

Theories of Light

Optics

Optics is the branch of physics which is concerned with light and its behavioral pattern and properties.

Light and Its Optical Properties: Light is a form of energy that is in the form of an electromagnetic wave and is almost everywhere around us. The visible light has wavelengths measuring between 400–700 nanometres. The Sun is the primary source of light by which plants utilize this to produce their energy.

In physics, the term light also refers to electromagnetic radiation of different kinds of wavelengths, whether it is visible to the naked eye or not. Hence, by this, the gamma rays, microwaves, X-rays, and radio waves are also types of light.

- **Ray optics** also called geometrical optics, describes light propagation in terms of “rays”.
- **Wave optics** is the branch of optics that studies the diffraction, interference, polarization, and other phenomena for which the ray approximation of geometric optics is not valid.
- The wave properties of light can be grouped into 3 categories:
 - Interference
 - Diffraction
 - Polarization
- **Wavefront** is defined as *the imaginary surface constructed by the locus of all points of a wave that have the same phase*, i.e. have the identical path length from the source of that wave. Or

A **wavefront** is a line or surface in the path of wave motion on which the disturbances at every point have the same phase.

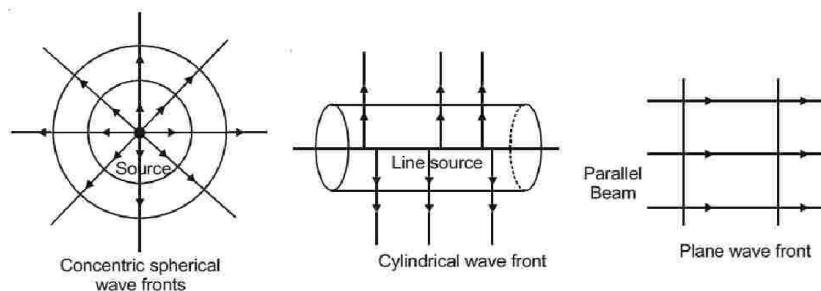
Wavefronts can be of three types depending on the source of light as follows:

- Cylindrical wavefront
- Spherical wavefront
- Plane wavefront

Spherical Wavefront: When a point source in an isotropic medium, it sends out waves in three dimensions, the wavefronts are spheres centered on the source. Such wavefront is called a spherical wavefront.

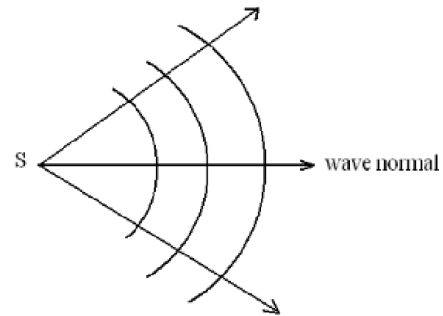
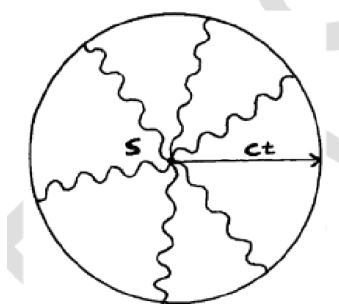
Cylindrical wavefront: When the source of light is linear, all the points equidistant from the linear source lie on the surface of a cylinder. Such a wavefront is called a cylindrical wavefront.

Plane wavefront: At a large distance from the source, a small portion of the spherical wave or cylindrical wavefront can be approximated by a plane wavefront.



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Wave surface: If point source s emits light waves with velocity c in a medium, these waves will reach distance ct in time t . If we draw a sphere with centre s and radius ct , it is called as spherical wave surface.



Wave Normal: Perpendicular drawn to surface of wave front at any point in direction of propagation of light is called as wave normal.

Optics basics: The three major branches of optical science

Most people associate the word ‘optics’ with the engineering of lenses for eyeglasses, telescopes, and microscopes, in physics the term more broadly refers to the study of the behavior of light and its interactions with matter. The connection to eyeglasses and the like is not accidental, however: the development of various optical tools led scientists to study more closely the behavior of the light that those tools channeled.

