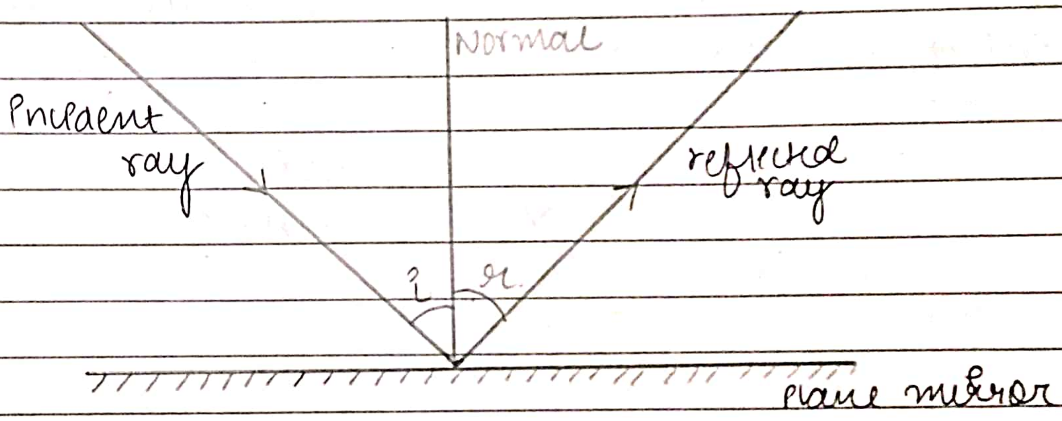
Date 30/09/20.

Chapter-9

Ray optics

> Ray optics

Bouncing back of light after striking an optical plane surface is called Reflection.



$\angle i \rightarrow$ angle of incidence
$\angle r \rightarrow$ angle of reflection.

when $\angle i = \angle r$, we can see our image and is called regular reflection. It is done on smooth surface. And $\angle i = \angle r$ always.

when $\angle i \neq \angle r$, no image is formed and formed on rough surfaces; Always $\angle i \neq \angle r$.

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Laws of reflection

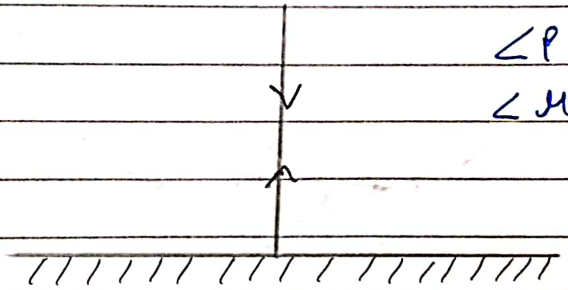
I] Incident, reflected ray and Normal at the point of incidence all lie in the same plane.

II] Angle of incidence = Angle of reflection.

$[\angle i = \angle r]$

Q If a incident ray goes along the normal. Trace the path of reflected ray.

Ans



$\angle i = 0$

$\angle r = 0$

Reflected ray will re-trace its path.

Types of Reflection :-

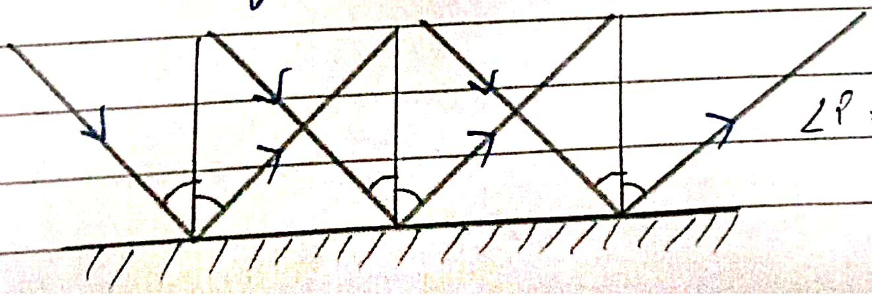
(i) Regular reflection

Characteristics :-

1) $\angle i = \angle r$ [always]

2) Images are seen.

3) Reflected surface is smooth and plane.



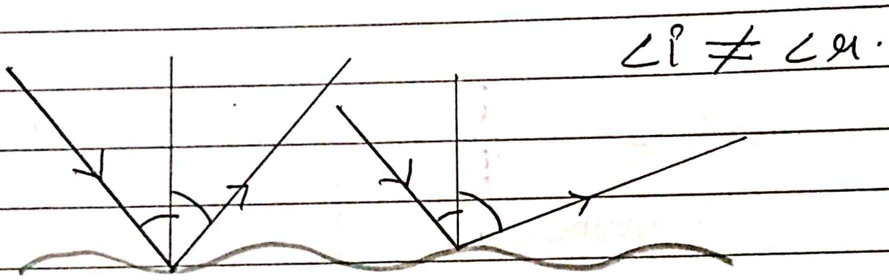
$\angle i = \angle r$

Spiral

2) Diffused reflection

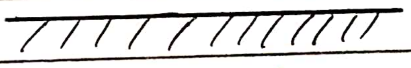
characteristics :-

1) $\angle i \neq \angle r$ [always]
2) No image is formed
3) The surfaces are rough or uneven.



:- Types of mirror

1) Plane mirror

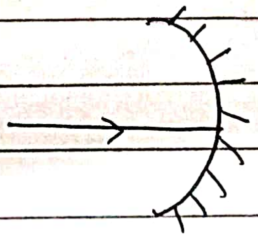


$f = \infty$
Infinity

2) Spherical mirror

1) Convex mirror

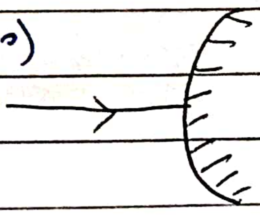
°)



°) convergent

2) concave mirror

°)



°) divergent

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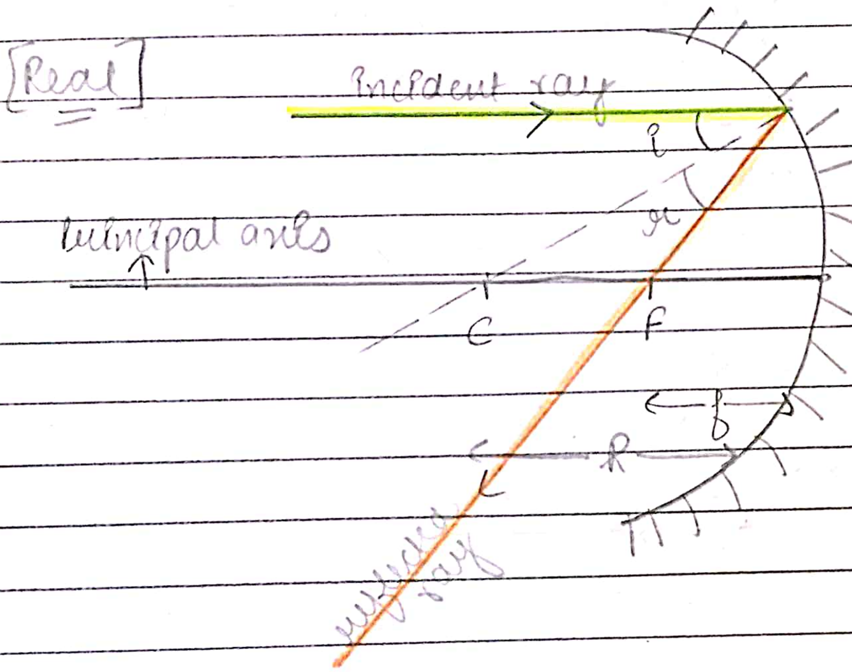
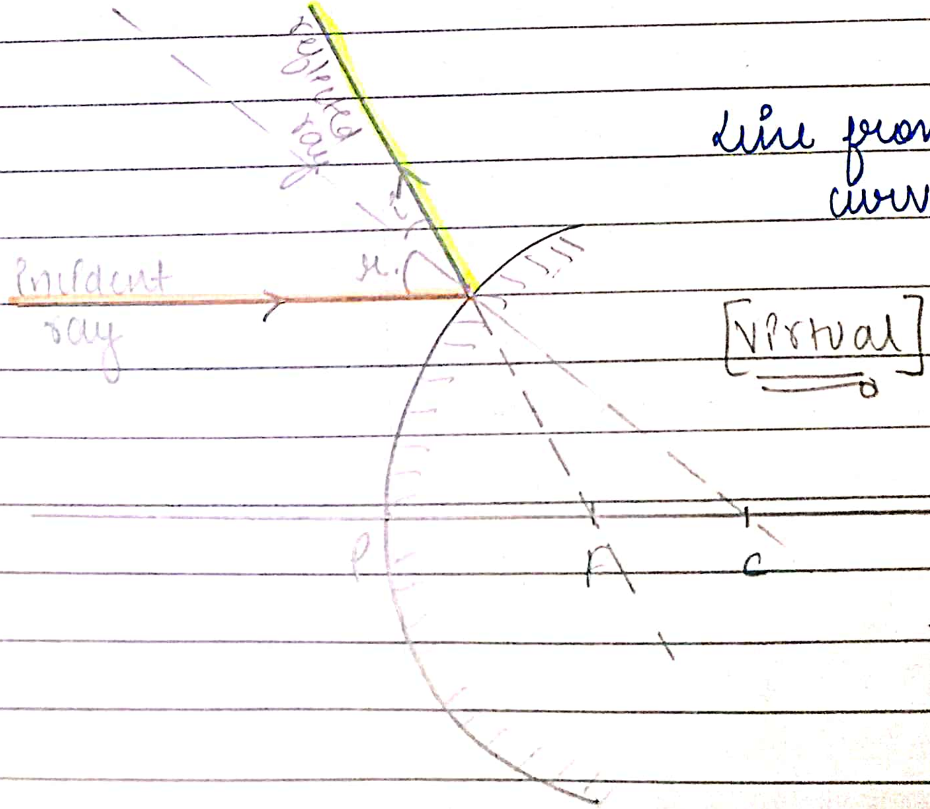
- Ray & sign conventions in mirrors

1) Any ray parallel to principal axis will pass or appear to pass through focus.



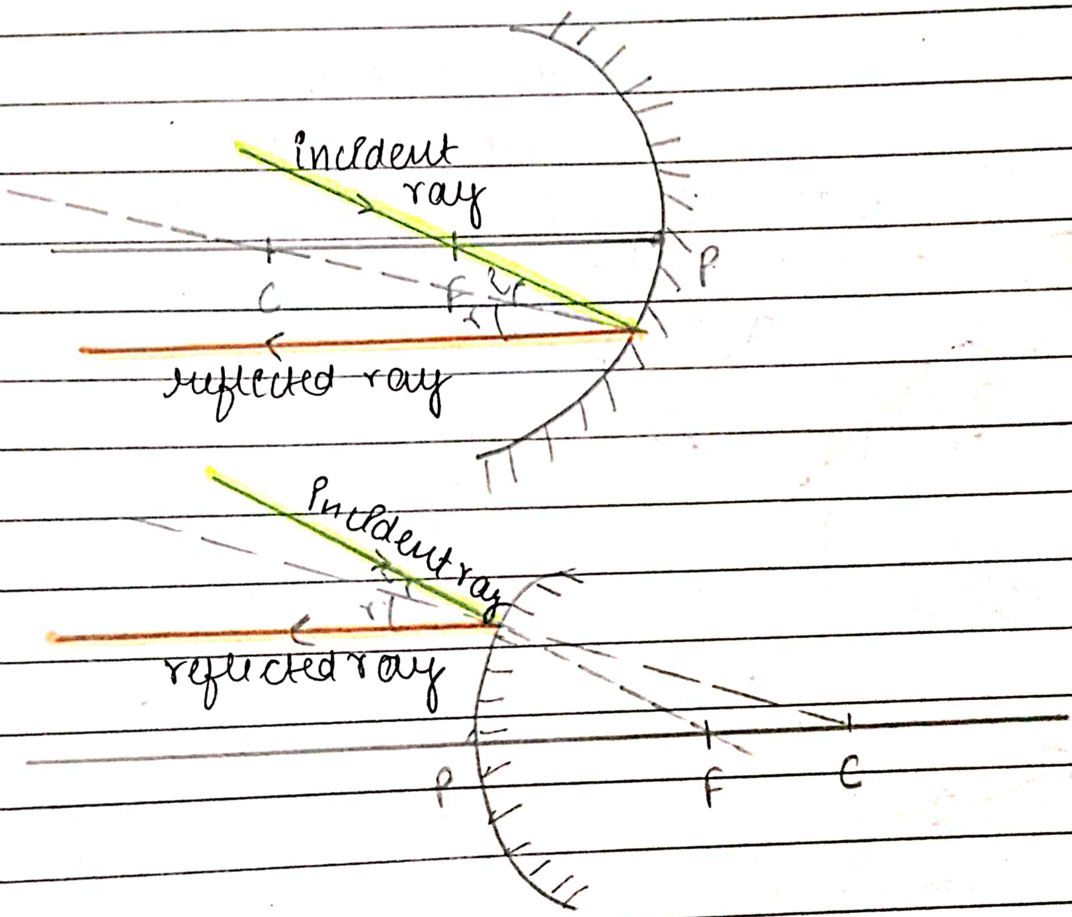
P → Pole
C → centre of curvature
F → Focus
f → focal length.
[Dis b/w pole and focus].

R → Radius of curvature
[Dis b/w pole and centre of curvature]

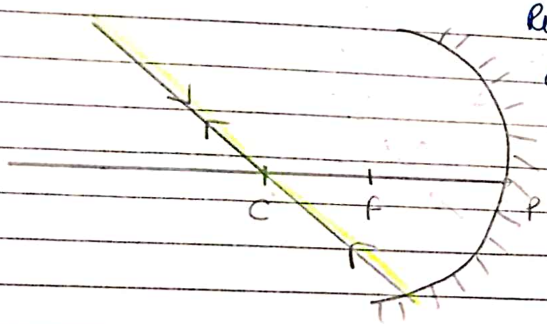


Line from the centre of curvature becomes NORMAL

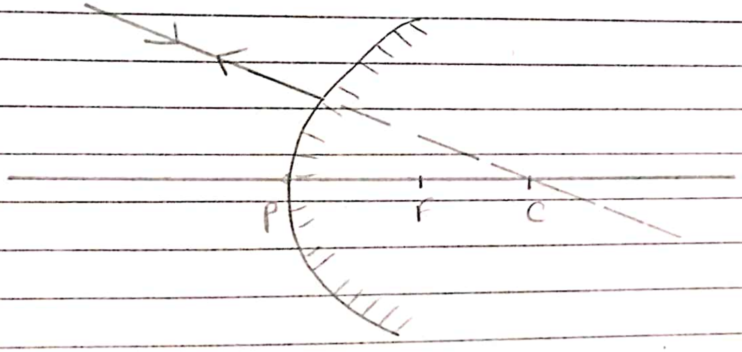
2) Any ray passing through focus after reflection becomes parallel to principal axis.



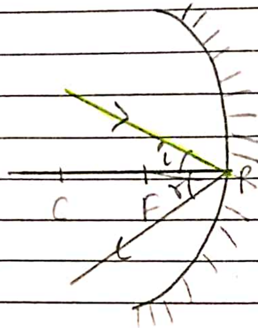
3) Any ray passes through centre of curvature will re-trace its path after reflection.



Reason → Normal is drawn from centre of curvature.



4) A ray incident obliquely at pole is reflected obliquely.



