The Nature of Light

Before the beginning of the nineteenth century, light was considered to be a stream of particles that either was emitted by the object being viewed or emanated from the eyes of the viewer. Newton, the chief architect of the particle theory of light, held that particles were emitted from a light source and that these particles stimulated the sense of sight upon entering the eye. Using this idea, he was able to explain reflection and refraction.

Most scientists accepted Newton's particle theory. During his lifetime, however, another theory was proposed—one that argued that light might be some sort of wave motion.

In 1678, the Dutch physicist and astronomer Christian Huygens showed that a wave theory of light could also explain reflection and refraction.

In 1801, Thomas Young (1773–1829) provided the first clear demonstration of the wave nature of light. Young showed that, under appropriate conditions, light rays interfere with each other. Such behavior could not be explained at that time by a particle theory because there was no conceivable way in which two or more particles could come together and cancel one another. Additional developments during the nineteenth century led to the general acceptance of the wave theory of light, the most important resulting from the work of Maxwell, who in 1873 asserted that light was a form of high-frequency electromagnetic wave.

Although the wave model and the classical theory of electricity and magnetism were able to explain most known properties of light, they could not explain some subsequent experiments. The most striking of these is the photoelectric effect, also discovered by Hertz: when light strikes a metal surface, electrons are sometimes ejected from the surface. As one example of the difficulties that arose, experiments showed that the kinetic energy of an ejected electron is independent of the light intensity. This finding contradicted the wave theory, which held that a more intense beam of light should add more energy to the electron. An explanation of the photoelectric effect was proposed by Einstein in 1905 in a theory that used the concept of quantization developed by Max Planck (1858–1947) in 1900. The quantization model assumes that the energy of a light wave is present in particles called *photons*; hence, the energy is said to be quantized. According to Einstein's theory, the energy of a photon is proportional to the frequency of the electromagnetic wave:

$$E = hf$$

where the constant of proportionality $h = 6.63 \times 10^{-34}$ J . s is Planck's constant

In view of these developments, light must be regarded as having a dual nature: Light exhibits the characteristics of a wave in some situations and the characteristics of a particle in other situations. Light is light, to be sure. However, the question "Is light a wave or a particle?" is inappropriate. Sometimes light acts like a wave, and at other times it acts like a particle.

Measurements of the Speed of Light:

Light travels at such a high speed ($c = 3.00 \times 10^{+8}$ m/s) that early attempts to measureits speed were unsuccessful. Galileo attempted to measure the speed of light by positioning two observers in towers separated by approximately 10 km. Each observer carried a shuttered lantern. One observer would open his lantern first, and then the other would open his lantern at the moment he saw the light from the first lantern. Galileo reasoned that, knowing the transit time of the light beams from one lantern to the other, he could obtain the speed. His results were inconclusive.

Roemer's Method :

In 1675, the Danish astronomer Ole Roemer (1644–1710) made the first successful estimate of the speed of light. Roemer's technique involved astronomical observations of one of the moons of Jupiter, Io, which has a period of revolution around Jupiter of approximately 42.5 h. The period of revolution of Jupiter around the Sun is about 12 yr; thus, as the Earth moves through 90° around the Sun, Jupiter revolves through only (1/12)90° = 7.5° (Fig. a).

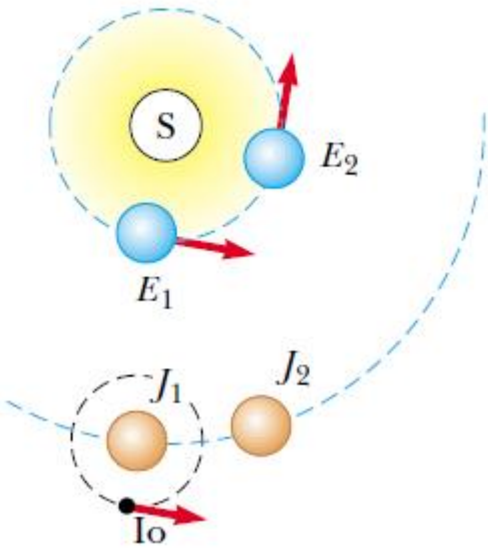


Figure a. Roemer's method for measuring the speed of light.

