Wave optics

Different theories have been given by different physicists regarding the nature of light.

(1) Descartes and Newton's Corpuscular theory (CM model)

In 1637, Descartes gave the corpuscular model of light and derived Snell's law. Newton developed his theory. This model explained laws of Reflection and refraction at an interface. Newton considered light as a stream of weightless particles called corpuscles travelling with very high speed. He assumed that different colours of light arise due to different sizes of the corpuscles.

- Newton predicted that if the ray of light on refraction bends towards normal, the speed of light (C) would be greater in 2nd medium. This was proved wrong later and speed of light in denser medium < C in rarer medium.
- The CM model uses the geometry of straight lines to account for the "macroscopic" phenomenon like
  - → rectilinear propagation of light
  - → Reflection
  - — Refraction. etc..
- However, CM model fails to explain properly the "microscopic" phenomena like interference, diffraction and polarization.

(2)

- Huygen proposed "wave model" (WM) that explains all properties of light (reflection, refraction, interference, diffraction, polarization etc.) except photo-electric effect. The wave theory is later modified by Fresnel. WM predicted that speed of light in denser medium < C in rarer medium, which is in agreement with experiments.
- After Young's interference experiment, it was confirmed that WM explains satisfactorily interference, diffraction and polarization.
- Maxwell proved that light could travel in vacuum (before that it was assumed light requires a medium for its propagation). Therefore light is a e-m wave

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- However, wave theory failed to account for the phenomenon of photoelectric emission. It is also failed to explain Compton effect. The photoelectric effect and the Compton effect thus demanded a return to ~~Corpus~~ CM ~~of~~ model of light.

- The present standpoint is to accept the fact that light is dualistic in nature. The phenomenon of light propagation can be best explained by the WM of light, while the interaction of light with matter in the processes of emission and absorption is a corpuscular phenomenon.

(3) Einstein's Quantum theory (light consists of packets of energy known as photons) explains photoelectric effect and Compton effect. This theory failed to explain interference, diffraction and polarization.

(4) ~~De~~ de-Broglie's theory of Dual Nature of light

→ Till now, it was established that some physical phenomenon like reflection, refraction, interference, diffraction and polarization were explained by ~~con~~ considering light as a wave, while the phenomenon like photoelectric effect and Compton effect were explained by considering light as a stream of photons.

→ Thus, ultimately de-Broglie ~~Concluded~~ concluded that like matter, light has dual nature. His conclusion was based on the fact that the nature loves symmetry.

→ Our universe is made up of "matter" (material particles like electrons, protons, neutrons etc.) and "radiation". If radiation can behave like a particle (photon), then the material particles can also behave like radiation.

→ According to de-Broglie, a moving material particle is always associated with ~~or~~ a wave known as "matter waves" or "de-Broglie waves". Thus, light has dual nature.

Different theories of Light

Descreter / Newton's Corpuscular theory

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Huygen's / Frensel's wave theory → See page 85

→ proposed "medium ether"

↓

Maxwell's electromagnetic wave theory — Light is e-m wave.

→ need no medium for propagation ... it can travel in vacuum (C in vacuum = $3 \times 10^8 ms^{-1}$)

→ Hence confusion created by concept of Ether was removed.

↓

Einstein's Quantum theory

↓

de-Broglie's "Dual Nature of light" theory

Huygen's wave theory of light. [wave Model → WM]

In 1678, Huygen proposed wave theory of light. According to this theory, light is a periodic disturbance transmitted through a medium in the form of waves.

→ the assumed medium as ether, which spreads throughout the space and is noticeable in all parts of space (pervading space) including vacuum and it has very high elasticity.

→ WM explained reflection and refraction ~~of~~ of light successfully.

→ WM failed to explain "rectilinear propagation of light".

→ Huygen assumed that light waves are longitudinal (like sound waves)

→ However, ~~later~~ later Fresnel concluded that light is transverse in nature (not ~~by~~ longitudinal as proposed by Huygen). The speed of light in the medium ether was assumed to be

$$c = \sqrt{\frac{E}{\rho}}$$ where E → Elasticity of the medium, ρ → ~~is~~ density of the medium.

→ Since c is very large $3 \times 10^8\ ms^{-1}$, E of ether should be very large and ρ of ether should be very small.

