Wave Optics

Objectives

After going through this lesson, the learners will be able to

- Distinguish between Ray and Wavefront
- Understand the Huygens' principle
- Distinguish between the spherical, cylindrical and plane wavefront.
- Understand the shape of wave fronts after reflection and refraction through mirrors, lenses and prism.
- Apply the Huygens' Principle to explain laws of reflection and refraction

Content Outline

- Unit syllabus
- Module wise distribution of unit syllabus
- Words you must know
- Introduction
- Wavefront and Huygens's Principle
- Refraction and reflection of plane wavefront using Huygen's principle
- Verification of Laws of refraction and reflection of light using Huygen's principle
- Summary

Unit Syllabus

UNIT 6: Optics

Chapter–9: Ray Optics and Optical Instruments

Ray optics: Reflection of light; spherical mirrors; mirror formula; refraction of light; total internal reflection and its applications; optical; fibers; refraction at spherical surfaces; lenses; thin lens formula; lens maker's formula; magnification, power of a lens; combination of thin lenses in contact; refraction and dispersion of light through a prism.

Scattering of light – blue color of sky and reddish appearance of the sun at sunrise and sunset

Optical instruments – microscopes and astronomical telescopes (refracting and reflecting) and their magnifying powers

Chapter-10: Wave Optics

Wave optics: Wavefront and Huygens's principle, reflection and refraction of plane waves at a plane surface using wave fronts. proof of laws of reflection and refraction using Huygens's principle. Interference, Young's double slit experiment and expression for fringe width, coherent sources and sustained interference of light; diffraction due to a single slit width of central maximum; resolving power of microscope and astronomical telescope. Polarisation, plane polarised light, Malus's law, Brewster's law, uses of plane polarised light and polaroid.

Module Wise Distribution Of Unit Syllabus - 15 Modules

Module 1	● Introduction ● How we will study optics ● Light facts ● Ray optics, beams ● Light falling on surfaces of any shape texture ● Peculiar observations
Module 2	● Reflection of light ● Laws of reflection ● Reflection of light by plane and spherical surfaces ● Spherical Mirrors aperture, radius of curvature, pole principal axis ● Focus, Focal length, focal plane ● Image – real and virtual ● Sign convention ● The mirror equation, magnification ● To find the value of image distance v for different values of object distance u and find the focal length of a concave mirror ● Application of mirror formula
Module 3	● Refraction of light ● Optical density and mass density ● Incident ray, refracted ray emergent ray ● Angle of incidence, angle of refraction angle of emergence

	To study the effect on intensity of light emerging through different colored transparent sheets using an LDR ● Refractive index ● Oblique incidence of light, Snell's law ● Refraction through a parallel sided slab Lateral displacement, factors affecting lateral displacement ● To observe refraction and lateral displacement of a beam of light incident obliquely on a glass slab ● Formation of image in a glass slab
Module 4	● Special effects due to refraction ● Real and apparent depth ● To determine the refractive index of liquid using a travelling microscope ● Total internal reflection ● Optical fibers and other applications
Module 5	● Refraction through a prism ● Deviation of light -angle of deviation ● Angle of minimum deviation ● Expression relating refractive index for material of the prism and angle of minimum deviation ● To determine the angle of minimum deviation for given prism by plotting a graph between angle of incidence and angle of deviation ● Dispersion, spectrum
Module 6	● Refraction at spherical surfaces ● Radius of curvature ● Refraction by a lens ● Foci, focal plane, focal length, optical center, principal axis ● Formation of images real and virtual ● Lens maker's formula ● Lens formula and magnification ● Sign convention

	- Application of lens formula - Power of lens - Combination of thin lenses in contact
Module 7	- To study the nature and size of image formed by a ii. convex lens iii. concave mirror using a candle and a screen - To determine the focal length of convex lens by plotting graphs between u and v, between 1/u and 1/v - To determine the focal length of a convex mirror using a convex lens - To find the focal length of a concave lens using a convex lens - To find the refractive index of a liquid by using a convex lens and a plane mirror
Module 8	- Scattering of light – - Blue color of sky - Reddish appearance of the sun at sunrise and sunset - Dust haze
Module 9	- Optical instruments - Human eye - Microscope - Astronomical telescopes reflecting and refracting - Magnification - Making your own telescope
Module 10	- Wave optics - Wavefront - Huygens's principle shapes of wavefront - Plane wavefront - Refraction and reflection of plane wavefront using Huygens's principle - Verification of Laws of refraction and reflection of light using Huygens's principle
Module 11	- Superposition of waves

	● Coherent and incoherent addition of waves
Module 12	● Interference of light ● Young’s double slit experiment ● Expression for fringe width ● Graphical representation of intensity of fringes ● Effect on interference fringes in double slit experiment ● Black and white or colored fringes
Module 13	● Diffraction ● Diffraction at a single slit ● Width of the central maxima ● Comparison of fringes in young’s experiment and those in diffraction from a single slit
Module 14	● Diffraction in real life ● Seeing the single slit diffraction pattern ● Resolving power of optical instruments ● Validity of ray optics ● Fresnel distance
Module 15	● Polarisation ● to observe polarization of light using two polaroid ● Plane polarised light ● Polariser analyser Malus law ● Brewster/s law ● Polarisation due to scattering ● Uses of plane polarised light and polaroids

Module 10

Words You Must Know

Let us remember the words we have been using in our study of this physics course.

Incident ray: path of light from a source in any preferred direction of propagation

Reflected ray: path of light bounced off from a surface at the point of incidence

Refracted ray: path of light when it propagates from one transparent medium to another.

Normal at the point of incidence: normal to the surface at the point of incidence. Important when the surface is spherical or uneven

Converging and diverging rays: rays of light may converge to or seem to diverge from a point after reflection or refraction such rays are called converging or diverging rays.

Laws of reflection: Laws followed by light rays whenever they interact with a surface

- The incident ray, reflected ray and the normal ,at the point of incidence, lie in the same plane
- The angle of reflection is equal to the angle of incidence

  Snell's law: For oblique incidence of light on a transparent medium surface

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

- The incident ray, refracted ray and the normal at the point of incidence all lie in the same plane.
- The angle of refraction is not equal to the angle of incidence.
- A ray of light propagating from a rarer to a denser medium moves towards the normal. This can be observed for obliquely incident rays.

Plane mirror: a polished surface with infinite radius of curvature

Spherical mirror - concave and convex: spherical mirrors are part of spherical surfaces. The polished surface makes them concave or convex.