An observer using the orbital motion of Io as a clock would expect the orbit to have a constant period. However, Roemer, after collecting data for more than a year, observed a systematic variation in Io's period. He found that the periods were longer than average when the Earth was receding from Jupiter and shorter than average when the Earth was approaching Jupiter. If Io had a constant period, Roemer should have seen it become eclipsed by Jupiter at a particular instant and should have been able to predict the time of the next eclipse. However, when he checked the time of the second eclipse as the Earth receded from Jupiter, he found that the eclipse was late. If the interval between his observations was three months, then the delay was approximately 600 s. Roemer attributed this variation in period to the fact that the distance between the Earth and Jupiter changed from one observation to the next. In three months (one quarter of the period of revolution of the Earth around the Sun), the light from Jupiter must travel an additional distance equal to the radius of the Earth's orbit. Using Roemer's data, Huygens estimated the lower limit for the speed of light to be approximately 2.3 x 10^{+8} m/s. This experiment is important historically because it demonstrated that light does have a finite speed and gave an estimate of this speed.

Fizeau's Method:

The first successful method for measuring the speed of light by means of purely terrestrial techniques was developed in 1849 by French physicist Armand H. L. Fizeau(1896–1819). Figure B. represents a simplified diagram of Fizeau's apparatus. The basic procedure is to measure the total time interval during which light travels from some point to a distant mirror and back. If d is the distance between the light source (considered to be at the location of the wheel) and the mirror and if the time interval for one round trip is Δt, then the speed of light is $c=2d/\Delta t$.

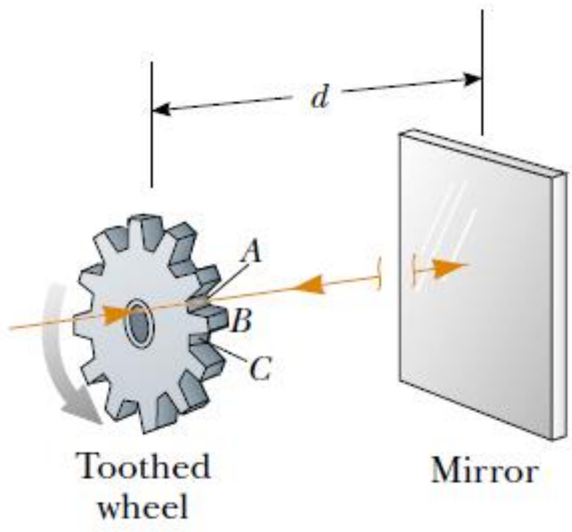


Figure b. Fizeau's method for measuring the speed of light using a rotating to othed wheel.

To measure the transit time, Fizeau used a rotating toothed wheel, which converts a continuous beam of light into a series of light pulses. The rotation of such a wheel controls what an observer at the light source sees. For example, if the pulse traveling toward the mirror and passing the opening at point *A* in Figure b. should return to the wheel at the instant tooth *B* had rotated into position to cover the return path, the pulse would not reach the observer. At a greater rate of rotation, the opening at point *C* could move into position to allow the reflected pulse to reach the observer. Knowing the distance *d*, the number of teeth in the wheel, and the angular speed of the wheel, Fizeau arrived at a value of 3.1 x 10^{+8} m/s. Similar measurements made by subsequent investigators yielded more precise values for *c*, which led to the currently accepted value of $2.997\,9 \times 10^{+8}$ m/s.

Example1: Measuring the Speed of Light with Fizeau's Wheel:
Assume that Fizeau's wheel has 360 teeth and is rotating at 27.5 rev/s when a pulse of light passing through opening *A* in Figure b is blocked by tooth *B* on its return. If the distance to the mirror is 7500 m, what is the speed of light?