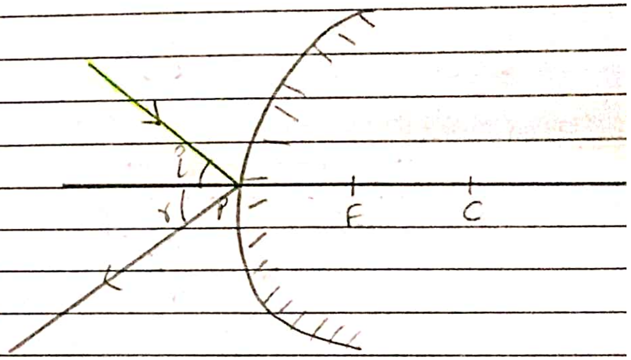


Image formation in concave mirror

1) when object is at infinity.

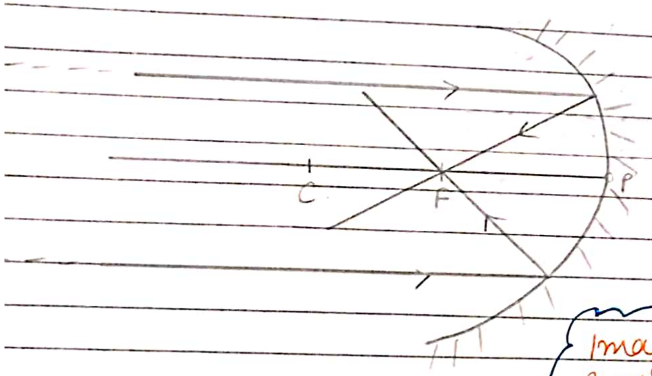


Image formed at Focus
Real & point in size.
Magnification = 0.

when object is kept beyond C.

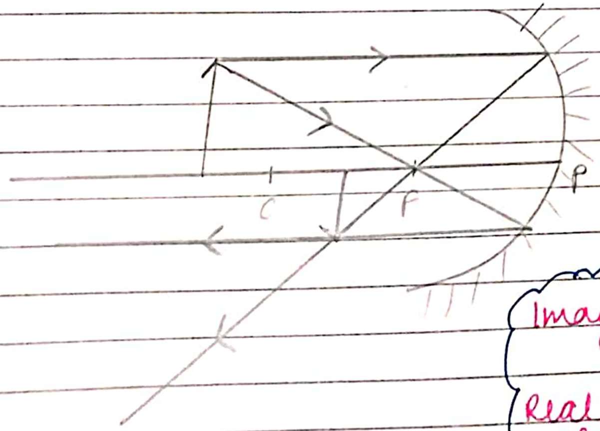
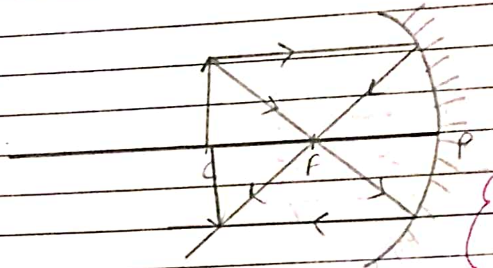


Image is formed b/w
F and C.
Real Inverted & smaller in
size.
$m = -ve$ / $m < 1$.

3) when object is kept at C.

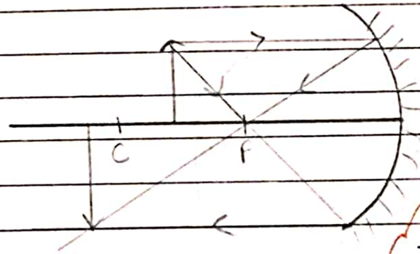


→ Image is formed at C.

→ Real; Inverted & same in size.

→ $m = -1$.

4) when object is kept b/w F and C.

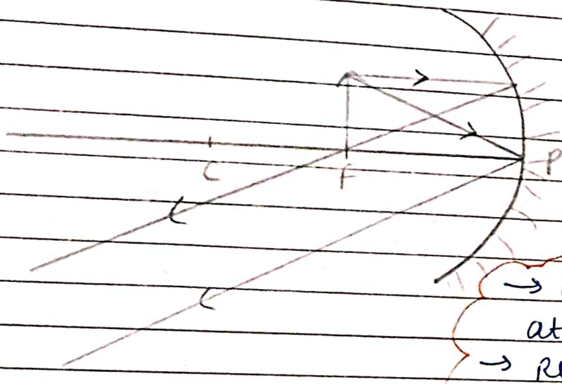


→ Image is formed beyond C.

→ Real; Inverted and la
in size.

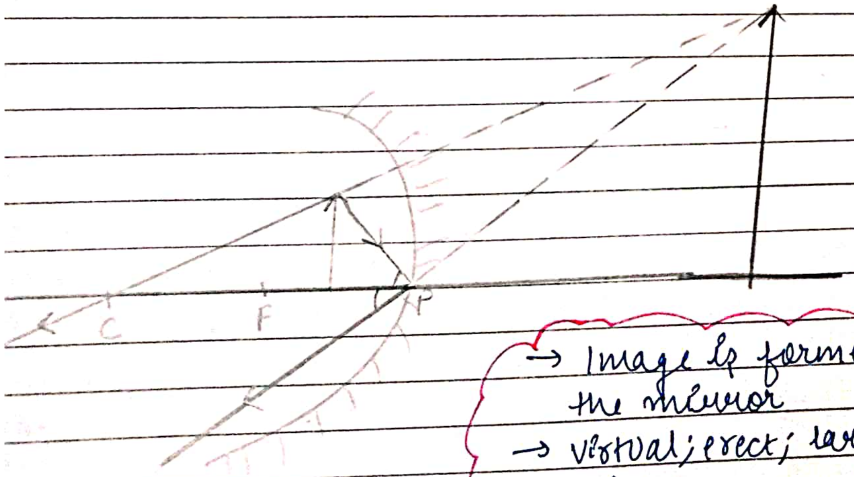
→ $m = -ve$
$m > 1$.

) when object is kept at focus.



→ Image is formed at infinity.
→ Real & infinite in size.
→ m = −∞.

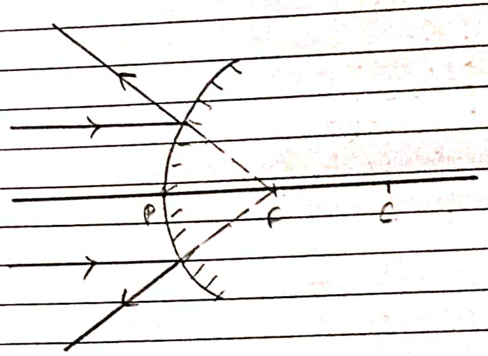
when object is kept b/w P and F.



→ Image is formed behind the mirror
→ virtual; erect; large in size
→ m = +ve; m = >1.

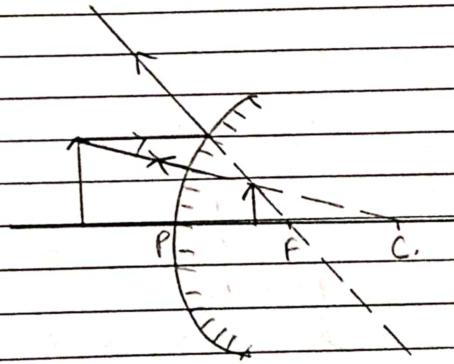
Image formation by convex mirror

(1.) when object is kept at infinity.



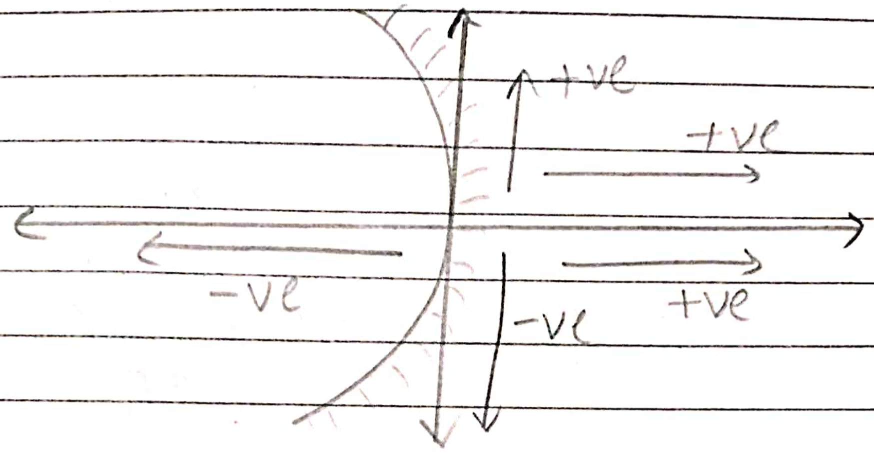
→ Image is virtually formed at focus
→ m = +ve
m = 0

(2.) when object is kept anywhere on principal axis



→ Image is formed b/w P & F
→ Virtual; erect; smaller in size.
→ used in vehicles are rear view mirror.
→ m = +ve ; <1

Sign conventions



→ Distance above principal axis = +ve.
→ Distance below principal axis = -ve.
→ LHS of mirror = -ve
→ R.H.S of mirror = +ve.

Signs

Concave mirror

$u = -ve$
$f = -ve$
$h = +ve$
$h' = ?$
$v = ?$

Convex mirror.

$u = -ve$
$v = +ve$
$f = +ve$
$h = +ve.$
$h' = +ve.$

Q $m = +1$.
which mirror is this
a) concave b) convex c) Plane d) None of these.
→ Plane mirror

Q $m = +\frac{1}{3}$.
which mirror is this
a) Concave b) convex c) Plane d) None of these.
→ convex mirror

Q $m = -3$
which mirror is this
a) concave b) convex c) Plane d) None of these.
→ concave mirror

Q $m = +2$.
which mirror is this
a) concave b) convex c) Plane d) None of these.
→ concave mirror

Q $m = -1$
which mirror is this
(a) concave b) convex c) Plane d) None of these.
→ Concave mirror.

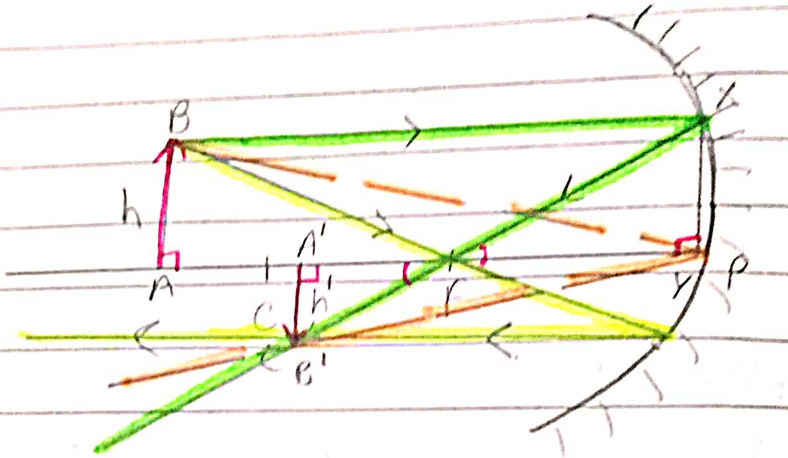
Imp.

Mirror formula:-

$$\frac{1}{f} = \frac{1}{v} + \frac{1}{u}.$$

$PA = -u$
$PA' = -v$
$PF = -f$
$h = +ve$
$h' = -ve.$

Using concave mirror.



$\Delta ABP \sim \Delta A'BP'$

$$\frac{AB}{A'B'} = \frac{PA}{PA'} \longrightarrow ①$$

$\Delta XYF \sim \Delta A'B'F$

$$\frac{XY}{A'B'} = \frac{YF}{FA'}$$

$$\frac{AB}{A'B'} = \frac{PF}{PA' - PF} \longrightarrow ②$$

Comparing ① & ②;

$$\frac{PA}{PA'} = \frac{PF}{PA' - PF.}$$

$$\frac{+u}{+v} = \frac{-f}{-v+f}$$

Reciprocal;

$$\frac{v}{u} = \frac{-v+f}{-f}$$

$$\frac{v}{u} = \frac{v}{f} - 1.$$

Dividing by v;

$$\frac{1}{u} = \frac{1}{f} - \frac{1}{v}$$

$$\boxed{\frac{1}{v} + \frac{1}{u} = \frac{1}{f}}$$ —— mirror formula.

- Magnification - Ratio of size of image to size of object.

$$m = \frac{h'}{h}.$$

eqⁿ ①;

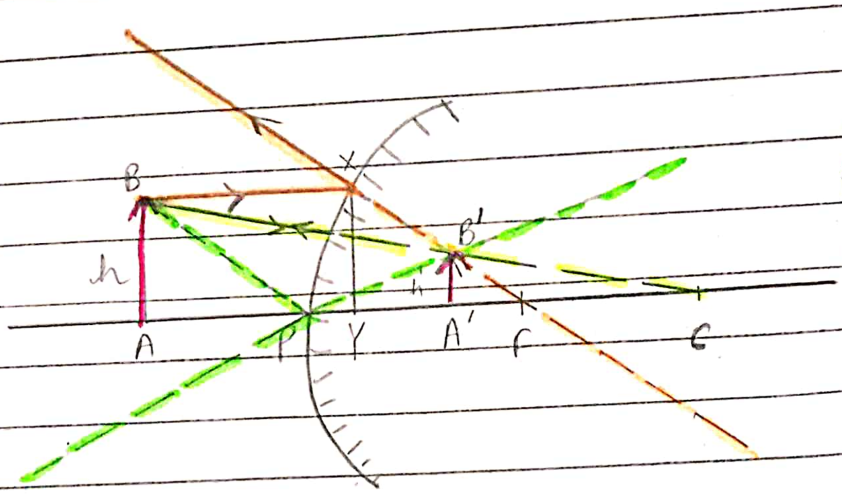
$$\frac{AB}{A'B'} = \frac{PA}{PA'}$$

$$\frac{h}{h'} = \frac{+u}{+v}$$

$$\frac{-h'}{h} = \frac{v}{u}$$

$$\boxed{m = \frac{-v}{u}}$$

Mirror formula using convex mirror



PA = −u

PA' = +v

PF = +f

AB = +h

A'B' = +h'

Δ ABP ∼ Δ A'B'P

$$\frac{AB}{A'B'} = \frac{PA}{PA'} \quad \text{——} \quad ①$$

Δ XYF ∼ Δ A'B'F.

$$\frac{XY}{A'B'} = \frac{YF}{FA'} \quad \text{——}$$

$$\frac{AB}{A'B'} = \frac{PF}{PF-PA'} \rightarrow ②$$

Dividing ① & ②;

$$\frac{PA}{PA'} = \frac{PF}{PF-PA'}$$

$$\frac{-u}{+v} = \frac{+f}{+f-v}$$

Reciprocal;

$$\frac{-v}{u} = \frac{f-v}{f}.$$

$$\frac{-v}{u} = 1 - \frac{v}{f}.$$

Dividing by v;

$$-\frac{1}{u} = \frac{1}{v} - \frac{1}{f}$$

$$\boxed{\frac{1}{v} + \frac{1}{u} = \frac{1}{f}}$$ —— Mirror formula.

Ratio of size of image to the size of object:

$$m = \frac{h'}{h}.$$

eqn ① ;

$$\frac{AB}{A'B'} = \frac{PA}{PA'}$$

$$\frac{h}{h'} = \frac{-v}{+u}$$

$$\boxed{\frac{h'}{h} = \frac{-v}{u}}$$

Q An object of size 4 cm is kept at 20cm from a convex mirror of focal length 15cm. Find position; size & nature of image.

→ $h = +4\text{cm}$.

$u = -20\text{cm}$.

