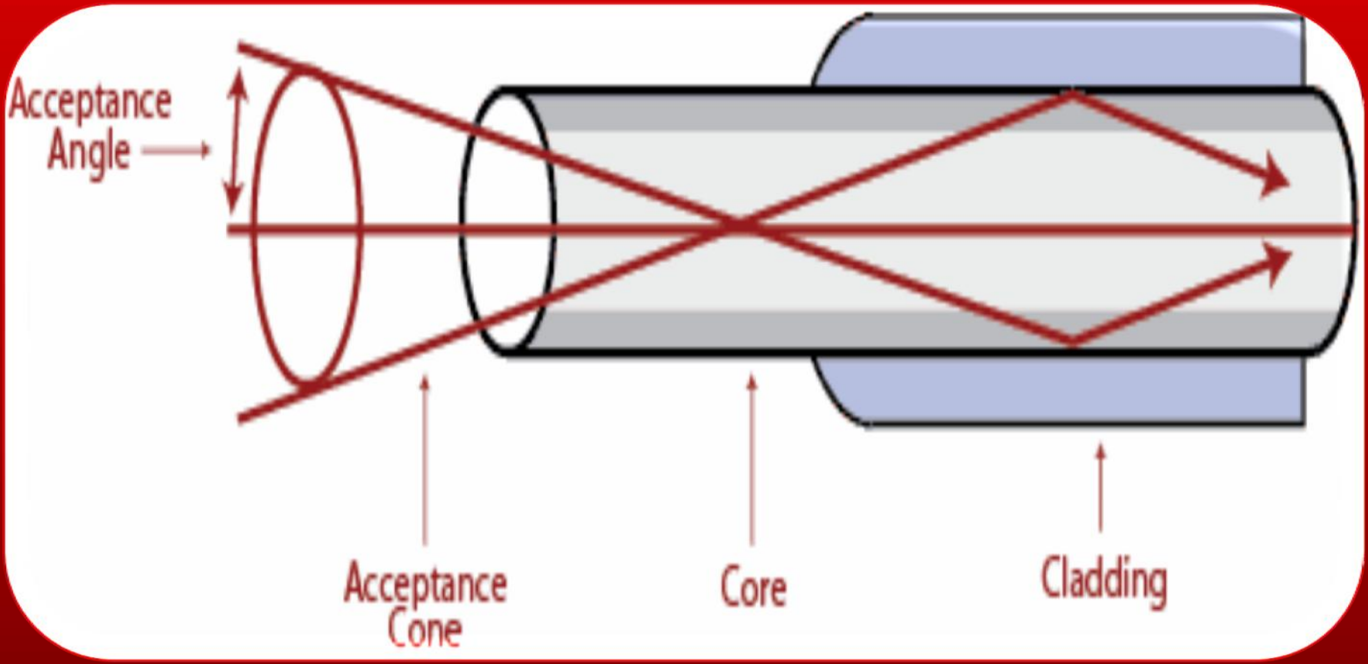
$\theta c = \sin^{-1}({}^{n}{}_{2}/n_1)$ $\rightarrow (1)$

Equation (1) is the expression for condition for total internal reflection.

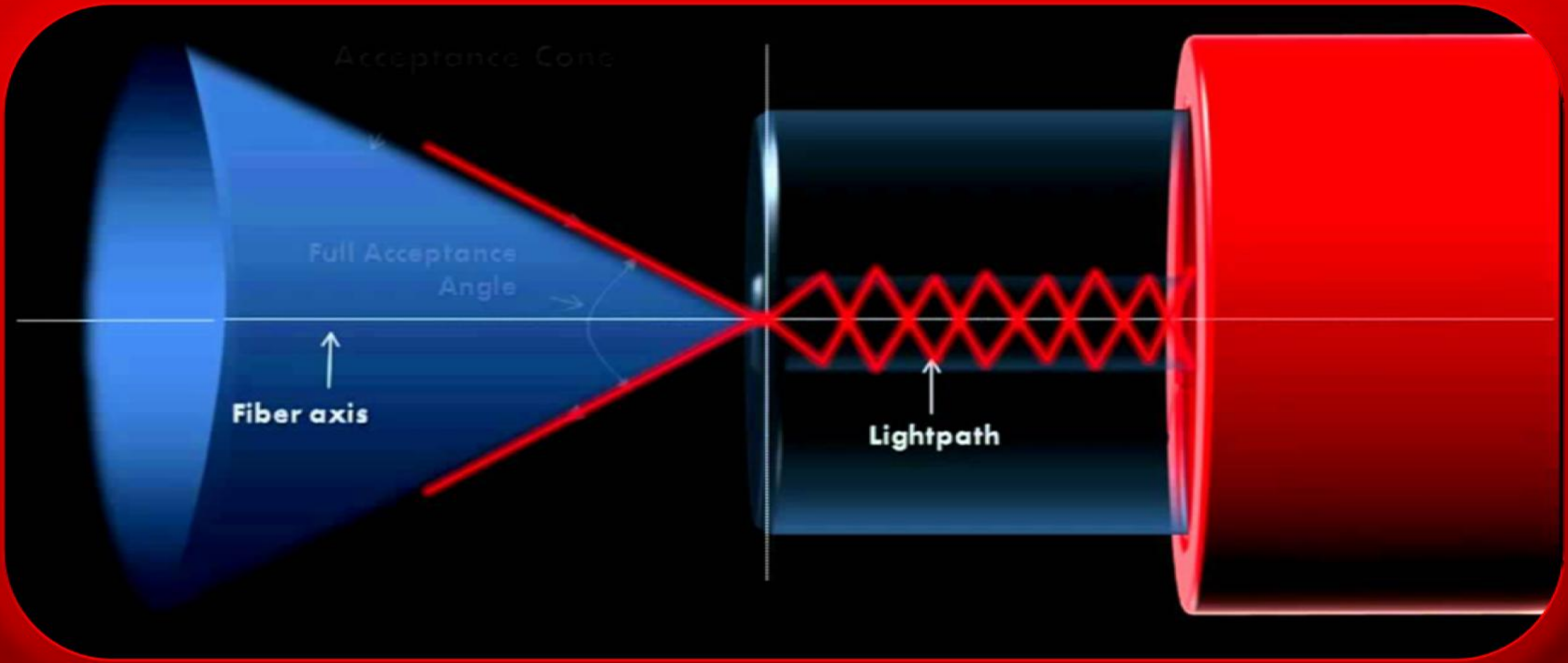
In case of total internal reflection, there is absolutely no absorption of light energy at the reflecting surface.

Acceptance angle and Acceptance cone

- **Acceptance angle** is the angle at which the beam has to be launched at one of its ends, in order to enable the entire light to propagate through the core.
- The **acceptance angle** is the maximum angle that a light ray can have with the axis of the fiber to propagate through the fiber.
- **Acceptance angle:** It is defined as the maximum angle of incidence at the end face of the optical fibre, for which the ray can be propagated through the core material. It is also called as **Acceptance cone half angle.**



- **Acceptance cone:** The cone obtained by rotating a ray at the end face of an optical fibre, around the fibre axis with the acceptance angle, is known as acceptance cone.
- Light launched at the fiber end within this acceptance cone alone will be accepted and propagated to the other end of the fiber by total internal reflection.
- Larger acceptance angles make launching easier.



Acceptance cone

Equation for Acceptance angle

- For light rays to propagate through the optical fibre, by total internal reflection, they must be incident on the fibre core within the angle θ_o, called the acceptance angle.
- Applying Snell's law at B,

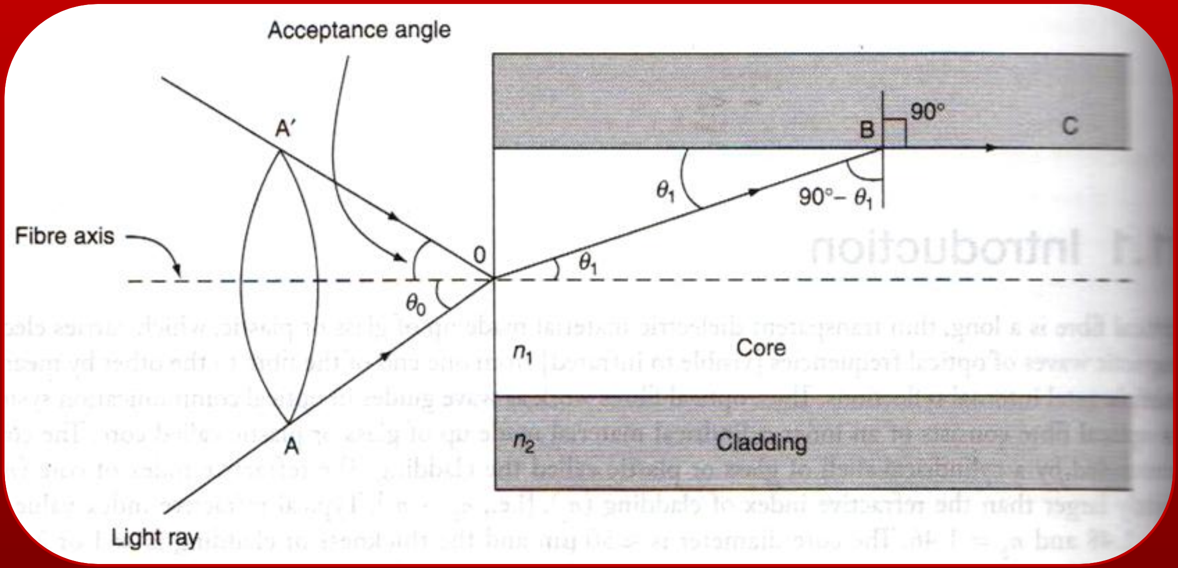
$$n_1 \sin(90^o - \theta_1) = n_2 \sin 90^o$$

$$n_1 \cos \theta_1 = n_2$$

$$\cos \theta_1 = n_2/n_1$$

$$\text{or } \sin\theta_1 = (1-\cos^2\theta_1)^{1/2}$$

$$= \{1-(n_2^2/n_1^2)\}^{1/2} \ldots\ldots\ldots (1)$$



- Applying Snell's law at O,

$$n_o \sin\theta_0 = n_1 \sin\theta_1$$

$$\text{or } \sin\theta_0 = (n_1/n_0) \sin\theta_1 \ \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Substituting eq. (1) in eq. (2),

$$\text{Sin } \theta_0 = (n_1/n_0)\,(1 - n_2^2/n_1^2)^{1/2}$$

$$= \frac{(n_1^2 - n_2^2)^{1/2}}{n_0} \ \ldots\ldots\ldots\ldots\ldots\ldots\ (3)$$

- As the fibre is in air, $n_0 = 1$

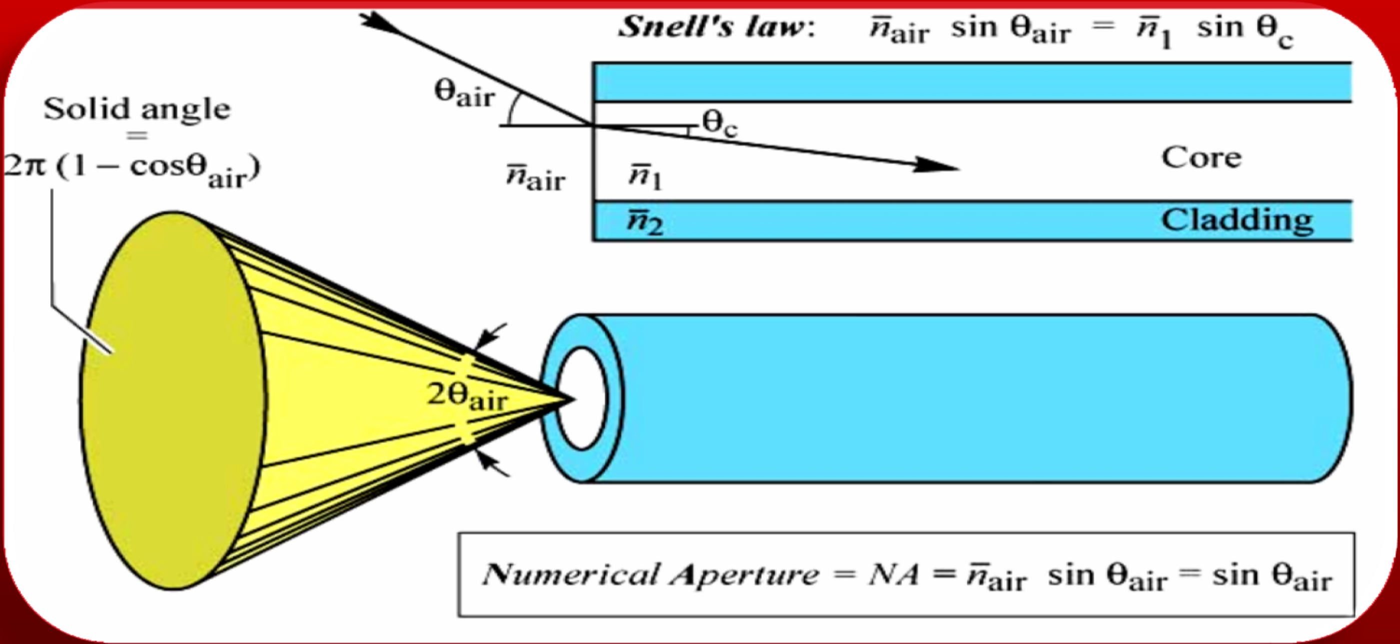
  Therefore, eq. (3) becomes

$$\text{Sin } \theta_0 = (n_1^2/n_2^2)^{1/2} \ \ldots\ldots\ldots\ldots\ldots\ldots(4)$$

Eq. (4) is the equation for Acceptance angle.

Numerical Aperture (NA)

- Light gathering capacity of the fiber is expressed in terms of maximum acceptance angle and is termed as "**Numerical Aperture**".
- Light gathering capacity is proportional to the acceptance angle θ_o.
- So, numerical aperture can be represented by the sine of the acceptance angle of the fibre i.e., sin θ_o.
- For example, the light acceptance angle in air is $\theta_{air} = 11.5^o$ for a numerical aperture of NA=0.2.



Expression for Numerical aperture:

- According to the definition of Numerical aperture (NA),

$NA = \sin\theta_0 = (n_1^2 - n_2^2)^{1/2}$ → (1)

- Let 'Δ,' the fractional change in the refractive index, be the ratio between the difference in the refractive indices of core and cladding material respectively.

i.e., $\Delta = \frac{n_1 - n_2}{n_1}$ → (2)

or $\Delta n_1 = n_1 - n_2$ → (3)

Eq. (1) can be written as,

$NA = (n_1^2 - n_2^2)^{1/2}$

$= \{(n_1 - n_2)(n_1 + n_2)\}^{1/2}$ → (4)

- Substituting eq. (3) in eq. (4),

$NA = \{(\Delta n_1)(n_1 + n_2)\}^{1/2}$

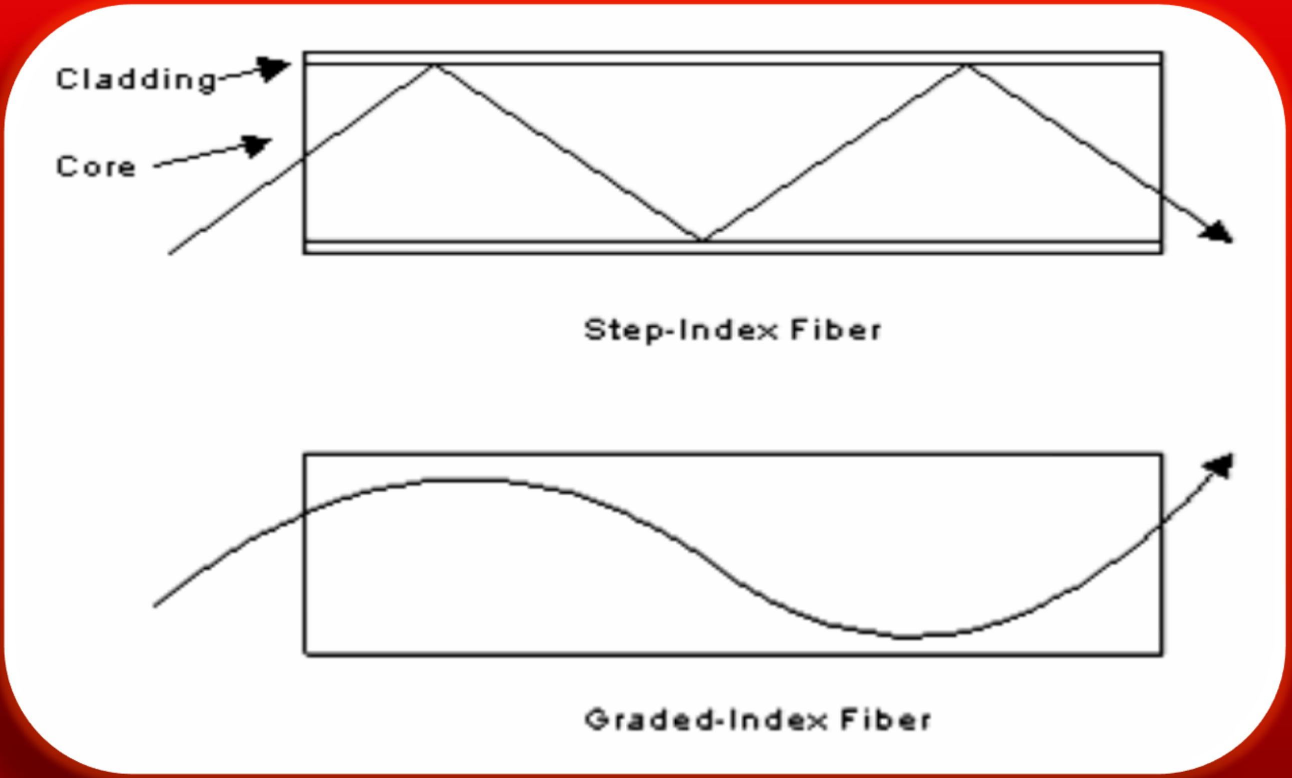
- As $n_1 \approx n_2$, $n_1 + n_2 = 2n_1$

And therefore, Numerical Aperture $= (2n_1^2\Delta)^{1/2} = n_1 (2\Delta)^{1/2}$ → (5)

From equation (5) it is seen that numerical aperture depends only on the refractive indices of core and cladding materials and it is independent on the fiber dimensions.