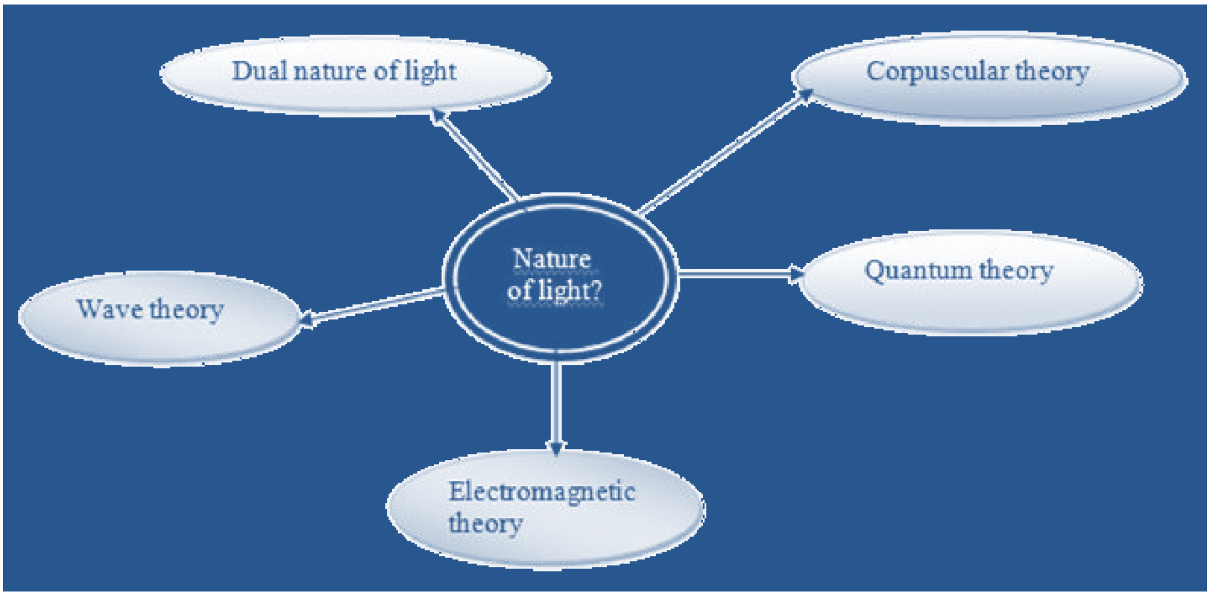
Spherical lens-convex and concave: transparent medium bounded by spherical surfaces, if a thin block of medium has two surfaces bulge out, they form a convex lens

Prism: a rectangular block cut along its diagonal gives two prisms. Each piece has two refracting surfaces, a base and the angle between the refracting surfaces is called angle of prism.

Light Wave: Light is the part of the electromagnetic spectrum. They are transverse waves. light is an electromagnetic wave, produced by transitions of electrons inside the atoms. The frequency depends upon the source atoms. Wavelength depends upon both the source and the medium in which light is travelling.

Introduction

There have been conflicting opinions regarding the nature of light in the history of scientific investigation. Various theories on the nature of light had been put forward by many scientists at different times but **none** by itself could explain all the properties satisfactorily.



Let us briefly describe some of these theories.

In **1637,** Descartes gave the corpuscular model of light and used it to derive Snell's law. His model could explain the laws of reflection and refraction of light at an interface.

The corpuscular model predicted that if the ray of light (on refraction) bends towards the normal then the speed of light would be greater in the second medium. This corpuscular model of light was further developed by Isaac Newton in his famous book entitled **OPTICKS.**

In **1678**, the Dutch physicist Christiaan Huygens put forward the wave theory of light. The wave model could satisfactorily explain the phenomena of reflection and refraction; however, it predicted that on refraction if the wave bends towards the normal, the speed of light would be less in the second medium. This was in contradiction to the prediction made by using the corpuscular model of light.

It was (much) later confirmed by experiments carried out by Foucault that the speed of light in water is less than the speed in air confirming the prediction of the wave model.

The wave theory was not readily accepted primarily because of Newton's authority and also because light could travel through vacuum and it was felt that a wave would always require a medium to propagate from one point to the other.

However, when Thomas Young performed his famous interference experiment in **1801**, it was firmly established **that light is indeed a wave phenomenon**.

After the interference experiment of Young in 1801, for the next 40 years or so, many experiments were carried out involving the interference and diffraction of light waves; these experiments could only be satisfactorily explained by assuming a wave model of light.

Thus, around **the middle of the nineteenth century**, the wave theory seemed to be very well established.

Christian Huygens proposed that light energy propagates from one-point to the other in the form of a wave motion.He assumed the presence of a medium called ether as the medium for propagation of light.

The wave theory explained **Reflection, Refraction, Interference and Diffraction** but could not explain **polarisation,** because light waves were assumed to be longitudinal.

This difficulty was overcome by **Fresnel** who assumed light waves to be transverse in nature but the drawback of his theory was his assumption that the ether was a solid elastic medium.

Since the speed of light waves was large, the elasticity of the ether should be large, which was a strange property possessed by a practically unobservable medium.

Later on **Michelson-Morley's** experiment disproved the existence of ether.

When the mathematical description of the light as an **electromagnetic wave** was published by **James Clerk Maxwell** in **1864**, it was thought that a final understanding on the wave nature of light had been reached.

But the **Photoelectric effect and Compton Effect** demanded a revisit to a particle -like nature of light. **Einstein** interpreted it in terms of quantum **theory**. The present stand therefore, is to accept that light is **dualistic in nature, meaning light behaves both as waves and particles** .

Ray Optics accounts for **macroscopic phenomenon** like **Reflection, Refraction** etc, and deals with interaction of a light beam with surfaces and mediums

Microscopic phenomena like **Interference, Diffraction and Polarisation** could be explained on the basis of **wave theory**.

The laws of reflection and refraction; some basic examples of both; some basic ideas about how they relate to the wave nature of light.

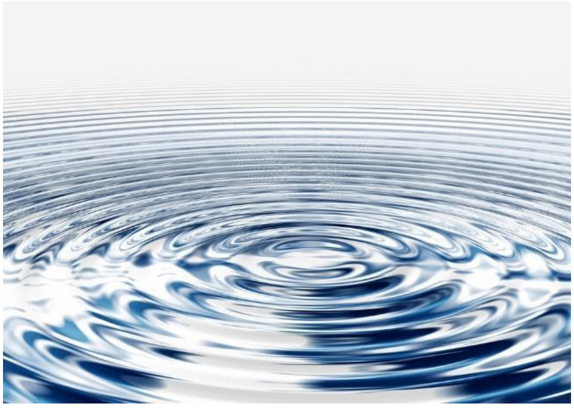
https://www.youtube.com/watch?v=nOS0TGeuLoc

Modules 10-15 deal with various phenomena related to wave nature of light

Wavefront

Consider dropping a small stone on a calm pool of water. Waves spread out from the point of impact. Every point on the surface starts oscillating one by one. At any instant, a photograph of the surface would show circular rings on which the disturbance is maximum.

You might have seen these circles, when you gently disturb a still water surface (pond, river water, bucket of water).



Ripples on the surface of water

https://pixabay.com/en/wave-concentric-waves-circles-water-64170/

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We can see concentric circular rings or ripples on the surface of the water which grow as the disturbance travels. The circular rings on the water surface are points where the particles of the water have constant or zero phase difference.

Similarly, if we consider a light source, placed in a homogeneous medium, the velocity of light waves in all directions is the same.

Therefore, the disturbance reaches all points, which are at the same distance from the source at the same time.

Clearly, **all points on such a surface are oscillating in phase because they are at the same distance from the source.**

It is defined as the locus of points having a zero or constant phase difference.

Such a locus of points, which oscillate in same phase, is called a **WAVEFRONT**.

Thus *a* **wavefront** *is* **defined as a surface of constant phase**.