→ However, medium with high E and low ρ cannot exist.

→ Moreover, medium ether was never detected. Ultimately, the concept of ~~ether~~ medium ether was rejected by famous experiment known as "Michelson – Morley" experiment.

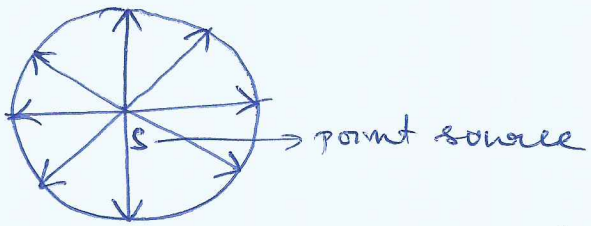
Huygen's principle :

- He introduced a term "wavefront"
- A wavefront is defined as the continuous locus of all particles of a medium, which are vibrating in the same phase.
  - Thus wavefront is defined as a surface of constant phase.
- In fact, a source of light sends out disturbance in all directions.
  - In a homogeneous medium, the velocity of light waves in all the directions is the same. Therefore, disturbance reaches at the same time, at all such particles which are at the same distance from the source. So, these particles will naturally vibrate in phase with one another. The locus of all such particles is being called the wave front.

Depending on shape of source of light, wavefront can be of 3 types.

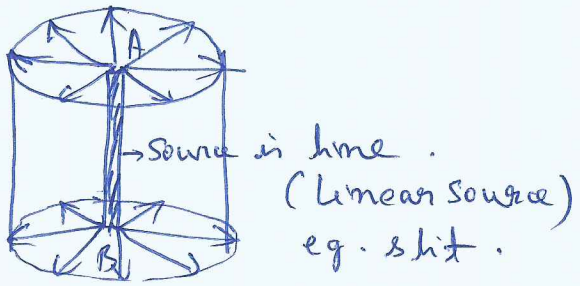
(1) Spherical wavefront

- For point source, wavefront is spherical.



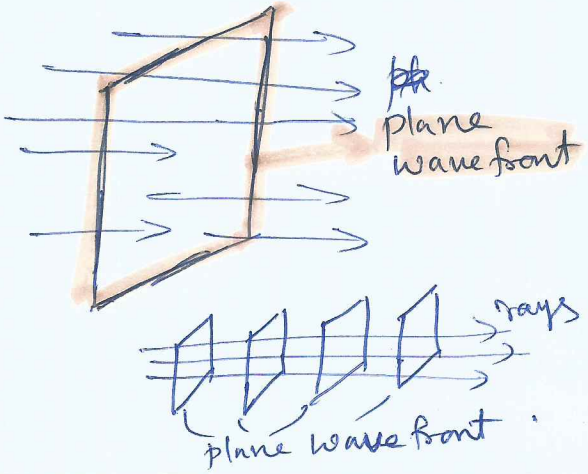
(2) Cylindrical wavefront

If the source of light (or disturbance) is a slit AB (ie. line source), then the wavefront is cylindrical, because all the points equidistant from line source lie on the surface of the cylinder.



(3) ~~plane~~ plane wave front.

When the point source or linear source of light is at very large distance, a small portion of spherical or cylindrical wavefront appears to be plane. Such a wavefront is called a plane wave front.