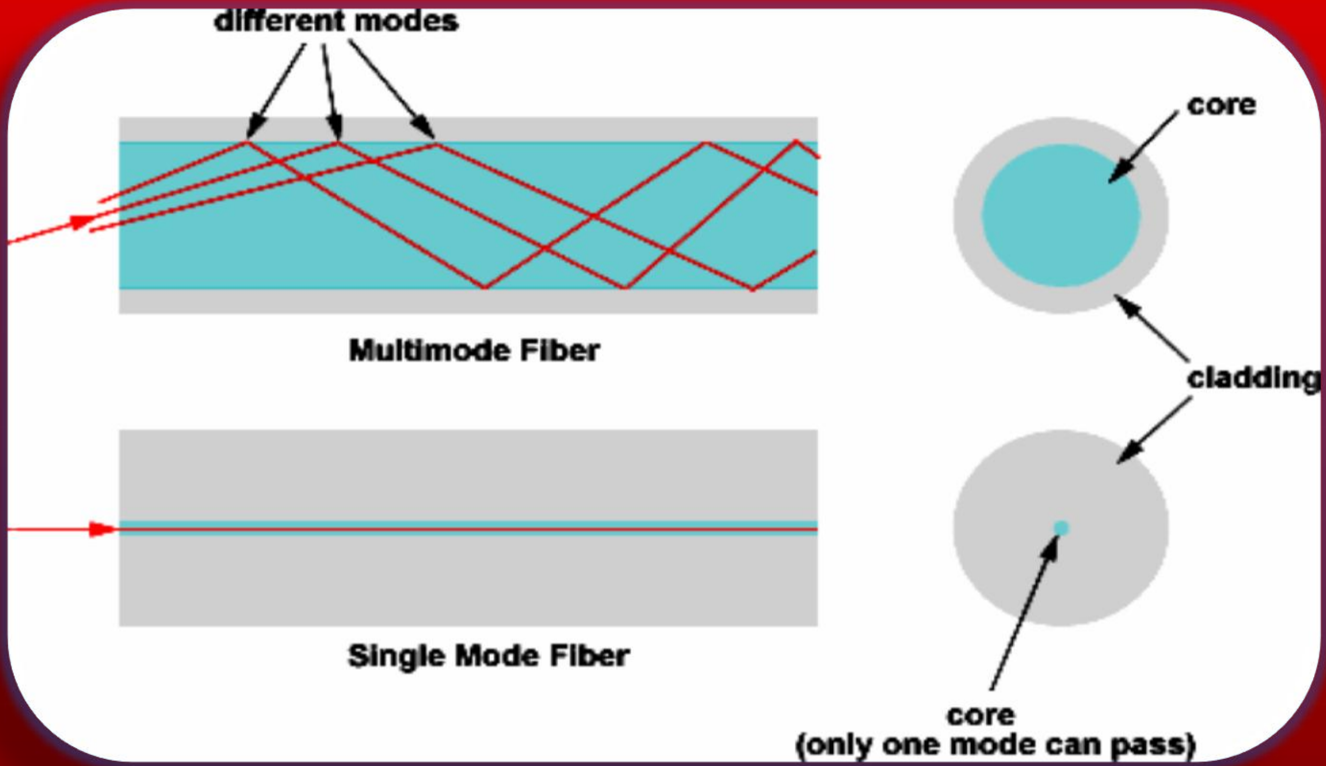
Types of Optical Fibres

- Based on the variation of refractive index of core, optical fibers are divided into: **(1) step index and (2) graded index fibers.**
- In all optical fibers, the refractive index of cladding material is uniform.



Light path through Step- index and Graded index Fibre

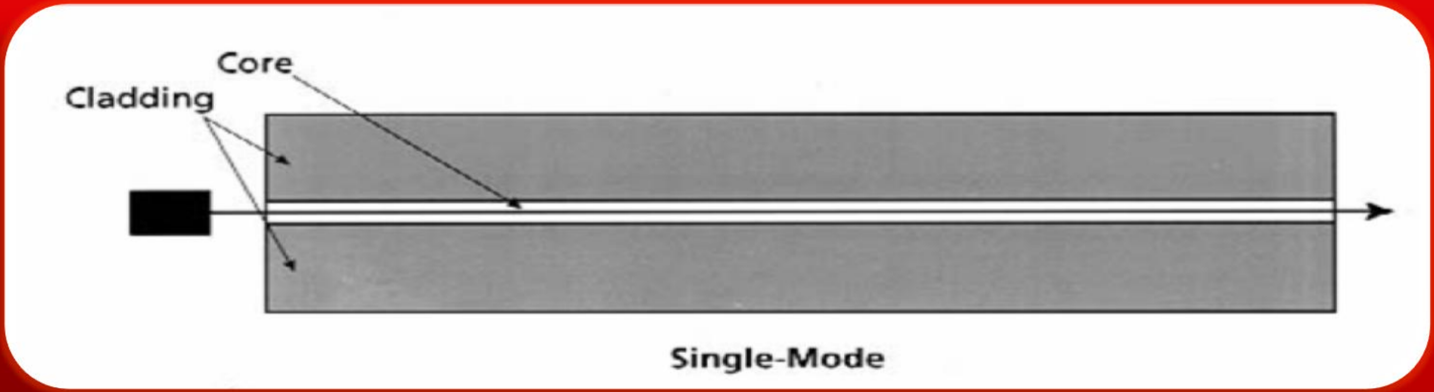
- Based on the mode of propagation, all the fibers are divided into: **(1) single mode and (2) multimode fibers.**
- Mode means, the number of paths available for light propagation in the fiber.
- If there is only one path for the ray propagation, it is called a single mode fiber.
- If the number of paths is more than one, then it is called a multi mode fiber.



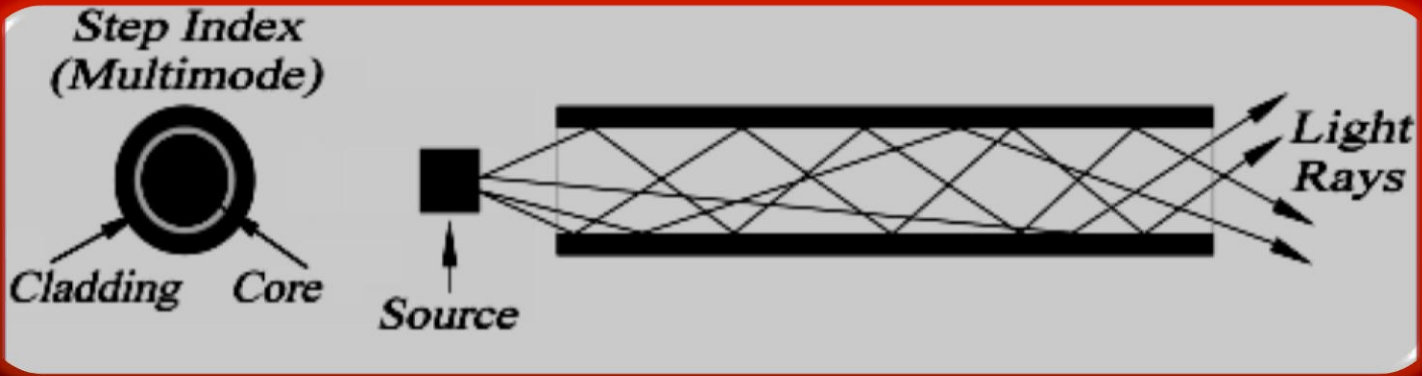
Single mode and Multi mode propagation of light

Step index optical fibre

- Based on the mode of propagation of light rays, step index fibers are of 2 types: **a) single mode step index fiber & b) multimode step index fibers.**
- The light rays propagate in zigzag manner inside the core.



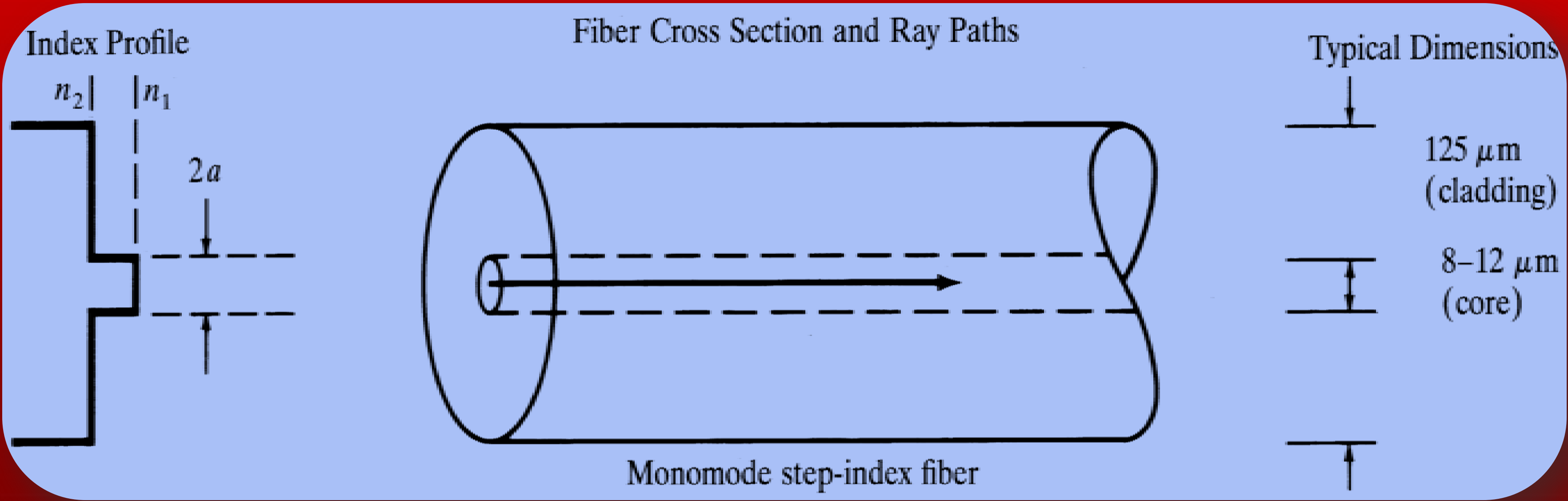
Single mode Step index optical Fibre



Multi mode Step index optical Fibre

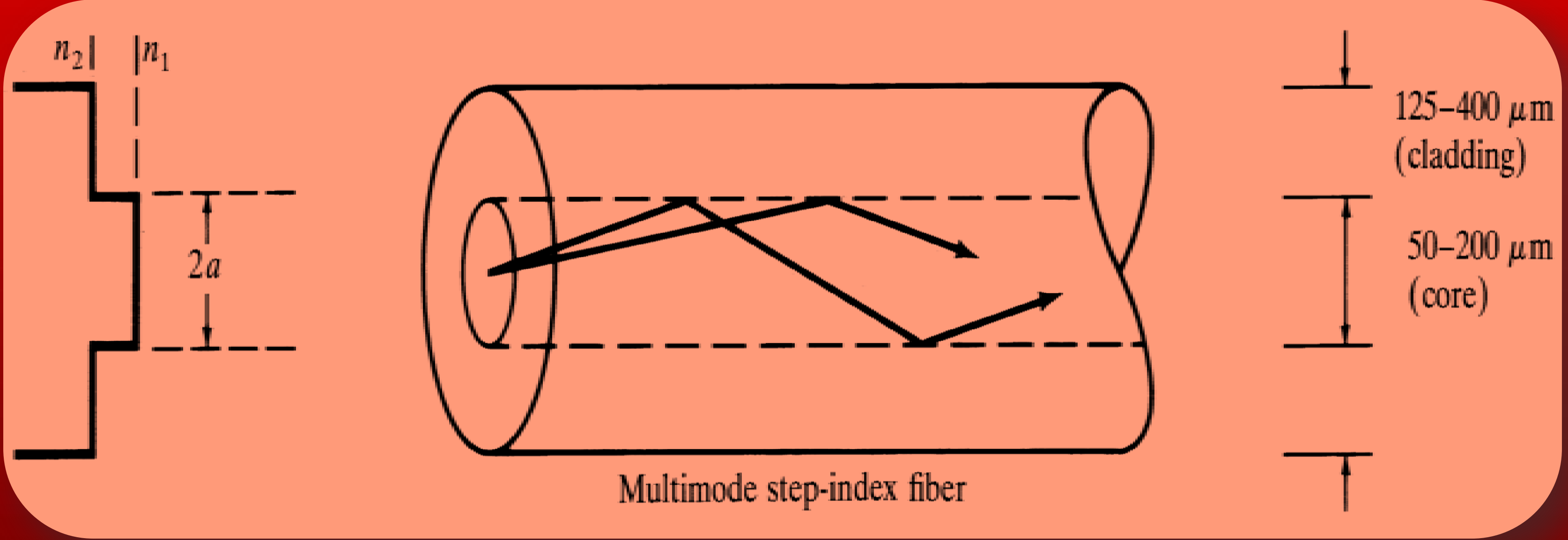
Refractive index profile in Single mode Step index fibre

- The refractive index is uniform throughout the core of this fibre.
- As we go radially in this fibre, the refractive index undergoes a step change at the core-cladding interface.
- The core diameter of this fibre is about 8 to 10 μm and outer diameter of cladding is 60 to 70 μm.
- In this fibre, the transmission of light is by successive total internal reflections i.e. it is a reflective type fiber.
- These fibres are mainly used in submarine cable system.



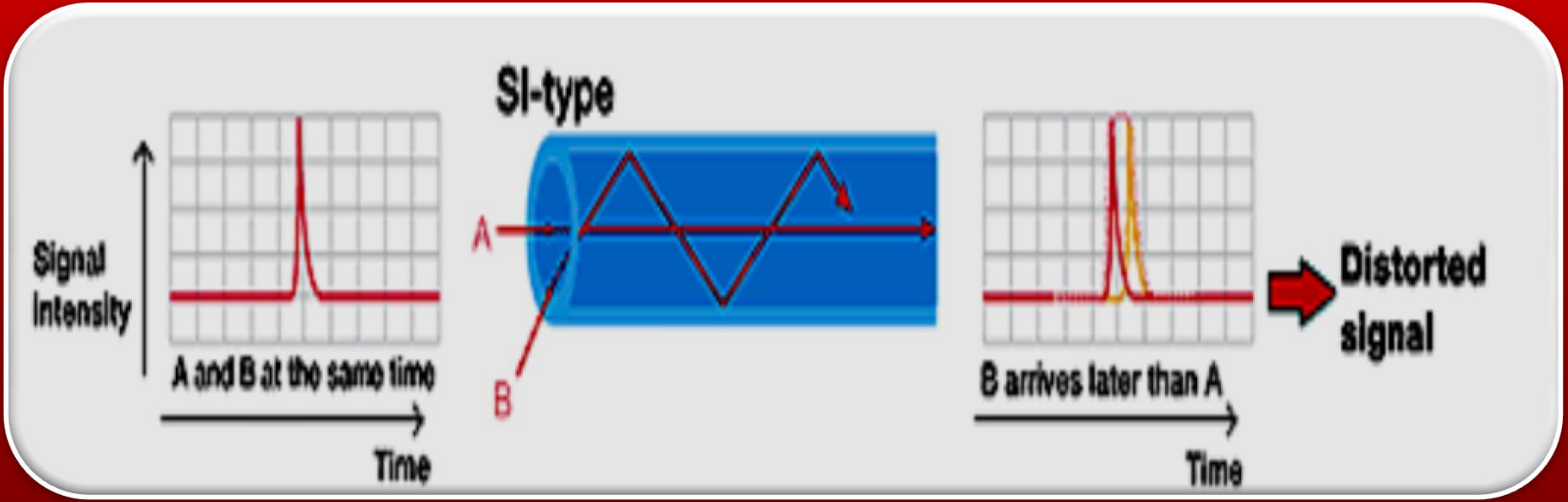
Refractive index profile in Multimode Step index fibre

- Its core and cladding diameters are much larger to have many paths for light propagation.
- The core diameter of this fiber varies from 50 to 200 μm and the outer diameter of cladding varies from 100 to 250 μm.
- Light propagation in this fiber is by multiple total internal reflections i.e., it is a reflective type fiber.
- It is used in data links, which have lower band width requirements.



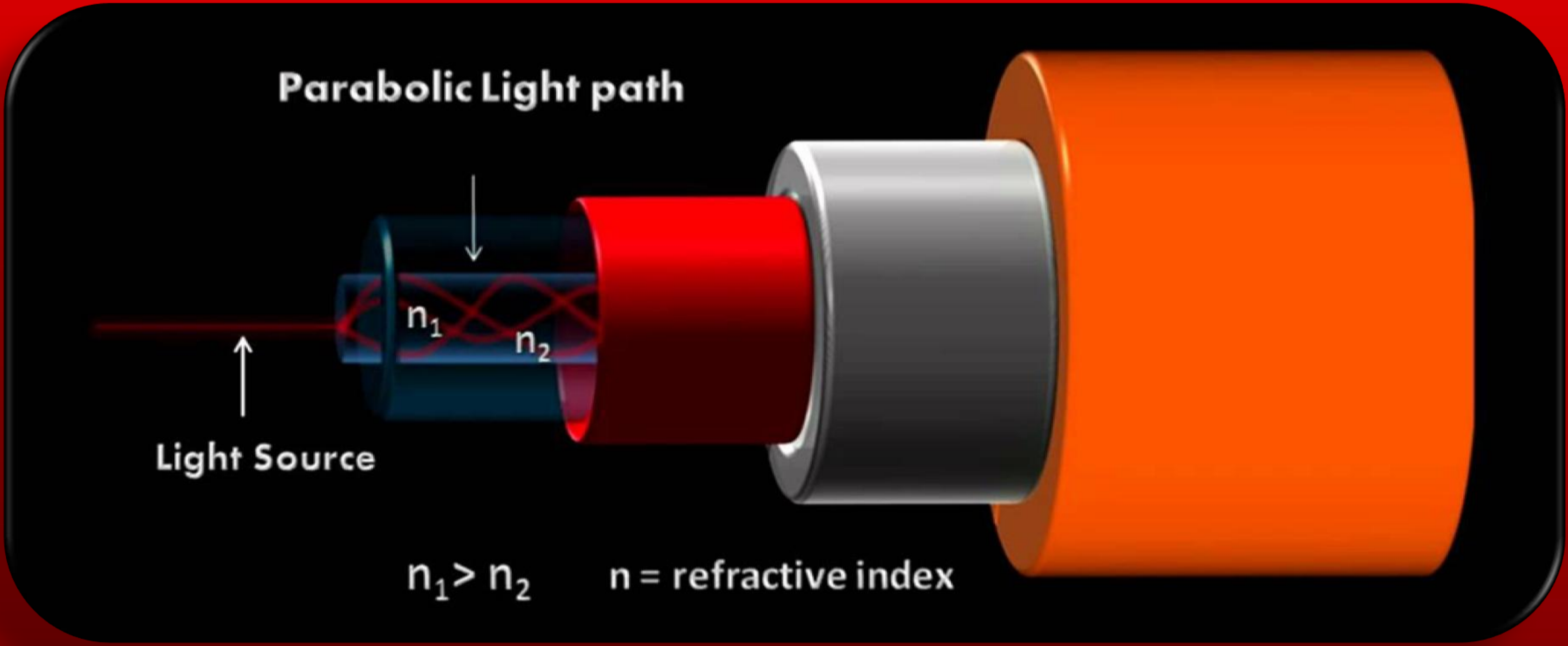
Transmission of signal in step index fibre

- Generally the signal is transmitted through the fiber in digital form i.e. in the form of 1's and 0's.
- In multimode fibre, the pulse which travels along path A (straight) will reach first at the other end of fiber. Next, the pulse that travels along with path B (zigzag) reaches the other end.
- Hence, the pulsed signal received at the other end is broadened. This is known as **intermodal dispersion.**
- This imposes limitation on the separation between pulses and reduces the transmission rate and capacity.



Graded index optical fibre

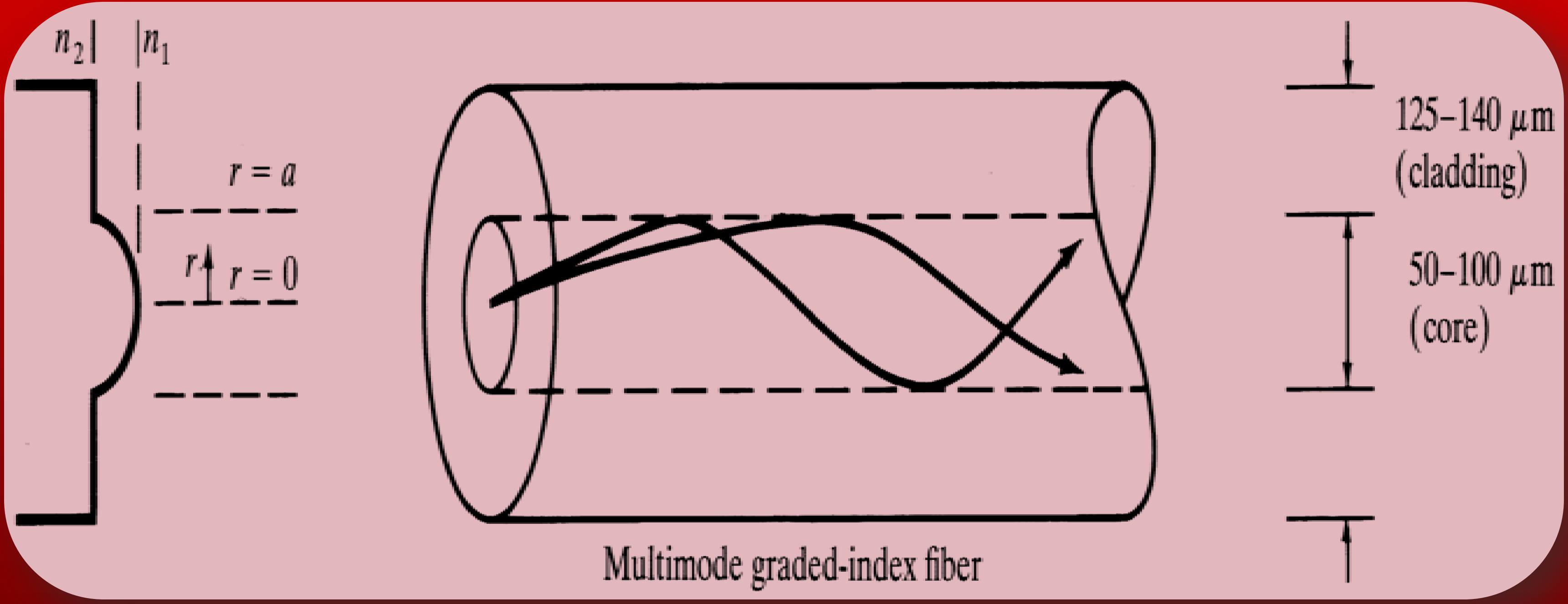
- To overcome the problem of inter modal dispersion caused due to step index optical fibres, graded index fibers are used.
- This fiber can be single mode or multimode fiber.
- Light rays propagate in the form of skew rays or helical rays. They will not cross the fiber axis.