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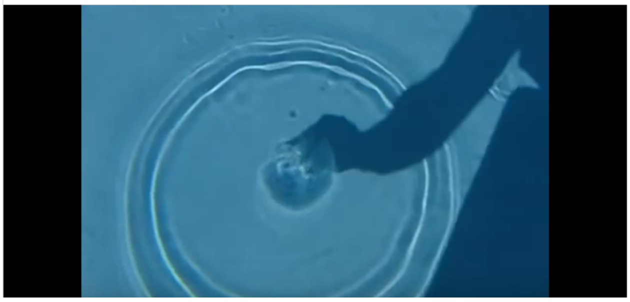
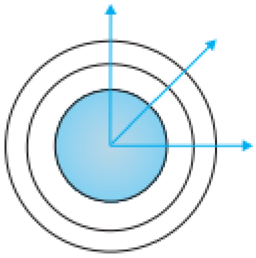


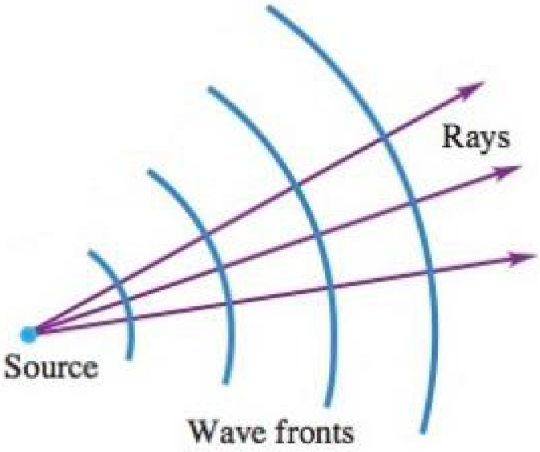
The speed with which the wavefront moves outwards from the source is called **the speed of the wave.**

The energy of the wave propagates in a direction perpendicular to the wavefront. Such directions of energy flow, which are always perpendicular to the wavefront, are called rays.

If we have a point source emitting waves uniformly in all directions, then the locus of points which have the same amplitude and vibrate in the same phase are spheres and we have what are known as a ***spherical wavefront*** as shown in figure



A diverging spherical wave emanating from a point source. The wave fronts are spherical



Or

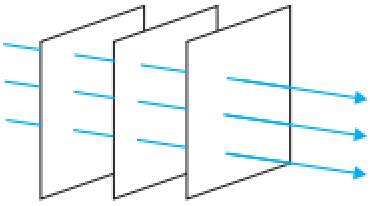
When if it is an extended (light slit) source, with more dimensions in length, the wavefront is cylindrical in nature and are called **cylindrical wavefront.**

If we look at a small portion of a spherical wavefront, very far away from the source then the part of the spherical wavefront would look like parallel planes.

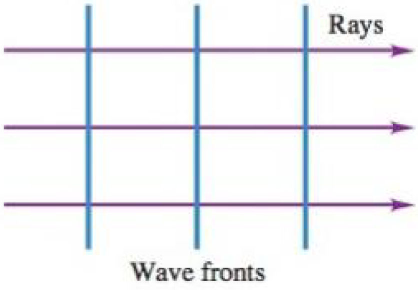
The corresponding rays are parallel lines perpendicular to these planes as shown in figure.

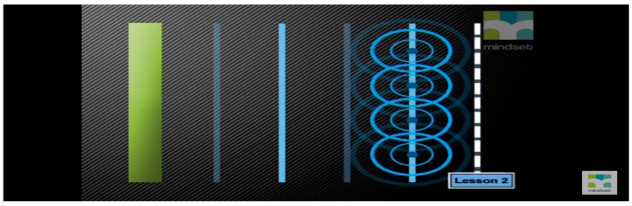
These planes are called **plane wavefront**.

A linear source such as an illuminated slit gives rise to **cylindrical wavefronts**. Again at very far distances a portion of these wavefronts can be regarded as plane wavefronts.



Plane wavefront is a cross section of a cylindrical wavefront in a plane; a cross section of spherical wavefront are concentric circles.



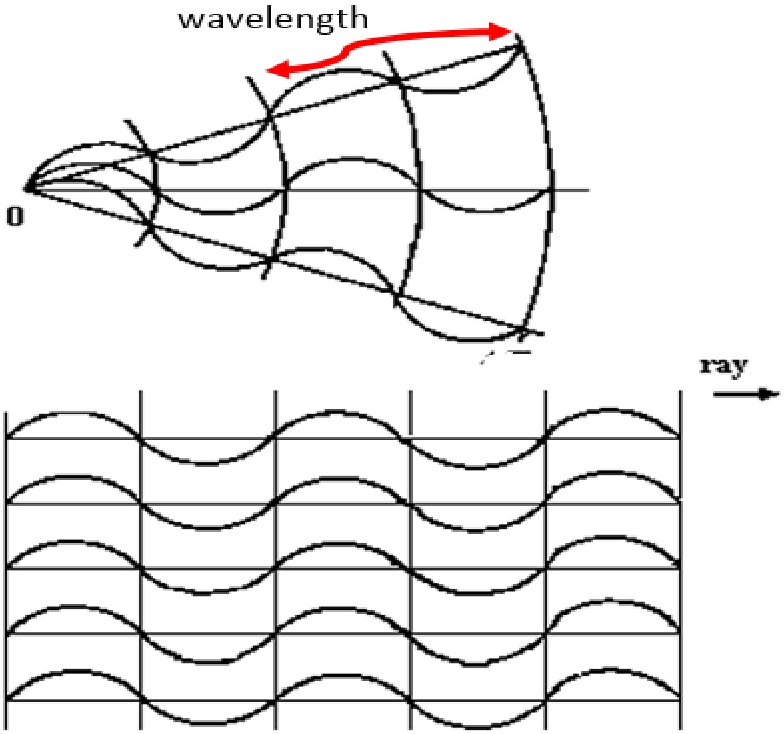


https://www.youtube.com/watch?v=vqa4L0DuWbM

The light waves emerging from a point source, always form a spherical wavefront in **homogeneous 3D space** as shown in the figure

You may understand it better by considering the wave and parts of concentric circles showing particles in the same phase.

Here **alternate lines /circles** are in the same phase. Consecutive wavefronts are one wavelength apart.



Notice the **alternate lines /circles** are in the same phase, forming the wavefront, each wavefront is one **wavelength** apart**.**

Huygens Principle

Christian Huygens, a Dutch, in 1678, proposed a method to predict a new wavefront from an existing wavefront, as the wave propagated in any direction.

Now, if we know the shape of the wavefront at an instant $t = 0$.Huygens principle allows us to determine the shape of the wavefront at a later time τ.

Thus, **Huygens principle is a pure geometrical construction, which given the shape of the wavefront at any time t = 0, allows us to determine the shape of the wavefront at a later time** τ.

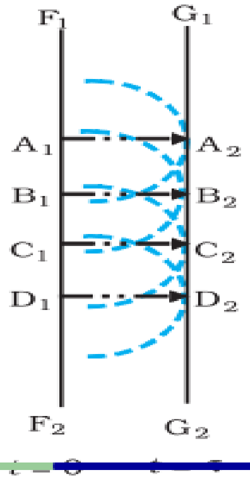
Also Huygens's proposal gives the position and shape of a wavefront at any time from its initial position in the same or in any other medium.