Solution The wheel has 360 teeth, and so it must have 360 openings. Therefore, because the light passes through opening *A* but is blocked by the tooth immediately adjacent to *A*, the wheel must rotate through an angular displacement of (1/720) rev in the time interval during which the light pulse makes its round trip. From the definition of angular speed, that time interval is

$$\Delta t = \frac{\Delta\theta}{\omega} = \frac{(1/720)\text{ rev}}{27.5\text{ rev/s}} = 5.05 \times 10^{-5}\text{ s}$$

Hence, the speed of light calculated from this data is

$$c = \frac{2d}{\Delta t} = \frac{2(7\,500\text{ m})}{5.05 \times 10^{-5}\text{ s}} = 2.97 \times 10^{8}\text{ m/s}$$

The Ray Approximation in Geometric Optics:

The field of geometric optics involves the study of the propagation of light, with the assumption that light travels in a fixed direction in a straight line as it passes through a uniform medium and changes its direction when it meets the surface of a different medium or if the optical properties of the medium are nonuniform in either space or time. To understand this approximation, first note that the rays of a given wave are straight lines perpendicular to the wave fronts as illustrated in Figure C. for a plane wave. In the ray approximation, we assume that a wave moving through a medium travels in a straight line in the direction of its rays.

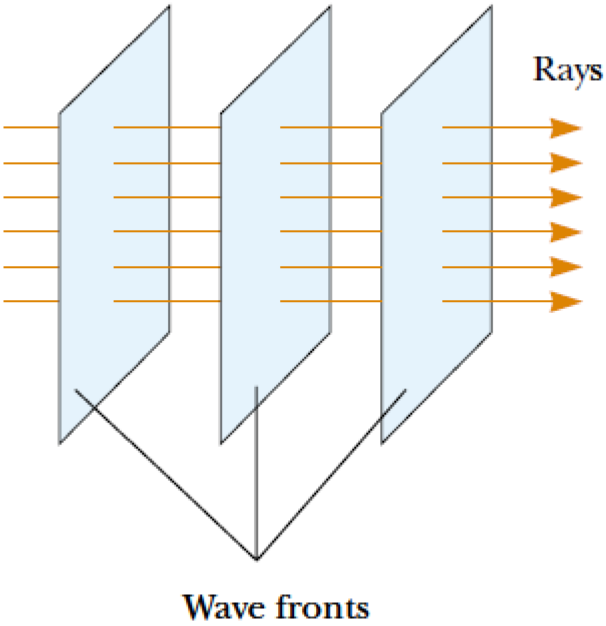
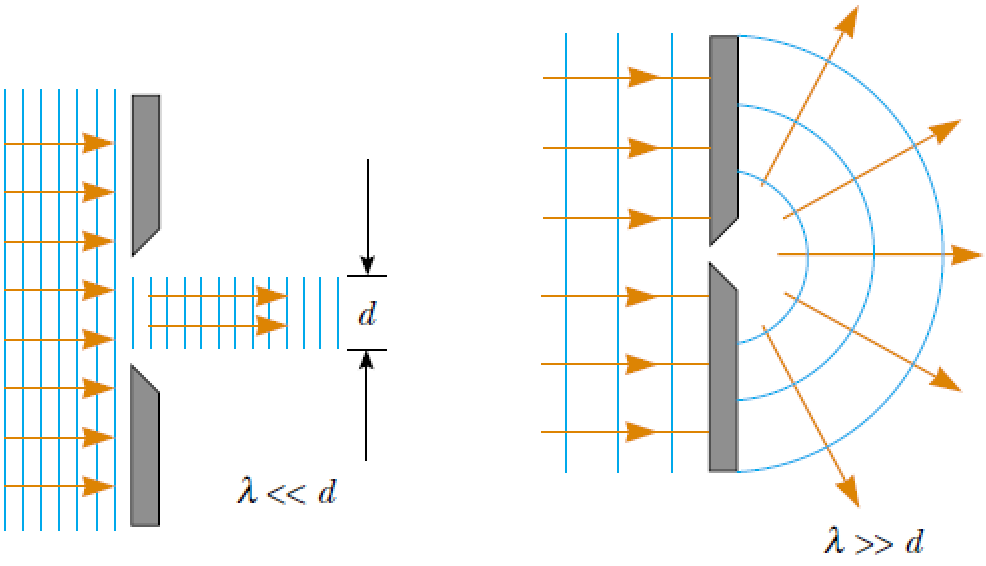
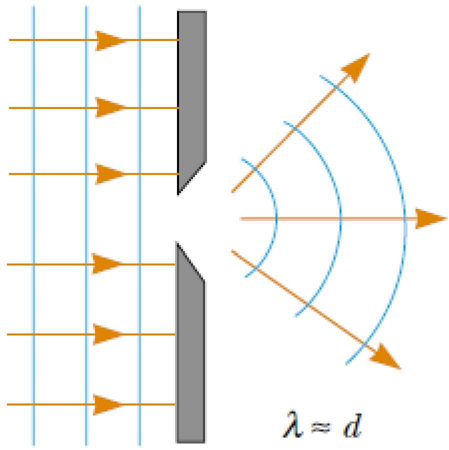