Multimode Graded index optical fibre

Refractive index profile in Multimode graded index fibre

- In this fiber, the refractive index decreases continuously from center radially to the surface of the core.
- The refractive index is maximum at the center and minimum at the surface of core.
- The diameter of the core varies from 50 to 200μm and the outer diameter of the cladding varies from 100 to 250 μm.
- The refractive index profile is circularly symmetric.

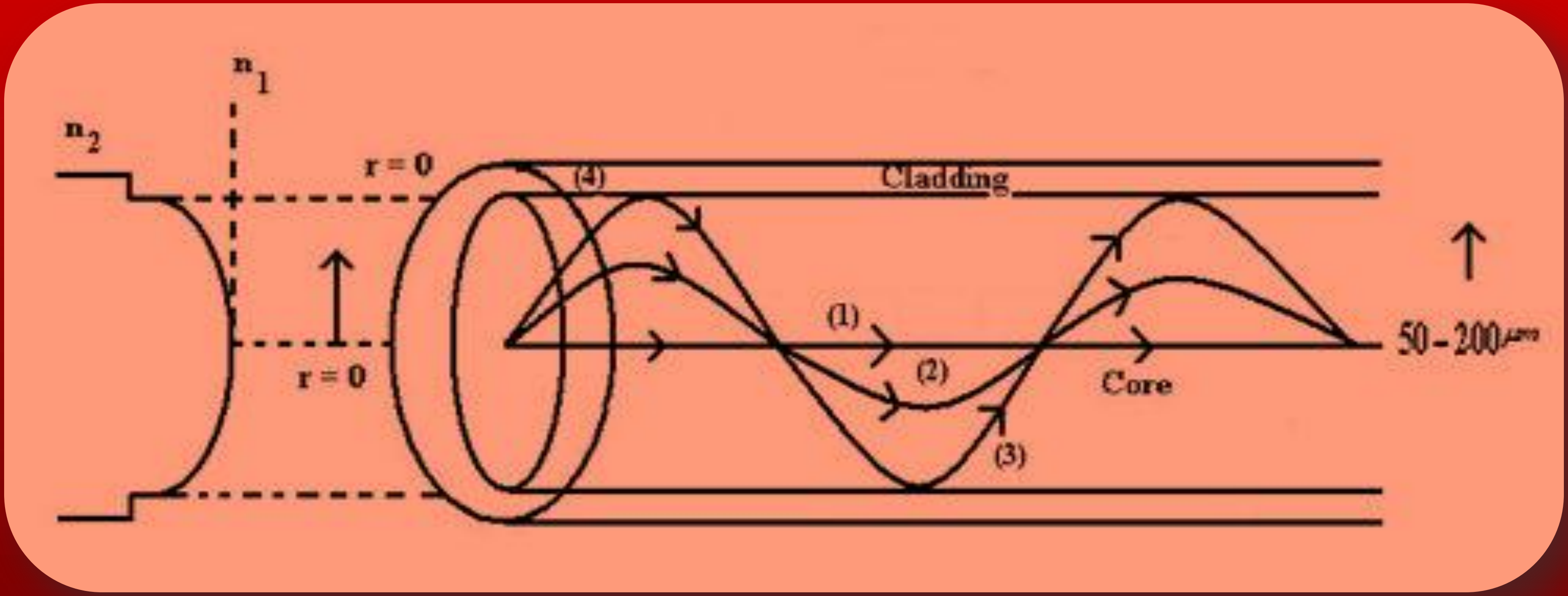


Explanation:

- As refractive index changes continuously radially in core, light rays suffer continuous refraction in core.
- The propagation of light ray is not due to total internal reflection but by refraction.
- In graded index fiber, light rays travel at different speed in different paths of the fiber.
- Near the surface of the core, the refractive index is lower, so rays near the outer surface travel faster than the rays travel at the center.
- Because of this, all the rays arrive approximately at the same time, at the receiving end of the fiber.

Transmission of signal in graded index fibre

- consider ray path 1 along the axis of fiber and another ray paths 2 and 3.
- Along the axis of fiber, the refractive index of core is maximum, so the speed of ray along path 1 is less.
- Path 2 is sinusoidal and it is longer. This ray mostly travels in low refractive region and so the ray 2 moves slightly faster.
- Hence, the pulses of signals that travel along path 1, path 2 and path 3 reach the other end of the fiber simultaneously. Thus, the problem of intermodal dispersion can be reduced to a large extent using graded index fibers.



Differences between step index and graded index fibers

Step index Fibre	Graded index Fibre
✓ The refractive index of core is uniform and step or abrupt change in refractive index takes place at the core cladding interface	✓ The refractive index of core is non-uniform. It decreases parabolically from the axis of the fiber to its surface.
✓ The light rays propagate in zigzag manner inside the core. The rays cross the fiber axis for every reflection.	✓ Light rays propagate in the form of skew rays or helical rays. They will not cross the fiber axis.
✓ Signal distortion is more in multimode step index fibre. There is no distortion in Single mode fibre.	✓ Signal distortion is very low even though the rays travel with different speeds inside the fibre.
✓ The bandwidth is about 50 MHz km for multimode fibre and it is more than 1000 MHz km in case of single mode fibre.	✓ The bandwidth of the fibre lies in between 200 MHz km to 600 MHz km, though the theoretical value is infinity.
✓ Attenuation of light rays is more in multimode fibres but in Single mode fibres it is very less.	✓ Attenuation is light rays is less in graded index fibres.
✓ NA of multimode fibre is more, but in Single mode fibres, it is very less.	✓ NA of Graded index fibres is less.

Differences between Single mode and Multimode fibers

Single mode Fibre	Multimode Fibre
✓In single mode fiber there is only one path for ray propagation.	✓In multimode fiber, large number of paths are available for light ray propagation.
✓A single mode step index fiber has less core diameter (<10 μm) and the difference between the refractive indices of core and cladding is very small.	✓Multi mode step index fibers have larger core diameter (50-200μm) and the difference between the refractive indices of core and cladding is large.
✓In single mode fibers, there is no dispersion.	✓Signal distortion and dispersion takes place in multimode fibers.
✓Signal transmission capacity is less but the single mode fibres are suitable for long distance communication.	✓Signal transmission capacity is more in multimode fibres. They are less suitable for long distance communication.
✓Launching of light into single mode fibers is difficult.	✓ Launching of light into multimode fibers is easy.
✓Fabrication cost is very high.	✓ Fabrication cost is less.

Attenuation in Optical Fibres

- **Attenuation** is the loss of power suffered by the optical signal as it propagates through the fiber.
- It is also called fiber loss.
- **Signal attenuation is** defined as "the ratio of the input optical power (P_i) into the fiber to the output optical power received (P_o) at the other end of the fiber".
- The attenuation coefficient of the signal per unit length is given as,

$$\alpha = 10/L \log (Pi/Po) \text{ dB/km}$$

Where, L is the length of the fibre.

- The mechanisms through which attenuation takes place are

1.Absorption losses.

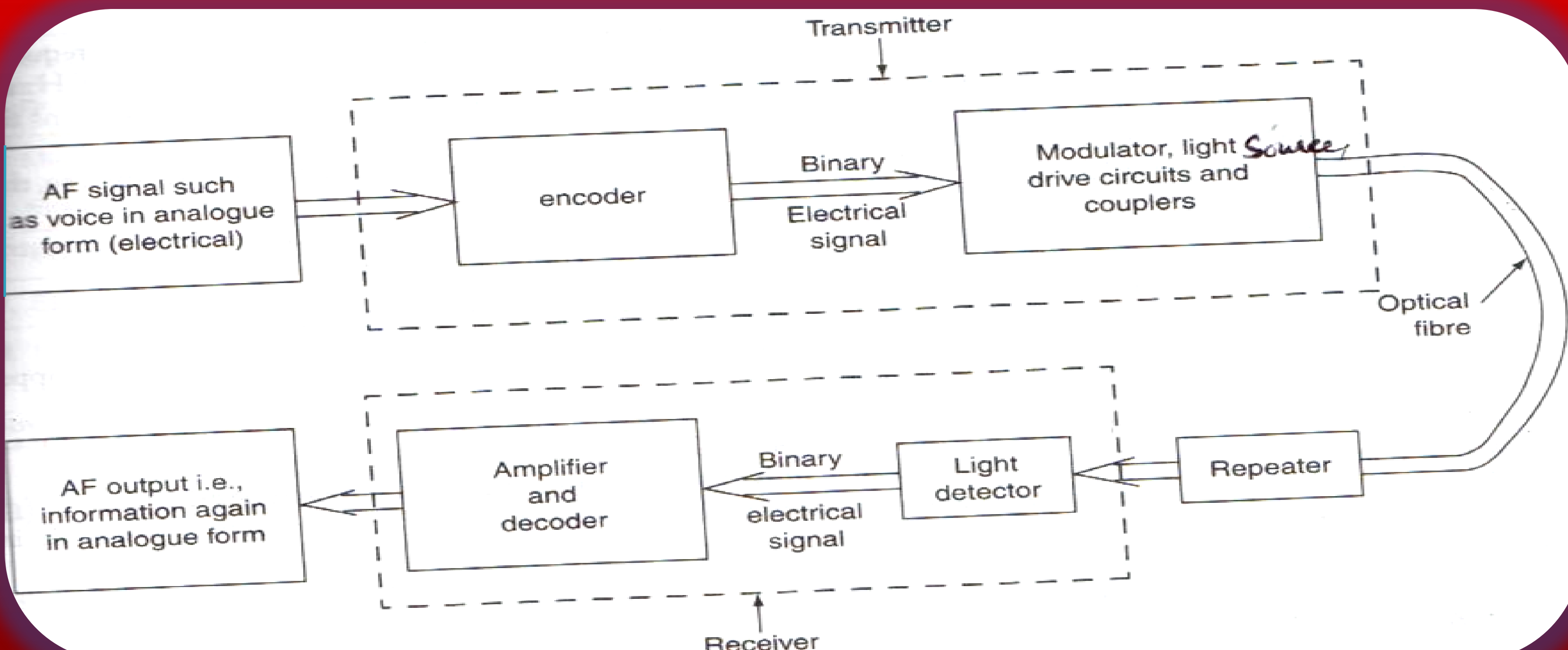
2.Scattering losses.

` 3. Bending losses.

4.Microbending and Wave guide losses.

Optical Fibres in Communication

- Optical fibre communication system essentially consists of three parts namely, **(a) Transmitter (b) Optical fibre and (c) Receiver.**
- The Transmitter includes modulator, encoder, light source, drive circuits and couplers.
- Basically, the fibre optic system simply converts an electrical signal to binary data by an encoder.



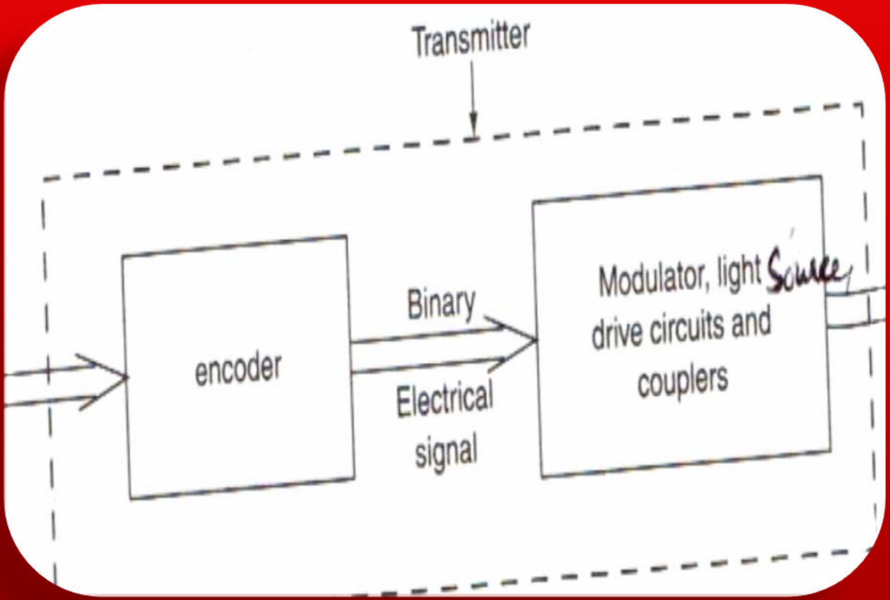
Block diagram of Optical Fibre communication system

- This binary data comes out as a stream of electrical pulses and these pulses are converted into pulses of optical power, by modulating the light emitted by the light source.

- This means that the laser drive circuit directly modulates the intensity of the laser light with the encoded digital signal.

- This digital optical signal is launched into the optical fibre cable.

- The Couplers in the transmitter, couple the transmitted light signals with the fibre.

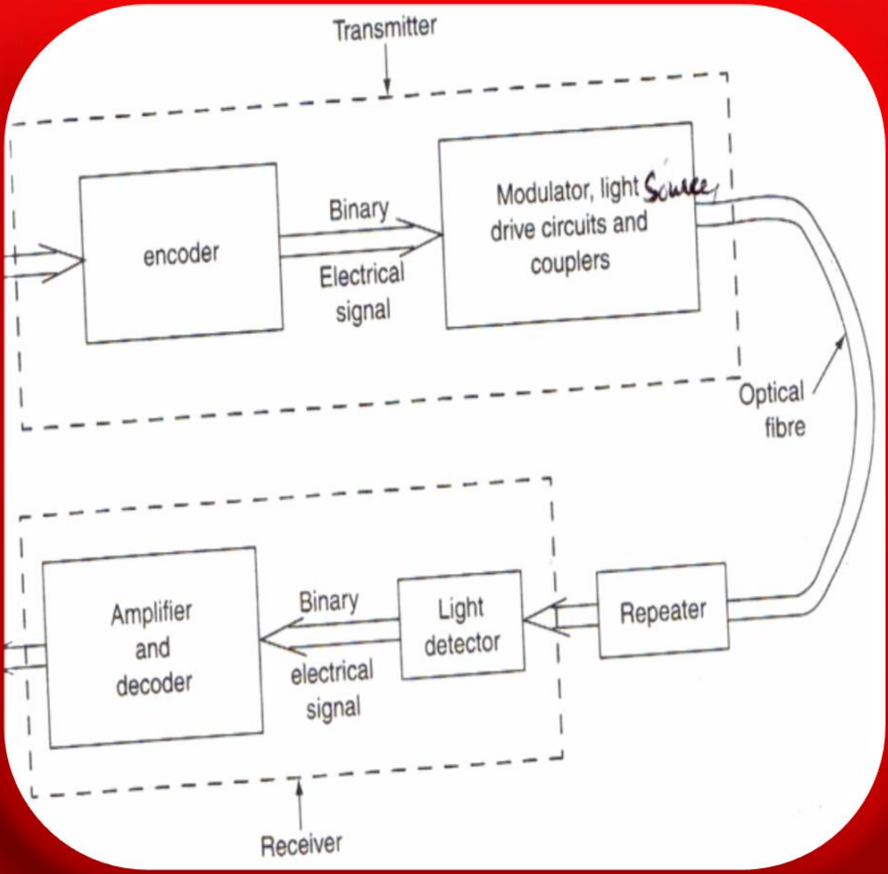


- To transmit signals to long distances, repeaters are used after certain lengths in the optical fibre.

- **An optical repeater consists of a receiver and a transmitter arranged adjacently.**
- The receiver section converts the optical signal into corresponding electrical signal.

- Further this electric signal is amplified by means of an electrical regenerator and is sent into the transmitter section.

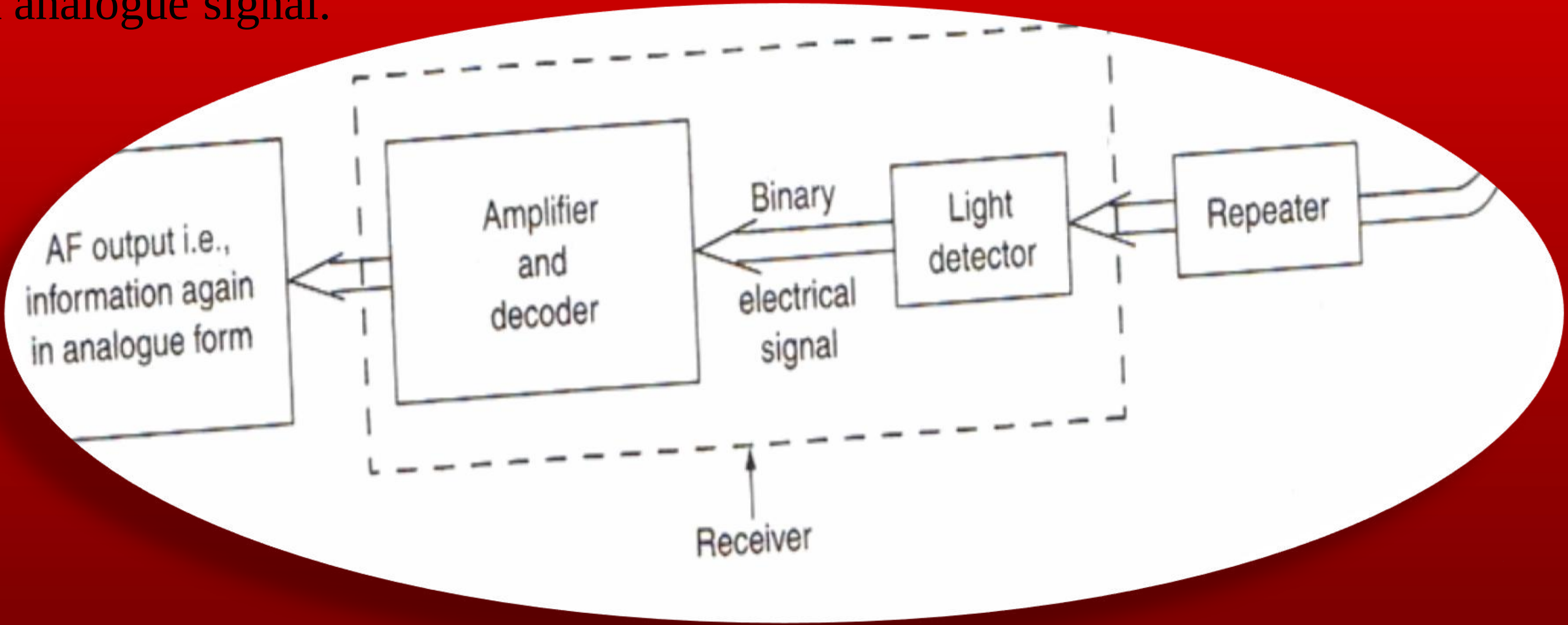
- In transmitter section, the electrical signal is again converted back to optical signal and fed into the optical fibre.