$f = +15\text{cm}$.

$$\frac{1}{f} = \frac{1}{v} + \frac{1}{u}$$

$$\frac{1}{25} = \frac{1}{v} - \frac{1}{20}$$

$\frac{25}{2}$

$$\frac{1}{15} + \frac{1}{20} = \frac{1}{v}$$

$$\frac{20+15}{300} = \frac{1}{v}$$

$$\frac{\overset{7}{\cancel{35}}}{\underset{60}{\cancel{300}}} = \frac{1}{v}$$

$$v = \frac{60}{7}\text{ cm}.$$

Hence; the image formed is virtual; erect & smaller in size.

$$\frac{h'}{h} = \frac{-v}{u}$$

$$\frac{h'}{4} = \frac{-60}{70} \times \div 20$$

$$h' = \frac{-\overset{3}{\cancel{60}}}{7} \times \frac{\cancel{20} \times 4}{\cancel{20}}$$

$$h' \Rightarrow +\frac{12}{7}\text{ cm}.$$

Q. A concave mirror of focal length 20cm form the real image twice the size of object. Find position of object & image.

→ $f = -20$ cm.

$h' = -2$ (size of object).

$$h' = -2h$$

$$\frac{h'}{h} = \frac{-v}{u}$$

$$\frac{+2}{1} = \frac{+v}{u}$$

$$\boxed{v = 2u}$$

$$\frac{1}{f} = \frac{1}{v} + \frac{1}{u}$$

$$-\frac{1}{20} = \frac{1}{2u} + \frac{1}{u}$$

$$-\frac{1}{20} = \frac{1+2u}{2u^2}.$$

$$-\frac{1}{20} = \frac{3u}{2u^2}$$

$$-\frac{1}{20} = \frac{3}{2u} \qquad \boxed{u = -30 \text{ cm}}$$

$$-60 = 2u \qquad \boxed{v = -60 \text{ cm}}$$

Refraction → Bending of light when it travels from one medium to another. There are two types of optical medium:-

① Rarer medium → in which particles are away from each other. speed of light is more in rarer medium.

② Denser medium → in which particles are closer and speed of light will be less.

① When a ray goes from rarer to denser medium; it bends itself towards the normal.

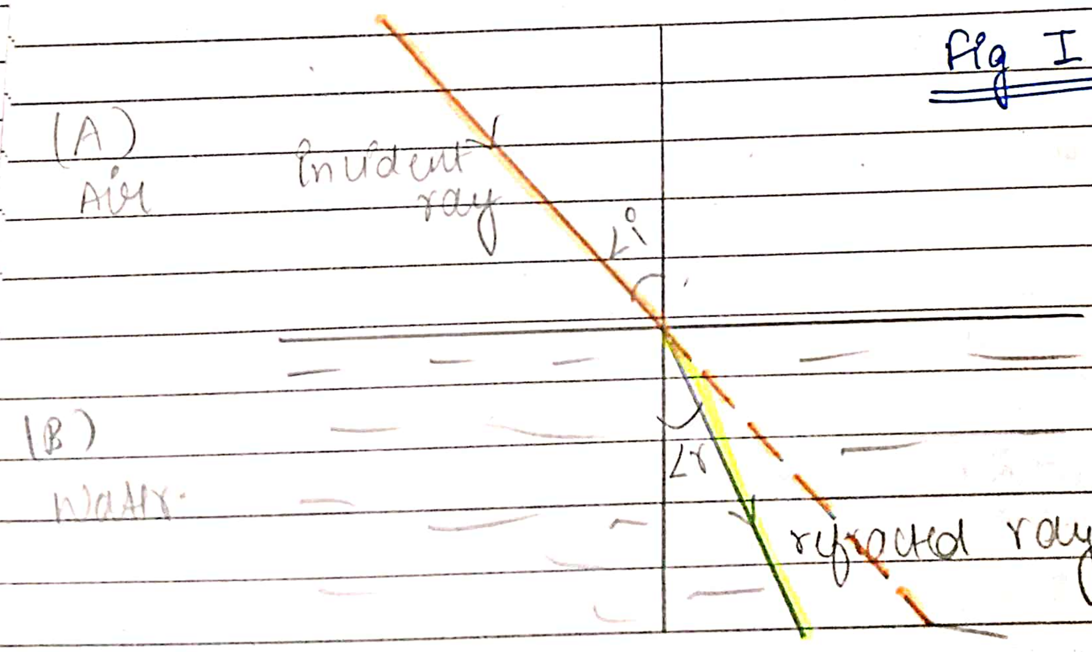


Fig I

$\angle i$ → angle of incidence

$\angle r$ → angle of refraction

$\angle i \neq \angle r$.

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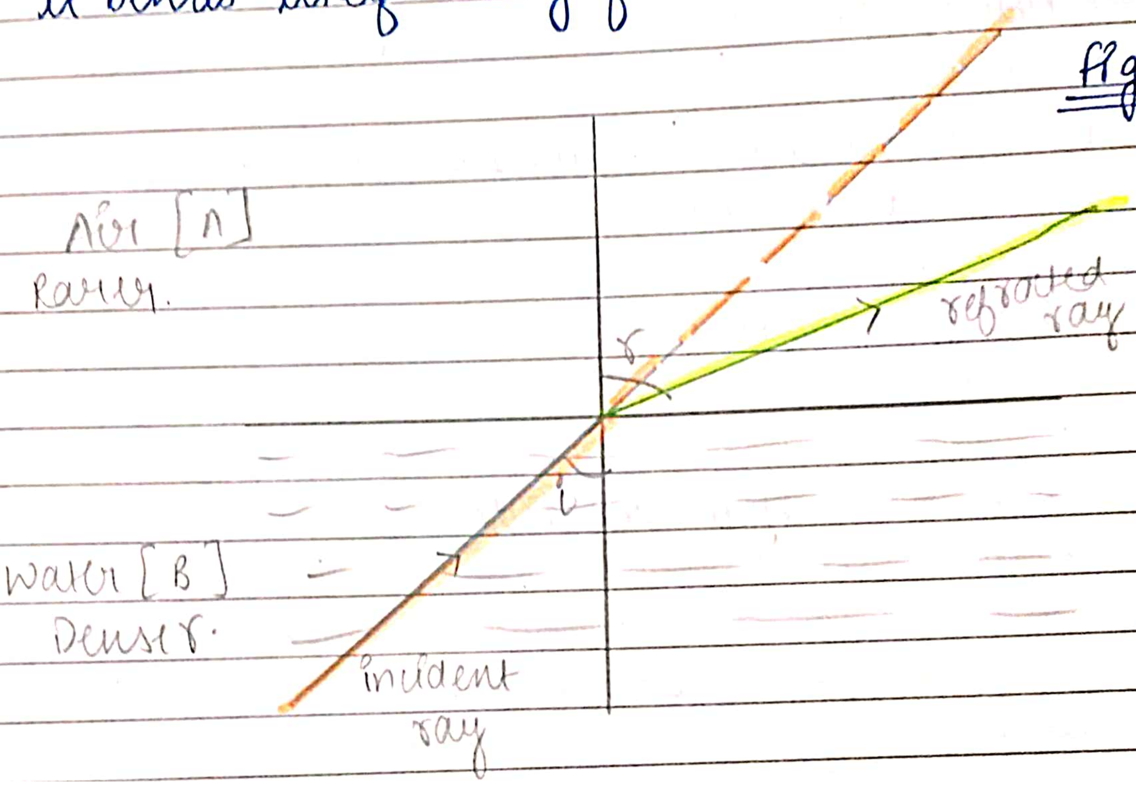
② When a ray goes from denser to rarer medium; it bends itself away from normal.

Fig II



Laws of refraction :-

① Incident ray ; refracted ray & normal all lie in the same plane.

② Ratio of sine angle of incidence to sine angle of refraction is a constant.

$$\frac{\sin i}{\sin r} = \text{constant}$$

$$\frac{\sin i}{\sin r} = \text{refractive index}$$

$$\boxed{\frac{\sin i}{\sin r} = n} \longrightarrow \text{Snell's law}$$

[n → always find in comparison to something]

n_{ba} → ref. index of medium b with respect to medium a.

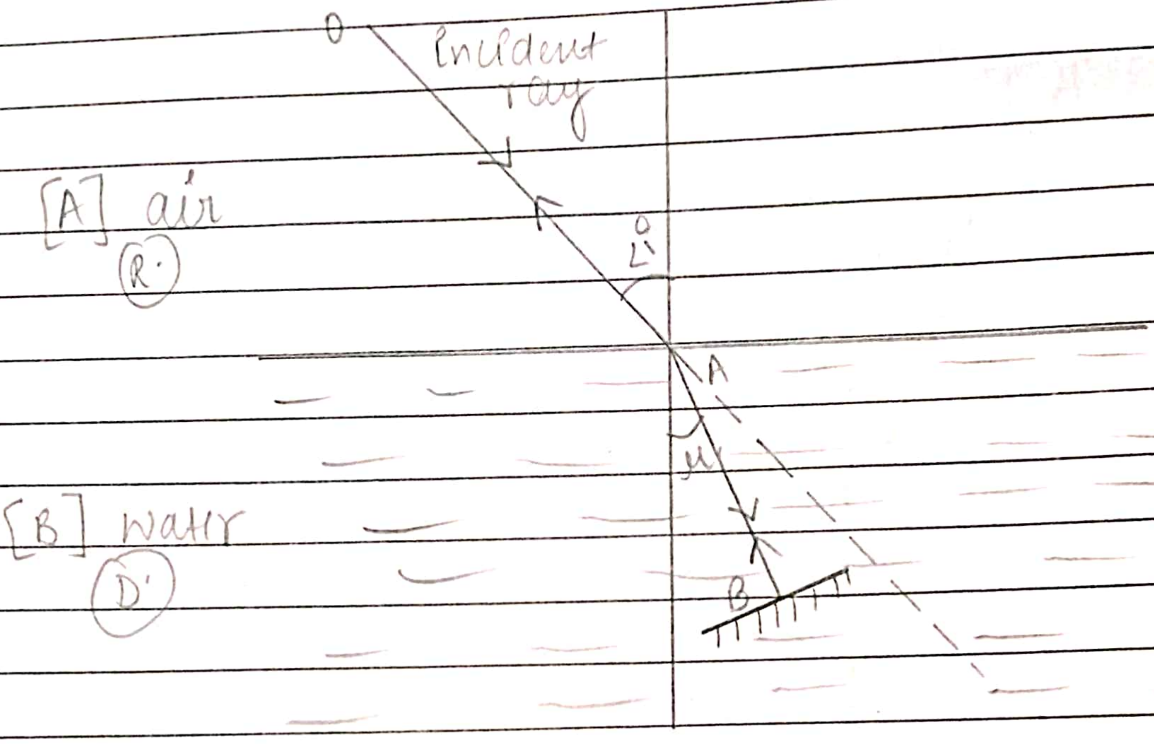
In fig I :- $n_{ba} \Rightarrow \frac{\sin i}{\sin r}$.

$$\boxed{n = \frac{c}{v}}$$

$$\boxed{n_{ba} = \frac{V_{air}}{V_{med}}}$$

In fig II :- $n_{ba} = \frac{\sin r}{\sin i}$

Principle of Reversibility :-



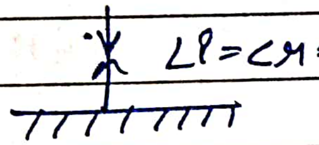
$$n_{ba} = \frac{\sin i}{\sin r}$$

$$n_{ab} = \frac{\sin r}{\sin i}$$

$$n_{ba} \times n_{ab} = 1$$

$$\boxed{n_{ba} = \frac{1}{n_{ab}}}$$

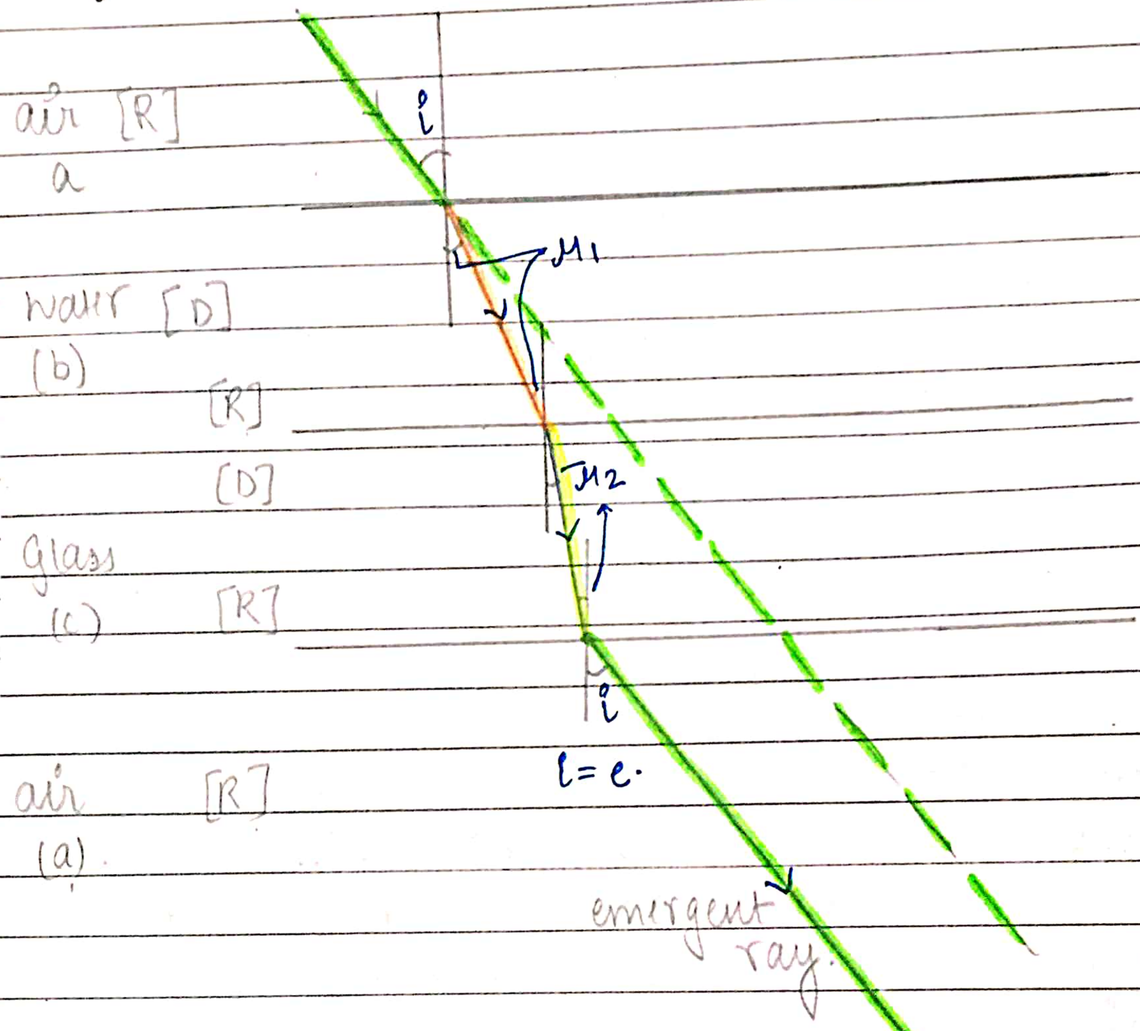
when the ray passes from rarer to denser it moves towards the ~~water~~ normal and placed a plane mirror by which it ~~passes~~ retrace its path.



And then; when moving from denser to medium; It moves away from the normal & retraces all its path.

hence; it follows princip of reversibility.