Today, we may roughly group the study of optics into three broad subfields of study:

1. *Geometrical optics*, the study of light as rays
2. *Physical optics*, the study of light as waves
3. *Quantum optics*, the study of light as particles

1. Geometrical optics: Geometrical optics is a branch of optics where light is described by rays. **The ray in geometric optics is an abstraction** useful for approximating the paths along which light propagates under certain circumstances.

The simplifying assumptions of geometrical optics include that light rays:

- **propagate in straight-line** paths as they **travel in a homogeneous medium**
- **bend, and in particular circumstances may split in two**, at the interface between two dissimilar media
- **follow curved paths in a medium in which the refractive index changes**
- may be **absorbed or reflected**.

Geometrical optics does not account for certain optical effects such as diffraction and interference. This simplification is useful in practice; **it is an excellent approximation when the wavelength is small compared to the size of structures with which the light interacts**. The techniques are particularly useful in describing geometrical aspects of imaging, including optical aberrations (optical defect).

2. Physical optics: Physical optics, also called wave optics, is the study of phenomena where light behaves like a **classical wave and not like a ray or particle**. A rainbow is a classic example of this, where different colors of light separate based on their wavelength. Physical optics studies interference, diffraction, polarization, and other phenomena for which the ray approximation of geometric optics is not valid.

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3. Quantum optics: Quantum optics is a branch of atomic, molecular, and optical physics dealing with how individual quanta of light, known as **photons, interact with atoms and molecules**. The most prominent applications quantum optics is lasers and quantum computing.

According to quantum theory, light may be considered not only to be as an electro-magnetic wave but also as a "stream" of particles called **photons** which travel with c , the vacuum speed of light. Each particle carries one quantum of energy, equal to hf , where h is Planck's constant and f is the frequency of the light. **That energy possessed by a single photon corresponds exactly to the transition between discrete energy levels in an atom (or other system) that emitted the photon**; material absorption of a photon is the reverse process. Einstein's explanation of spontaneous emission also predicted the existence of stimulated emission, the principle upon which the laser rests.

Area of Applications of Three Branches

- All three branches are still actively being researched. **Geometrical optics is commonly used in the design of complicated optical systems**, and researchers are studying ways to 'improve' the geometric models to provide better overlap with the wave theory of light.
- Physical optics **lies on the boundary of engineering and pure science**, as new physical consequences of the wave nature of light are still being uncovered and optical devices are being built which take advantage of this wave nature.
- Quantum optics is used as a tool **to better understand the theory of quantum mechanics, though a number of highly speculative applications, such as quantum computing and quantum cryptography, are being explored.**

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Many theories are proposed over the discovery of various effects of light. Though the light is in existence since the existence of sun but all the effects of light are not discovered since early 15th century A.D. these theories explain how the light is and how the light transmits. Some of the most important theories on light are

- 1) Newton's corpuscular theory
- 2) Huygen's wave theory
- 3) Maxwell's Electro-Magnetic wave theory
- 4) Planck's quantum theory

Newton's corpuscular theory

Newton's corpuscular theory was based on postulates as follows:

1. Newton proposed that a **source of light emits many minute, elastic, rigid and massless particles called corpuscles**.
2. These particles travel through a transparent medium at very high speed in **all direction along a straight line**.
3. These corpuscles enter our eyes and produce the **sensation of vision**.
4. Due to different sizes of the corpuscles, they produce different colors.
5. These light particles are repelled by a reflecting surface and attracted by transparent materials.