Finally, at the end of the optical fibre, the signal is fed to the receiver.

The **Receiver** consists of a light detector, which can either be an Avalanche Photo Diode (ADP) or a Positive Intrinsic Negative(PIN) diode.

In the photo detector, the signal is converted into pulses of electric current, which is then fed to the decoder, which converts the sequence of binary data stream into an analogue signal.



Advantages of Optical fibres in Communication

Enormous bandwidths:

- The information carrying capacity of a transmission system is directly proportional signal frequency.
- Light which has a very high frequency in the range of 10^{14} to 10^{15} Hz, can transmit information at a higher rate.

Smaller diameter and light weight:

- Optical fibres are of light weight having smaller diameter and are flexible compared to that of a copper cable.
- This makes them to be used in air craft's and satellites more effectively.

Lack of cross talk between parallel fibres:

- Since optical fibers are dielectric wave guides, they are free from any electromagnetic interference (EMI) and radio frequency interference (RFI). Therefore, cross talk is negligible even when many fibers are cabled together.

Longer life span:

- The life span of optical fibres is expected to be 20-30 years as compared to copper cables, which have a life span of 12-15 years.

Electrical isolation:

- Optical fibers are made from silica which is an electrical insulator.
- Therefore they do not pick up any electromagnetic wave or any high current lightening and so optical fibres are suitable in explosive environment too.

Signal security:

- The transmitted signal through the fiber does not radiate.
- Unlike in copper cables, a transmitted signal cannot be drawn from a fiber without tampering it.
- Thus, the optical fiber communication provides 100% signal security.

- **Low transmission loss:**
- Due to the usage of ultra low loss fibers and the erbium doped silica fibers as optical amplifiers, one can achieve almost loss less transmission.
- For long distance communication fibers of 0.002db/km are used. Thus the repeater spacing is more than 100km.

- **Ruggedness and flexibility:**

- The fiber cable can be easily bent or twisted without damaging it.
- Further the fiber cables are superior than the copper cables in terms of handling, installation, storage, transportation, maintenance, strength and durability.

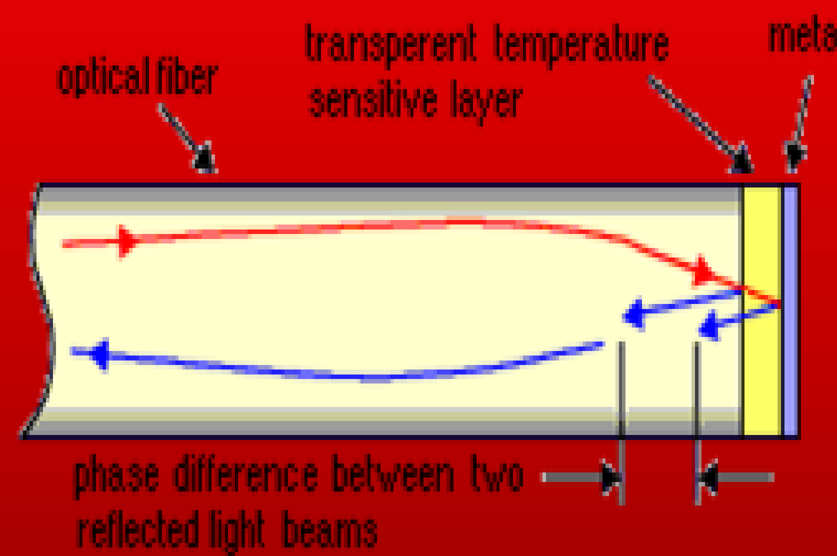
- **Low cost and availability**:

- Optical fibers are made of silica which is available in abundance.
- Hence, there is no shortage of material and optical fibers offer the potential for low cost communication.

Applications of Optical Fibres

Sensors:

- Fibers have many uses in remote sensing. In some applications, the sensor is itself an optical fiber.
- Optical fibers can be used as sensors to measure strain, temperature, pressure and other quantities.
- Extrinsic fiber optic sensors has the ability to reach places which are otherwise inaccessible. An example is the measurement of temperature inside aircraft jet engines.
- Extrinsic sensors can also be used in the same way to measure the internal temperature of electrical transformers.



Fibre optic temperature sensor using Phase interference

Power transmission:

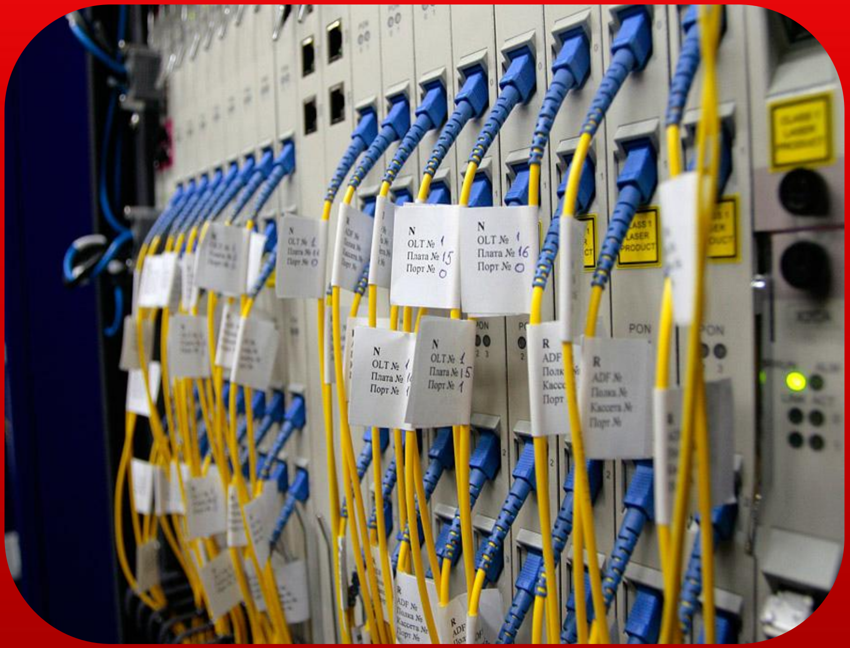
- Optical fiber can be used to transmit power using a photovoltaic cell to convert the light into electricity.
- Fiber optics are used to connect users and servers in a variety of network settings and help increase the speed and accuracy of data transmission.
- They are also used in military as hydrophones for seismic and SONAR uses, as wiring in aircraft, submarines and other vehicles and also for field networking.
- Broadcast/cable companies are using fiber optic cables for wiring CATV, HDTV, internet, video on-demand and other applications.

Fibre optics used in SONAR

Fibre optic cable system in Internet

Telecommunication:

- Optics fiber is used by many telecommunications companies to transmit telephone signals, Internet communication, and cable television signals.
- Unlike electrical cables, fiber optics transport information far distances with few repeaters.
- Fiber optic cables can carry a large number of different signals simultaneously through a technique called wavelength division multiplexing.
- Optical fibers are ideally suited for carrying digital information, which is especially useful in computer and cellular networks.



Optical fibres used in Telecommunication

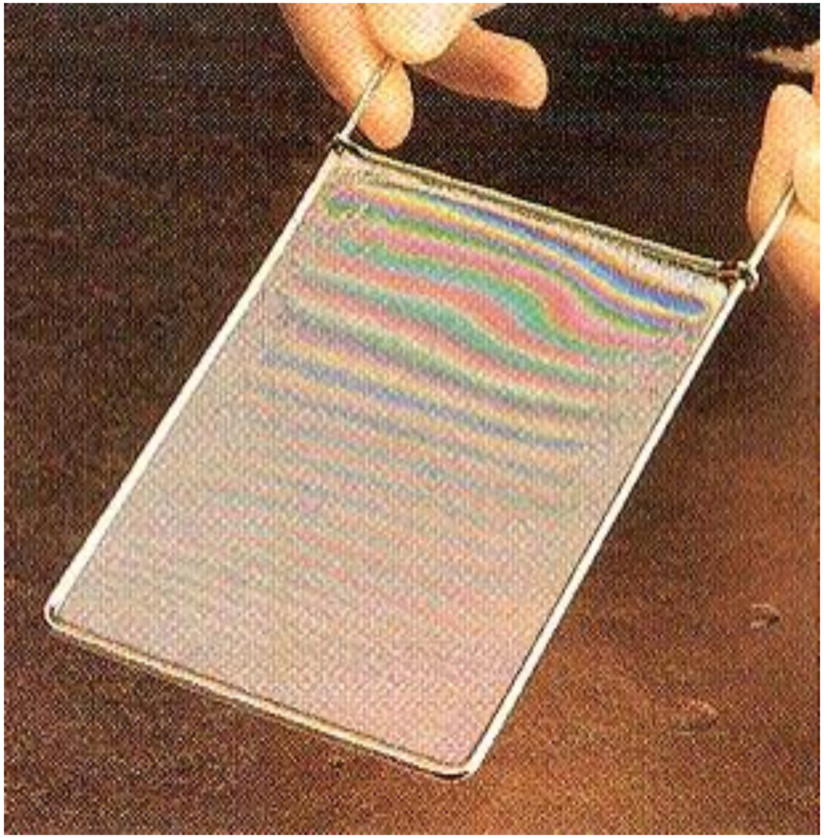
OPTICS

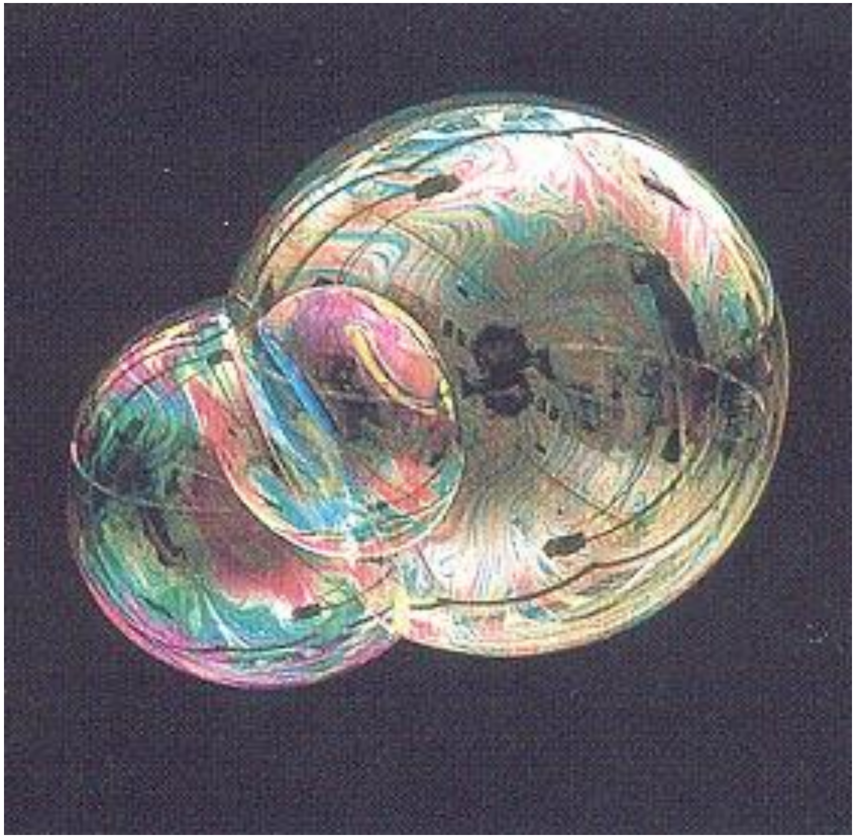
INTERFERENCE

Interference is…

- *the process in which two or more light, sound, or electromagnetic waves of the same frequency combine to reinforce or cancel each other, the amplitude of the resulting wave being equal to the sum of the amplitudes of the combining waves.*

Striking colors observed on thin films due to interference





PRINCIPLES OF SUPERPOSITION

When two or more waves reach a point simultaneously, the resultant displacement at that point is the algebraic sum of the displacements produced by the individual waves in absence of others.

Explanation: Let us consider the two waves of same frequency "ν" is $\frac{\omega}{2\pi}$

If y_1 is the displacement produced by one wave and
y_2 is the displacement produced by second wave
δ is the phase difference between these two waves

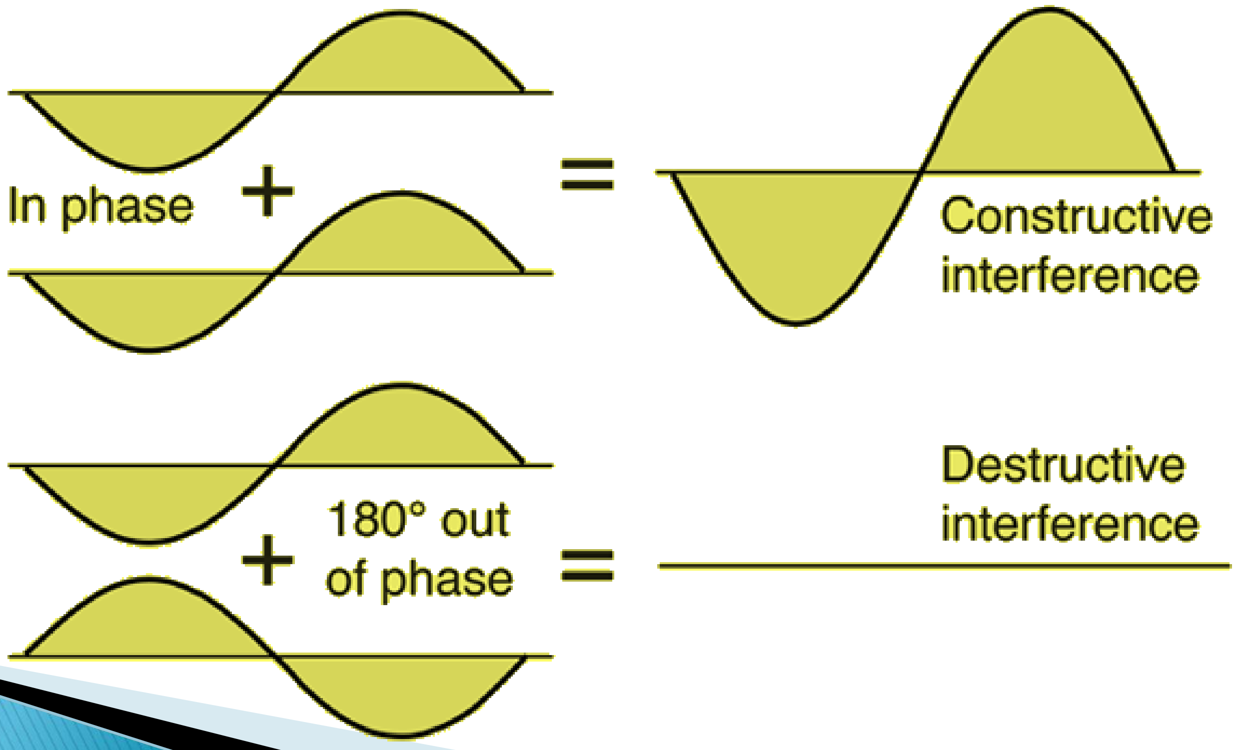
The resultant displacement produced by the superposition of these waves is

$$y = y_1 + y_2 \rightarrow (1)$$

TYPES OF INTERFERENCE

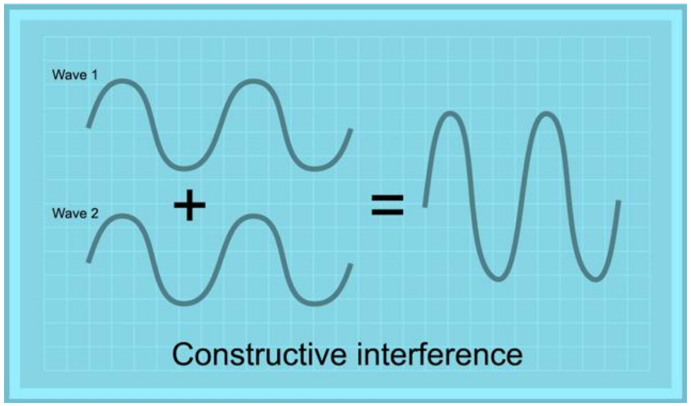
Interference is of two types.

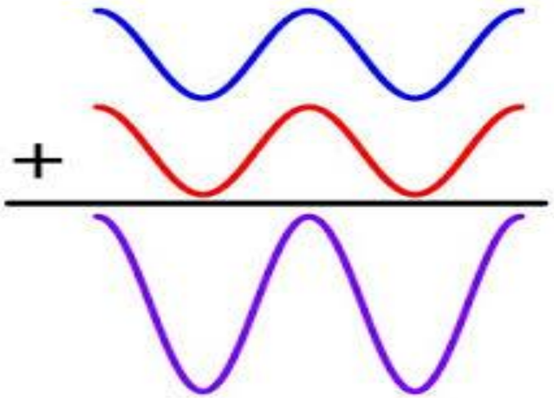
1. Constructive interference / constructive superposition
2. Destructive interference / destructive superposition

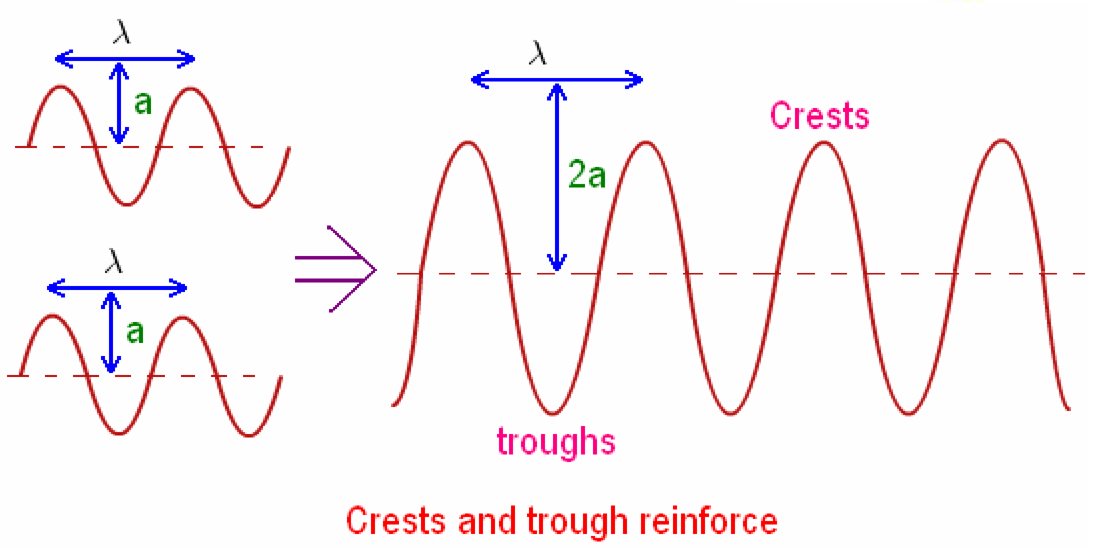


1. CONSTRUCTIVE INTERFERENCE:

When crest of one light wave falls on the crest of another wave then the resultant intensity increases and this type of interference is called constructive interference. Here we get maximum intensity.