Refraction through multiple medium :-



$$n_{ba} = \frac{\sin i}{\sin r} \; ; \; n_{cb} = \frac{\sin r_1}{\sin r_2} \; ; \; n_{ac} = \frac{\sin r_2}{\sin i}$$

$$n_{ba} \times n_{cb} \times n_{ac} = 1$$

$$n_{ba} \times n_{ac} = \frac{1}{n_{cb}}.$$

$$\boxed{n_{ba} \times n_{ac} = n_{bc}}$$

Q. $n_{ga} = \frac{3}{2}$

$n_{wa} = \frac{4}{3}$.

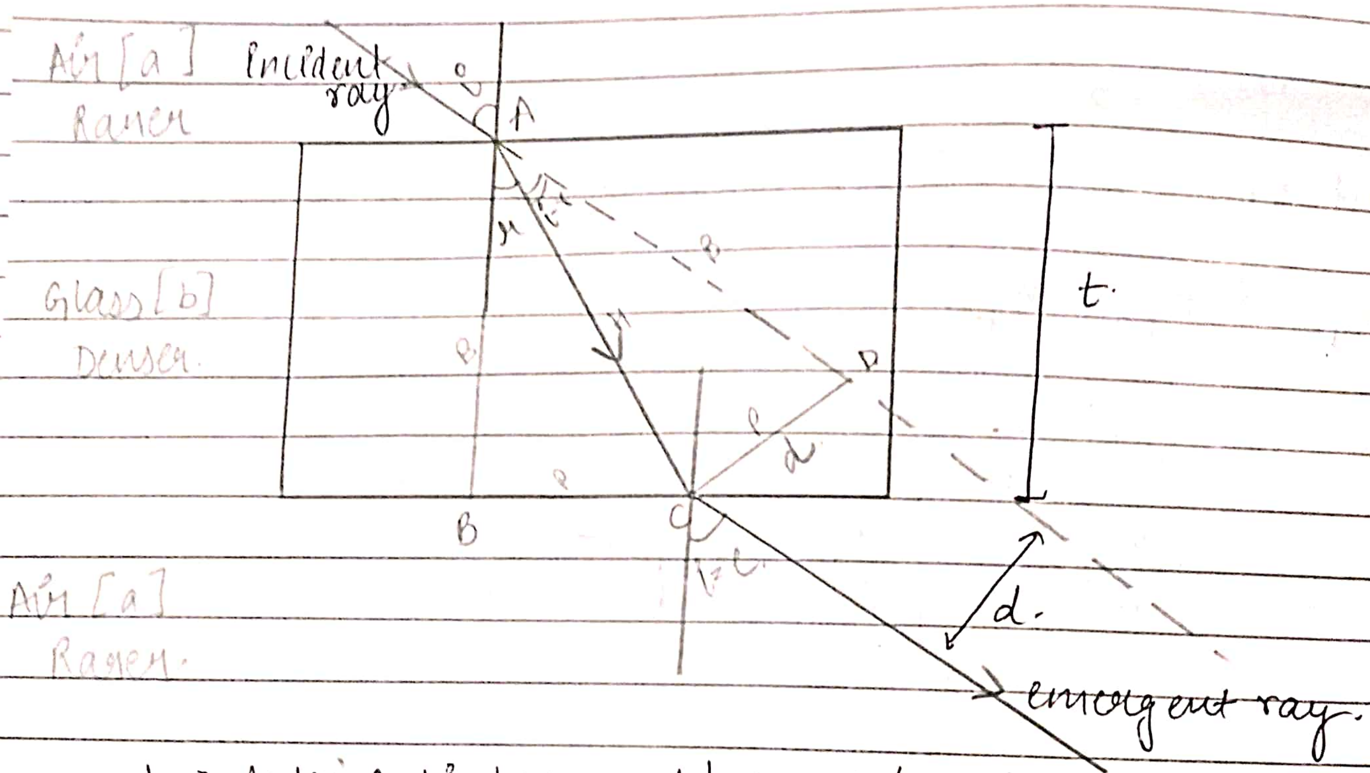
find $n_{gw} = ?$

$$n_{gw} = n_{ga} \times n_{aw}$$

$$= \frac{3}{2} \times \frac{1}{n_{wa}}$$

$$\Rightarrow \frac{3}{2} \times \frac{3}{4} = \boxed{\frac{9}{8} = n_{gw}}$$

Refraction through Glass slab :-



d → lateral displacement | shift | deviation.

In ΔABC;

$$\frac{AB}{AC} = \cos r.$$

$$\frac{t}{AC} = \cos r$$

$$AC = \frac{t}{\cos r} \longrightarrow ①$$

In ΔACD;

$$\frac{d}{AC} = \sin(i-r)$$

$$d = AC \sin(i-r).$$

$$\boxed{d = \frac{t}{\cos r} \sin (i - r)}$$

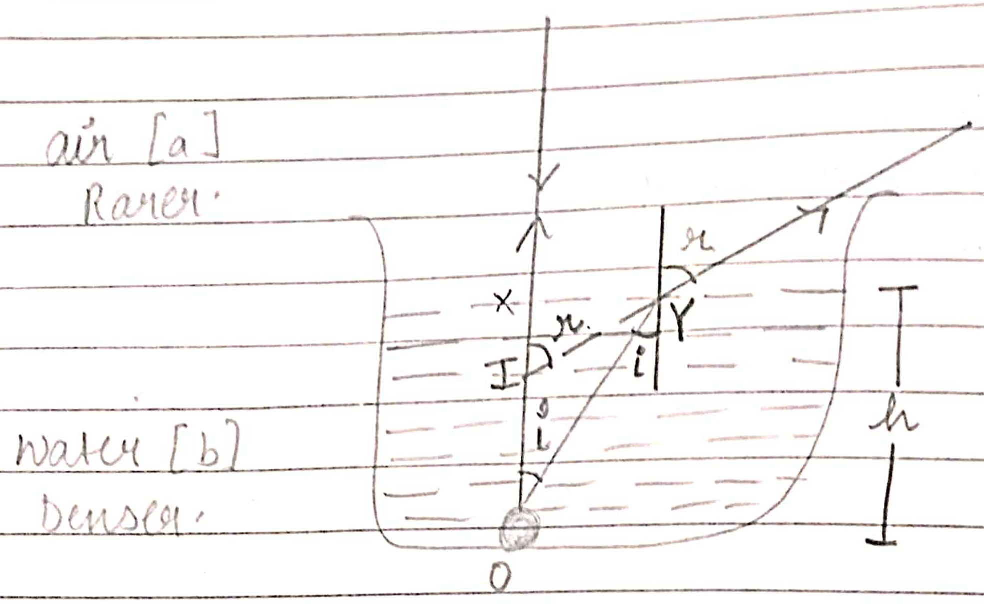
Lateral Disp. depends on;

(i) Thickness of glass ~~plate~~ slab

(ii) Angle of i

(iii) Ref. index

•) Real And Apparent depth.



XO → Real Depth.
XI → Apparent Depth.

$$n_{ba} = \frac{\sin r}{\sin i}$$

Since angles are very small.

$$n_{ba} = \frac{r}{i} \longrightarrow ①$$

In ΔXOY;

$$\frac{XY}{XO} = \tan i$$

$$\frac{XY}{XO} = i \longrightarrow ②$$

In ΔXYI

$$\frac{XY}{XI} = \tan r.$$

$$\frac{XY}{XI} = r \longrightarrow ③$$

Put ② & ③ in ①;

$$n_{ba} = \frac{\frac{\cancel{XY}}{XI}}{\frac{\cancel{XY}}{XO}} \Rightarrow \frac{XO}{XI}$$

$n_{ba} =$ ~~Rea~~ ~~Real Apparent~~. $\frac{R\cdot D}{A\cdot D}$.

~~Mirror~~ Normal Shift:

$\Rightarrow R\cdot D - A\cdot D$

$\Rightarrow R\cdot D\left(1 - \frac{AD}{RD}\right)$

Q Velocity of light in a liquid is 1.8×10^8 m/s. Find by how much the bottom of vessel containing this liquid appears to be raised if the depth of the liquid is 25 cm.

→ $n = \frac{\text{Real Depth}}{\text{Apparent Depth}}$.

$$\Rightarrow \frac{C}{V} = \frac{RD}{AD}.$$

$$\frac{\overset{\cancel{10}\ 5}{\cancel{30}} \times \cancel{10^8}}{\underset{\cancel{6}\ 3}{\cancel{18}} \times \cancel{10^8}} \Rightarrow \frac{25}{AD}$$

$$A \cdot D = \frac{\overset{5}{\cancel{25}} \times 3}{\cancel{5}}$$

$$\boxed{A \cdot D = 15}$$

Normal shift $\Rightarrow R \cdot D - A \cdot D$

$\Rightarrow 25 - 15$

$\Rightarrow$ 10 cm.

NCERT BACK EXERCISE

Q The bottom of a container is 4.0 cm thick glass [n=1.5 slab. The container contains two immissible liquid A and B of depths 6.0 cm & 8.0 cm respectively. what is the apparent position of a scratch on the outer surface of the bottom of the glass slab when viewed through the container? Refractive indeses of A & B are 1.4 & 1.3 respectively.

$$\Rightarrow \underset{\text{Glass}}{N.S_1} + \underset{\text{liq.1}}{N.S_2} + \underset{\text{liq.2}}{N.S_3}.$$

$$\Rightarrow h_1\left(1-\frac{1}{h_1}\right) + h_2\left(1-\frac{1}{h_2}\right) + h_3\left(1-\frac{1}{h_3}\right).$$

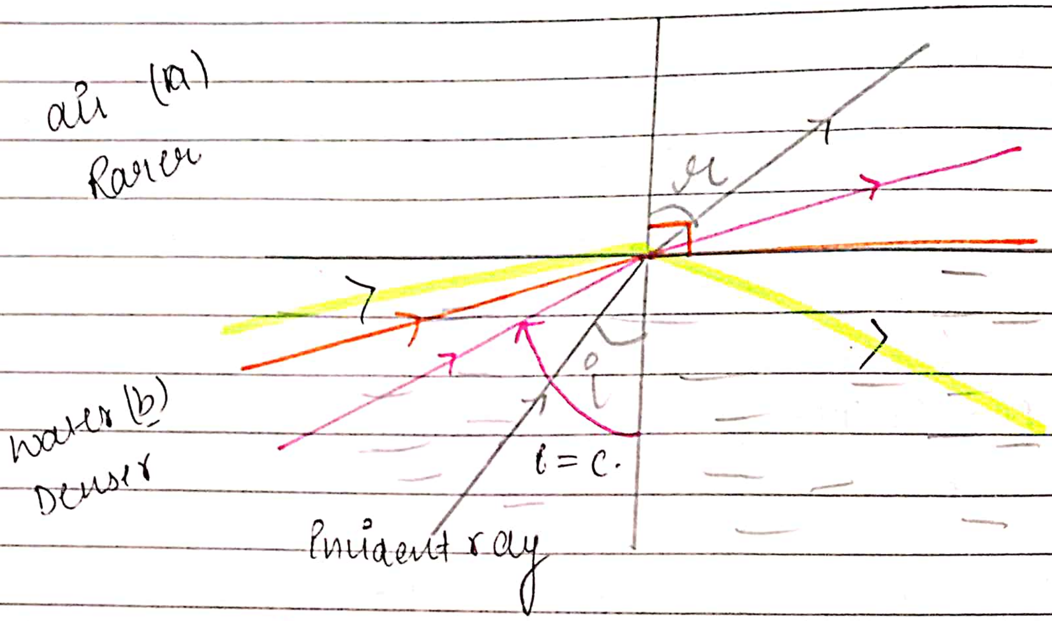
$$\Rightarrow 4\left(1-\frac{\overset{2}{\cancel{1}}}{\underset{3}{\cancel{1.5}}}\right) + 6\left(1-\frac{\overset{2}{\cancel{1}}}{\underset{7}{\cancel{1.4}}}\right) + 8\left(1-\frac{10}{13}\right).$$

$$\Rightarrow 4\left(\frac{1}{3}\right) + \frac{12}{7} + \frac{24}{13}$$

$$\Rightarrow \frac{4}{3} + \frac{12}{7} + \frac{24}{13} \Rightarrow 1.3 + 1.5 + 1.8 = 4.6$$

Imp.

Total Internal Reflection



When a ray is going from Denser to rarer medium it bends itself away from the normal. If we increase angle of incidence angle of reflection will also increase. At a particular angle of incidence angle of refraction becomes 90°. This angle of incidence is called critical angle. If we increase angle of incidence even beyond critical angle the ray instead of going in second medium will bounce back in the same medium. This is called Total Internal reflection. [TIR].

$i = c$

$r = 90°$

$$n_{ba} = \frac{\sin r}{\sin i}$$

At critical Angle

$$n_{ba} = \frac{\sin 90°}{\sin c}$$

$$n_{ba} = \frac{1}{\sin c}.$$

Essential conditions of TIR:-

(a) Ray should go from denser to rarer medium.
(b) Angle of incidence should be greater than critical angle.