Figure C: A plane wave propagating to the right.

If the wave meets a barrier in which there is a circular opening whose diameter is much larger than the wavelength, as in Figure d-a, the wave emerging from the opening continues to move in a straight line (apart from some small edge effects); hence, the ray approximation is valid. If the diameter of the opening is on the order of the wavelength, as in Figure d-b, the waves spread out from the opening in all directions. Finally, if the opening is much smaller than the wavelength, the opening can be approximated as a point source of waves (Fig. d-c). Similar effects are seen when waves encounter an opaque object of dimension *d*. In this case, when $\lambda \ll d$, the object casts a sharp shadow.



a b



c

Figure d. A plane wave of wavelength (is incident on a barrier in which there is an opening of diameter *d*. (a) When λ<< *d* , the rays continue in a straight-line path, and the ray approximation remains valid. (b) When λ≈ *d*, the rays spread out after passing through the opening. (c) When λ>> *d* , the opening behaves as a point source emitting spherical waves.

Wave front and rays;

It is convenient to represent a train of wave of any sort by means of wave front. A wave front is defined as the locus of points, all of which are in the same phase. Thus in the case of sound wave spreading out in all directions from appoint source, any spherical surface concentric with the source is a possible wave front.

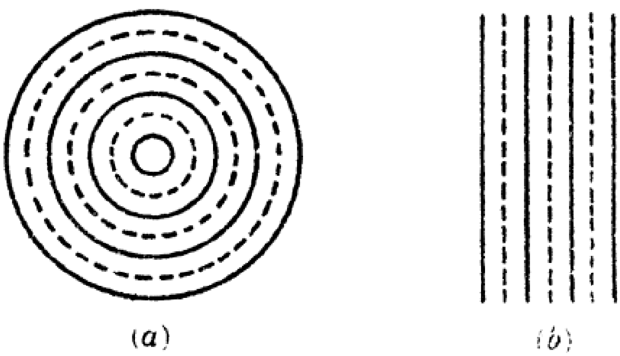
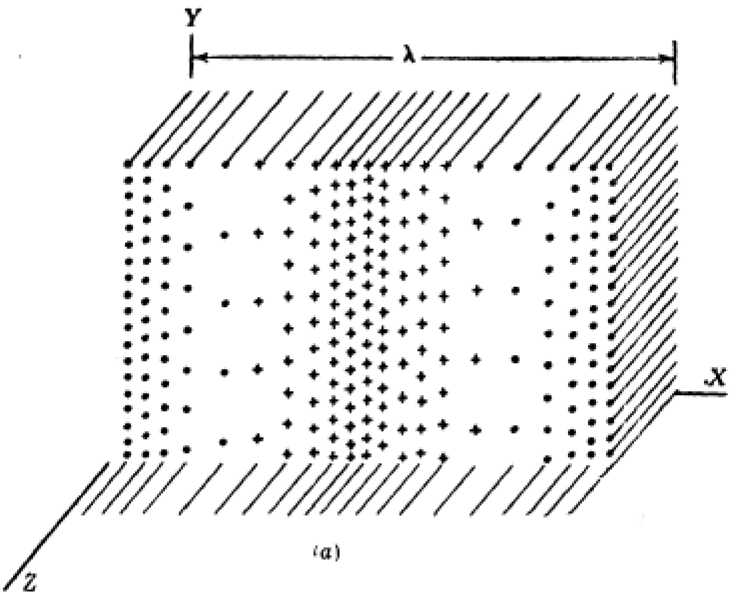


FIG. 1-1. Wave fronts.