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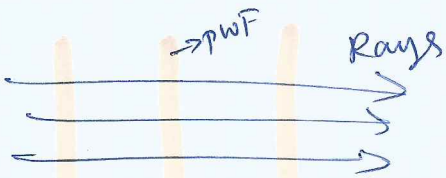
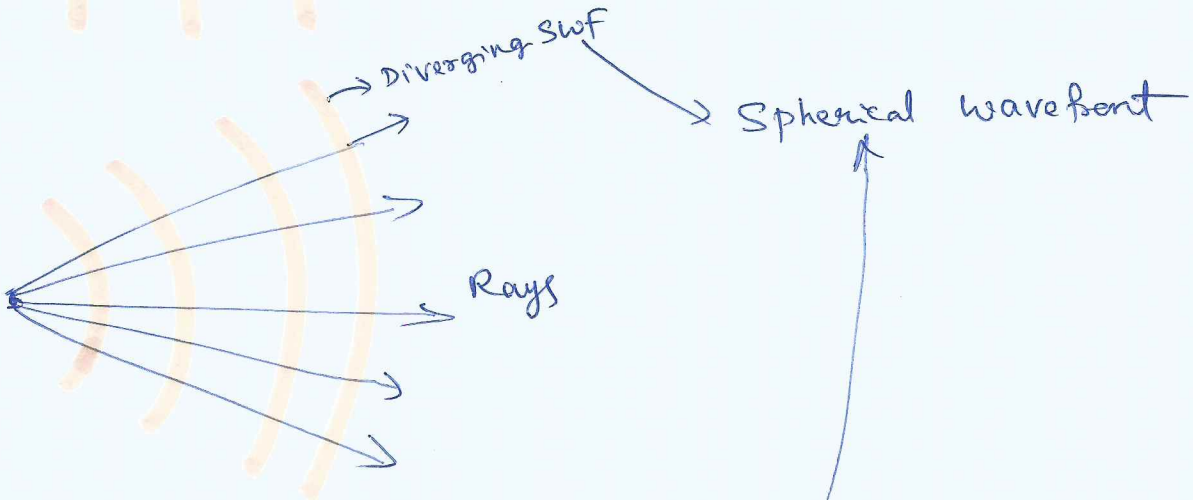
→ the speed with which the wavefront moves outwards from the source is called the speed of the wave.

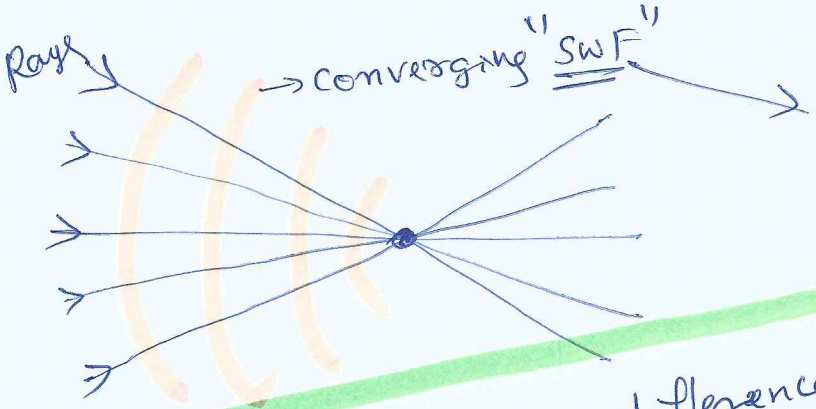
→ The energy of the wave travels in a direction ⊥r to the wavefront.

→ In a given medium, we can draw a set of straight lines which are ⊥r to the wavefront. These straight lines are the rays of light. Thus rays are always normal (⊥r) to the wavefront. As per Huygen, light energy flows along rays.