According to **Huygens Principle**:

- **Each point of the wavefront is a source of a secondary disturbance and the wavelets emanating from these points spread out in all directions with the speed of the wave. These wavelets emanating from the wavefront are usually referred to as secondary wavelets.**
- **If we draw a common tangent (in the forward direction) to all these spheres, we obtain the new position of the wavefront at a later time.**

  Hence common tangents in the forward direction drawn to all the secondary wavelets give the position and shape of the new wavefront. This new wavefront is called the secondary wavefront.

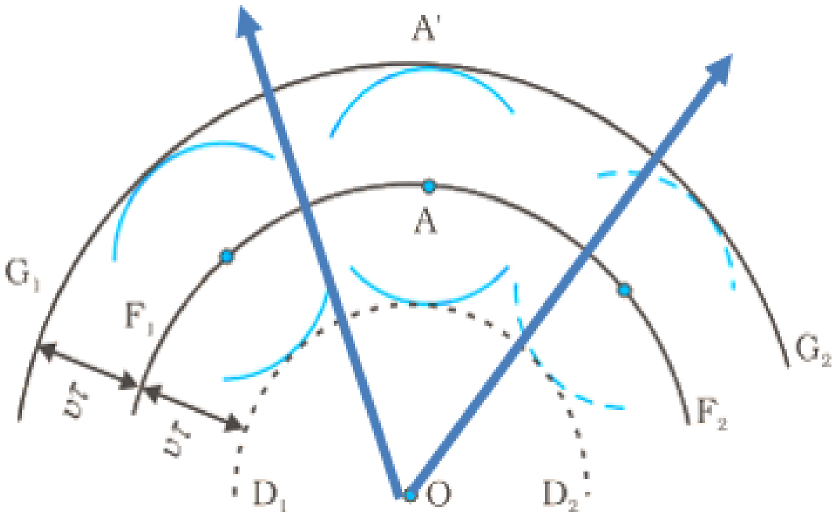
  Suppose the light energy travels outwards along straight lines emerging from the source, i.e. radii of spherical wavefront.



Huygens geometrical construction for a plane wave propagating to the right. F_1 F_2 is the plane wavefront at t = 0 and G_1 G_2 is the wavefront at a later time τ.

The lines $A_{1,}$ A_2, B_1 B_2 … etc. are normal to both F_1 F_2 and G_1 G_2 and represent rays.

The blue dotted lines represent spherical wavelets reaching G_1 G_2 at the same instant.



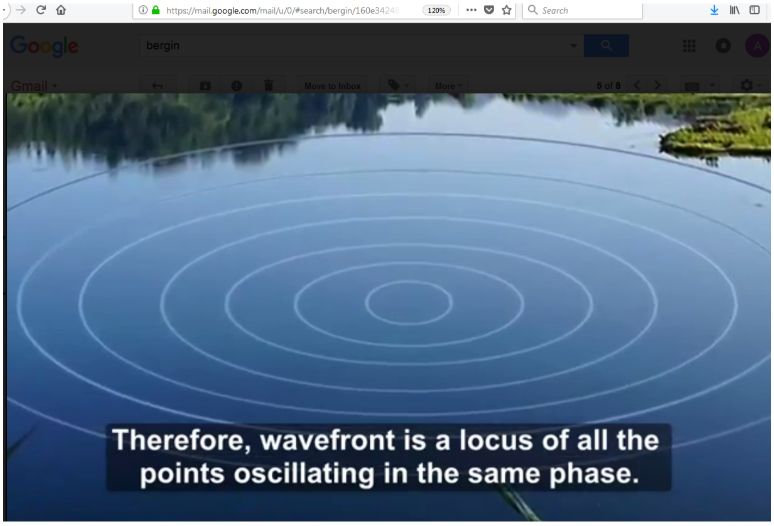
F_1 F_2 represents the spherical wavefront (with O as center) at t = 0.

The envelope of the secondary wavelets emanating from F_1 F_2 produces the forward moving wavefront G_1 G_2. The back wave D $_1D_2$ is supposed not to exist.

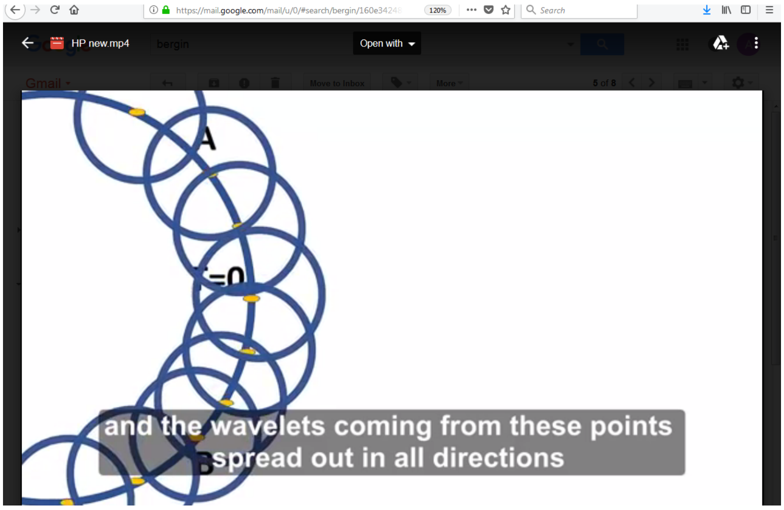
Note

- The tangent to the blue dotted circles, as proposed by Huygens is the new wavefront G_1 G_2
- The envelope, which would exist in all directions in 3 D space is ignored and only the envelope in the forward direction of the ray is selected.
- So if O is the source the bold lines show the rays.
- D_1 D_2 is the ignored wavefront andG_1 G_2 the forward envelope is the new wavefront.
- the construction helps us understand several phenomenon **Reflection Refraction Interference and Diffraction**

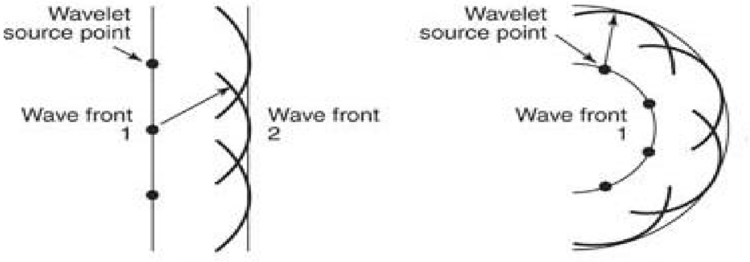
Watch animation



Therefore, wavefront is a locus of all the points oscillating in the same phase.



and the wavelets coming from these points spread out in all directions



(a) (b)

We can thus conclude that-

- The spacing between a pair of wavefronts is constant along any ray and it is equal to one wavelength between consecutive wavefront.
- Rays are perpendicular to wavefronts.
- The time taken for light waves to travel from one wavefront to another wavefront is the same for any ray.

Example

What is the shape of the wavefront in each of the following cases?