Q. Critical angle of a medium is 30°. find speed of light in the medium.

Ans $n = \frac{1}{\sin C}$

$$\frac{c}{v} \Rightarrow \cancel{\sin}\ \frac{1}{\sin C}$$

$$\frac{3\times10^8}{v} \Rightarrow \frac{1}{\sin 30^\circ}$$

$$\frac{1}{2\sqrt{3}}$$

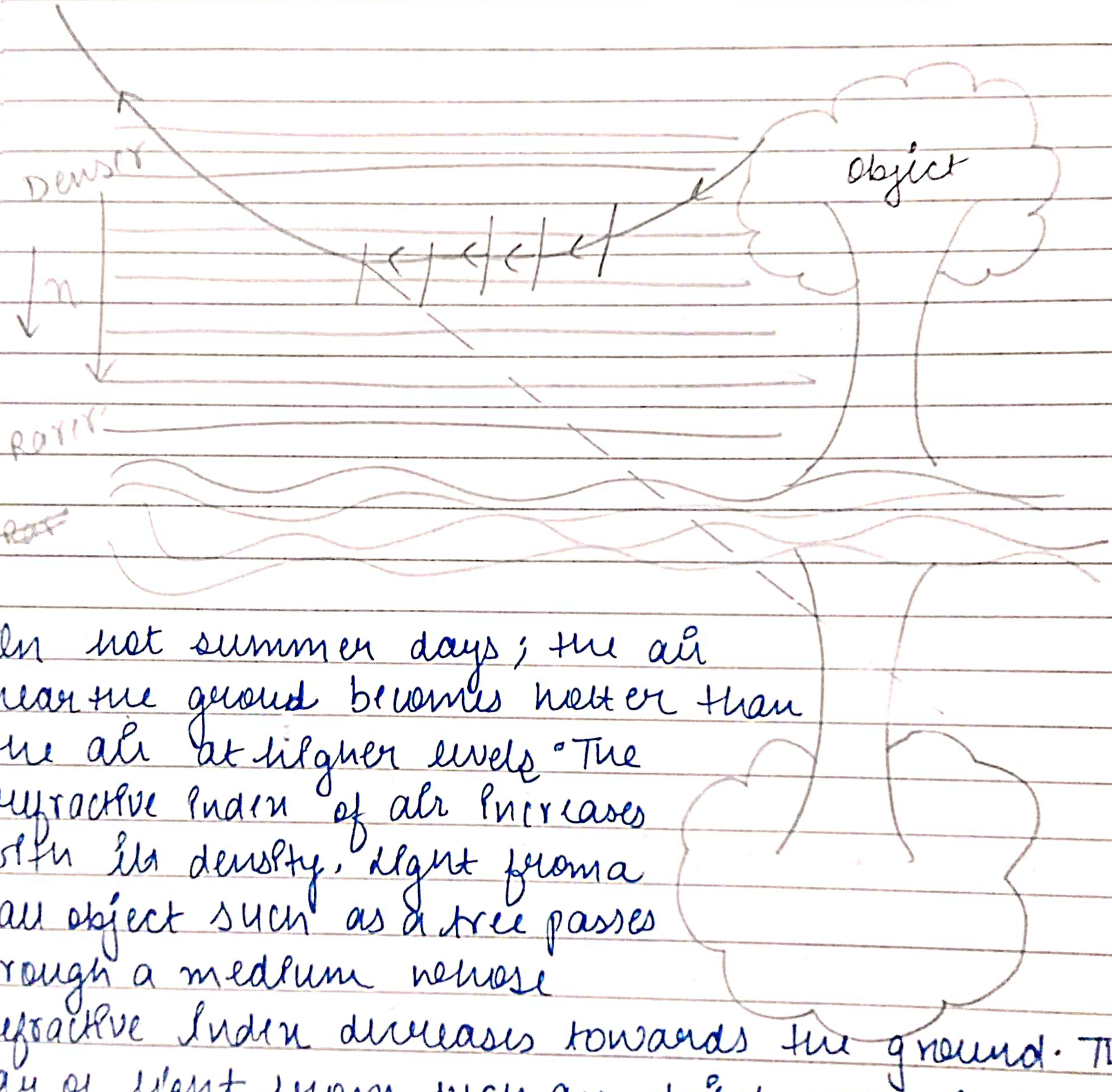
$$\frac{3\times10^8}{v} \Rightarrow 2$$

$$\frac{\cancel{3}\times10^8}{\cancel{2}} \Rightarrow v$$

$$\boxed{v = 1.5\times10^8}$$

#. Applications of TIR :-

1) Mirage

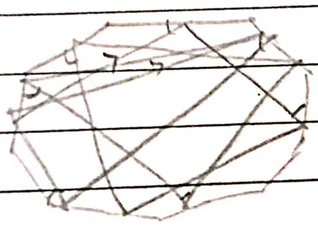


In hot summer days; the air near the ground becomes hotter than the air at higher levels. The refractive index of air increases with its density. Light from a tall object such as a tree passes through a medium whose refractive index decreases towards the ground. Thus a ray of light from such an object successively bends away from the normal & undergoes total internal reflection. The observer naturally assumes that light is being ~~reflection~~ reflected from the ground; say by a pool of water near a tall object;

such inverted images of distant tall objects cause an optical illusion to the observer. This phenomena is called mirage.

Brilliance of Diamond:

Diamonds are known for their spectacular brilliance; Their brilliance is mainly due to the TIR of light inside them. The critical angle for diamond - air interface. (≅ 24.4°) is very small; therefore once light enters in diamond it is likely to undergo TIR. Hence diamond shines.

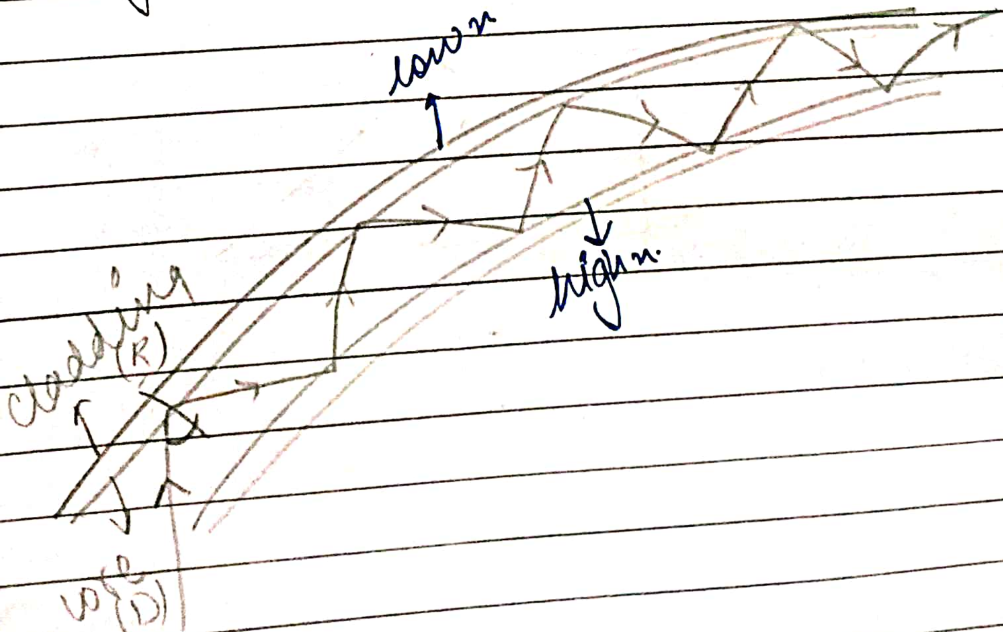


$n = \text{high} = 2.47$

$n \uparrow ; C \downarrow$

$C \cong 24°.$

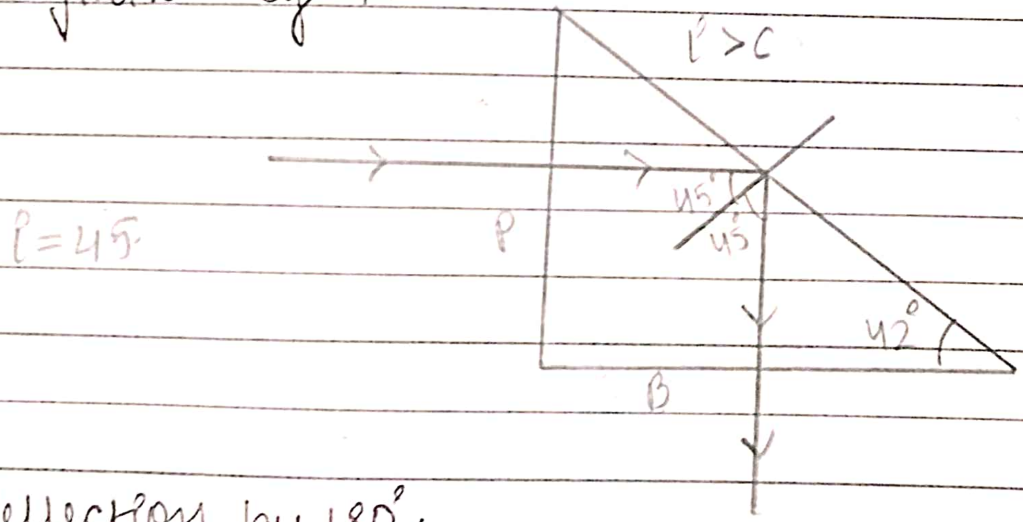
Optical fibers



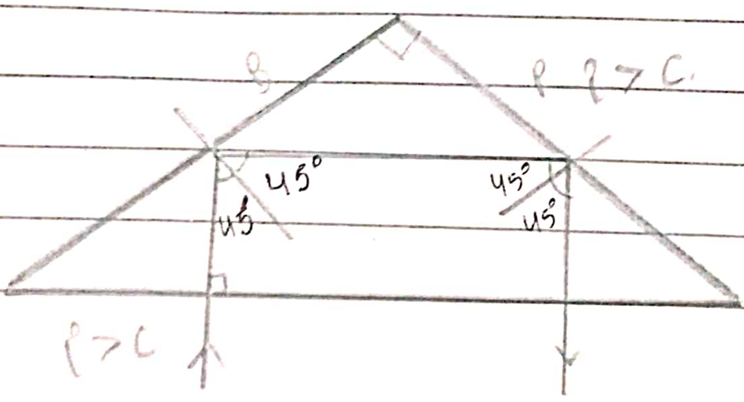
Optical fibers are extensively used for transmitting audio and video signals through long distances. Optical fibers too make use of the phenomenon of TIR. ~~optic~~ Each fiber consists of a core & cladding. The refractive index of the material of the core is higher than that of the cladding. When a signal in the form of light is directed at one end of the fiber at a suitable angle; it undergoes repeated total internal reflections along the length of the fiber and finally comes out at the other end. There is no appreciable loss in the intensity of the light signal.

4) Totally reflecting prism.

(i) Reflection by 90°.



(ii) Reflection by 180°.



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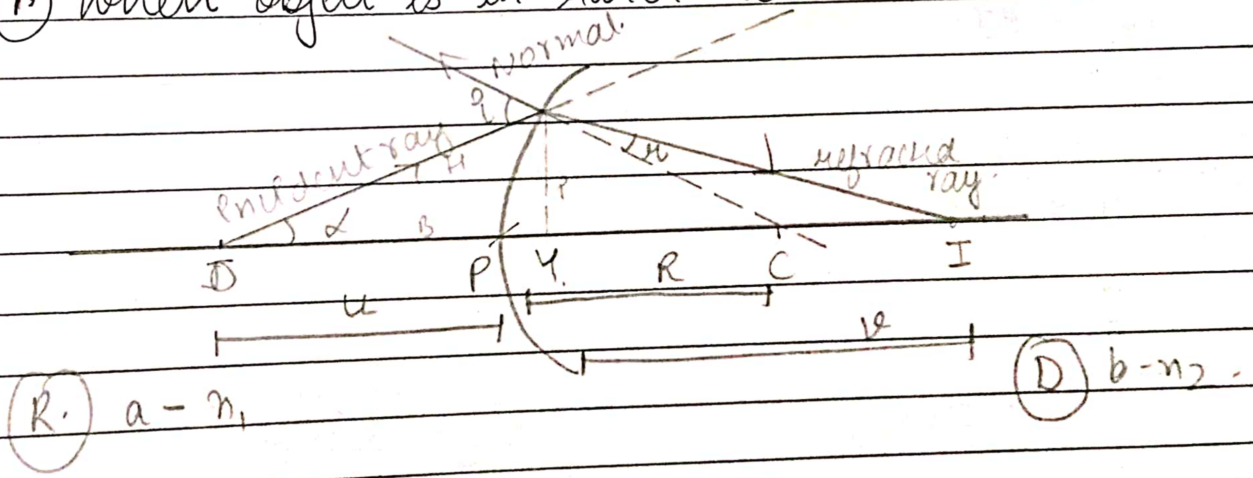
Spherical refracting surface :-

Assumptions :-

1. Object & image should be point in size.
2. Angle made by object & image should be very very small.
3. All distances should be measured from pole.
4. Distances in the direction of incident ray should be taken as positive & opp. to incident ray should be taken as negative.
5. Object should always be kept on the left hand side of the spherical surface.

① When object is in rarer medium :-



Y & P are close to each other;

$PO = -u$

$PC = +R$

$PI = +v$.

In ΔXCO;

$i = \alpha + \gamma$

$i = \tan\alpha + \tan\gamma$

$$i = \frac{XY}{YO} + \frac{XY}{YC}.$$

Spiral

$$i = \frac{XY}{PO} + \frac{XY}{PC} \longrightarrow ①$$

In ΔXCI;

$$\gamma = r + \beta$$
$$r = \gamma - \beta$$
$$r = \tan\gamma - \tan\beta$$

$$r = \frac{XY}{YC} - \frac{XY}{YI}$$

$$r = \frac{YY}{PC} - \frac{XY}{PI}$$

$$n_{ba} = \frac{\sin i}{\sin r} = \frac{i}{r}.$$

$$\frac{n_2}{n_1} = \frac{i}{r}$$

$$n_2 r = n_1 i$$

$$n_2\left[\frac{XY}{PC} - \frac{XY}{PI}\right] = n_1\left[\frac{XY}{PO} + \frac{XY}{PC}\right].$$

$$\frac{n_2}{PC} - \frac{n_2}{PI} = \frac{n_1}{PO} + \frac{n_1}{PC}.$$

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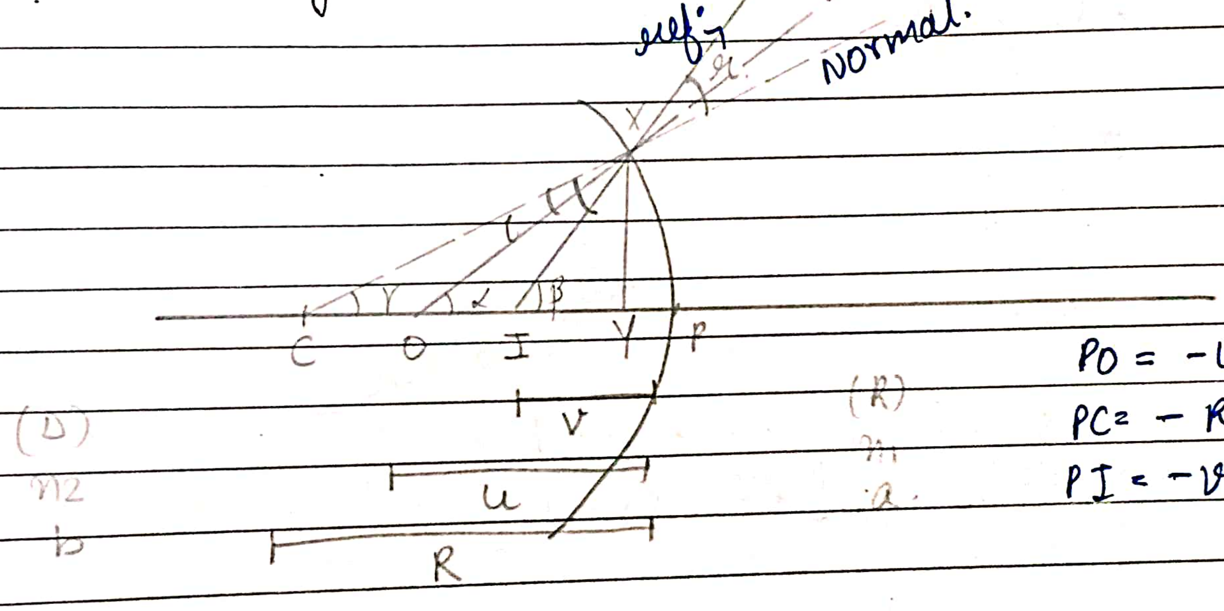
$$\frac{n_2}{PC} - \frac{n_1}{PC} = \frac{n_1}{PO} + \frac{n_2}{PI}$$

$$\frac{1}{PC}(n_2 - n_1) = \frac{n_1}{PO} + \frac{n_2}{PI}.$$

$$\left\{ \frac{1}{R}(n_2 - n_1) = \frac{-n_1}{u} + \frac{n_2}{v} \right\} \#$$

II] when object is in denser medium -



PO = -u

PC = -R

PI = -v.