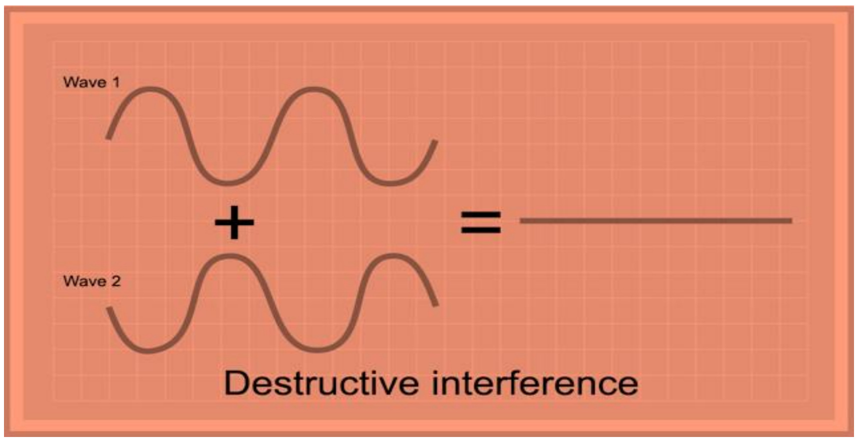


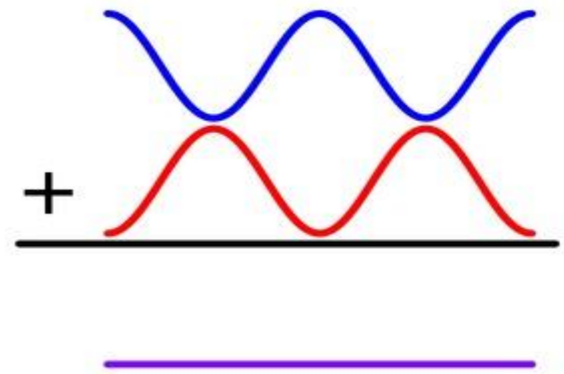


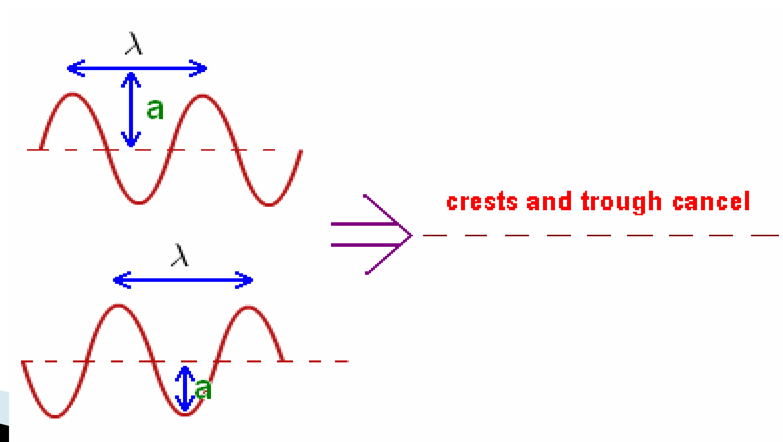


2. DESTRUCTIVE INTERFERENCE:

When crest of one light wave falls on the trough of another wave then the resultant intensity decreases. This type of interference is called destructive interference. Here we get minimum intensity.







Interference in thin films

Optical Path:

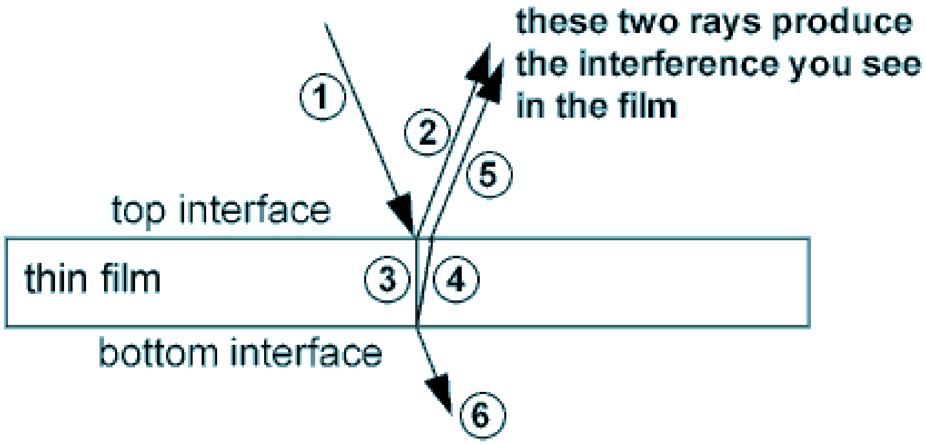
•The optical path travelled by a light ray in a medium of refractive index 'μ' is not equal to actual path travel led by the light ray.

Thin film planes can be parallel to each other or inclined. That is why, the concept of interference in thin films can be studied under two categories, namely,

1. **Interference in parallel plate film and**
2. **Interference in wedge-shaped films.**

➢We observes colors in such thin films as soap bubbles, coatings on camera lenses and in a butterfly's wings or peacock's feathers.

Soap Film – Why Color?



✓ When ray 1 strikes the top interface, some of the light is partially reflected, ray 2, and the rest is refracted, ray 3.

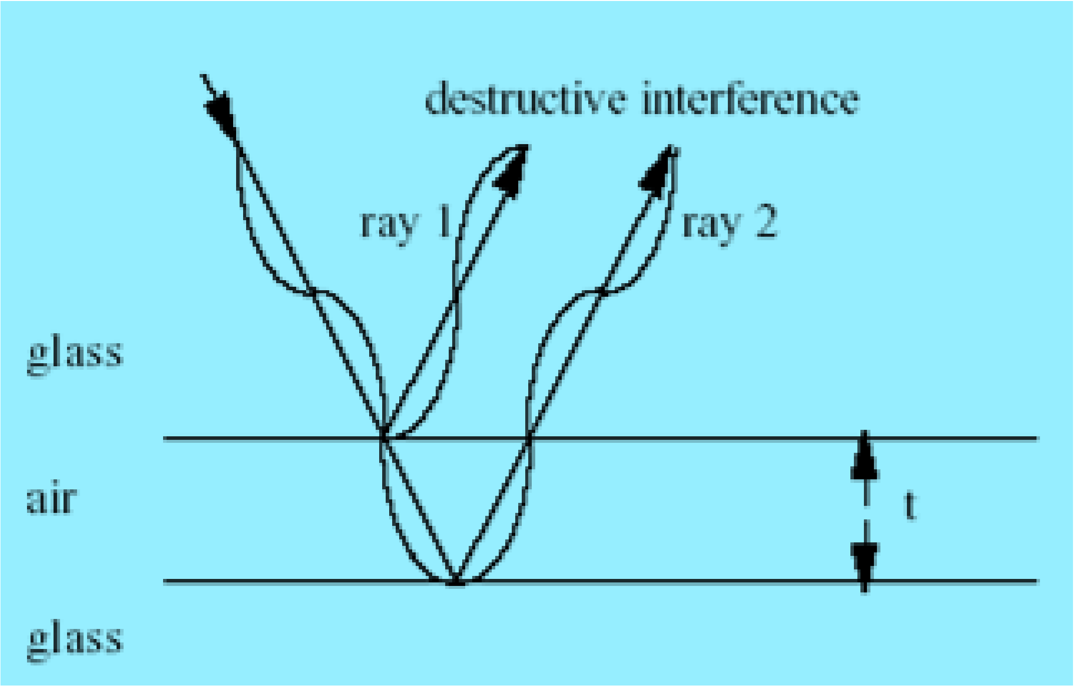
✓ When ray 3 strikes the bottom interface, some of it is reflected, ray 4, and the remainder is refracted, ray 6.

✓When ray 4 strikes the top interface from underneath, some is reflected (not shown) and some is refracted, ray 5.

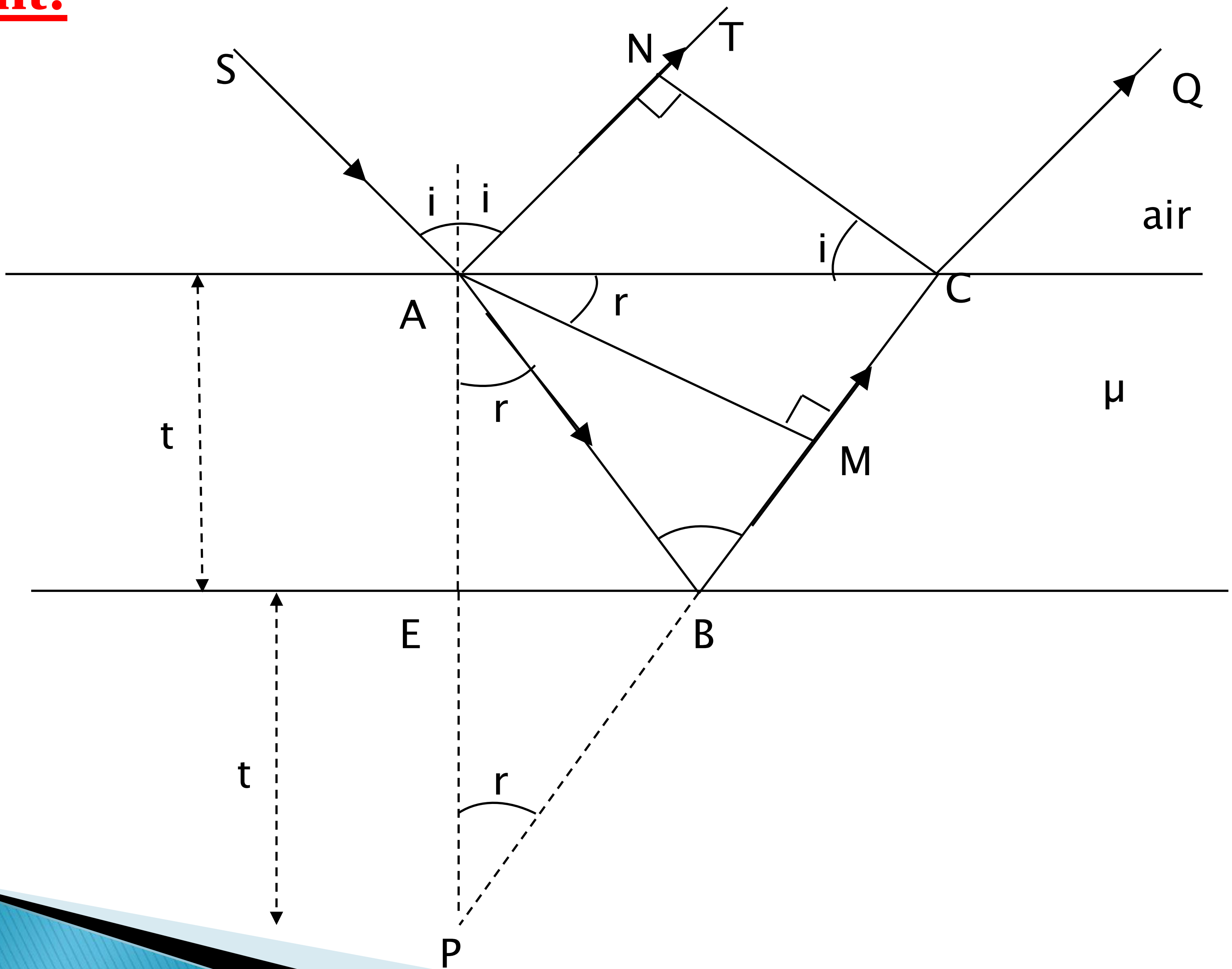
It is the interference between rays 2 and 5 that produces a thin film's color when the film is viewed from above.

Interference in plane parallel films due to reflection of light:

- Ray 2 undergoes a phase change of 180° with respect to the incident ray
- Ray 1, which is reflected from the lower surface, undergoes no phase change with respect to the incident wave



Interference in plane parallel films due to reflection of light:



Interference in plane parallel films due to reflection of light:

- **For constructive interference**

  $$2\,\mu\,t\cos r = (2n\pm1)\,\lambda/2 \quad n = 0, 1, 2 \ldots$$

  - For normal incidence $\angle r = 0^0$

  $$2\,\mu\,t = (2n\pm1)\,\lambda/2 \quad n = 0, 1, 2 \ldots$$

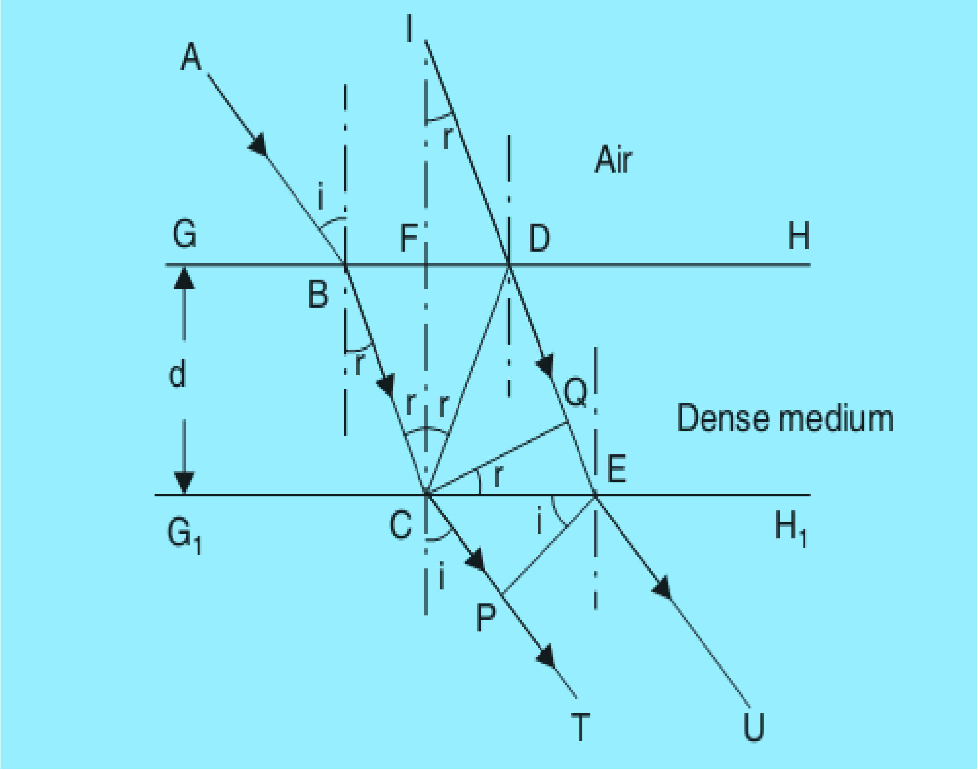
- **For destruction interference**

  $$2\,\mu\,t\cos r = n\,\lambda \quad n = 0, 1, 2 \ldots$$

  - For normal incidence $\angle r = 0°$

  $$2\,\mu\,t = n\,\lambda \quad n = 0, 1, 2 \ldots$$

Interference in plane parallel films due to transmitted of light:



The conditions for bright is

$2\mu d \cos r = n\lambda$

$n = 0, 1, 2 \ldots$

The conditions for dark is

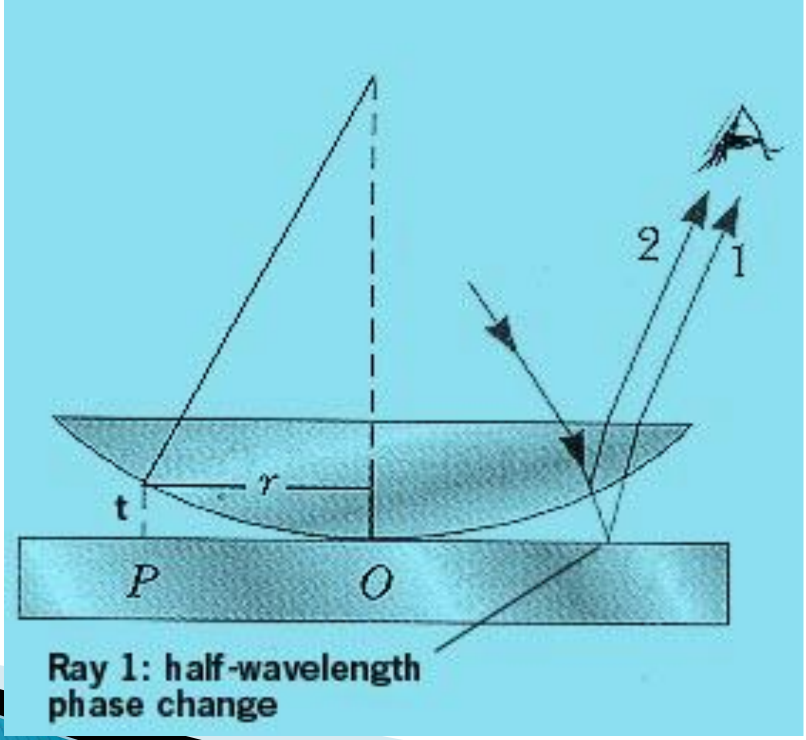
$2\mu d \cos r = (2n \pm 1)\lambda/2$

$n = 0, 1, 2 \ldots$

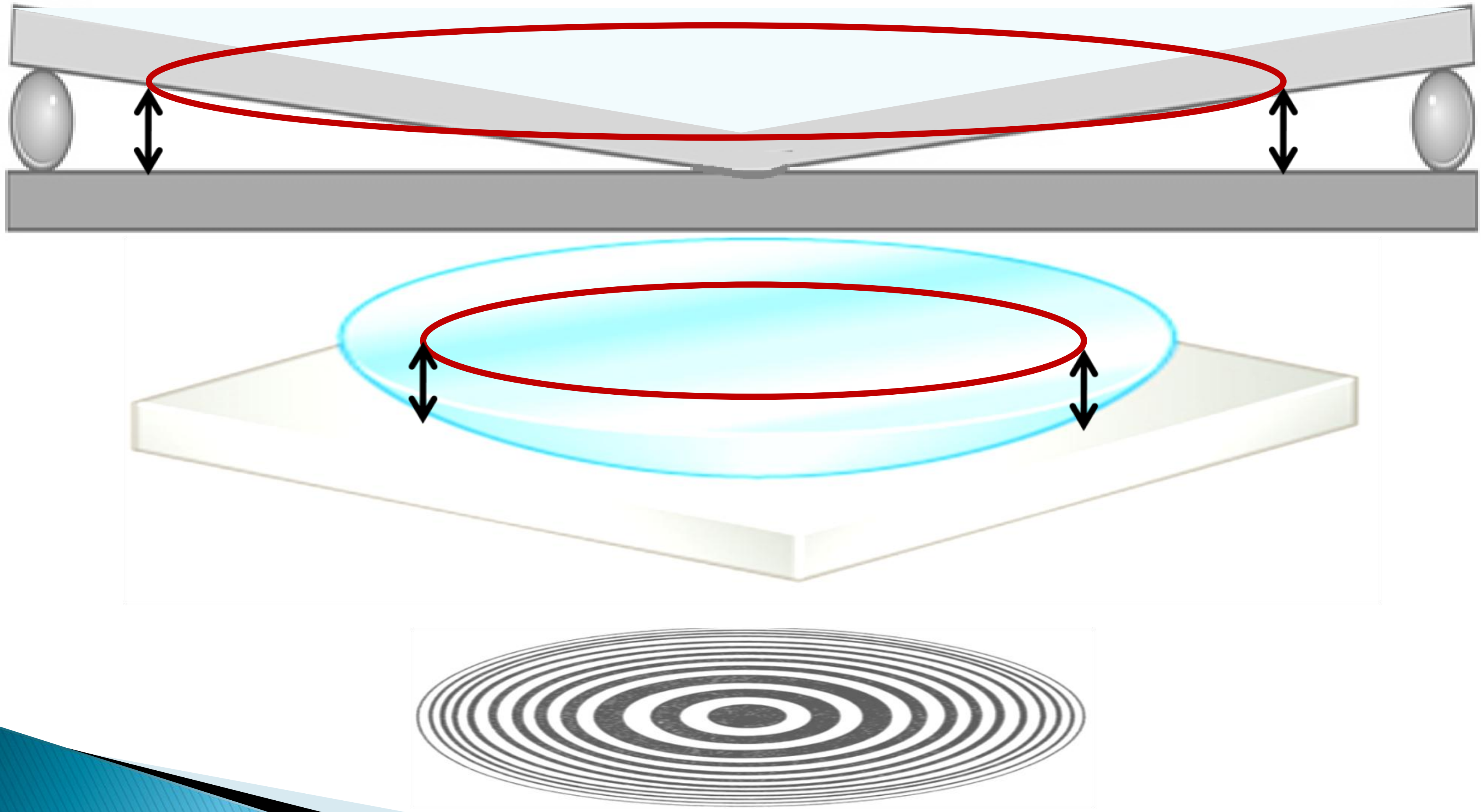
We can say the interference pattern due to reflected and transmitted rays are complementary each other.