PWF → plane wavefront

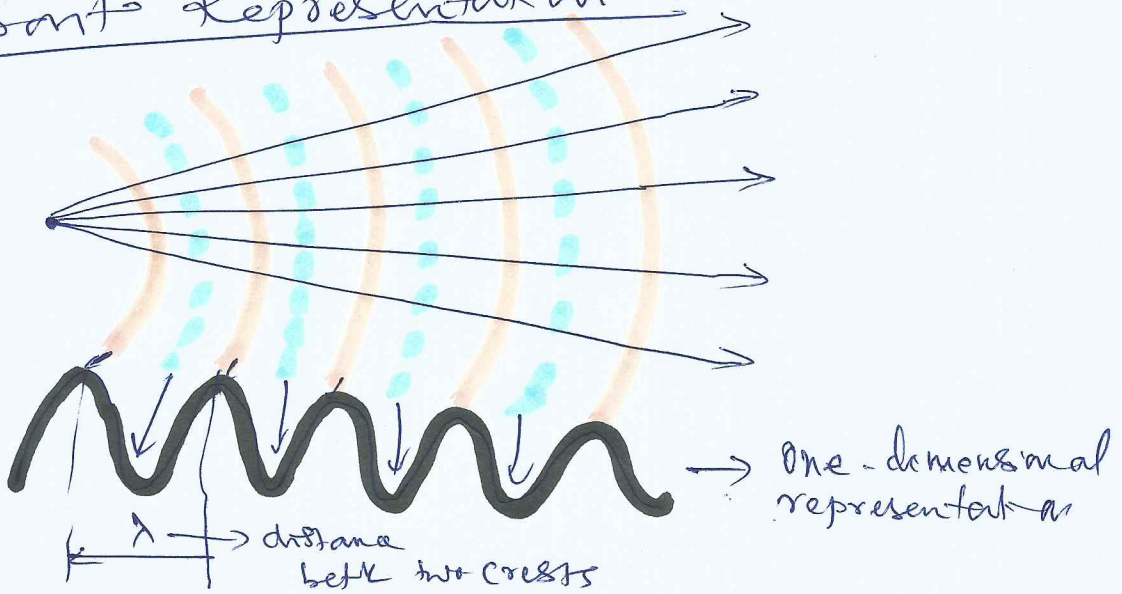


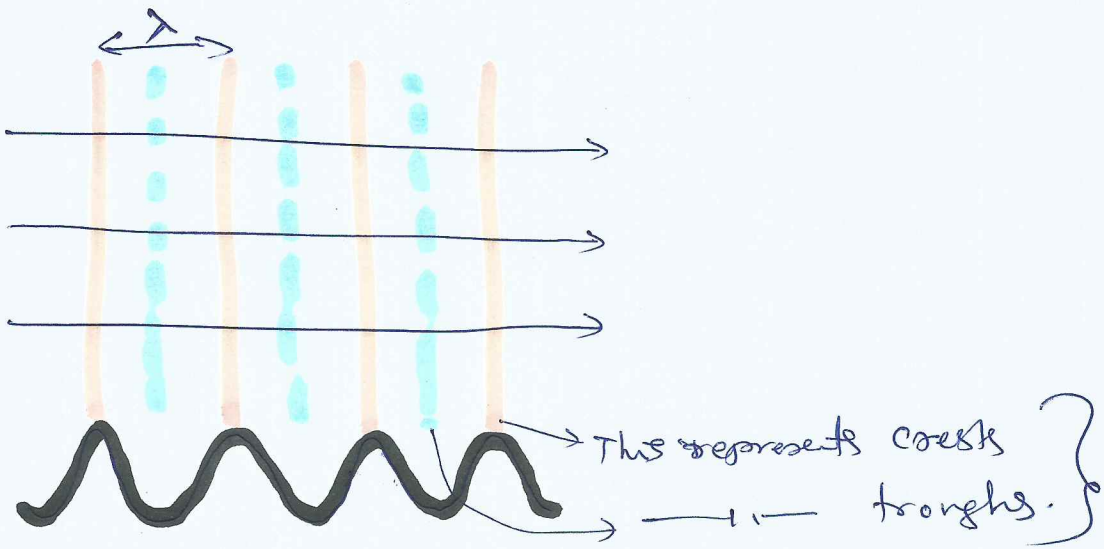


Imp: the phase difference between any two points situated on the same wavefront is zero.

Wavefront Representation

(two-dimensional representation)