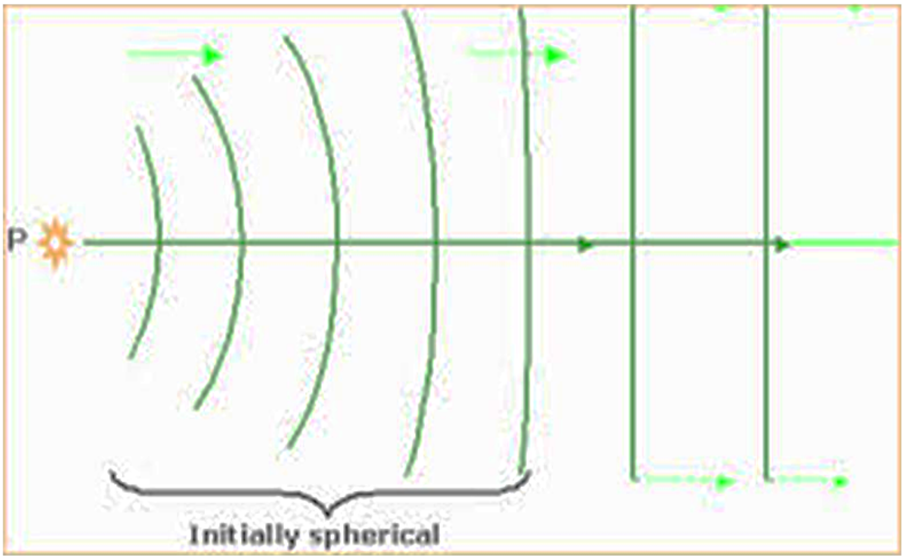
(a) Light diverging from a point source.

(b) The portion of the wavefront of light from a distant star intercepted by the Earth.

Solution

(a) Spherical wavefront

(b) Plane wavefront



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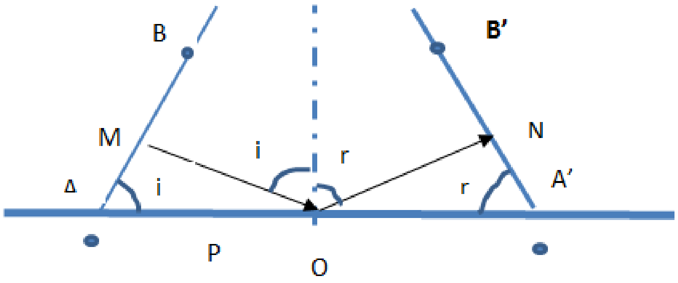
Reflection Of A Plane Wave By A Plane Surface

Using Huygens's principle explaining Reflection of a plane wave at plane surface which means, considering the wave nature of light to explain the phenomenon of reflection

Now we will be able to use Huygens's principle to understand the laws of reflection of light.

Consider an incident plane wavefront AB incident at an angle *i* on a reflecting surface P. We can see that when the point A on the incident wavefront strikes the surface, the point B still has to move through a distance BA'.



If v represents the speed of the wave in the medium and if **τ** represents the time taken by the wave front to advance from the point B to A'

then the distance $BA'' = v\,\tau$

By this time τ, the secondary wavefront of radius $v\,\tau$ with A as center, would have travelled forward whereas the secondary wavefront, with A′ as center, would have just started i.e. would have zero radius.

In order to construct the reflected wavefront we draw a sphere of radius $v\,\tau$ from the point A as shown in Figure.

Let A′B′ represent the tangent plane drawn from the point A′ to this sphere.

This secondary wavefront from A represents the reflected wavefront making an angle r with reflecting surface P. **This angle r is called the angle of reflection.**

Let us try and prove the laws of reflection

The angle of incidence (i) and angle of reflection (r) are the angles made by the incident and reflected rays respectively with the normal. These are also the angles between the wave fronts and the surface as shown in the figure.

The time taken by the ray to travel from M to N after striking the surface at O.

Total time from M to N = $t = \frac{MO}{v} + \frac{ON}{v}$

where v is the velocity of the wave.

$$t = \frac{OA\sin i}{v} + \frac{OB\sin r}{v}$$

or

$$t = \frac{OA\sin i}{v} + \frac{(AB-OA)\sin r}{v}$$

or

$$t = \frac{AB\sin r}{v} + \frac{OA(\sin i - \sin r)}{v}$$

Since time taken by each ray from incident wavefront to reflected wavefront, must be same so,

the right side of the equation must be independent of OA.

This conditions happens only if (sin i - sin r) = 0

Or $i = r$

Thus the law of reflection states that angle of incidence i and angle of reflection are always equal.

Alternately

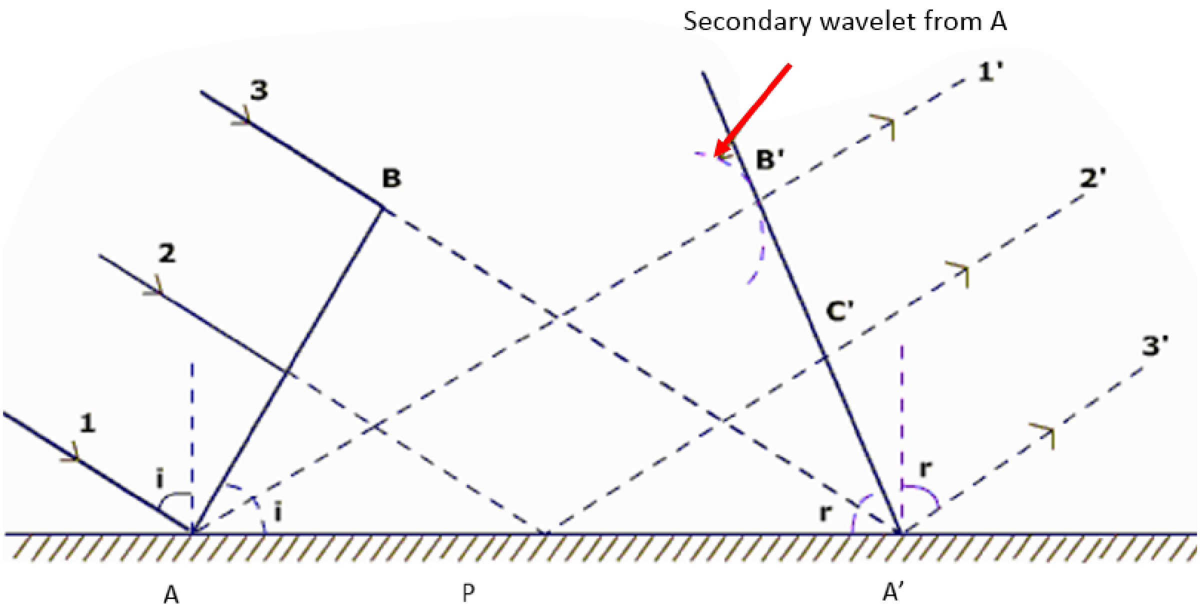
In order to draw a figure to explain the new wavefront position, we can make use of rays along with the wavefront

Remember rays are to show the direction of propagation the light waves, they are perpendicular to the tangent drawn at any point on the wavefront .

Rays are easy to draw for a plane wavefront.

1, 2 and 3 are incident rays for the incident plane wavefront AB.

The angle of incidence is i for the wave front as well as for the incident rays.



Note

In case of incident rays, angle of incidence is the angle between the incident ray and the normal at the point of incidence.

For a wavefront it is the angle between the plane wavefront and the surface.

It is easy to visualize this, since the normal is perpendicular to the surface and the ray is perpendicular to the wavefront angle of incidence is the same whether we consider a ray or a wavefront.