Newton’s Rings

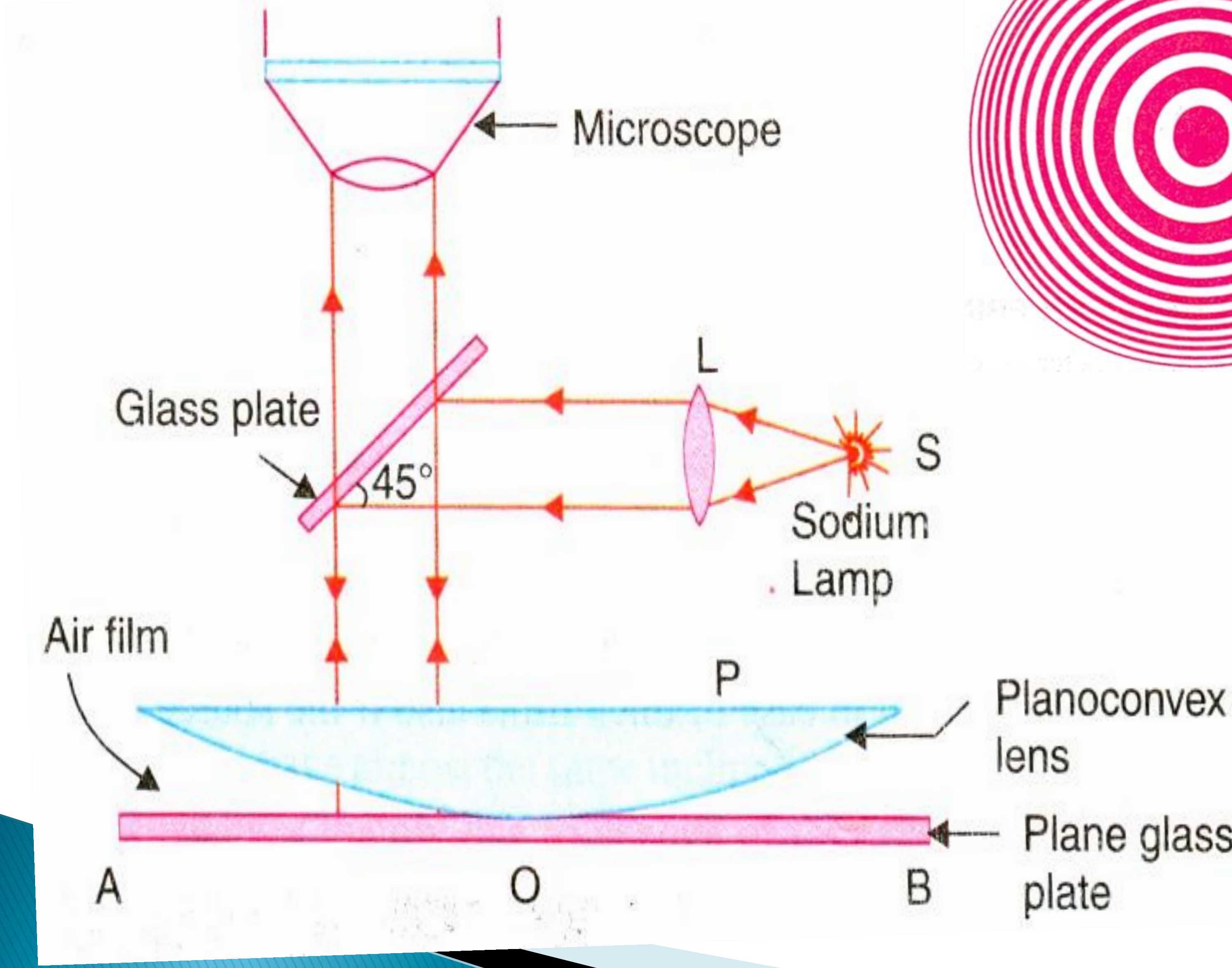
❖Newton’s rings are formed due to interference between the waves reflected from the top and bottom surfaces of the air film formed between the plano convex lens and plane glass plate. This phenomenon was first described by Newton that why they are known as Newton’s rings



Newton's Rings



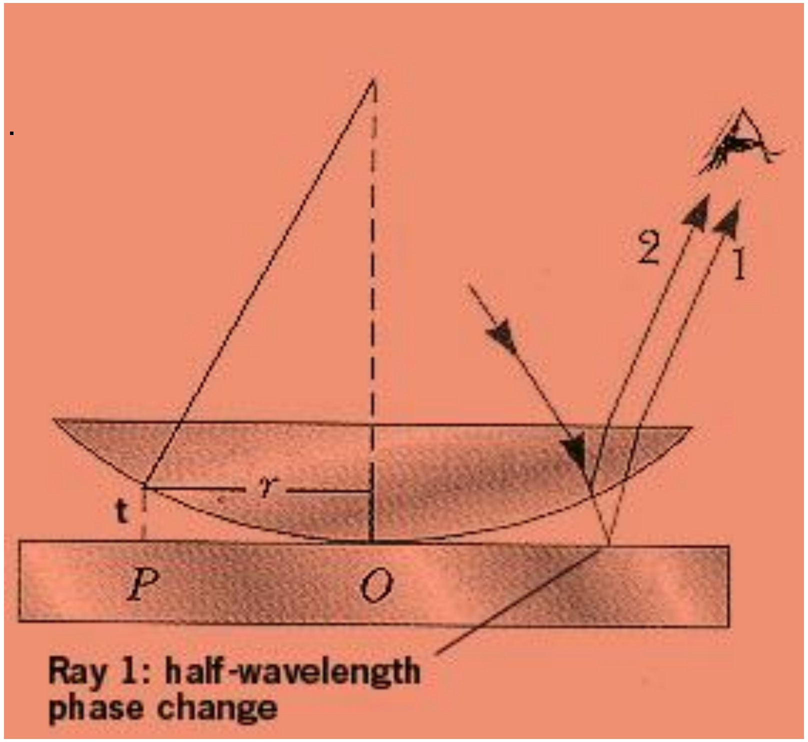
Newton's Rings

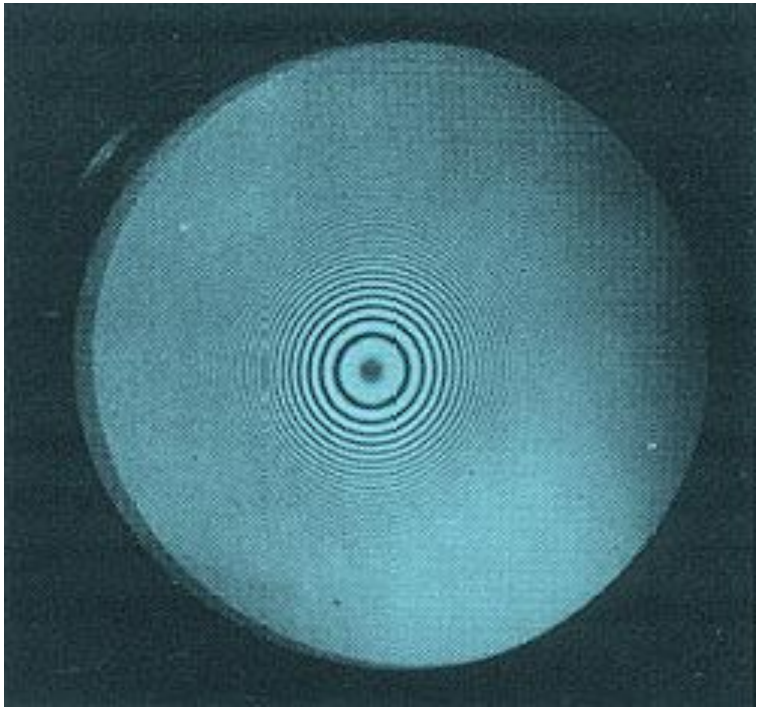


Experimental arrangement

- L is a planoconvex lens with large radius of curvature .
- G is a plane glass plate
- L is placed with its convex surface on G.
- monochromatic light is incident on L normally by using 45° arrangement of glass plate.
- A part of light is reflected from curved surface of lens and another one is reflected from plane surface of glass plate.
- Now interference take place between these two rays

  i.e one is reflected from upper surface of air film and another one reflected from lower surface of air film.
- Thus we get alternative bright and dark fringes .





Newton’s rings are formed due to interference between the light rays reflected from the top and bottom surfaces of air film between the plate and the lens.

The formation of Newton’s rings can be explained with the help of Fig

A part of the incident monochromatic light AB is reflected at B (glass-air boundary) in the form of the ray (1) with any additional phase (or path) change. The other part of light is refracted along BC. Then at C (air-glass boundary), it is again reflected in the form of the ray (2) with additional phase change of π or path change of $\frac{\lambda}{2}$.

As the rings are observed in the reflected light, the path difference between them is $2\mu t \cos r + \frac{\lambda}{2}$. For air film $\mu = 1$ and for normal incidence r=0, path difference is $2t + \frac{\lambda}{2}$.

At the point of contact t=0, path difference is $\frac{\lambda}{2}$, i.e., the reflected light at the point of contact suffers phase change of π. Then the incident and reflected lights are out of phase and interfere destructively. Hence the central spot is dark.

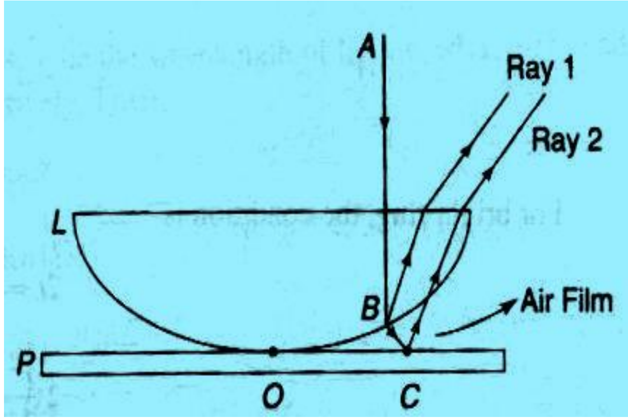
The condition for bright ring is $2t + \frac{\lambda}{2} = n\lambda$

$$2t = (2n-1)\frac{\lambda}{2} \qquad \text{where } n=1, 2, 3\ldots$$

The condition for dark ring is

$$2t + \frac{\lambda}{2} = (2n+1)\frac{\lambda}{2}$$

$$2t = n\lambda \text{ where } n = 0,1,2,3\ldots$$



Formation of Newton's rings

Theory of Newton's Rings

To find the diameters of dark and bright rings, let 'L' be a lens placed on a glass plate P. The convex surface of the lens is the part of spherical surface (Fig) with center at 'C'. Let R be the radius of curvature and r be the radius of Newton's ring corresponding to the film thickness 't'.

From the property of a circle, NA x NB = NO x ND

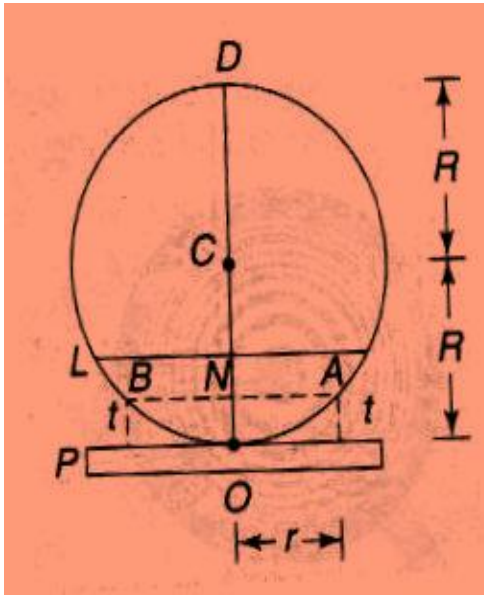
Substituting the values, r x r = t x (2R-t)

$$r^2 = 2Rt - t^2$$

As 't' is small, t^2 will be negligible

$$r^2 = 2Rt$$

$$t = \frac{r^2}{2R}$$



For bright ring, the condition is

$$2t = (2n-1)\frac{\lambda}{2}$$

$$2\frac{r^2}{2R} = (2n-1)\frac{\lambda}{2}$$

$$r^2 = \frac{(2n-1)\lambda R}{2}$$

Replacing r by $\frac{D}{2}$, the diameter of n^{th} bright ring will be

$$\frac{D^2}{4} = \frac{(2n-1)\lambda R}{2}$$

$$D = \sqrt{2n-1}\sqrt{2\lambda R}$$

$$D\ \alpha \sqrt{2n-1}$$

$$D\sqrt{odd\ natural\ number}$$

For dark ring, the condition is

$$2t = n\lambda$$

$$2\frac{r^2}{2R} = n\lambda$$

$$r^2 = n\lambda R$$

$$D^2 = 4n\lambda R$$

$$D = 2\sqrt{n\lambda R}$$

$$D \propto \sqrt{n}$$

$$D \propto \sqrt{natural\ number}$$

Thus, the diameters of dark rings are proportional to the square root of natural numbers.

With the increase in the order (n), the rings get closer and the fringe width decreases and are shown in Fig.

Determination of Wavelength of a Light Source

Let R be the radius of curvature of a Plano-convex lens, λ be the wavelength of light used. Let D_m and D_n are the diameters of m[th] and n[th] dark rings respectively. Then

$$D_m^2 = 4m\lambda R$$

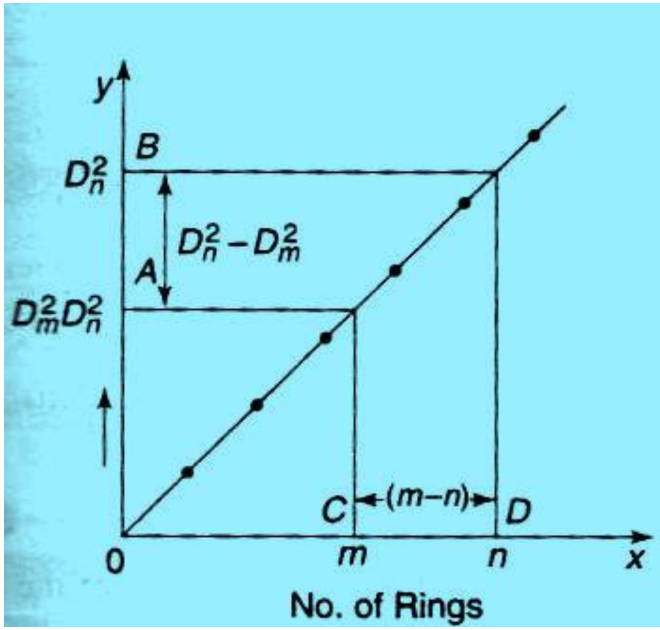
$$\text{and } D_n^2 = 4(n)\,\lambda R$$

$$D_n^2 - D_m^2 = 4(m-n)\;\lambda R$$

$$\lambda = \frac{D_n^2 - D_m^2}{4(m-n)R}$$

Newton's rings are formed with suitable experimental setup. With the help of travelling microscope, the readings for different orders of dark rings were noted from one edge of the rings to the other edge. The diameters of different orders of the rings can be known. A plot between D^2 and the number of rings gives a straight line as shown in the fig.

λ



Plot of D^2 with respect to number of rings

From the graph,

$$\frac{D_n^2 - D_m^2}{(m-n)} = \frac{AB}{CD}$$

The radius R of the Plano-convex lens can be obtained with the help of a Spherometer. Substituting these values in the formula, λ can be calculated.

Determination of Refractive Index of a Liquid

The experiment is performed when there is an air film between glass plate and the Plano-convex lens. The diameters of m^{th} and n^{th} dark rings are determined with the help of travelling microscope. We have

$$D_n^2 - D_m^2 = 4(m-n)\lambda R \qquad \rightarrow (8)$$

The system is placed into the container which consists of the liquid whose refractive index 'μ' is to be determined. Now, the air film is replaced by the liquid film. Again, the diameters of the same m^{th} and n^{th} dark rings are to be obtained. Then we have

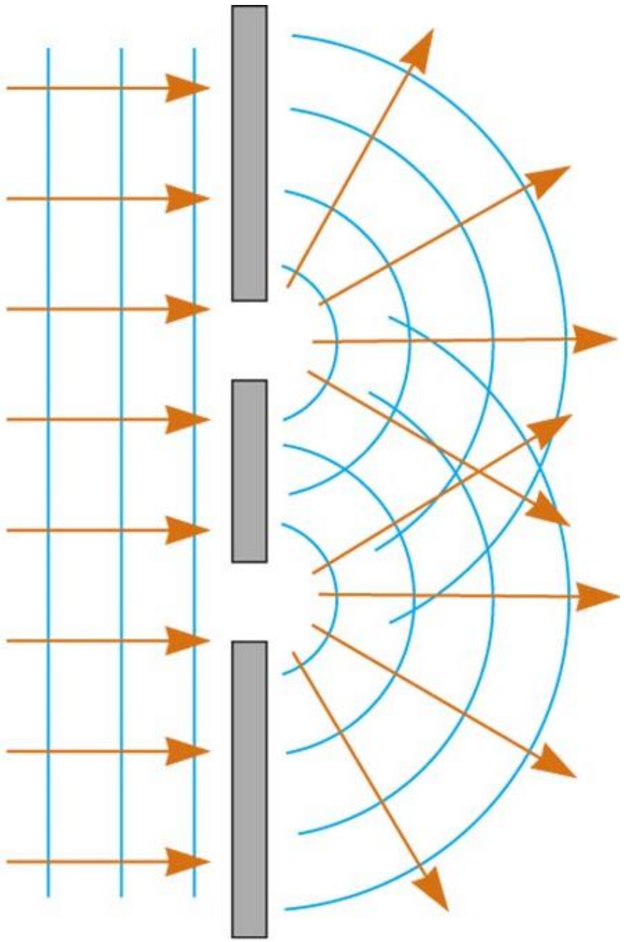
$$D_n'^2 - D_m'^2 = \frac{4(m-n)\lambda R}{\mu} \qquad \rightarrow (9)$$

$$\mu = \frac{D_n^2 - D_m^2}{D_n'^2 - D_m'^2} \qquad \rightarrow (10)$$

Using the above formula, 'μ' can be calculated.

Diffraction is…

- *the bending of waves, esp. sound and light waves, around obstacles in their path.*



Waves tend to curve round the edges of the barriers.

The diffraction phenomena are broadly classified into two types:

1. **Fresnel diffraction,**
2. **Fraunhofer diffraction**

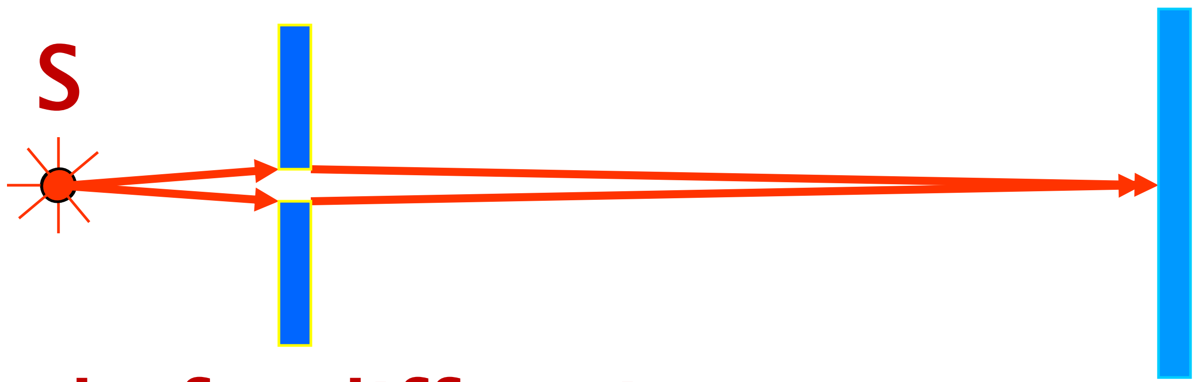
Fresnel diffraction

To study diffraction, there should be a light source, obstacle and screen. In this class of diffraction, the source and screen are placed at finite distances from the obstacle. To study this diffraction, lenses are not necessary as the source and screen are at a finite distance. This diffraction can be studied in the direction of propagation of light. The incident wave fronts are either spherical or cylindrical.