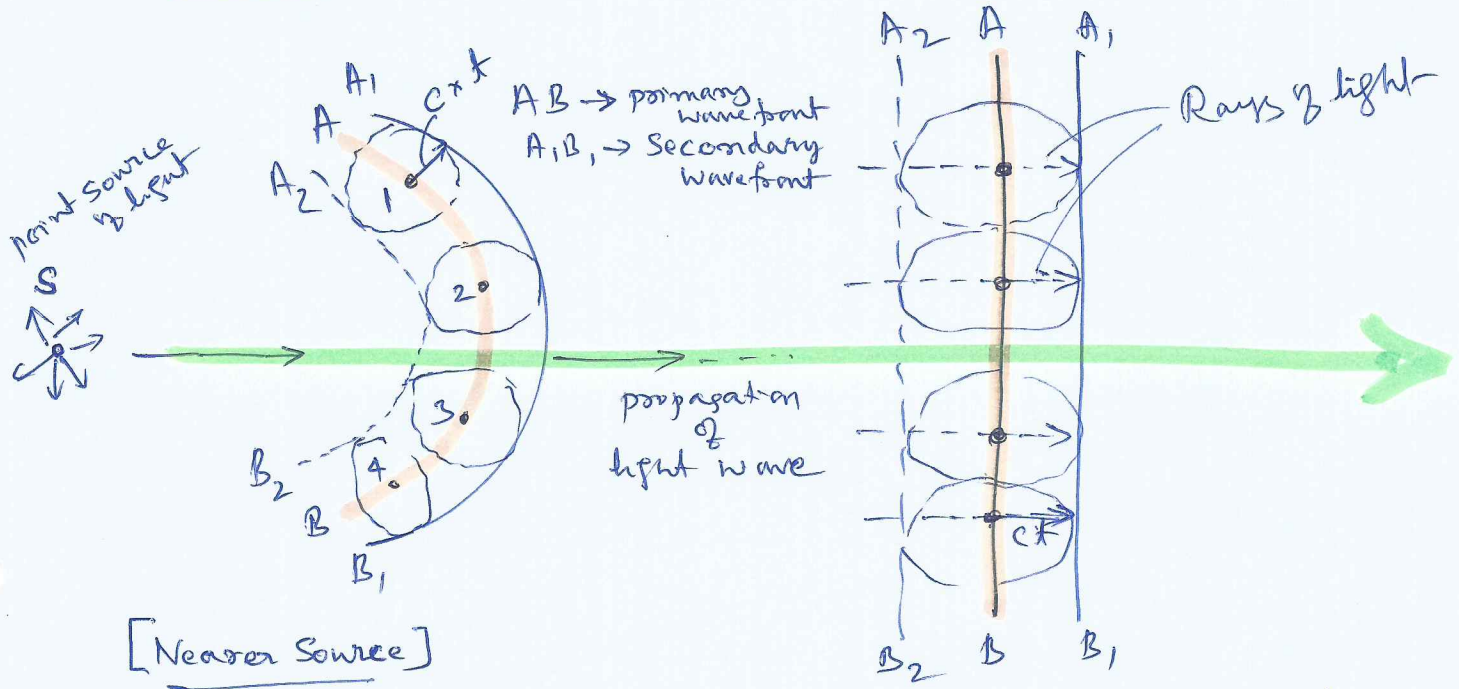
Huygen's principle : Geometrical Construction of Wavefront

Huygen's principle gives geometrical details of travelling of a wave. This principle is used to find the position of the given wavefront at any instant of time if its present position is known.

According to Huygen,

(a) Every point on the given wavefront (called primary wavefront) acts as a fresh source of new disturbance, called secondary wavelets, which travel in all directions with the velocity of light in the medium.

(b) A surface touching these secondary wavelets, tangentially in the forward direction at any instant gives the new wavefront at that instant. This is called secondary wavefront.



- Let AB is given wavefront (called primary wavefront). Consider points 1, 2, 3, 4 on AB.
- To find Sec. wavefront after a time 't', the distance travelled by light in t second = ct (where c → velocity of light in the given medium)
- Taking each point (1, 2, 3, 4 on AB), draw spheres of radius ct. Draw tangents on every sphere in the forward direction and join them to get a surface A_1B_1 → Secondary wavefront.
- Similarly in the backward direction, we get A_2B_2 surface → Backward propagation is not considered as per Huygen's principles.
- The amplitude and hence the intensity due to the secondary wavelets depends on the "Obliquity Factor" = $1 + \cos\theta$.