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Merits of corpuscular theory:

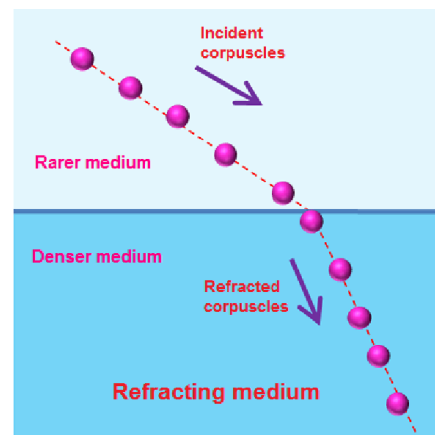
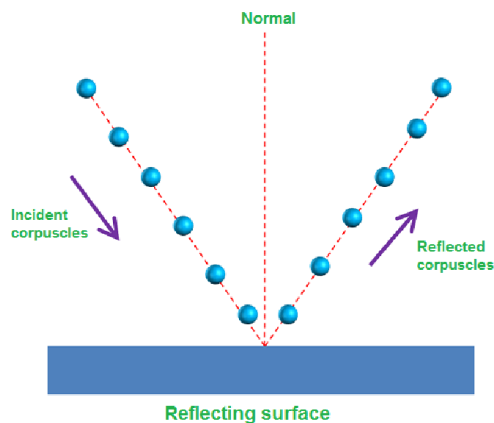
1. It explains the rectilinear propagation of light.
2. It could explain the reflection and refraction of light separately.

Drawbacks of corpuscular theory:

1. Newton's corpuscular theory fails to explain simultaneous phenomenon of partial reflection and refraction on the surface of transparent medium such as glass or water.
2. The corpuscular theory fails to explain optical phenomena such as interference, diffraction, polarization etc.
3. According to this theory, velocity of light is larger in the denser medium than in the rarer medium, experimentally it is proved wrong ($v_a < v_d$).
4. As the particles are emitted from the source, mass of the source of light should decrease but experiment proved that mass of the source of light is constant.

Corpuscular theory about reflection of light

The corpuscular theory explains the reflection of light in exactly the same way as the reflection of a perfectly elastic ball from a rigid plane. When the corpuscles (particles) hit the reflecting surface, they are reflected from it in such a way that the angle of incidence is equal to the angle of reflection. This is due to the repulsion between the corpuscles and the reflecting surface.



Corpuscular theory about refraction of light

According to Newton, when corpuscles (light particles) approach the refracting surface, they are attracted near the surface. When they enter the denser medium from a rarer medium, their speed increases and hence change their direction.

Wave Theory of Light

In the late 17th century, scientists were embroiled in a debate about the fundamental nature of light – whether it was a wave or a particle. Sir Isaac Newton was a strong advocate of the particle nature of light. But, the Dutch physicist, Christian Huygens believed that light was made up of waves vibrating up and down perpendicular to the direction of the wave propagation, and therefore formulated a way of visualizing wave propagation. The wave theory of light proposed by Huygens is considered the backbone of optics.

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Huygen's wave theory

In 1678 Dutch scientist Christiaan Huygens (1629–1695) developed a useful technique to understand as well as describe the movements of waves. Waves generally do not move in a straight line and they have got certain characteristics that allow them to move in all directions. Huygens's principle states that:

“Every point on a wave front is a source of wavelets that spread out in the forward direction at the same speed as the wave itself. These wavelets emanating from the wavefront are usually referred to as secondary wavelets and if we draw a common tangent to all these spheres, we obtain the new position of the wavefront.”

The Huygens Principle, also known as the Huygens–Fresnel Principle, emphasizes the wave propagation behavior as follows:

- Secondary sources generate wavelets that are comparable to the original source's wavelets.
- The new wavefront is determined by the common tangent on the wavelets in the forward direction at any given time.
- The total of the spherical wavelets is the wavefront.

Advantages:

- Huygens concept proved the reflection and refraction of light.
- The concepts like diffraction of light, as well as interference of light, were proved by Huygens.