In Δ XCO;

$$\alpha = i + \gamma$$

$$i = \alpha - \gamma$$

$$i = \tan\alpha - \tan\gamma$$

$$i = \frac{XY}{YO} - \frac{XY}{YC}$$

$$i = \frac{XY}{PO} - \frac{XY}{PC} \longrightarrow ①$$

Spiral

in ΔXCI;

$$\beta = r + \gamma$$
$$r = \beta - \gamma$$
$$r = \tan\beta - \tan\gamma$$
$$r = \frac{XY}{PI} - \frac{XY}{PC}.$$

$$n_{ba} = \frac{\sin r}{\sin \ell} = \frac{r}{\ell}$$

$$\frac{n_2}{n_1} = \frac{r}{\ell}$$

$$n_2 \ell = n_1 r.$$

$$n_2\left[\frac{XY}{PO} - \frac{XY}{PC}\right] = n_1\left[\frac{XY}{PI} - \frac{XY}{PC}\right].$$

$$\frac{n_2}{PO} - \frac{n_2}{PC} = \frac{n_1}{PI} - \frac{n_1}{PC}$$

$$-\frac{n_2}{PC} + \frac{n_1}{PC} = \frac{n_1}{PI} - \frac{n_2}{PO}.$$

$$\frac{1}{PC}(n_1 - n_2) \Rightarrow \frac{n_1}{PI} - \frac{n_2}{PO}.$$

$$\Rightarrow \cancel{\frac{f}{PC}} \Rightarrow -\frac{1}{R}(n_1 - n_2) = \frac{n_1}{-v} + \frac{n_2}{u}$$

$$\Rightarrow \frac{1}{R}(n_2 - n_1) = \frac{n_2}{u} - \frac{n_1}{v}.$$

Lens Maker formula.

Assumption:-

- Object & Image should be point sized.
- All distances should be measured from the centre of the lens.
- Distance in the direction of incident ray should be taken as positive & oposite to incident ray should be taken as negative.

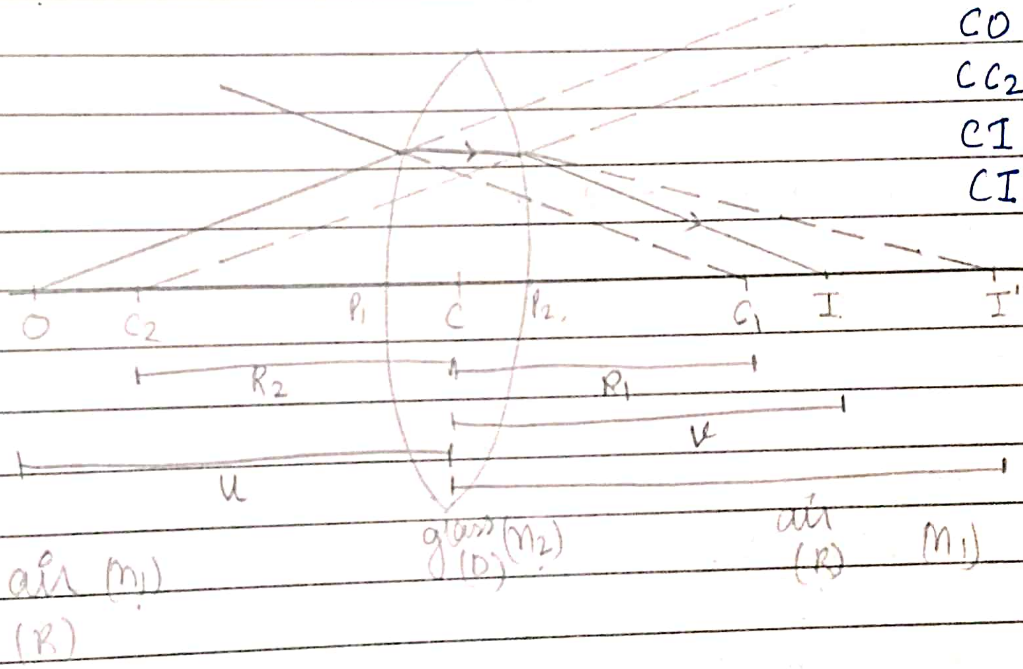
$CC_1 = +R_1$

$CO = -u$

$CC_2 = -R_2$

$CI = +v$

$CI' = +v'$



P_1 & P_2 & C are close to each other.

XP_1Y
Object = O
Image = I'
centre = C_1

XP_2Y
Object = I'
Image = I
centre = C_2.

XP_1Y :-

$$(n_2-n_1)\frac{1}{PC} = \frac{n_1}{PO} + \frac{n_2}{PI}$$

$$(n_2-n_1)\frac{1}{P_1C_1} = \frac{n_1}{P_1O} + \frac{n_2}{P_1I'}$$

$$\frac{n_2-n_1}{CC_1} = \frac{n_1}{CO} + \frac{n_2}{CI'}$$

$$\frac{n_2-n_1}{CC_1} = \frac{n_1}{CO} + \frac{n_2}{CI'}$$

$$\frac{n_2-n_1}{R_1} = -\frac{n_1}{u} + \frac{n_2}{v'} \longrightarrow ①$$

For XP_2Y :-

$$\frac{n_2-n_1}{P_2C_2} = -\frac{n_2}{P_2I'} + \frac{n_1}{P_2I}.$$

$$\frac{n_2-n_1}{CC_2} = -\frac{n_2}{CI'} + \frac{n_1}{CI}$$

$$\frac{n_2-n_1}{RE_2} = \cancel{-\frac{n_2}{CJ}} \; -\frac{n_2}{v'} + \frac{n_1}{v} \longrightarrow ②$$

Adding ① & ②;

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$$n_2 - n_1 \left(\frac{1}{R_1} - \frac{1}{R_2}\right) = \frac{n_1}{v} - \frac{n_1}{u}.$$

Diviđing by n_1

$$\left(\frac{n_2}{n_1} - 1\right)\left(\frac{1}{R_1} - \frac{1}{R_2}\right) = \frac{1}{v} - \frac{1}{u} \text{ — } ③$$

Using lens eq^n

$$\frac{1}{f} = \frac{1}{v} - \frac{1}{u} \longrightarrow ④$$

Put ④ in ③;

$$\boxed{\frac{1}{f} = \left(\frac{n_2}{n_1} - 1\right)\left(\frac{1}{R_1} - \frac{r}{R_2}\right)}$$

This is lens maker formula

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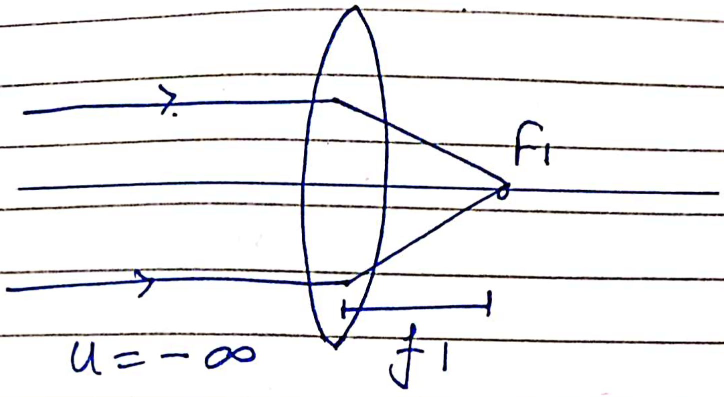
After eqⁿ ③ :-

1st Principal focus :-

It is a point where image is formed when object is kept at infinity.

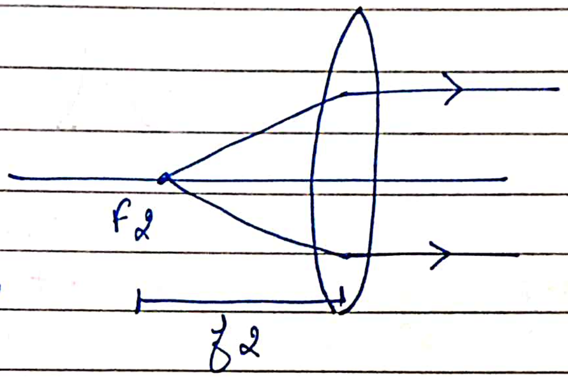


eqⁿ ③ ;

$$\left(\frac{n_2}{n_1} - 1\right)\left(\frac{1}{R_1} - \frac{1}{R_2}\right) = \frac{1}{f_1} \longrightarrow Ⓐ$$

IInd Principal focus :-

It is a point where image is formed at focus when object is kept at infinity.



$u = -f ; \quad v = \infty$

eq^n; ③

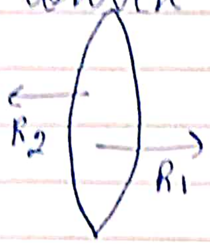
$$\left(\frac{n_2}{n_1} - 1\right)\left(\frac{1}{R_1} - \frac{1}{R_2}\right) = \frac{1}{f_2} \quad \text{— (B.)}$$

comparing ① & ② ;

$$\boxed{\left(\frac{n_2}{n_1} - 1\right)\left(\frac{1}{R_1} - \frac{1}{R_2}\right) = \frac{1}{f}}$$

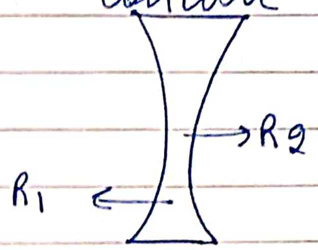
Sign conventions :-

Convex



$R_1 = +ve$
$R_2 = -ve$
$u = -ve$
$f = +ve$
$v = -?$

Concave



$R_1 = -ve$
$R_2 = +ve$
$u = -ve$
$f = -ve$
$v = -ve.$

Q. A convex lens made up of glass of $n = \frac{3}{2}$; is kept in air ; if radii of curvature of each half of the lens is 20cm ; find focal length.

Ans $n_2 = \frac{3}{2}$.

$n_2 \rightarrow$ refractive index of lens
$n_1 \rightarrow$ " " " med. in which lens is kept.

$n_1 = 1$
$R_1 = +20$ cm
$R_2 = -20$ cm.

$$\frac{1}{f} = \left(\frac{n2}{n1} - 1\right)\left(\frac{1}{R1} - \frac{1}{R2}\right)$$

$$= \left(\frac{3}{2} - 1\right)\left(\frac{1}{20} + \frac{1}{20}\right)$$

$$\frac{1}{f} \Rightarrow \left(\frac{1}{2}\right)\left(\frac{2}{20}\right) \Rightarrow \frac{1}{f} = \frac{1}{20} \quad \boxed{f = 20cm}$$

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Imp

Q2 A convex lens made up of glass of refractive index $\frac{3}{2}$ when kept in air has focal length 20 cm; How focal length will change when it is kept in a medium of refractive index $\frac{4}{3}$. [water].

Ans $n_2 = \frac{3}{2}$; $n_1 = 1$; $f = +20$ cm.

$$\Rightarrow \frac{1}{20} = \left(\frac{3}{2} - 1\right)\left(\frac{1}{R_1} - \frac{1}{R_2}\right).$$

$$\Rightarrow \frac{1}{20} = \left(\frac{3-2}{2}\right)\left(\frac{1}{R_1} - \frac{1}{R_2}\right).$$

$$\Rightarrow \frac{1}{20} = \frac{1}{2}\left(\frac{1}{R_1} - \frac{1}{R_2}\right).$$

$$\Rightarrow \boxed{\frac{1}{10} = \frac{1}{R_1} - \frac{1}{R_2}}.$$

$$\Rightarrow \& \quad \frac{1}{f} = \left(\frac{n_2}{n_1} - 1\right)\left(\frac{1}{10}\right)$$

$$\cancel{\frac{1}{f'} = \frac{8}{90}}$$

$$\cancel{\Rightarrow f' = \frac{90}{8}}$$

$$\Rightarrow \frac{1}{f'} \Rightarrow \left(\frac{3}{2} \times \frac{3}{4} - 1\right)\left(\frac{1}{10}\right)$$

$$\Rightarrow \frac{1}{f} = \left(\frac{9}{8} - 1\right)\left(\frac{1}{10}\right).$$

$$\Rightarrow \frac{1}{f} = \frac{1}{8} \times \frac{1}{10}$$

$$\Rightarrow \boxed{f = 80 \text{ cm}} -$$

Q3 A double convex lens has focal length 25 cm. when dipped in the liq. of $\frac{4}{3}$. focal length is increased to 100 cm. find refractive index of lens.

Ans $f = 25$ cm.

$$\frac{1}{f} = \left(\frac{n_2}{n_1} - 1\right)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

$$\cancel{\frac{1}{25}} = \cancel{\left(\frac{4}{3} - 1\right)}\ \cancel{\left(\frac{1}{R_1} - \frac{1}{R_2}\right)}$$

$$\cancel{\frac{1}{25}} = \cancel{\frac{1}{3}}\ \cancel{(}$$

$$\frac{1}{25} = \left(\frac{n_2}{1} - 1\right)\left(\frac{1}{R_1} - \frac{1}{R_2}\right) \text{ --- } ①$$

$$\frac{1}{100} = \left(\frac{3n_2}{4} - 1\right)\left(\frac{1}{R_1} - \frac{1}{R_2}\right) \text{ --- } ②$$

Dividing ① & ②;

$$\cancel{4} = \frac{(n_2 - 1)\cancel{4}}{3n_2 - 4}$$

$$1 = \frac{n_2 - 1}{3n_2 - 4}.$$

$$1 = \frac{n_2 - 1}{3n_2 - 4}$$

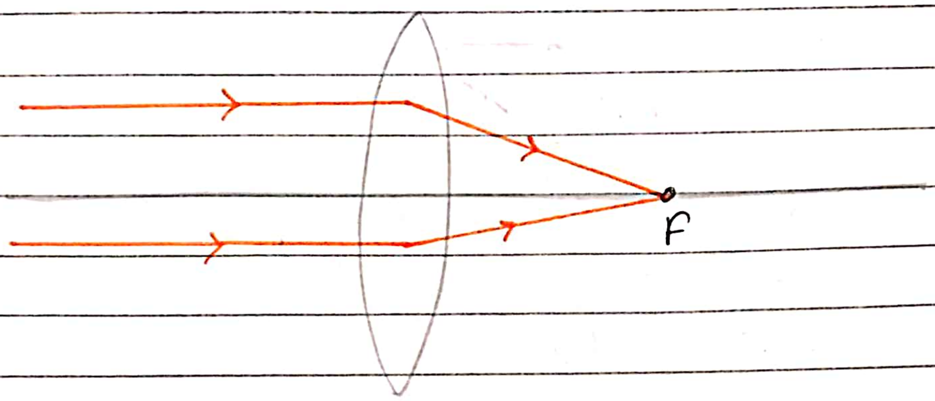
$$3n_2 - 4 = n_2 - 1$$

$$2n_2 = 3$$

$$\boxed{n_2 = \frac{3}{2}}$$

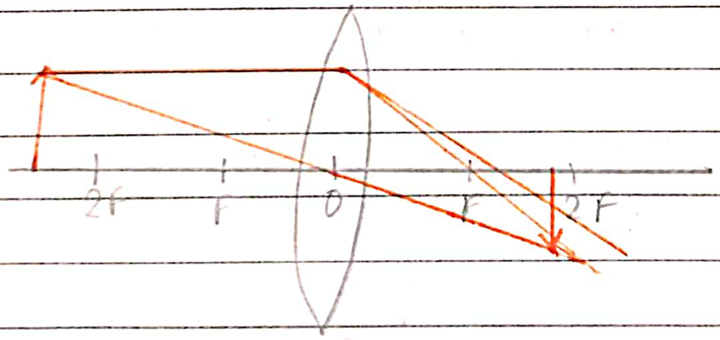
#Image formation by convex lens

① when object is at infinity.



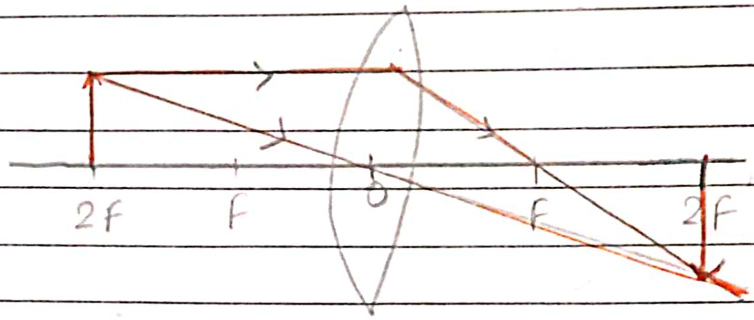
→ Image is formed at focus
→ Real ; inverted & point in size.