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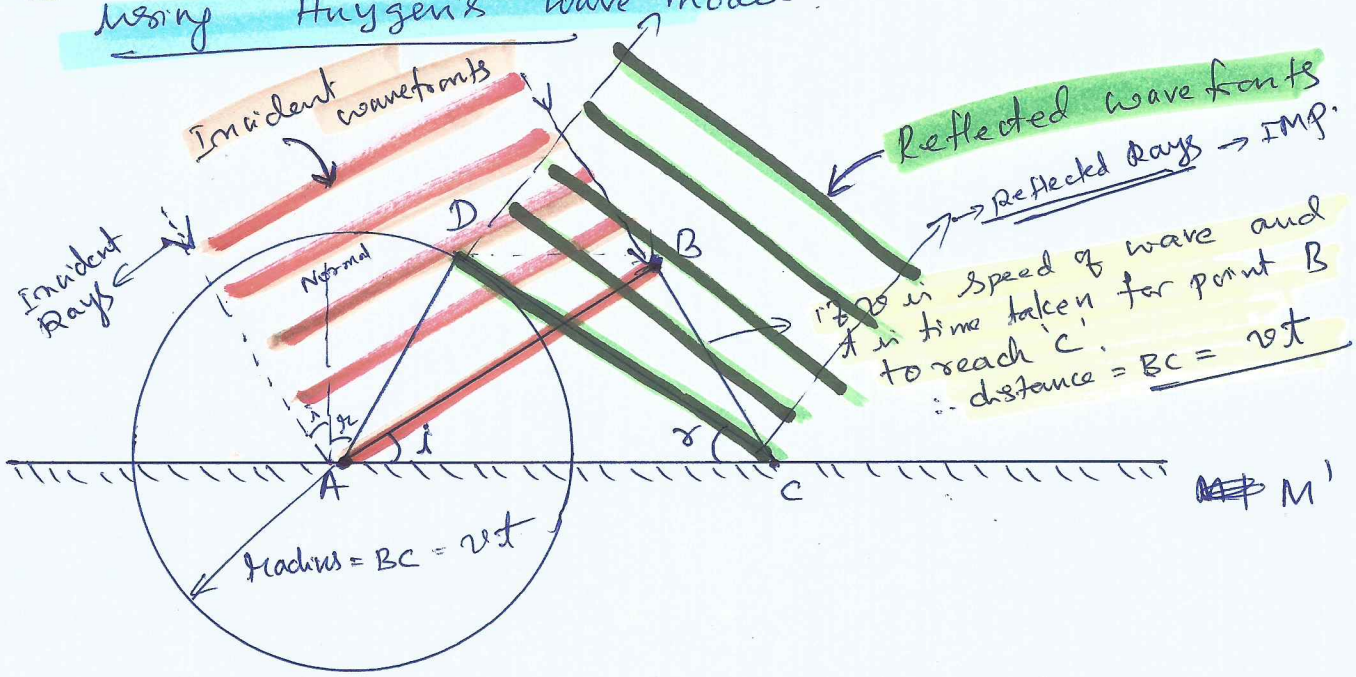
- Along backward direction, $\theta = 180^\circ$

  ∴ Obliquity Factor $= 1 + \cos 180 = 1 - 1 = 0$. Hence, the intensity in the backward direction is zero so the wavefront A_2B_2 does not exist. There is no backward flow of energy when a wave travels in the forward direction. However, it is not precisely ~~true~~ true.

- From the above discussion, it is noted that in a homogeneous isotropic medium, during the wave propagation, the radius of the spherical divergent wavefront increases uniformly with time and a wavefront is propagated parallel to itself.

"Reflection" of a "plane wavefront" by a plane surface using Huygen's wave model



→ MM' → Reflecting Surface

→ Consider AB → plane wavefront AB incident on MM' at A at ∠le i

→ We need to construct reflecting wavefront and prove $\hat{i} = \hat{r}$

proof: As per Huygen's principle, each point on ~~the~~ incident wavefront AB acts as a source of new disturbance.

- ~~point B~~ If v is velocity of wave and if t is the time taken for ~~point~~ wavelet B to reach C, then BC = vt
- During this time "~~t~~" t, the ~~point~~ wavelet A has acquired radius = vt.
- Draw a sphere of r = vt with centre as 'A'.
- Draw CD tangent to this sphere. Then AD = BC = vt
- Δles ADC and ABC are congruent and right angled also
  - → In Δ ABC, ; BC = AC Sin i
  - → In Δ ADC , ; AD = AC Sin r

  { Sin i = BC/AC ; Sin r = AD/AC }

Since AD = BC

AC Sin i = AC Sin r

Sin i = Sin r

→ $\boxed{i = r}$ Hence law of Reflection stating that angle of incidence i = angle of reflection r is proved (one part of reflection)