We now, consider the triangles A′BA and AB′A′

- side AB′= side BA′ as according to Huygens construction secondary wavelets from B and A travel the same distance, both = $v\,\tau$

v is the velocity of wave, also the velocity of secondary wavelets in the homogeneous medium and τ is the time after which wavelets from point B on the wavefront AB reach A′ on surface P.

- side AA′ is common

- ∠ ABA′= ∠ AB′A′ = 90^0 angle between ray and the plane wavefront

The triangles are congruent and therefore, the angles *i* and *r* (as shown in Fig.) would be equal.

Laws of reflection if you recall are

- The angle of reflection is equal to angle of incidence.
- The incident ray, reflected ray and the normal at the point of incidence lie in the same plane.

Thus we have used Huygens principle to prove laws of reflection treating light as a wave.

Think About These

- Would you explain a spherical wavefront being intercepted by a plane reflecting the surface in the same way?

- What if the reflecting surface is not plane?
- What if the medium is not air around the surface?
- What if the medium is heterogeneous (say made of different densities of dissimilar gases)?

Tips for drawing the diagram

To draw the above diagram, bear in mind

i) Draw the rays first,

ii) Take angle of incidence less than 45^0 or more than 45^0

iii) Draw the incident wavefront AB

iv) Take BA' as radius and draw a circle with A as center

v) Draw a tangent to the circular arc from A'

vi) This will be the reflected wavefront.

Examples

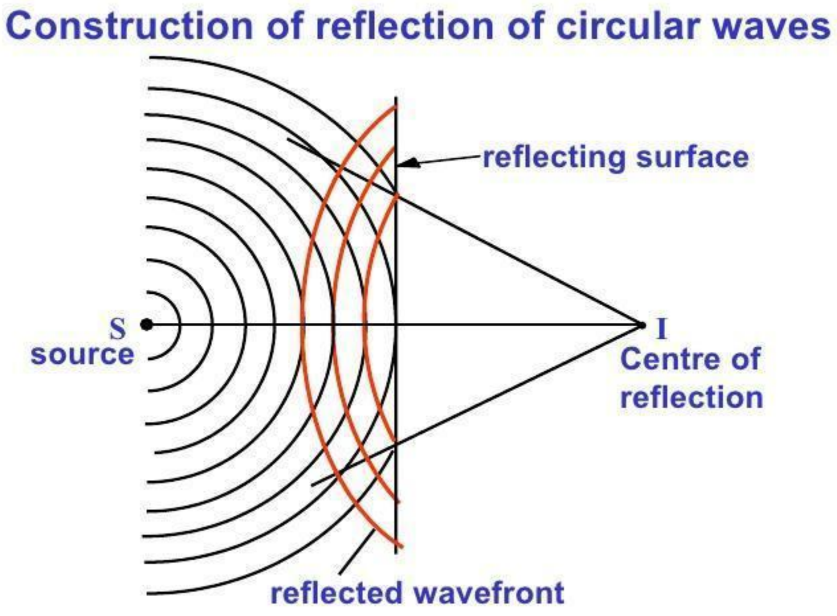
Light from a point source is incident on a plane surface.

i) Draw the incident and the reflected wavefront

ii) Explain the location of the image of the source due to reflection.

Solution

i) A point source will emanate spherical wavefronts. We will draw circular wavefronts to represent spherical wavefront in 2 dimension (on a plane sheet of paper)



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ii) The image is located at the center of the reflected wave front, from geometry it would be located as far behind the surface as S in front of the surface.

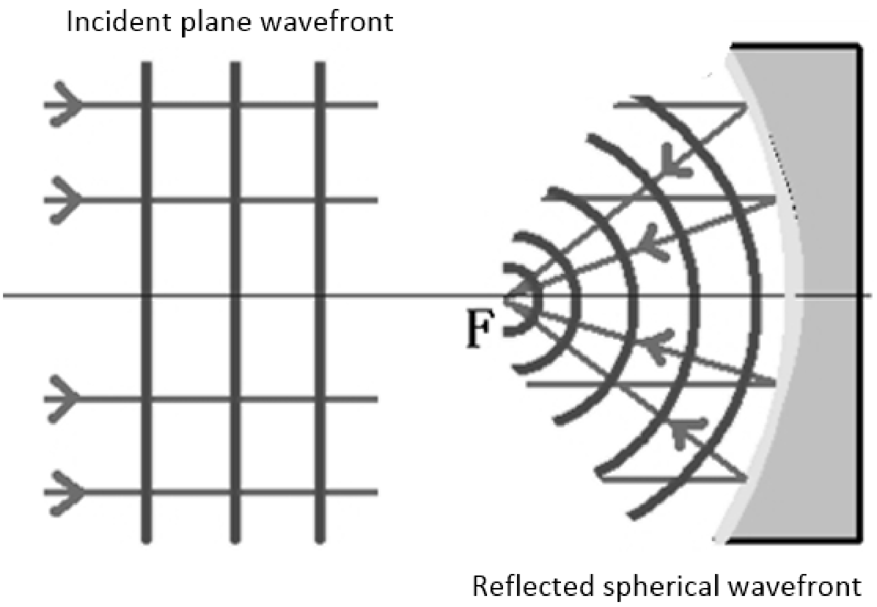
Example

A plane wavefront is incident on a curved concave spherical surface (concave mirror)

i) Draw the reflected wavefront.
ii) Explain the location of focus in 3 dimensions and 2 dimensions
iii) Draw the reflected wavefront beyond F

Solution

i) Draw the ray diagram then draw the circular wavefront using F as the center, **remember** to keep the separation between wavefront same as for the incident plane wavefront as the velocity /wavelength does not change on reflection



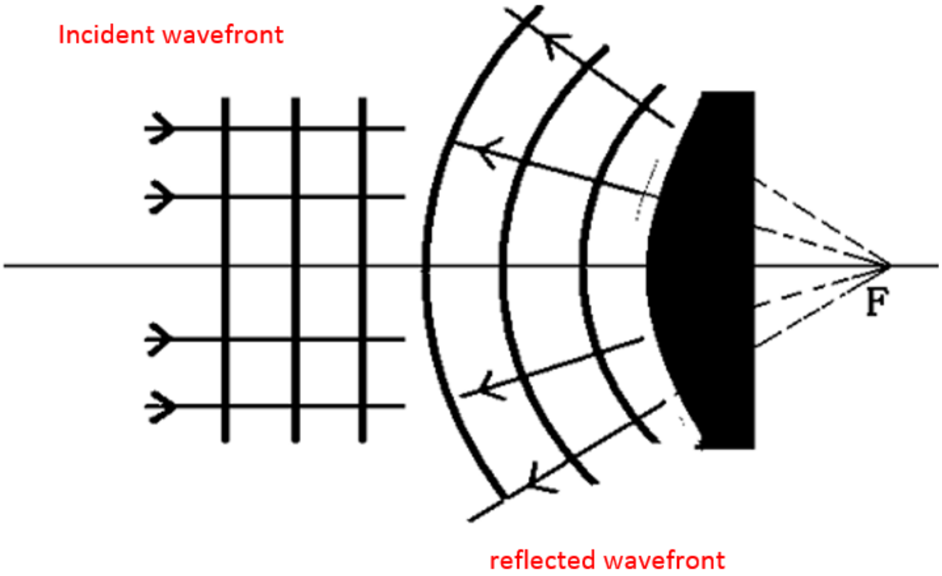
ii) In 3 D the focus would be the center of the spherical reflected wavefront, in 2 D it would be the center of the circular reflected wavefront.
iii) Trace the path of the reflected rays beyond F, next complete the concentric circles to show the reflected wavefront beyond F.