② when object is kept beyond 2F.



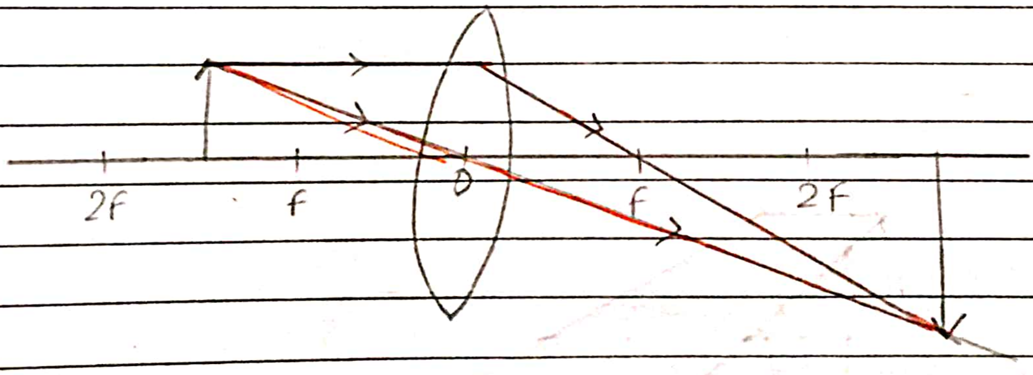
→ Image is formed b/w F & 2F.
→ Real ; inverted and smaller in size.

③ When object is kept at 2F.



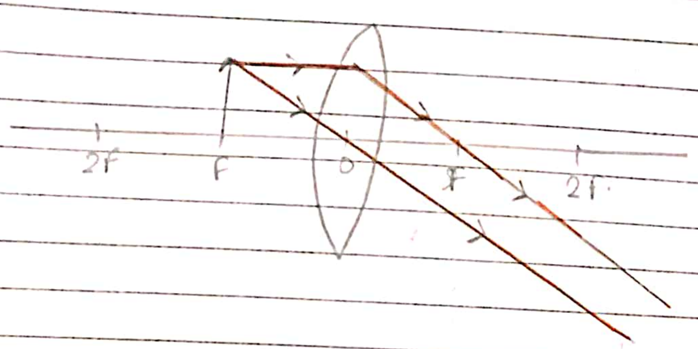
→ Image is formed at 2F.
→ Real; Inverted; same in size.

④ When object is kept b/w F & 2F.



→ Image is formed Beyond 2F.
→ Real; Inverted; large in size.

5· When object is kept at F.



→ Image is formed at infinity.
→ Real & infinity in size.

When object is kept b/w optical centre & focus.

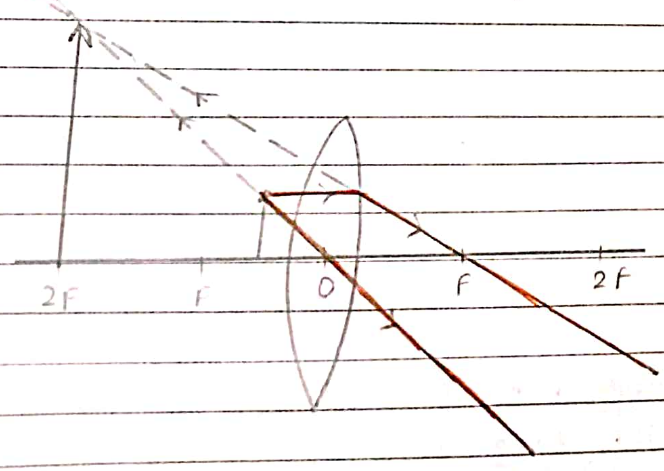
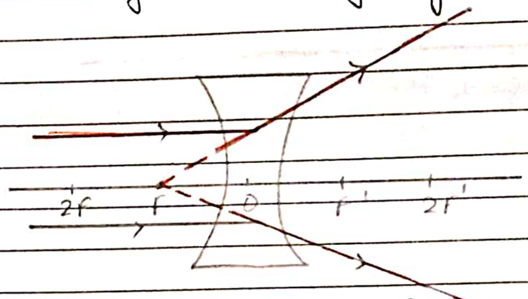


Image is formed on same side of the object.
Virtual; erect; large in size.

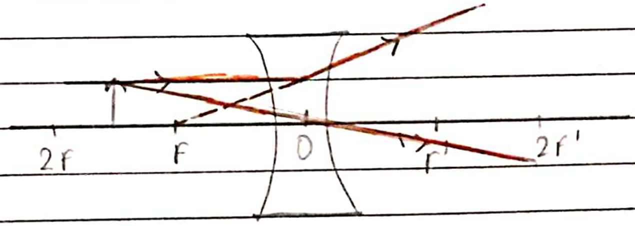
Image formation by concave lens

① When object is at infinity.



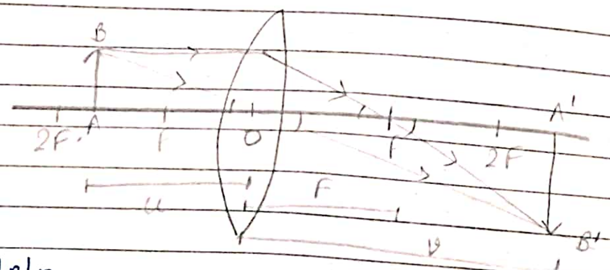
→ Image is formed at Focus
→ Virtual & erect
→ Point sized.

② When object is kept b/w Optical centre and infinity



→ Image is formed b/w O and F.
→ Virtual & Erect.
→ Diminished | Small in size.

+ Lens eq^n for convex lens :-



$\Delta ABO \sim \Delta A'B'O$

$\frac{AB}{A'B'} = \frac{OA}{OA'} \longrightarrow ①$

$OA = -u$
$OA' = +v$
$OF = +F$

In $\Delta XOF \sim \Delta A'B'F$

$\frac{XO}{A'B'} = \frac{OF}{FA'} = \frac{AB}{A'B'} = \frac{OF}{OA'-OF} \longrightarrow ②$

comparing ① & ②;

$$\frac{OA}{OA'} = \frac{OF}{OA'-OF}$$

$$\frac{-u}{+v} = \frac{+F}{+v-F}$$

Reciprocal;

$$\frac{-v}{u} = \frac{+v-F}{F}.$$

$$\frac{-v}{u} = \frac{v}{f} - 1.$$

Dividing by v;

$$\frac{-1}{u} = \frac{1}{f} - \frac{1}{v}.$$

$\boxed{\frac{1}{f} = \frac{1}{v} - \frac{1}{u}} \longrightarrow$ Lens eq^n.

Magnification $\rightarrow \left(m = \frac{h'}{h}\right)$

Ratio of size of image to size of object.

eq^n ① ;

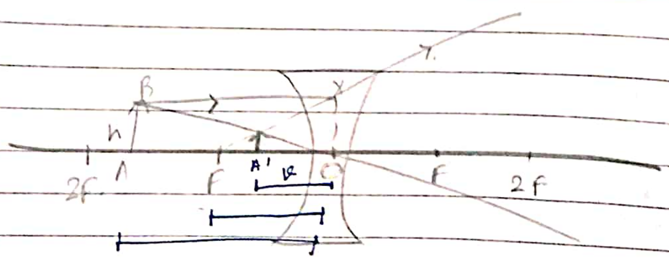
$$\frac{AB}{A'B'} = \frac{OA}{OA'}.$$

$$\frac{+h}{-h'} = \frac{-u}{v}$$

$$\frac{+h'}{h} = \frac{+v}{u}$$

$\boxed{\frac{h'}{h} = \frac{v}{u}} \Rightarrow \boxed{m = \frac{v}{u}}$

Lens eq^n for concave lens.



$\Delta ABO \sim \Delta A'B'O$

$\frac{AB}{A'B'} = \frac{OA}{OA'} \rightarrow$ ①

$OA = -u$
$OA' = -v$
$OF = -f$

$\Delta XOF \sim \Delta A'B'F.$

$\frac{XO}{A'B'} = \frac{OF}{FA'} \Rightarrow \frac{AB}{A'B'} = \frac{OF}{OF-OA'} . \longrightarrow$ ②

omparing; ① & ②;

$\frac{OA}{OA'} = \frac{OF}{OF-OA'}$

$\frac{-u}{-v} = \frac{-f}{-f+v}$

Reciprocal;

$\frac{1-\frac{v}{f}}{x}$

$\frac{v}{u} \Rightarrow \frac{-f+v}{-f}$

$\frac{v}{u} = 1 - \frac{v}{f}.$

Dividing by v;

$\frac{1}{u} = \frac{1}{u} - \frac{1}{f}.$

$\boxed{\frac{1}{f} = \frac{1}{v} - \frac{1}{u}} \rightarrow$ lens eq^n.

Magnification:- Ratio to the height of ~~object~~ Image to the object.

$\boxed{m = \frac{h'}{h} = \frac{v}{u}}$

$m = \frac{h'}{h} = \frac{v}{u}$

Convex	Concave.
$u = -ve$	$u = -ve$
$f = +ve$	$f = -ve$
$h = +ve$	$v = -ve$
$h' = ?$	$h = +ve$
$v = ?$	$h' = +ve$.

Q. An object of size 5 cm. is kept at 20 cm. from a convex lens of focal length 15 cm. Find position size; nature of image.

Ans
$h = 5 cm.$
$u = -20 cm.$
$f = +15 cm.$

$$\frac{1}{f} = \frac{1}{v} - \frac{1}{u}.$$

$$\frac{1}{15} = \frac{1}{v} - \left(\frac{-1}{20}\right)$$

$$\frac{1}{15} = \frac{1}{v} + \frac{1}{20}$$

$$\frac{1}{v} = \frac{1}{15} - \frac{1}{20}$$

$$\Rightarrow \frac{1}{v} = \frac{20-15}{300}$$

$$\Rightarrow \frac{1}{v} = \frac{5}{\cancel{300}}$$

$$\Rightarrow \boxed{v = 60 cm.}$$

$$\Rightarrow \frac{h'}{h} = \frac{v}{u}$$

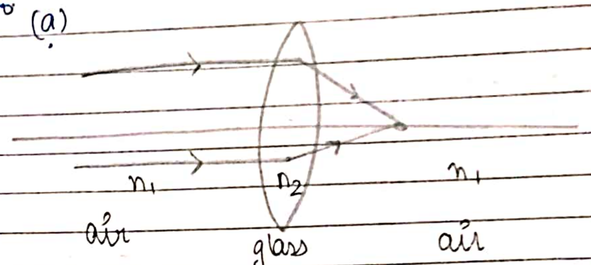
$$\Rightarrow \frac{h'}{5} = \frac{\cancel{60}^{3}}{\cancel{-20}}$$

$$\Rightarrow \boxed{h' = -15 cm}$$

Real; Inverted; larger in size.

Imp Q. Trace the path of ray; if ① $n_2 > n_1$ ② $n_2 = n_1$ ③ $n_2 < n_1$

Ans (a)

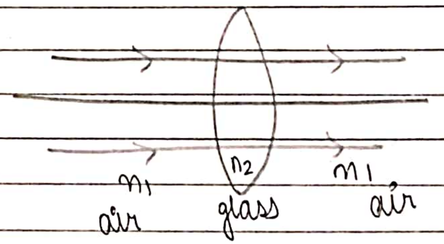


$$\frac{1}{f} = \left(\frac{n_2}{n_1} - 1\right)\left(\frac{1}{R_1} - \frac{1}{R_2}\right).$$

$f = +ve$

converging.

(b)

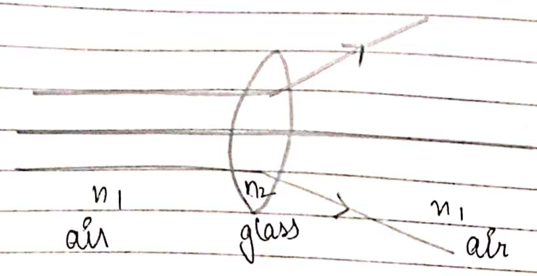


$$\frac{1}{f} = \left(\frac{n_2}{n_1} - 1\right)\left(\frac{1}{R_1} - \frac{1}{R_2}\right).$$

$f = \infty.$

lens will disappear.

(c)



$$\frac{1}{f} = \left(\frac{n_2}{n_1} - 1\right)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

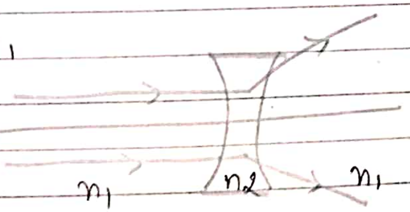
$f = -ve$ Diverging

Q Imp A convex lens of refractive index of 1.5 is dipped in a liquid and it disappears what should be the refractive index of the liquid.

→ The refractive index of the liquid will be same 1.5.

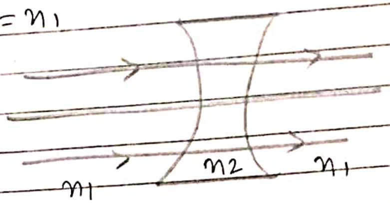
Q Imp Trace the path of ray:-

(i) $n_2 > n_1$



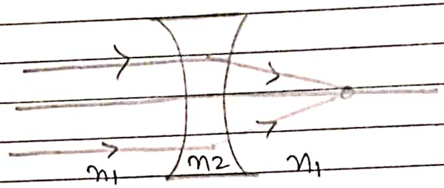
$f = -ve$ Divergent

(ii) $n_2 = n_1$



$f = \infty$ lens will disappear.

(iii) $n_2 < n_1$



$f = +ve$ Converging

Q Imp Convex lens of $n = 1.5$ is dipped in:-

(i) liq. of $n = 1.33$

(ii) liq. of $n = 1.63$.

How does it behave?

Ans (i) It will diverge.

(ii) It will converge.

Power of a lens :-

→ Power is defined as reciprocal of focal length; when it is measured in metres.
S.I unit of Power of a lens is **Dioptre**.

Power of convex lens ⟶ +ve
Power of concave lens ⟶ −ve

$$P = \frac{1}{f(m)}$$

Q A convex lens has f = 25cm; find Power?

$$\rightarrow f = 25\ cm; = \frac{25}{100}\ \frac{1}{4} =$$

$$P = \frac{1}{F(m)} = \frac{1}{\frac{1}{4}} = \underline{\underline{+4D}}$$

Cauchy's formula :-

VIBGYOR

λred > λviolet

$$n \propto \frac{1}{\lambda}$$

$$\left\{ \frac{1}{f} = \left(\frac{n_2}{n_1} - 1\right)\left(\frac{1}{R_1} - \frac{1}{R_2}\right) \right.$$

f on a convex lens; red light is incident instead of violet; how focal length will change?
Acc. to cauchy's formula; $n \propto \frac{1}{\lambda}$; ∴ as λ ↑ ;
= ↓ ; ∴ f will ↑se.

Combination of lenses.

$$\boxed{\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} \cdots}$$

$$\boxed{P = P_1 + P_2}$$

Q A convex lens of focal length 30cm is cut in two equal parts as shown. Find the focal length of each half.