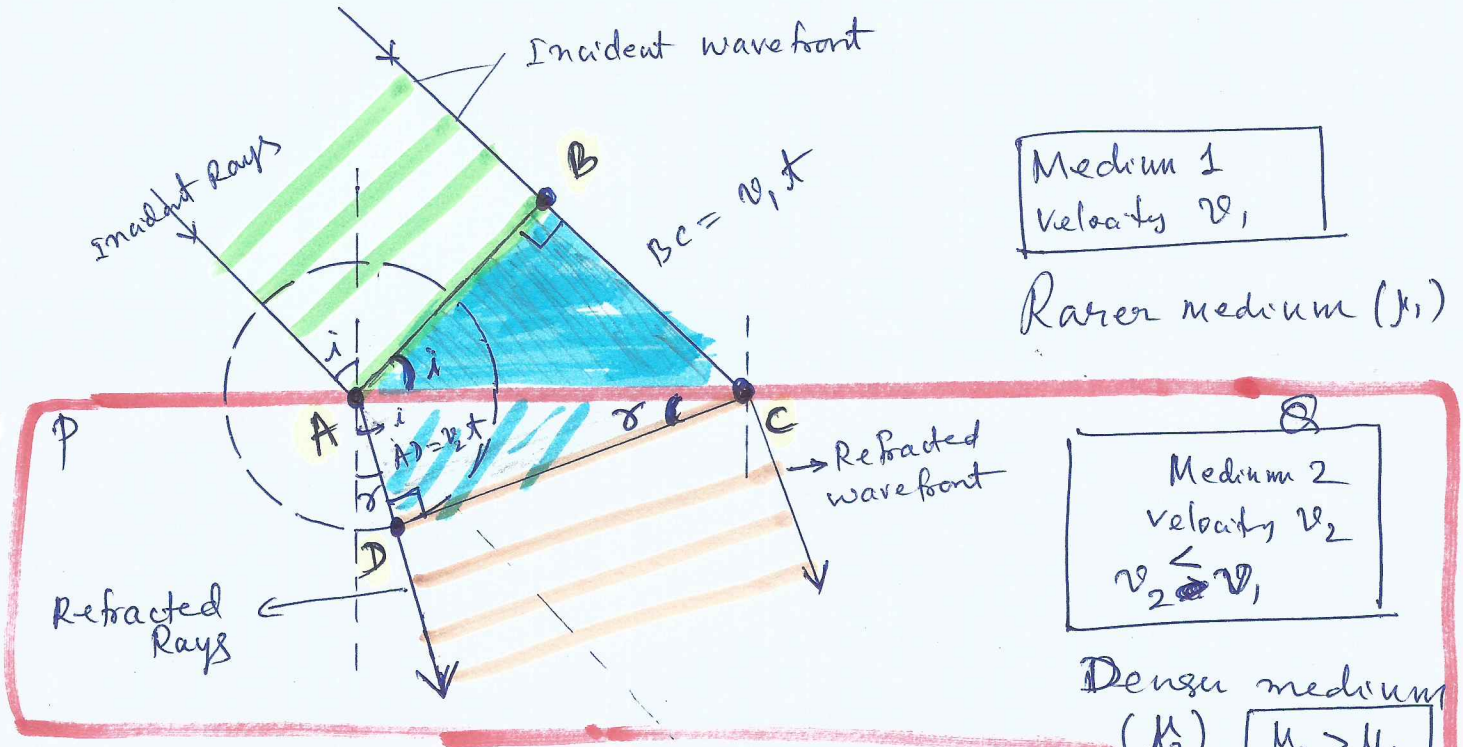
I Law of reflection.

→ ~~Further, incident wavefront AB, reflected wavefront ABDC~~

→ Further, incident wavefront AB, reflected wavefront DC and the reflecting surface MM' are all ⊥r to plane of paper. In constrast, the ~~and~~ incident ray, reflected ray and the normal all lie in the plane of paper. This proves second law of Reflection.