Disadvantage:

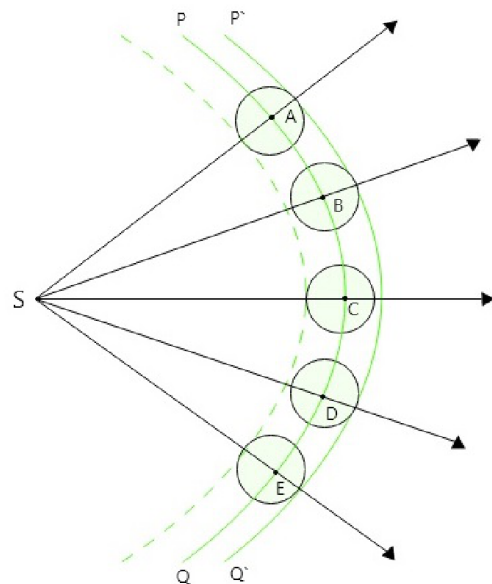
- Concepts like emission of light, absorption of light and polarization of light were not explained by Huygens principle.
- Huygens principle failed to explain the photoelectric effect.
- A serious drawback is that the theory proposes an all-pervading medium required to propagate light called luminiferous ether. This was proved to be false in the 20th century.

Huygen's Construction of a spherical wavefront

Let PQ be a cross-section of a spherical wavefront due to a point source (S), at any instant. This can be called as primary wavefront. Now consider points A, B, C, D, E on PQ. They act as secondary sources and send out secondary wavelets as per Huygens' principle.

If c is the speed of light in the isotropic medium, in time t , each wave will describe a distance ' ct '. With A, B, C, D, E as centers of circles, each radius ct will be traced. Each circle will represent a secondary wavefront.

The common tangential surface (envelope) P'Q' drawn to these secondary wavefronts represents the (new) position of the wavefront after time ' t '. The secondary waves moving in the backward direction do not exist.



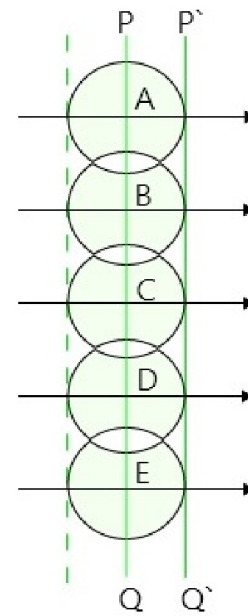
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Huygen's Construction of a plane wavefront

Let PQ be a plane wavefront perpendicular to the plane of the paper due to a point source (S), at any instant and at a very large distance, This can be called a primary wavefront. Now consider points A, B, C, D on PQ. They act as secondary Huygens' sources and send out secondary wavelets as per Huygens' principle.

If 'c' is the speed of light in the isotropic medium, in time 't', each wave will describe a distance 'ct'. With A, B, C, D as centres, spheres each of radius 'ct' will be traced, each sphere will represent a secondary wavefront. The common tangential surface(envelope) i.e. P'Q' drawn to these secondary wavefronts represents the new position for the wavefront after time 't'.

The secondary waves moving in the backward direction do not exist and therefore they are shown with dotted lines.



What is Refraction?

Refraction is the bending of a wave when it passes from one medium to another. The bending is caused due to the differences in density between the two substances.

Refraction of light is one of the most commonly observed phenomena, but other waves like sound waves and water waves also experience refraction. Refraction makes it possible for us to have optical instruments such as magnifying glasses, lenses and prisms. It is also because of the refraction of light that we are able to focus light on our retina.

Laws of Refraction of Light

Laws of refraction state that:

- The incident ray, refracted ray, and the normal to the interface of two media at the point of incidence all lie on the same plane.
- The ratio of the sine of the angle of incidence to the sine of the angle of refraction is a constant. This is also known as Snell's law of refraction.

If i is the angle of incidence and r is the angle of refraction then $\frac{\sin i}{\sin r} = \text{constant}$

Refraction using Huygen's principle

A plane wave AB is incident at an angle i on the surface PP' separating medium 1 and medium 2 as shown in fig.-a. Let v_1 and v_2 represent the speed of the light in this medium 1 and medium 2 respectively and $v_2 < v_1$.

We assume a plane wavefront AB propagating in the direction A'A incident on the interface at an angle I as shown in the figure. Let τ be the time taken by the wavefront to travel the distance BC.