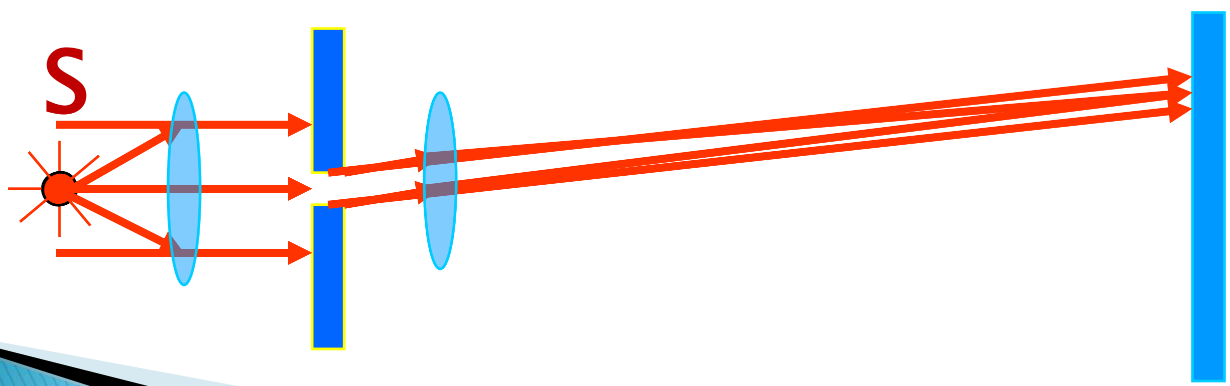
Fraunhofer diffraction

In this class of diffraction, the source and screen are placed at infinite distances from the obstacle. Due to the above fact, lenses are needed to study the diffraction. This diffraction can be studied in any direction. In this case, the incident wave front is plane.

Fresnel diffraction



Fraunhofer diffraction

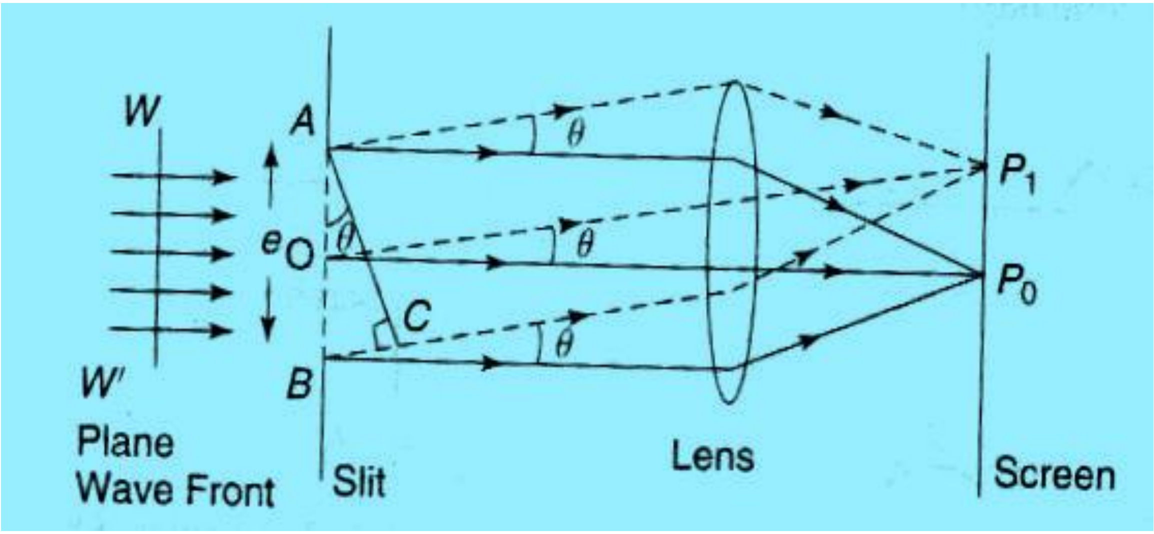


German Optician
Known for the discovery of dark absorption lines (Fraunhofer lines)
1814- Invented SPECTROSCOPE
1821- developed DIFFRACTION GRATING

Joseph von Fraunhofer
(1787-1826)

λ

Fraunhofer Diffraction at Single Slit



Fraunhofer diffraction - Single slit

- ❖ Consider a slit AB of width ‘e’.
- ❖ Let a plane wave front WW’ of monochromatic light of wavelength λ propagating normally towards the slit is incident on it. T
- ❖ he diffracted light through the slit is focused by means of a convex lens on a screen placed in the focal plane of the lens.
- ❖ According to Huygens-Fresnel, every point on the wave front in the plane of the slit is a source of secondary wavelets, which spread out to the right in all directions.

❖ Those wavelets travelling normal to the slit, i.e., along the direction OP_0 are brought to focus at P_0 by the lens. Thus, P_0 is a bright central image.

❖ The secondary wavelets travelling at an angle Θ with the normal are focused at a point P_1 on the screen.

❖ Depending on path difference, the point P_1 may have maximum or minimum intensities.

❖ To find the intensity at P_1, draw the normal AC from A to the light ray at B.

The path difference between the wavelets from A and B in the direction θ is given by

$$\text{Path diff} = BC = AB \sin\theta = e \sin\theta$$

$$\text{Corresponding phase diff} = \frac{2\pi}{\lambda} \text{ x path difference}$$

$$= \frac{2\pi}{\lambda} e \sin\theta$$

Let the width of the slit be divided into n equal parts and the amplitude of the wave from each part is 'a'. The phase difference between any two successive waves from these parts would be

$$\frac{1}{n}[\text{Total phase}] = \frac{1}{n}\left[\frac{2\pi}{\lambda} e \sin\theta\right] = d \text{ (say)}$$

Using the method of vector addition of amplitudes, the resultant amplitude R is given by

$$R = \frac{a \sin nd/2}{\sin d/2}$$

$$= \frac{a \sin(\pi e \sin \theta/\lambda)}{\sin(\pi e \sin \theta/n\lambda)}$$

$$= a \frac{\sin \alpha}{\sin \alpha/n} \text{ where } \boldsymbol{\alpha} = \pi e \sin \theta/\lambda$$

$$= a \frac{\sin \alpha}{\alpha/n} \ (\because \alpha/n \text{ is very small})$$

$$= n \frac{a \sin\alpha}{\alpha} \ (\because na = A)$$

$$= A \frac{\sin \alpha}{\alpha}$$

$$\text{Intensity} = I = R^2 = A^2 \left(\frac{\sin\alpha}{\alpha}\right)^2 \quad \rightarrow (1)$$

Principal Maximum

The resultant amplitude R can be written in ascending powers of $\propto$ as

$$R=\frac{A}{\alpha}\left|\alpha-\frac{\alpha^3}{3!}+\frac{\alpha^5}{5!}-\frac{\alpha^7}{7!}+\cdots\right|$$

$$=A\left|1-\frac{\alpha^2}{3!}+\frac{\alpha^4}{5!}-\frac{\alpha^6}{7!}+\cdots\right|$$

I will be maximum, when value of R is maximum. For maximum value of R, the negative terms must vanish, i.e.,

$$\propto=0$$

$$\frac{\pi e \sin\theta}{\lambda}=0$$

$$\sin\theta=0$$

$$\theta=0 \quad \rightarrow(2)$$

Then R=A

$$I_{max}=R^2=A^2 \quad \rightarrow(3)$$

The condition $\Theta=0$ means that the maximum intensity is formed at P_0 and is known as *principal maximum.*

Minimum Intensity Positions

'I' will be maximum, when $\sin\alpha=0$

$\alpha=\pm\pi, \pm2\pi, \pm3\pi$

$\alpha=\pm m\pi$

$\frac{\pi e \sin\theta}{\lambda}=\pm m\pi$

$e\sin\theta=\pm m\lambda$ where m = 1,2,3… $\rightarrow(4)$

Thus, the points of minimum intensity are obtained on either side of the principal maximum. For m=0, $\sin\theta=0$, which corresponds to principal maximum.

Secondary Maxima

In between these minima, we get secondary maxima. The positions can be obtained by differentiating the expression of I w.r.t **α** and equating to zero. We get

$$\frac{dI}{d\alpha}=\frac{d}{d\alpha}\left[A^2\left(\frac{\sin\alpha}{\alpha}\right)^2\right]=0$$

$$A^2 \cdot \frac{2\sin\alpha}{\alpha} \cdot \frac{\alpha\cos\alpha - \sin\alpha}{\alpha^2}=0$$

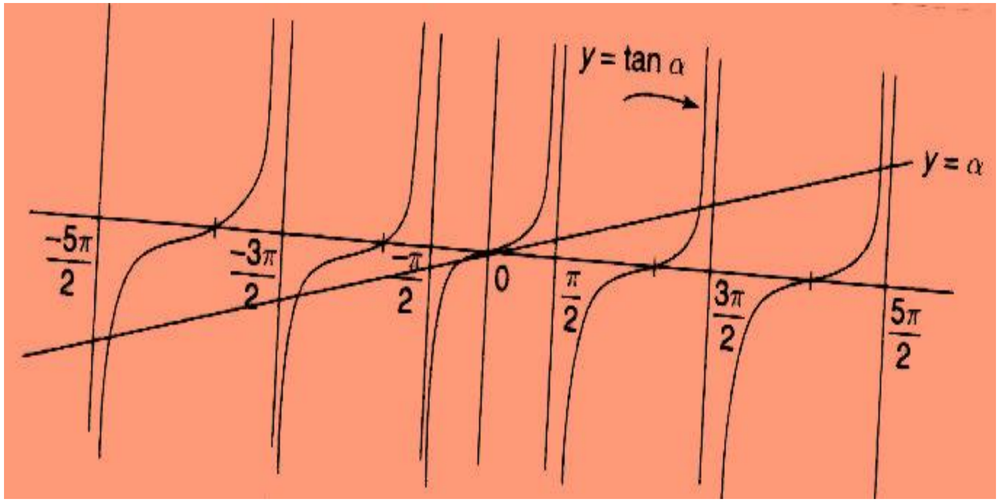
Either sin $\alpha=0$ or $\alpha\cos\alpha - \sin\alpha=0$

Sin $\alpha=0$ gives positions of minima.

Hence the positions of secondary maxima are given by

$$\alpha\cos\alpha - \sin\alpha=0$$

$$\alpha=\tan\alpha \qquad \rightarrow(5)$$



Plots of y=α and y= tanα

The values of α satisfying the above equation are obtained graphically by plotting the curves *y=α and y= tanα* on the same graph. The points of intersection of the two curves give the values of ∝ which satisfy the above equation. The plots of *y=α and y= tanα* are shown in fig.

The points of intersections are

$$\alpha = 0, \pm\frac{3\pi}{2}, \pm\frac{5\pi}{2}\ldots$$

Substituting the above values in equations (1), the intensities in various maxima are obtained.

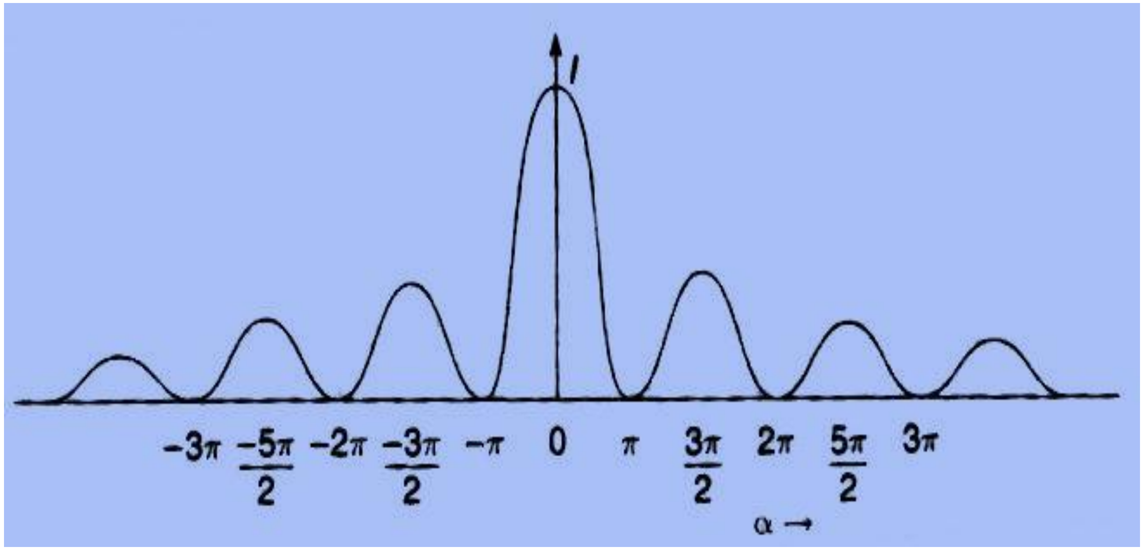
$\alpha = 0,\ I_0 = A^2$ (principal maximum)

$\alpha = \frac{3\pi}{2},\ I_1 = A^2\left[\frac{\sin\left(\frac{3\pi}{2}\right)}{\frac{3\pi}{2}}\right]^2 \approx \frac{A^2}{22}$ (1st secondary maximum)

$\alpha = \frac{5\pi}{2},\ I_2 = A^2\left[\frac{\sin\left(\frac{5\pi}{2}\right)}{\frac{5\pi}{2}}\right]^2 \approx \frac{A^2}{62}$ (2nd secondary maximum)

From the above expressions, it is evident that most of the incident light is concentrated in the principal maximum.

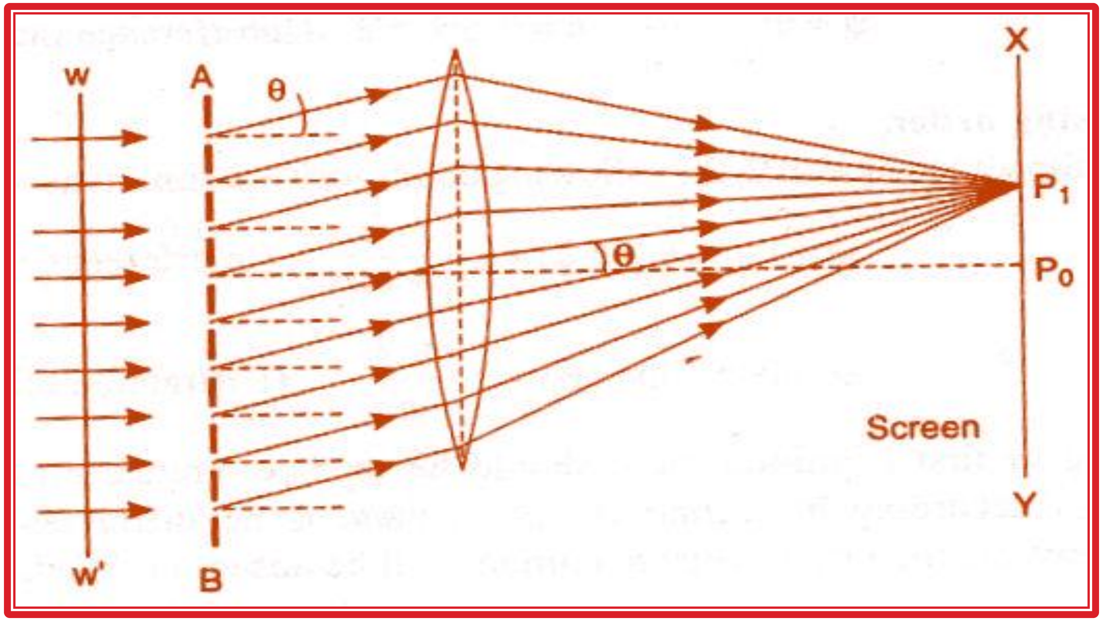
Intensity Distribution



Intensity distribution

The variation of I with respect to ∝ is shown in fig. The diffraction pattern consists of a central principal maximum for α=0. There are secondary maxima of decreasing intensity on either sides of it at positions $\alpha = \pm\frac{3\pi}{2}, \pm\frac{5\pi}{2}$. Between secondary maxima, there are minima at positions $\alpha = \pm\pi, \pm2\pi, \pm3\pi, \ldots$..

Diffraction Grating-Normal incidence–(Diffraction at N parallel slits)



Section of a Plane transmission grating

An arrangement consisting of large number of parallel slits of the same width and separated by equal opaque spaces is known as diffraction grating.

Construction

- ➢ Fraunhofer used the first grating consisting of a large number of parallel wires placed very closely side by side at regular intervals.
- ➢ The diameter of the wires was of the order of 0.05mm and their spacing varied from0.0533 mm to 0.687 mm.
- ➢ Now gratings are constructed by ruling equidistant parallel lines on a transparent material such as glass with a fine diamond point.
- ➢ The ruled lines are opaque to light while the space between any two lines is transparent to light and acts as a slit. This is known as ***Plane transmission grating.***
- ➢ On the other hand, if the lines are drawn on a silvered surface (plane or concave) then the light is reflected from the positions of mirrors in between any two lines and it forms a ***plane or concave reflection grating***.
- ➢ When the spacing between the lines is of the order of the wavelength of light, then an appreciable deviation of light is produced.

Theory

- Let ‘e’ be the width of each slit and ‘d’ be the width of each opaque part.
- Then (e+d) is known as grating element. XY is the screen placed perpendicular to the plane of a paper.
- Suppose a parallel beam of monochromatic light of wavelength λ be incident normally on the grating.
- By Huygen’s principle, each of the slit sends secondary wavelets in all directions.
- The secondary wavelets travelling in the same direction of incident light will come to a focus at a point P_0 of the screen as the screen is placed at the focal plane of the convex lens. The point P_0 will be the central maximum.
- Now, consider the secondary waves travelling in a direction inclined at an angle with the direction of the incident light.
- These waves reach the point P_1 on passing through the convex lens in different phases.
- As a result, dark and bright bands on both sides of the central maximum are obtained.

The intensity at point P_1 may be considered by applying the theory of Fraunhofer diffraction at a single slit. The wavelets proceeding from all points in a slit along the direction Θ are equivalent to a single wave of amplitude (A sin/α) starting from the middle point of the slit, where

α = (π e sinΘ/λ)

If there are N slits, then there will be N diffracted waves, one each from the middle points of the slits. The path difference between two consecutive slits is (e+d) sinΘ. Therefore, there is a corresponding phase difference of (2π/λ). (e+d) sinΘ between the two consecutive waves. The phase difference is constant and it is 2β.

Hence, the problem of determining the intensity in the direction Θ reduces to finding the resultant amplitude of N vibrations each of amplitude (A sinα/α) and having a common phase difference

$$\frac{2\pi}{\lambda}(e+d)\sin\theta = 2\beta \quad \rightarrow (1)$$

Now, by the method of vector addition of amplitudes, the direction of Θ will be

$$R^* = \frac{A\sin\alpha}{\alpha} \cdot \frac{\sin N\beta}{\sin\beta}$$

$$\text{And } I = R^2 = \left(\frac{A\sin\alpha}{\alpha}\right)^2 \left(\frac{\sin N\beta}{\sin\beta}\right)^2 = I_o \left(\frac{\sin\alpha}{\alpha}\right)^2 \left(\frac{\sin^2 N\beta}{\sin^2\beta}\right) \qquad \rightarrow (2)$$

The factor $\left(\frac{A\sin\alpha}{\alpha}\right)^2$ gives the distribution of intensity due to single slit while the factor ($\sin^2$ $\sin^2\beta$) gives the distribution of intensity as a combined effect of all the slits.