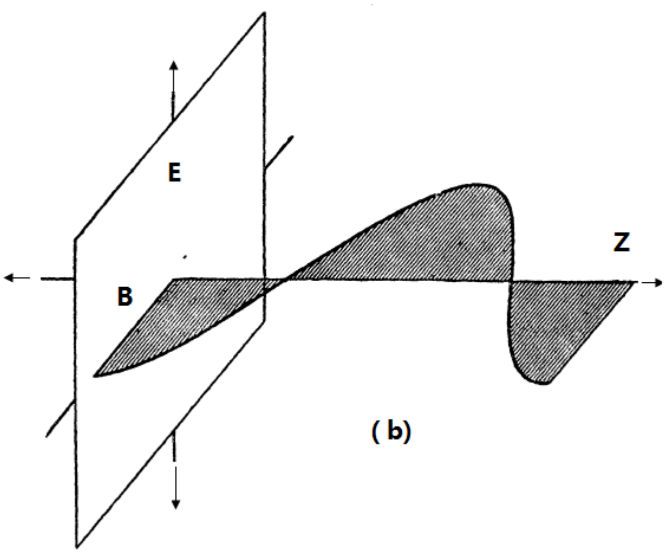


Fig. 1-2. (a) Electric and magnetic field distribution of a plane electromagnetic wave at any one instant. The electrostatic lines of force are drawn in red and the magnetic lines of force are drawn in black (b) A conventionalized diagram of the wave form at the same instant.

A train of light waves may often be represented more simply by means of *rays* than by wave fronts. In a corpuscular theory, a ray is simply the path followed by a light corpuscle. From the wave viewpoint, a ray is an imaginary line drawn in the direction in which the wave is traveling. Thus in Fig. 1-1 (a) the rays are the radii of the spherical wave fronts and in Fig. 1-1 (b) they are straight lines perpendicular to the wave fronts. In fact, in every case in which the waves are traveling in a homogeneous isotropic medium, the rays are straight lines, normal to the wave fronts. At a boundary surface between two media, such as the surface between a glass plate and the air outside it, the direction of a ray may change suddenly but it is a straight line both in the air and in the glass. If the medium is not homogeneous, for instance, if one is considering the passage of light through the earth's atmosphere where the density and hence the velocity vary with elevation, the rays are curved but are still normal to the wave fronts. If the medium is anisotropic, as is the case in certain crystals, the direction of the rays is not always normal to the wave fronts.

Huygens's Principle

In Huygens's construction,
all points on a given wave front are taken as point sources for the production of spherical secondary waves, called wavelets, which propagate outward through a medium with speeds characteristic of waves in that medium. After some time interval has passed, the new position of the wave front is the surface tangent to the wavelets.

First, consider a plane wave moving through free space, as shown in Figure 1a.
At $t = 0$, the wave front is indicated by the plane labeled AA^-. In Huygens's construction, each point on this wave front is considered a point source. For clarity, only three points on AA^- are shown. With these points as sources for the wavelets, we draw circles, each of radius $c\,\Delta t$, where c is the speed of light in vacuum and Δt is some time interval during which the wave propagates. The surface drawn tangent to these wavelets is the plane BB^-, which is the wave front at a later time, and is parallel to AA^-. In a similar manner, Figure 1 b shows Huygens's construction for a spherical wave.