Example

A plane wavefront is incident on a curved convex spherical surface (convex mirror)

i) Draw the reflected wavefront.
ii) Explain the location of focus in 3 dimensions and 2 dimensions.

Solution



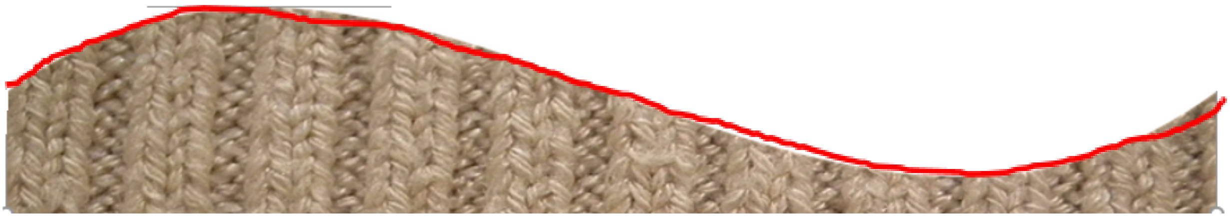
See more

https://www.tes.com/lessons/mvMq1sQNG-7ZEw/reflection-of-wavefronts

Try These

i) a plane wave incident on the following surfaces.

ii) a spherical wave incident on the following surfaces.



Important to note:

- **Frequency of reflected wave does not change .**

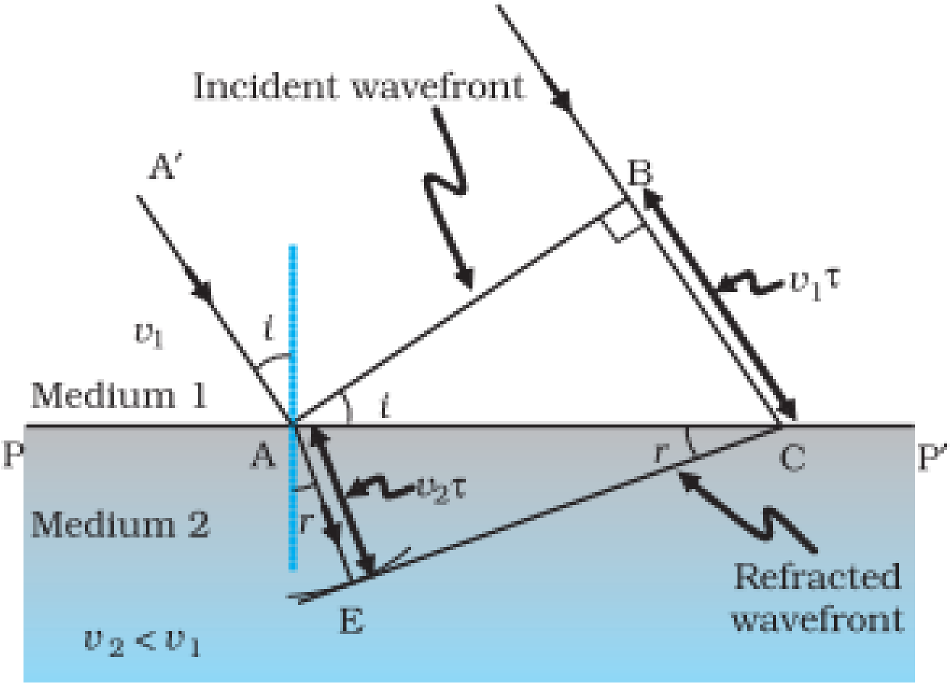
- **Wavelength of the reflected wave does not change.**
- **Amplitude changes as some energy may be absorbed by the reflecting surface .**

Refraction Of A Plane Wave By Plane Surface

We will now use Huygens principle to derive the laws of refraction

Refraction at a denser medium

Let PP′ represent the surface separating medium 1 and medium 2, as shown in figure.



A plane wave AB is incident at an angle i on the surface PP′ separating medium 1 and medium 2. The plane wave undergoes refraction and CE represents the refracted wavefront. The figure corresponds to $v_2 < v_1$ so that the refracted waves bends towards the normal.

A plane wave AB is incident at an angle i on the surface PP′ separating medium 1 and medium 2. Medium 1 is rarer as compared to medium 2.The plane wavefront AB is incident at an angle i undergoes refraction and CE represents the refracted wavefront.

Let v_1 and v_2 ($v_1 > v_2$) represent the speed of light in medium 1 and medium 2, respectively.

The figure corresponds to $v_2 < v_1$ so that the refracted waves bends towards the normal.

We assume a plane wavefront AB propagating in the direction A′A incident on the interface at an angle of incidence i as shown in the figure.In oblique incidence as shown, point A of the wavefront AB strikes the surface before point B.Let τ be the time taken by the secondary wavelet on the wavefront to travel the distance BC in the first medium. Thus, BC = v_1 τ
By this time τ the secondary wavefront of radius $v_2\tau$ with A as centre would have travelled forward in the second medium whereas the secondary wavefront with C as centre would have just started i.e. with zero radius.

In order to determine the shape of the refracted wavefront, We draw a sphere of radius $v_2\tau < v_1 \tau$ from the point A as centre in the second medium (the speed of the wave in the second medium is v_2). Let CE represent a tangent plane drawn from the point C on to the sphere.Then, AE = $v_2 \tau$ and CE would represent the refracted wave front. If we now consider the triangles ABC and AEC, we obtain

$$\sin i = \frac{BC}{AC} = \frac{v_1\tau}{AC}$$

$$\sin r = \frac{AE}{AC} = \frac{v_2\tau}{AC}$$

where i and r are the angles of incidence and refraction respectively.
Thus we obtain from the above two equations

$$\frac{\sin i}{\sin r} = \frac{v_1}{v_2}$$

From the above equation, we get the important result that if $r < i$ (i.e., if the ray bends toward the normal as $v_1 \tau > v_2 \tau$),
The speed of the light wave in the second medium (v_2) will be less than the speed of the light wave in the first medium (v_1).

This is in accordance with the wave theory.

Now, if c represents the speed of light in vacuum, then,

$$n_1 = \frac{c}{v_1} \quad \textbf{and} \quad n_2 = \frac{c}{v_2}$$

n_1 or μ_1 $and\ n_2\ or\ \mu_2$ **are known as the refractive indices of medium 1 and medium 2, respectively.**

In terms of the refractive indices, we can write a useful equation

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

This is the ***Snell's law of refraction***.

Further, if λ_1 and λ_2 denote the wavelengths of light in medium 1 and medium 2 respectively and if the distance BC is equal to λ_1 then the distance AE will be equal to λ_2

(Because if the crest from B has reached C in time τ, then the crest from A should have also reached *E* in time τ);

thus,

$$\frac{\lambda_1}{\lambda_2} = \frac{v_1}{v_2}$$

The above equation implies that when a wave gets refracted into a denser medium ($v_1 > v_2$)

- **the wavelength and**
- **the speed of propagation decreases**

  but the *frequency* f (= *v*/λ) remains the same.