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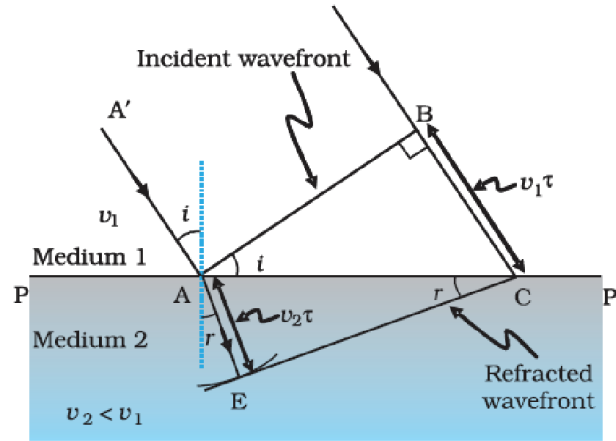


Figure – a

Thus $BC = v_1 \tau$

In order to determine the shape of the refracted wavefront, we draw a sphere of radius $v_2 \tau$ from the point A in the second medium. 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 wavefront. If we now consider the triangles $\triangle ABC$ and $\triangle AEC$, we readily 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

$$\frac{\sin i}{\sin r} = \frac{v_1}{v_2} \quad (a)$$

From the above equation, we get the important result that if $r < i$ (i.e., if the ray bends toward the normal), 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 prediction is opposite to the prediction from the corpuscular model of light and as later experiments showed, the prediction of the wave theory is correct.

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

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

where n_1 and n_2 are known as the refractive indices of medium 1 and medium 2, respectively. In terms of the refractive indices, Eq. (a) can be written as

$$\frac{\sin i}{\sin r} = \frac{n_2}{n_1} \quad (b)$$

This is the Snell's law of refraction.

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Reflection using Huygen's principle

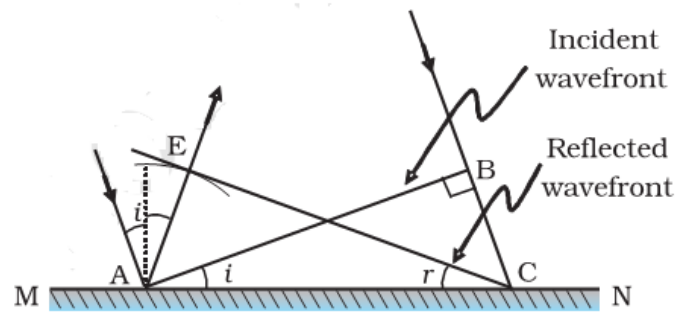


Figure – b

A plane wave AB incident at an angle i on a reflecting surface MN. If v represents the speed of the wave in the medium and if τ represents the time taken by the wavefront to advance from the point B to C then the distance

$$BC = v\tau$$

In order to construct the reflected wavefront we draw a sphere of radius $v\tau$ from the point A as shown in Fig. b. Let CE represent the tangent plane drawn from the point C to this sphere.

Obviously $AE = BC = v\tau$.

If we now consider the triangles EAC and BAC we will find that they are congruent and therefore, the angles i and r (as shown in Fig. b) would be equal. This is the law of reflection.

* Congruent: Two geometric figures are said to be congruent, or to be in the relation of congruence, if it is possible to superpose one of them on the other so that they coincide throughout.

Maxwell's Electromagnetic wave theory

The electric and magnetic fields in a electromagnetic wave are continuously varying with respect to time and space. At any instant electric and magnetic fields are perpendicular to each other and also perpendicular to the direction of light. The electromagnetic wave is a transverse wave. At every point in the wave at a given instant of time the electric and magnetic field strengths are equal. The velocity of propagation of electromagnetic wave depends on the electric and magnetic properties of the medium.

The main drawback of this theory is it failed to explain the photo electric effect and Compton effect. Electromagnetic theory also failed in explaining the black body radiation

Planck's Quantum theory

According to this theory, light energy is released from source discretely in the form of energy packets of specific frequencies called photons or quanta. Photons are propagated as waves and if necessary interact with matter as particles. This phenomena of Compton effect, photoelectric effect and black body radiation. The main drawback of this theory is it could not explain how it is connected with wave nature of light.