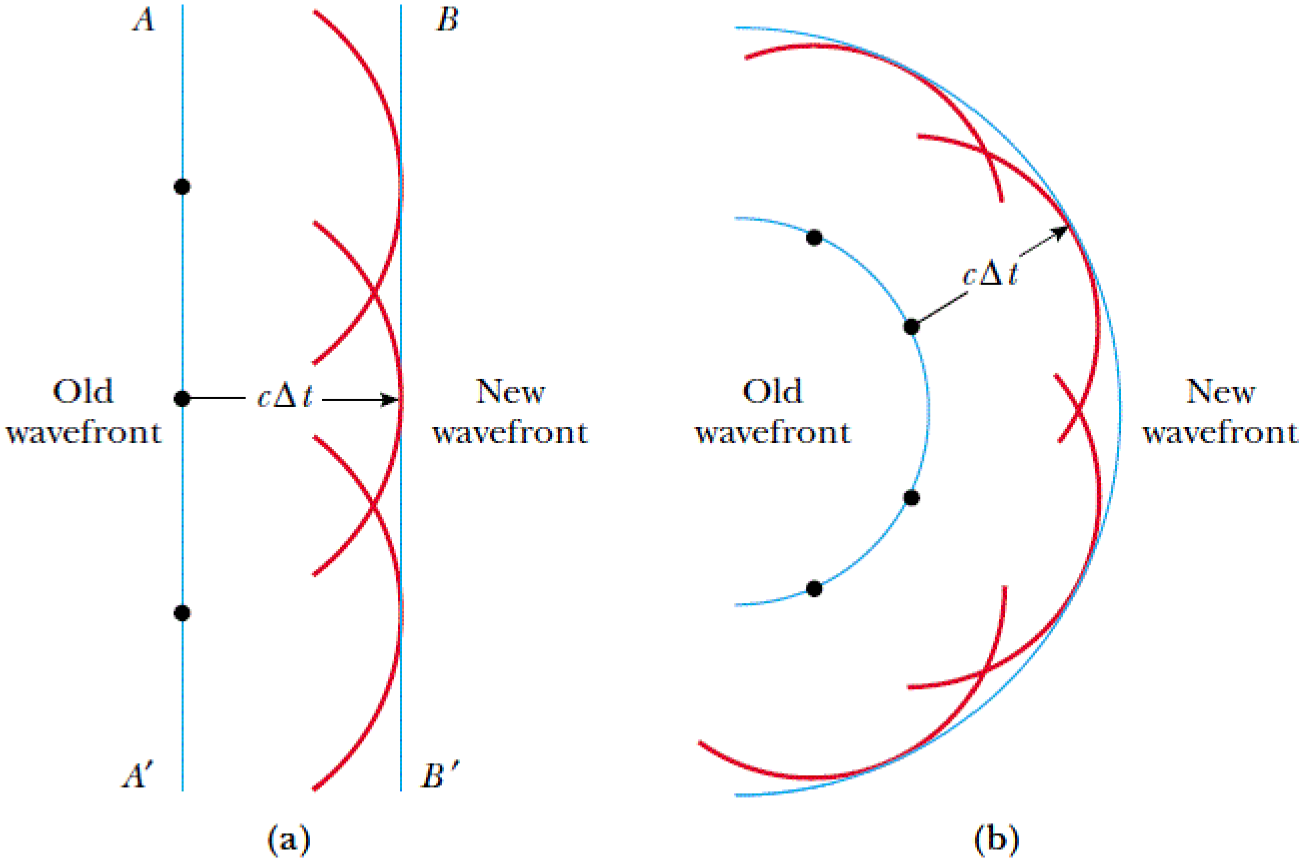


Figure 1- Huygens's construction for (a) a plane wave propagating to the right and (b) a spherical wave propagating to the right.

Index of Refraction

In general, the speed of light in any material is less than its speed in vacuum. In fact *light travels at its maximum speed in vacuum*. It is convenient to define the index of refraction n of a medium to be the ratio

$$n \equiv \frac{\text{speed of light in vacuum}}{\text{speed of light in a medium}} = \frac{c}{v} \qquad \text{............ (1)}$$

From this definition, we see that the index of refraction is a dimensionless number greater than unity because v is always less than c. Furthermore, n is equal to unity for vacuum.