Intensity distribution in N-Slits

Principle maxima

The intensity would be maximum when sinβ = 0.

or $\beta = \pm n\pi$ *where*, n=0, 1, 2, 3,…

but at the same time sin Nβ = 0, so that the factor (sinNβ/sinβ) becomes indeterminate. It may be evaluated by applying the usual method of differentiating the numerator and the denominator, i.e., by applying the Hospital’s rule. Thus,

$$\lim_{\beta \to \pm n\pi} \frac{\sin N\beta}{\sin\beta}$$

$$= \lim_{\beta \to \pm n\pi} \left(\frac{\frac{d}{d\beta}(\sin N\beta)}{\frac{d}{d\beta}(\sin\beta)} \right)$$

$$\lim_{\beta \to \pm n\pi} \left(\frac{N\cos N\beta}{\cos\beta} \right) = \pm N$$

$$\text{Hence, } \lim_{\beta \to \pm n\pi} \left(\frac{\sin N\beta}{\sin\beta} \right)^2 = N^2$$

The resultant intensity is $\left(\frac{A \sin\alpha}{\alpha}\right) N^2$. The maxima are most intense and are called as principal maxima.

The maxima are obtained for

$$\beta = \pm n\pi$$

$$\frac{\pi}{\lambda}(e+d)\sin\theta = \pm n\pi$$

$or\ (e+d)\sin\theta = \pm n\lambda$ Where, n= 0, 1, 2, 3….

$n = 0$ corresponds to zero order maximum. For n=1, 2, 3...etc., the first, second, third, etc., principal maxima are obtained respectively. The $\pm$ sign shows that there are two principal maxima of the same order lying on the either side of zero order maximum.

Minima

A series of minima occur, when

$$\sin N\beta = 0 \qquad \text{but } \sin\beta \neq 0$$

For minima,

$$\sin N\beta = 0$$

$$N\beta = \pm m\pi$$

$$N\frac{\pi}{\lambda}(e+d)\sin\theta = \pm m\pi$$

$$N(e+d)\sin\theta = \pm m\lambda$$

Where m has all integral values except 0, N, 2N …nN, because for these values sinβ becomes zero and the principal maxima is obtained. Thus, m = 1, 2, 3… (N-1). Hence, they are adjacent principal maxima.

Secondary maxima

As there are (N-1) minima between two adjacent principal maxima, there must be (N-2) other maxima between two principal maxima. To find out the position of these secondary maxima, equation (2) must be differentiated with respect to β and then equate it to zero. Thus,

$$\frac{dI}{d\beta} = \left(\frac{A\sin\alpha}{\alpha}\right)^2 . \, 2\left(\frac{\sin N\beta}{\sin\beta}\right)$$

$$\left[\frac{N\cos N\beta\,\sin\beta - \sin N\beta\,\cos\beta}{\sin^2\beta}\right] = 0 \text{ or}$$

$$N\cos N\beta\,\sin\beta - \sin N\beta\,\cos\beta = 0$$

$$N\tan\beta = \tan N\beta$$

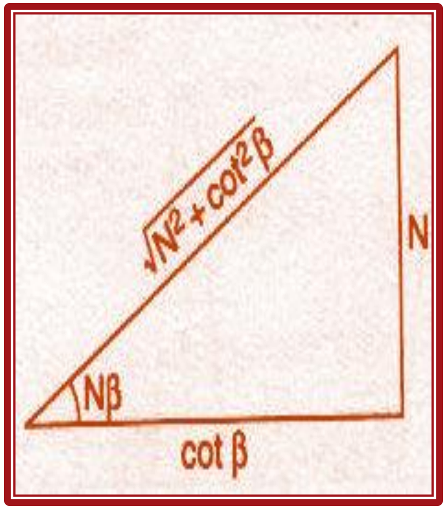
The roots of this equation other than those for which $\beta = \pm n\pi$ (which correspond to principal maxima) give the positions of secondary maxima. To find out the value of $(\sin^2 N\beta/\sin^2\beta)$ from equation $N\tan\beta = \tan N\beta$, a triangle shown below, in the figure is used.

$$\text{Sin } N\beta = \frac{N}{\sqrt{(N^2+\cot^2\beta)}}$$

$$\frac{\sin^2 N\beta}{\sin^2\beta} = \frac{N^2}{(N^2+\cot^2\beta)\times\sin^2\beta}$$

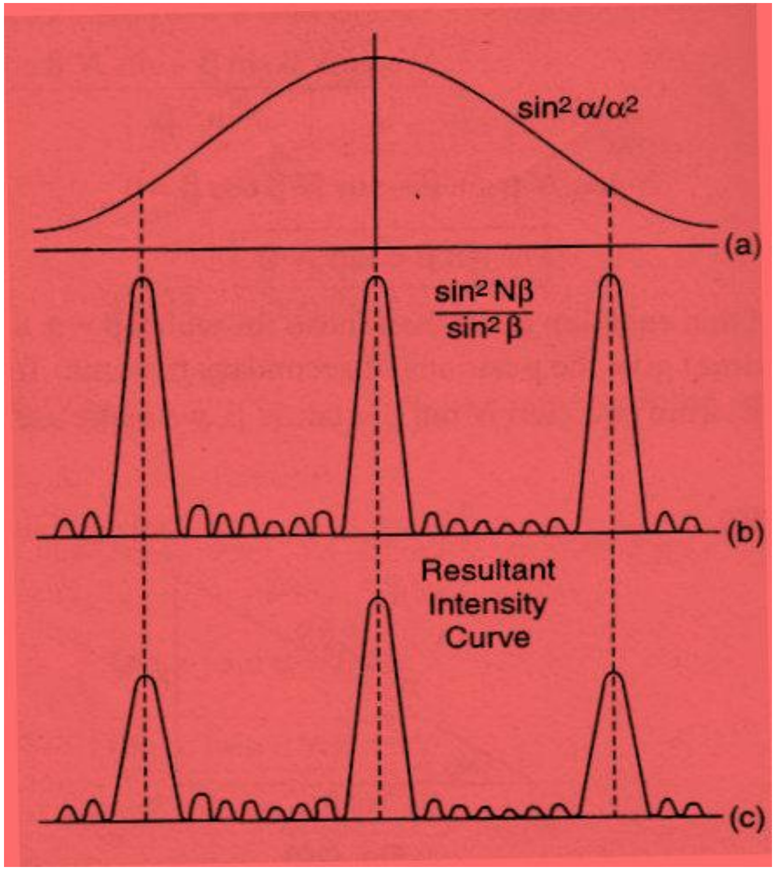
$$= \frac{N^2}{N^2\sin^2\beta+\cos^2\beta}$$

$$= \frac{N^2}{1+(N^2-1)\sin^2\beta}$$



Therefore, $$\frac{\text{Intensity of secondary maxima}}{\text{Intensity of principal maxima}} = \frac{1}{1+(N^2-1)\sin^2\beta}$$

As N increases, the intensity of secondary maxima relative to principal maxima decreases and becomes negligible when N becomes large.



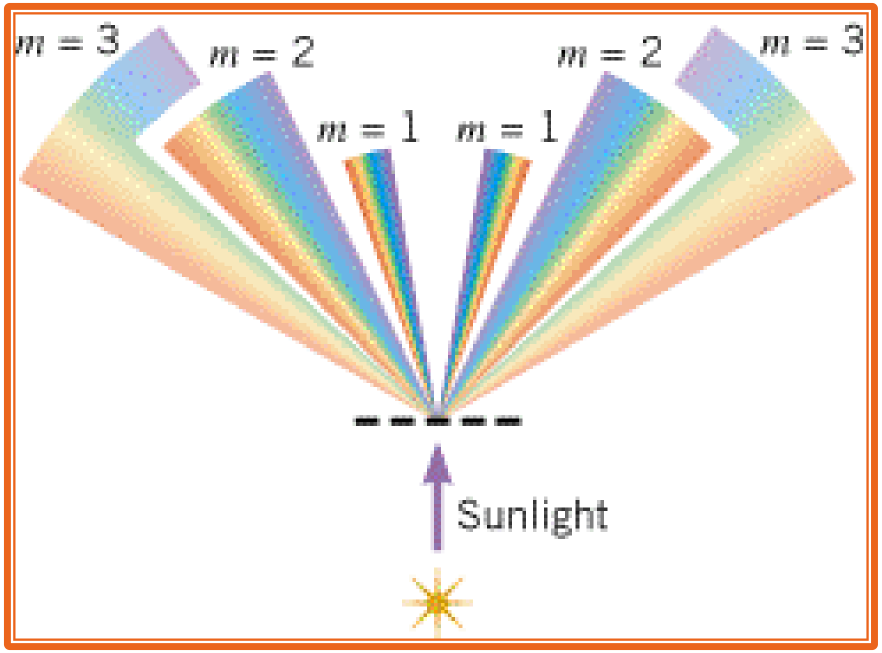
(a) & (b) Graphs showing the variation of intensity (c) The Resultant

Figures (a) and (b) show the graphs of variation of intensity due to the factors $sin^2 \alpha/\alpha^2$ and $sin^2 N\beta / sin^2 \beta$ respectively. The resultant is shown in figure (c).

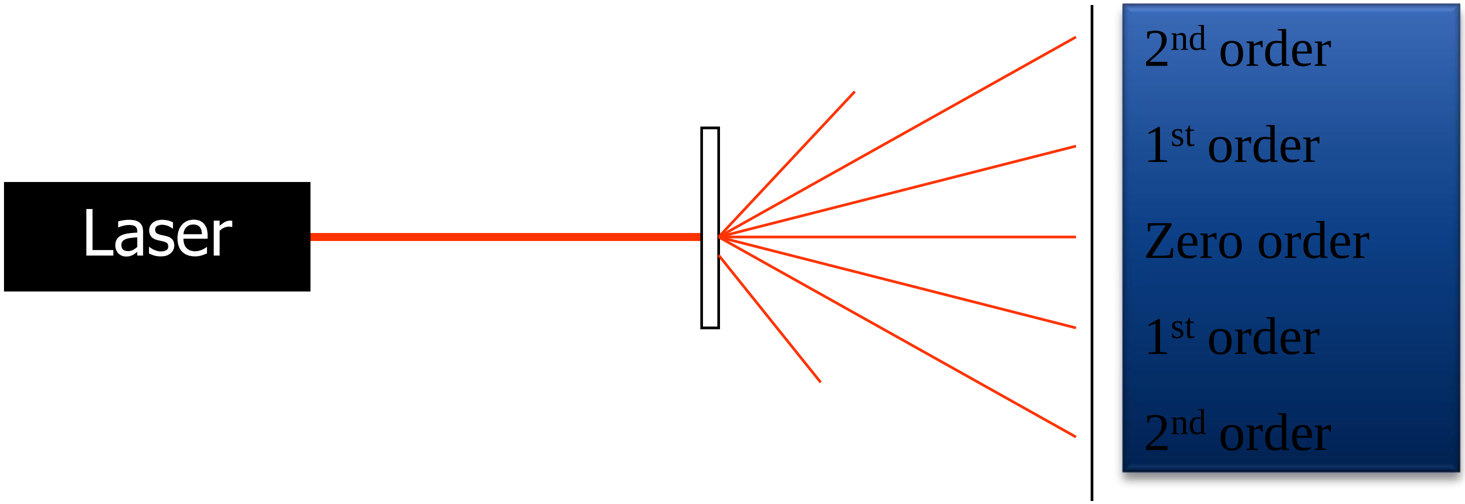
Diffraction Grating

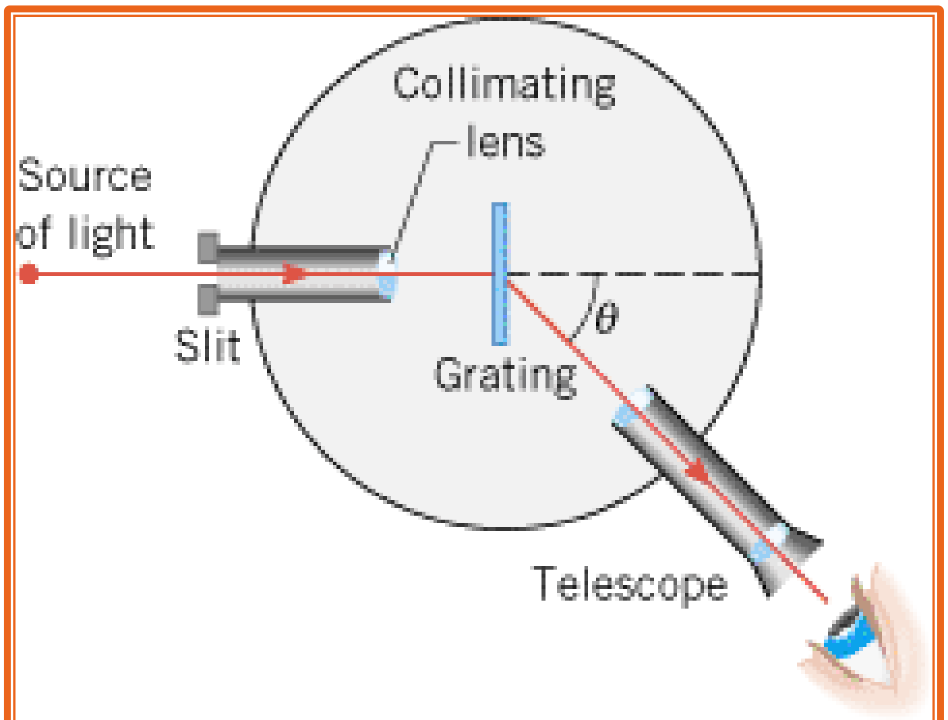
- To determine the wavelengths emitted by the atomic element in a discharge tube and to identify the element

A large number of equally spaced parallel slits is called a **diffraction grating.**



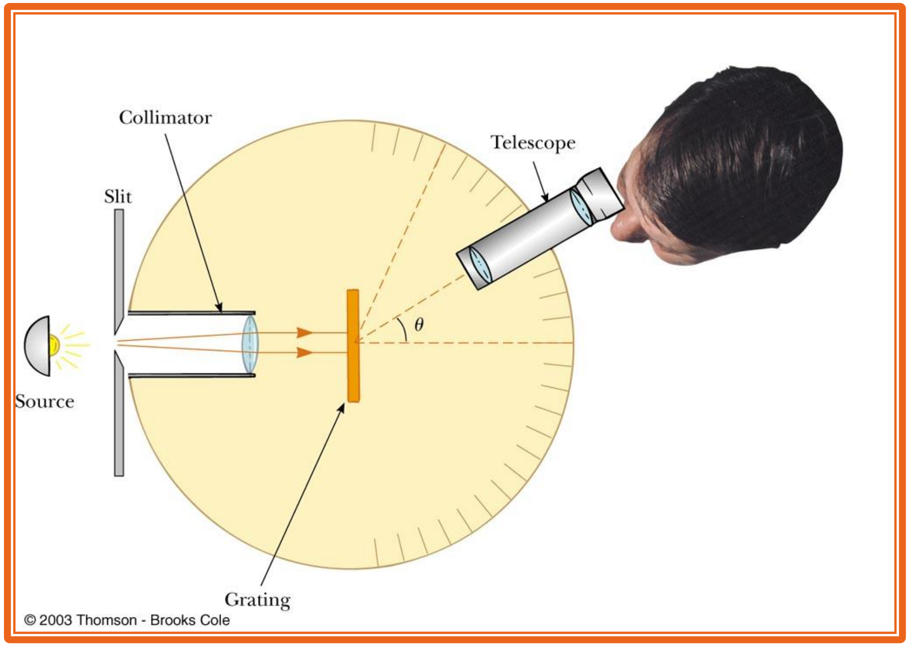
When sunlight falls on a diffraction grating, a rainbow of colors is produced at each principal maximum ($m = 1, 2, \ldots$). The central maximum ($m = 0$), however, is white but is not shown in the drawing.





A GRATING SPECTROSCOPE

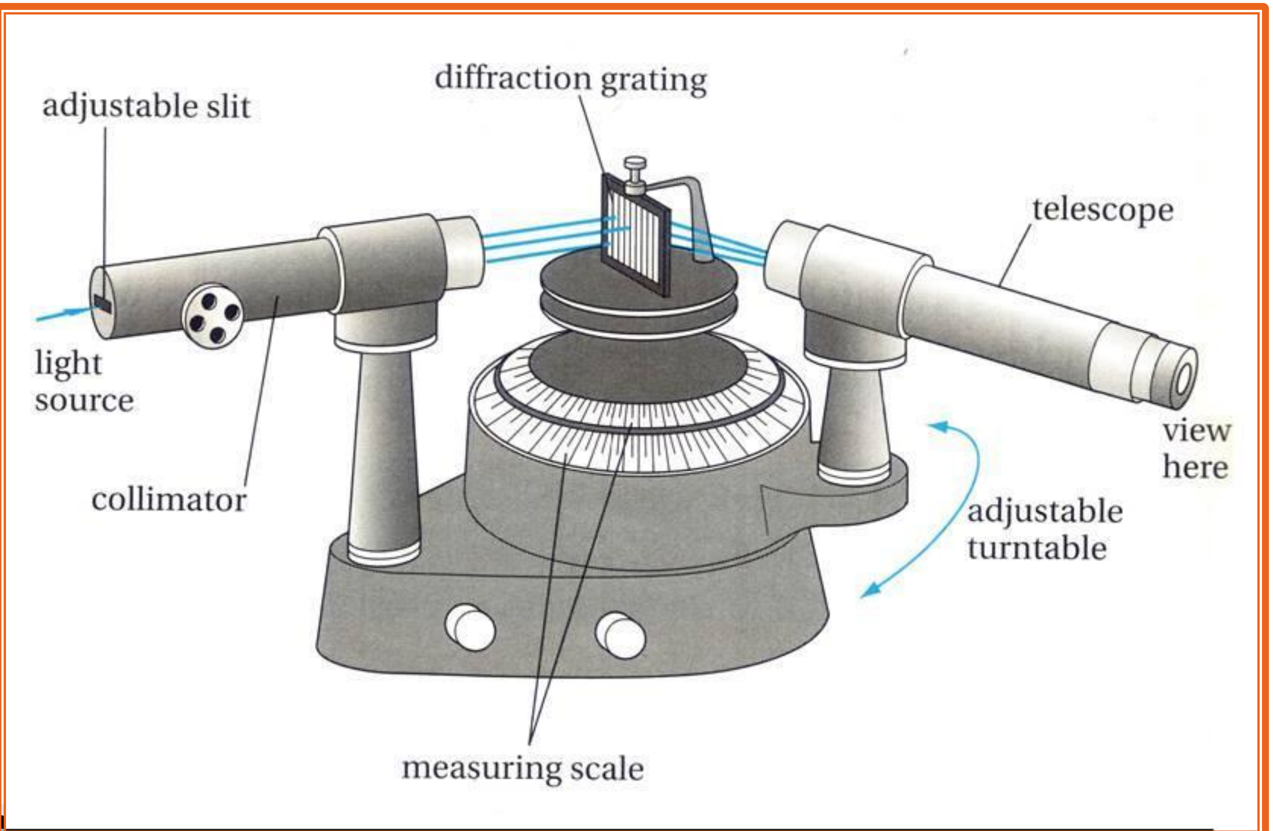
Grating spectrometer



- The light to be analyzed passes through a slit and is formed into a parallel beam by a lens. The diffracted light leaves the grating at angles that satisfy $d \sin\theta_{bright} = m\lambda$

Spectrometer

- Collimator → parallel light → diffraction grating
- Pattern observed
- θ measured ∴ find λ



Apparatus

The spectrometer is made up of three parts:

the collimator – an optical device which produces a parallel beam of light from your monochromatic light source

the telescope – an optical device which focuses a beam of parallel light in the plane of the crosshairs

the turntable – supports the diffraction grating and enables measurement of the angular position of the telescope

DO NOT TOUCH THE RULED SURFACE OF THE GRATING

Thank you