"Refraction" of a plane wave at a plane surface using Huygen's wave model

I From Rarer medium to Denser medium



- PQ → ~~Reflecting~~ surface separating two media with different μ.
- Consider a plane wave AB incident on surface PQ.
- From figure, $\mu_2 > \mu_1 \therefore v_2 < v_1$ (Velocity of wave decreases in medium 2).
- First ~~Acti~~ point ~~point~~ wavefront at A hits PQ. wavefront @ B reaches point C on PQ after t secs. ∴ ~~BC = v₁t~~ $BC = v_1 t$.
- During this time t, wavefront at A would travel in medium 2 with decreased velocity ($v_2 < v_1$) ∴ $AD = v_2 t$.
- Draw a sphere of $r = v_2 t$ with centre taken at A.
- Draw a tangent line from C to the tip of circle that it meets.
- DC is a ~~is~~ refracted wavefront.
- $\Delta ABC \rightarrow \sin i = BC/AC$
  $\Delta ADC \rightarrow \sin r = AD/AC$
  $\therefore \frac{\sin i}{\sin r} = \frac{BC}{AD} = \frac{v_1 t}{v_2 t} = \frac{v_1}{v_2}$

$$\therefore \frac{\sin i}{\sin r} = \frac{v_1}{v_2} = \frac{\mu_2}{\mu_1} = \mu_{21}$$

(μ_{21} → Refractive index of the 2nd medium wrt first medium)

$\because \mu_1 = c/v_1$, $\mu_2 = c/v_2$ (c → velocity of light in vacuum)

$\therefore \frac{\mu_2}{\mu_1} = \frac{c/v_2}{c/v_1}$

$$\boxed{\frac{\mu_2}{\mu_1} = \frac{v_1}{v_2}}$$

$$\therefore \boxed{\frac{\sin i}{\sin r} = \mu_{21}} \quad \text{or} \quad \boxed{\mu_1 \sin i = \mu_2 \sin r}$$

Since $\mu_2 > \mu_1$, $\sin i > \sin r$
$\therefore i > r$ → (1)

∴ Refracted ray bends towards normal.

P.T.O

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So, $\boxed{\frac{\sin i}{\sin r} = \mu_{21} = \frac{\mu_2}{\mu_1}}$

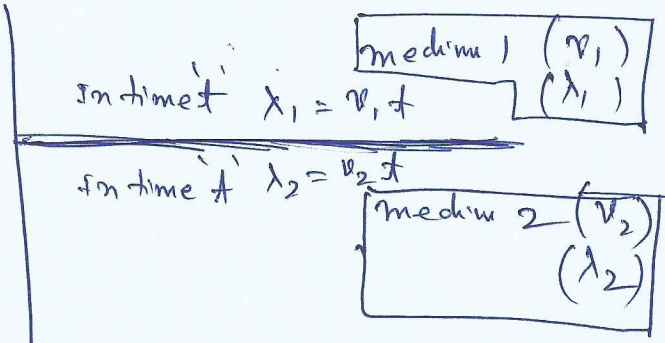
If λ_1 is wavelength in medium 1 $\quad \therefore BC = \lambda_1 = v_1 t$

λ_2 —— do —— 2 $\quad \therefore AD = \lambda_2 = v_2 t$

$$\therefore \boxed{\frac{BC}{AD} = \frac{\lambda_1}{\lambda_2} = \frac{v_1}{v_2} = \frac{\sin i}{\sin r} = \mu_{21}}$$

$$\therefore \boxed{\frac{v_1}{\lambda_1} = \frac{v_2}{\lambda_2}} \rightarrow (2)$$

Eq (2) implies when wave get refracted from rarer medium to denser medium, then v and λ decreases proportionately to keep frequency f constant.



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Famous formula of Speed of light in Vacuum (or air)

$$\boxed{c = f\lambda} \rightarrow (3)$$

- $c \rightarrow$ Speed of light in Vacuum (and also ≈ in air)
- $f \rightarrow$ freq. of light wave
- $\lambda \rightarrow$ wavelength of light wave
- $c = 3 \times 10^8 \, ms^{-1}$ (Vacuum and also in air)
- Notation 'c' is used to denote speed of light only in Vacuum (or sometimes in air also)
- 'c' decreases in material medium like water, glass etc..... then we need to use velocity notation as v

For material medium

$v_1 = f_1 \lambda_1$ $\qquad$ $v_2 = f_2 \lambda_2$

Since from eq (2) $\frac{v_1}{\lambda_1} = \frac{v_2}{\lambda_2}$, then $f_1 = f_2$

IMP { ↳ implies frequency of light wave does not change when passing through different media.