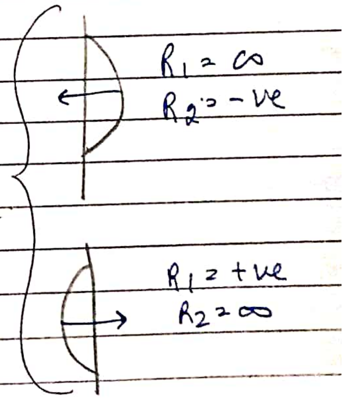
$$\Rightarrow \frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2}$$

$$\Rightarrow \frac{1}{30} = \frac{1}{x} + \frac{1}{x}.$$

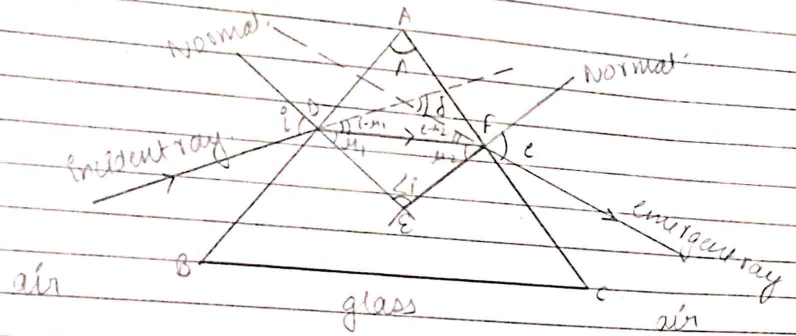
$$\Rightarrow \frac{1}{30} = \frac{2}{x}$$

$$\boxed{x = 60cm}$$

Plano convex



Refraction through prism.



i → angle of incidence
$r_1 ; r_2$ → angle of refraction
e → angle of emergance
A → angle of prism.

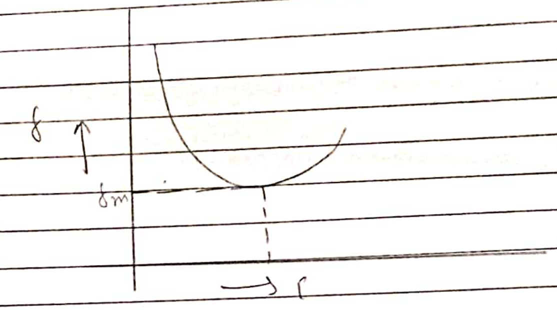
In ΔDEF;
$$r_1 + r_2 + \angle 1 = 180 \longrightarrow ①$$
In □ ADEF;
$$A + \angle 1 = 180° \longrightarrow ②$$

comparing ① & ②;
$$r_1 + r_2 + \cancel{\angle 1} = A + \cancel{\angle 1}$$
$$r_1 + r_2 = A \longrightarrow ③$$

In ΔADF;
$$\delta = i - r_1 + e - r_2 .$$

$$\delta = i + e - (r_1 + r_2).$$
$$\delta = i + e - A$$
$$\delta + A = i + e \longrightarrow ④$$

Plot a graph b/w i & δ.



for $\delta = \delta_m$ (mini. deviation)
$$\left. \begin{array}{l} i = e \\ r_1 = r_2 = r \end{array} \right\} - ⑤$$

Put ⑤ in ③;
$$A = r + r$$
$$r = \frac{A}{2} \rightarrow ⑥$$

Put ⑤ in ④;
$$\delta_m + A = i + i$$
$$\delta_m + A = 2i$$
$$\boxed{i = \frac{\delta_m + A}{2}}$$

$$n = \frac{n_2}{n_1}$$
$$n = \frac{\sin i}{\sin r}$$
$$\boxed{n = \frac{\sin\left(\frac{A + \delta_m}{2}\right)}{\sin \frac{A}{2}}}$$

Q. A ray of light passes through an equilateral prism of refractive index of 1.5 such that $\angle i = \angle e$ and latter is equal to $\frac{3}{4}$th of angle of prism. Calculate angle of deviation.

→ $n = 1.5$

$A = 60°$

$\angle i = \angle e$.

Imp

Q. An equilateral glass prism has R.I = 1.6 in air. Calculate the angle of minimum deviation when the prism is kept in a medium of $\frac{4\sqrt{2}}{5}$.

→ $$\cancel{n = \frac{\sin\left(\frac{A+\delta m}{2}\right)}{\sin\left(\frac{A}{2}\right)}}$$

$$\frac{n_2}{n_1} = \frac{\sin i}{\sin r}$$

$$\cancel{\frac{4\cdot\sqrt{2}}{5} = \frac{\sin\left(\frac{60+\delta m}{2}\right)}{\sin(30^\circ)}}$$

$$\cancel{\frac{4\sqrt{2}}{5} = \sin\left(\frac{60+\delta m}{2}\right)}$$

$$\cancel{\frac{4\sqrt{2}}{5} = \sin\left(\frac{60^\circ+\delta m}{2}\right) \times \frac{2}{1}}$$

$$\boxed{\frac{n_2}{n_1} = \frac{\sin i}{\sin r}}$$

$$\frac{1.6 \times 5}{4\sqrt{2}} = \frac{\sin\left(\frac{60+\delta m}{2}\right)}{\sin(30^\circ)}$$

$$\frac{8}{4\sqrt{2}} = \frac{\sin\left(\frac{60+\delta m}{2}\right)}{\sin(30^\circ)}$$

$$\begin{array}{r} \overset{3}{1.6} \\ \times 5 \\ \hline 8.0 \end{array}$$

$$\Rightarrow \frac{2}{\sqrt{2}} = \frac{\sin\left(\frac{60+\delta m}{2}\right)}{\sin 30^\circ}$$

$$\Rightarrow \frac{2}{\sqrt{2}} = \frac{\sin\left(\frac{60+\delta m}{2}\right)}{\frac{1}{2}}$$

$$\Rightarrow \frac{2}{\sqrt{2}} \times \frac{1}{\cancel{2}} \Rightarrow \sin\left(\frac{60+\delta m}{2}\right)$$

$$\Rightarrow \frac{1}{\sqrt{2}} \Rightarrow \sin\left(\frac{60+\delta m}{2}\right)$$

$$\Rightarrow (\sin^{-1} 45) \Rightarrow \frac{60+\delta m}{2}$$

$$= \frac{\pi}{4} \cdot 2 = \frac{\frac{\pi}{3} + 2\delta m}{2} \Rightarrow \frac{\pi}{2} - \frac{\pi}{3} = \frac{\pi}{6}$$

$$\Rightarrow \boxed{\delta m = \frac{\pi}{6}}$$

A ray of light incident on a equilateral glass prism of refractive index √3. moves ∥ to base line of the prism. find angle of incidence.

$n = \sqrt{3}$;

~~$A = \frac{r}{7}$~~ $r = \frac{A}{2}$ $(\underline{r = 30^\circ})$

$\Rightarrow \sin^{-1}\frac{\sqrt{3}}{2} = \frac{60 + \delta m}{2}$.

$\delta + A = 2i$ $\Rightarrow \delta m \Rightarrow 60^\circ \times 2 - 60^\circ$

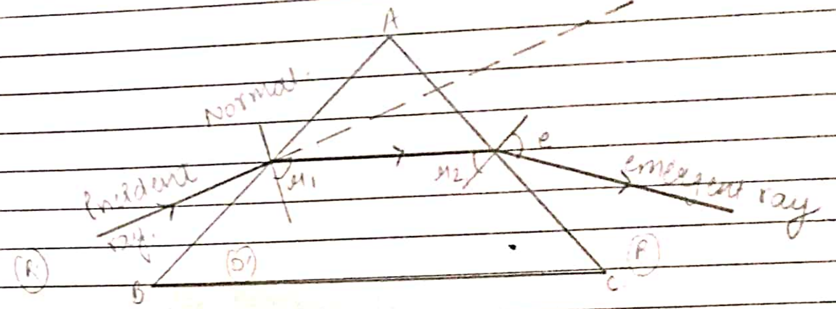
$\Rightarrow \underline{60^\circ}$

$i = \frac{\delta m + A}{2}$.

$i = \frac{60^\circ + 60^\circ}{2}$.

$\boxed{i = 60^\circ}$

- Refraction through small prism $(A < 10^\circ)$



Since angles are small.

Refraction at AB;

$n_{ba} = \frac{\sin i}{\sin r_1} = \frac{i}{r_1}$.

$i = n_{ba} r_1 \longrightarrow ①$

Refraction at AC;

$n_{ba} = \frac{\sin e}{\sin r_2} = \frac{e}{r_2}$.

$e = n_{ba} r_2 \longrightarrow ②$

$\delta + A = i + e$.

$\delta + A = n_{ba} r_1 + n_{ba} r_2$.

$\delta + A = n_{ba}(r_1 + r_2)$.

$\delta + A = n_{ba}(A)$.

$\delta + A = n_{ba} A$

$\delta = n_{ba} A - A$

$\boxed{\delta = (n_{ba} - 1) A}$

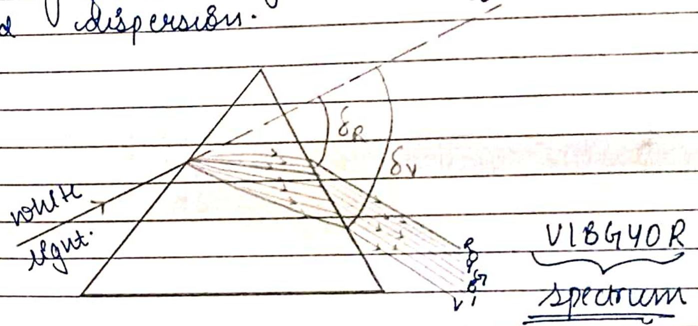
Q. Angle of deviation of a prism of angle 2° is 1°.
⇒ Find refractive index.

→ $\delta = A(n-1)$
$1^\circ = 2^\circ(n-1)$
$\frac{1}{2} + 1 = n$

$\boxed{n = \frac{3}{2}}$.

Dispersion :-

Splitting of white light in all diff. seven colours is called dispersion.



λ red (max)

λ violet (min.)

Cause of Dispersion:-

White light consist of VIBGYOR; which is called band of seven colours spectrum.
Acc. to Cauchy's formula; $n = a + \frac{b}{\lambda^2} + \frac{c}{\lambda^4} + \cdots$;

$n \propto \frac{1}{\lambda}$.

All the colours of VIBGYOR have different wavelength; therefore their refractive indexes are different.
Acc. to the formula; $\delta = A(n-1)$. As; R.I are different; Angle of deviation are also diff.; Hence; light splits after passing through prism & is called dispersion.

Red has maximum wavelength; therefore; its refractive index is minimum hence its angle of deviation is minimum; so; red is seen at the top and violet at the bottom.

Angular Dispersion.

Angle b/w 2 colours.

It is the diff. of angle of deviation of any two colours.

$$\theta = \delta_V - \delta_R.$$

$$\theta = A(n_V - 1) - A(n_R - 1)$$

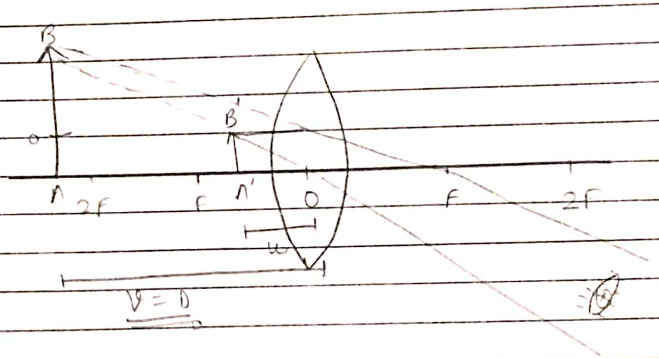
$$= A n_V - \cancel{A} - A n_R + \cancel{A}$$

$$\boxed{\theta = A(n_V - n_R)}$$

Optical instruments

1) Simple microscope :- uses a single convex lens; image is formed at D (least distance of distinct vision).

Object is kept b/w optical centre and focus.



In $\triangle ABC$; $\tan\beta = \frac{AB}{AC}$.

In $\triangle OA'C$;

$\tan\alpha = \frac{OA'}{CA'}$.

$$m = \frac{\beta}{\alpha}.$$

$$m = \frac{\tan\beta}{\tan\alpha}.$$

$$m = \frac{\frac{AB}{CA}}{\frac{OA'}{CA'}} = \frac{CA'}{CA}.$$

$$m = \frac{-D}{-u}$$

$$\boxed{m = \frac{D}{u}}$$

$$\frac{1}{f} = \frac{1}{v} - \frac{1}{u}$$

$$\frac{1}{f} = \frac{-1}{D} + \frac{1}{u}$$

Multiplicating by D;

$$\frac{D}{f} = -1 + \frac{D}{u}$$

$$\frac{D}{u} = 1 + \frac{D}{f}.$$

$$\boxed{m = 1 + \frac{D}{f}}$$

It is the ratio of angle made by image at the centre of lens to angle made by object at the center of the lens when both lie at least distance of distinct vision. → magnification

- Compound Microscope :-

Compound Microscope has 2 convex lenses one is called objective & other is called eye piece.

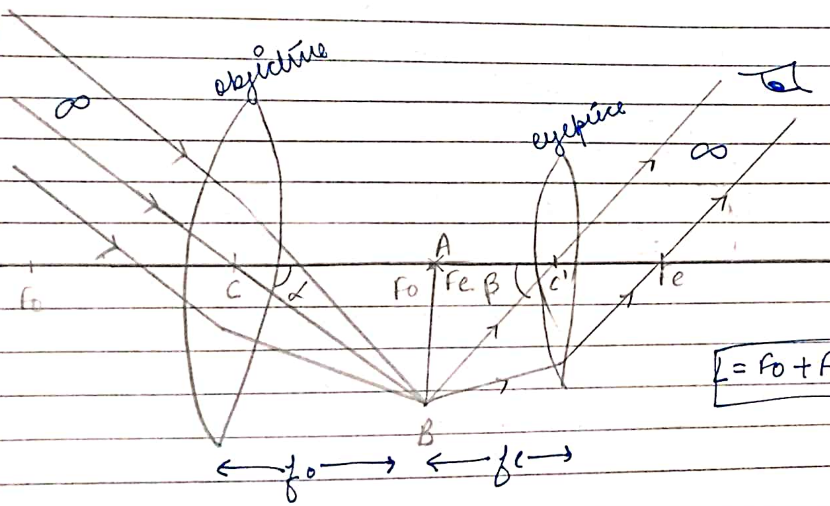
Objective have smaller focal length.
Eye piece has larger focal length.

Both are kept co-axially. Object is kept beyond focal length of objective and image is formed at least distance of distinct vision.

more aperture → more light gathering power.

Astronomical Telescope (Refracting type telescope).

It has two convex lenses of large aperture [diameter or thickness]. ~~obj~~ one ~~obje~~ lens is objective and other is eye piece. Objective have larger focal length and larger aperture as compared to eye piece. The object is kept at infinity and even if image is formed at infinity. It is called normal adjustment.



$\boxed{L = f_o + f_e}$

$$m = \frac{\beta}{\alpha} = \frac{\tan\beta}{\tan\alpha}$$

$$\boxed{m = \left|\frac{f_o}{f_e}\right|}$$

$$m = \frac{\frac{AB}{C'A}}{\frac{AB}{CA}} \Rightarrow \frac{CA}{C'A} = \frac{f_o}{|f_e|}.$$

Important

Reflecting type Telescope

Advantages of reflecting type over refracting type:—

(i) It has no spherical abrration.
(ii) No chromatic abrevation.
(iii) Mirror weight less than lens so they are less complicated.