Refraction at a rarer medium

We now consider refraction of a plane wave at a rarer medium, i.e. $\boldsymbol{v_2 > v_1}$.

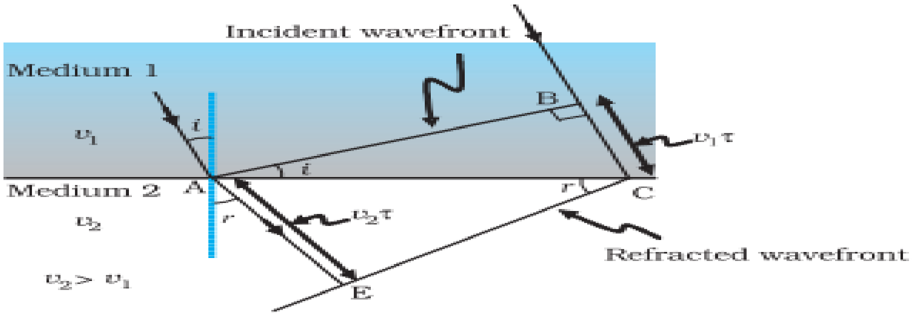
Proceeding in an exactly similar manner, we can construct a refracted wavefront as shown in figure.

The angle of refraction *r* will now be greater than angle of incidence *i* i.e., if the ray bends away from the normal as

$$\mathbf{v_1 \tau < v_2 \tau}$$

The speed of the light wave in the second medium (v_2) will be greater than the speed of the light wave in the first medium (v_1).

This is in accordance with the wave theory.



Refraction of a plane wave incident on a rarer medium for which $v_2 > v_1$

The plane wave bends away from the normal.

$$n_1 \sin i = n_2 \sin r$$

The **Snell's law of refraction** still holds in this situation. We define an angle i_c by the following equation

$$\sin i_c = \frac{n_2}{n_1}$$

Thus, if $i = i_c$ then $\sin r = 1$ and $r = 90°$.

Obviously, for $i > i_c$,

There cannot be any refracted waves.

The angle i_c is known as the **critical angle**. For all angles of incidence greater than the critical angle, we will not have any refracted wave and the wave will undergo what is known as **total internal reflection**.

The phenomenon of total internal reflection and its applications have already been discussed

Example

When monochromatic light is incident on a surface separating two media, the reflected and refracted light both have the same frequency as the incident frequency. Explain why?

Solution

Reflection and refraction arise through interaction of incident light with the atomic constituents of matter. Atoms may be viewed as oscillators, which take up the frequency of the external agency (light) causing forced oscillations.

The frequency of light emitted by a charged oscillator equals its frequency of oscillation. Thus, the frequency of reflected or refracted light equals the frequency of incident light.

Example

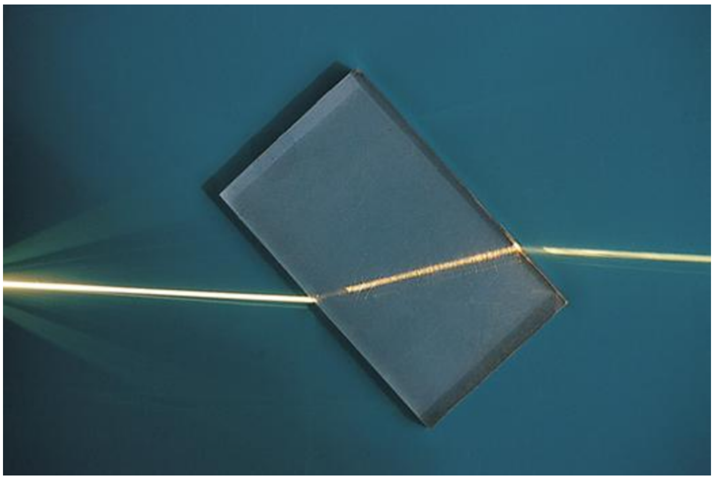
The speed decreases, when light travels from a rarer to a denser medium. Does the reduction in speed imply a reduction in the energy carried by the light wave?

Solution

No. Energy carried by a wave depends on the amplitude of the wave, not on the speed of wave propagation.

Try This

White light is incident on a rectangular glass block



Draw refracted wavefront for red and blue color components when

i) the ray corresponding to plane wavefront is normal to the surface
ii) the ray corresponding to spherical wavefront is normal to the surface
iii) plane wavefront is incident obliquely
iv) spherical wavefront is incident obliquely

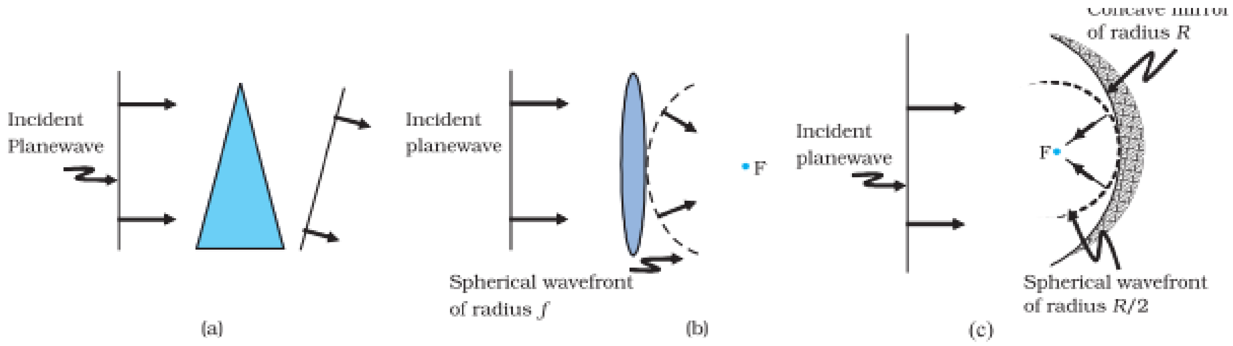
Change In Shape Of WaveFronts

Let us consider a plane wave passing through a thin prism. Since the speed of light waves is less in glass, the lower portion of the incoming wavefront (which travels through the greatest thickness of glass) will get delayed resulting in a tilt in the emerging wavefront as shown in the figure (a).

In figure (b) we consider a plane wave incident on a thin convex lens; the central part of the incident plane wave traverses the thickest portion of the lens and is delayed the most. The emerging wavefront has a depression at the centre and therefore the wavefront becomes spherical and converges to the point F which is known as the *focus*.

In figure (c) a plane wave is incident on a concave mirror and on reflection we have a spherical wave converging to the focal point F.

In a similar manner, we can understand refraction and reflection by concave lenses and convex mirrors.



Refraction of a plane wave by (a) a thin prism, (b) a convex lens (c) Reflection of a plane wave by a concave mirror

Summary

- Light is an electromagnetic wave.
- The Huygens principle tells us that each point on a wavefront is a source of new secondary waves, which can be used to give the new wavefront at a later time.
- Huygens construction tells us that the new wavefront is the forward envelope of the secondary waves.
- When the speed of light is independent of direction, the secondary waves are spherical. The rays are then perpendicular to both the wavefront and the time of propagation is the same measured along any ray.
- This principle leads to the well-known laws of reflection and refraction.