## 23-1 The Ray Model of Light

A great deal of evidence suggests that *light travels in straight lines* under a wide variety of circumstances. For example, a point source of light like the sun casts distinct shadows, and the beam of a flashlight appears to be a straight line. In fact, we infer the positions of objects in our environment by assuming that light moves from the object to our eyes in straight-line paths. Our whole orientation to the physical world is based on this assumption.

This reasonable assumption has led to the **ray model** of light. This model assumes that light travels in straight-line paths called light **rays**. Actually, a ray is an idealization; it is meant to represent an infinitely narrow beam of light. When we see an object, according to the ray model, light reaches our eyes from each point on the object; although light rays leave each point in many different directions, normally only a small bundle of these rays can enter an observer's eye, as shown in Fig. 23-1. If the person's head moves to one side, a different bundle of rays will enter the eye from each point.

We saw in Chapter 22 that light can be considered as an electromagnetic wave. Although the ray model of light does not deal with this aspect of light (we discuss the wave nature of light in Chapter 24), the ray model has been very successful in describing many aspects of light such as reflection, refraction, and the formation of images by mirrors and lenses. Because these explanations involve straight-line rays at various angles, this subject is referred to as **geometric optics**.

Light rays

This bundle
enters the eye
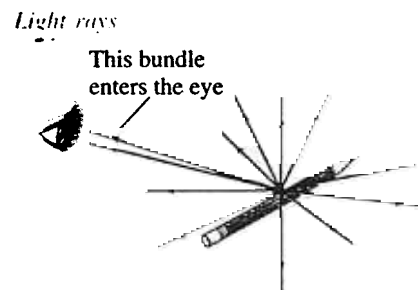
FIGURE 23-1 Light rays coming from each single point on an object. A small bundle of rays leaving one point is shown entering a person's eye.

23-2 The Speed of Light and Index of Refraction

Galileo attempted to measure the speed of light by trying to measure the time required for light to travel a known distance between two hilltops. He stationed an assistant on one hilltop, and himself on another, and ordered the assistant to lift the cover from a lamp the instant he saw a flash from Galileo's lamp. Galileo measured the time between the flash of his lamp and when he received the light from his assistant's lamp. The time was so short that Galileo concluded it merely represented human reaction time, and that the speed of light must be extremely high.

The first successful determination that the speed of light is finite was made by the Danish astronomer Ole Roemer (1644–1710). Roemer had noted that the carefully measured period of Io, one of Jupiter's moons (an average period of 42.5 h to make one complete orbit around Jupiter), varied slightly, depending on the relative motion of Earth and Jupiter. When Earth was moving away from Jupiter, the period of the moon was slightly longer, and when Earth was moving toward Jupiter, the period was slightly shorter. He attributed this variation to the extra time needed for light to travel the increasing distance to Earth when Earth is receding, or to the shorter travel time for the decreasing distance when the two planets are approaching one another. Roemer concluded that the speed of light—though great—is finite.
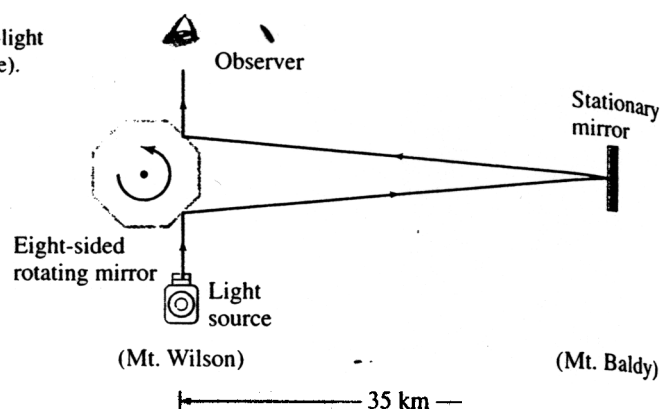
Since then a number of techniques have been used to measure the speed of light. Among the most important were those carried out by the American Albert A. Michelson (1852–1931; Fig. 23–2). Michelson used the rotating

FIGURE 23-2 Albert A. Michelson.

Michelso

FIGURE 23-3
Michelson's speed-of-light
apparatus (not to scale).

mirror apparatus diagrammed in Fig. 23-3 for a series of high-precision experiments carried out from 1880 to the 1920s. Light from a source was directed at one face of a rotating eight-sided mirror. The reflected light traveled to a stationary mirror a large distance away and back again as shown. If the rotating mirror was turning at just the right rate, the returning beam of light would reflect from one face of the mirror into a small telescope through which the observer looked. If the speed of rotation was only slightly different, the beam would be deflected to one side and would not be seen by the observer. From the required speed of the rotating mirror and the known distance to the stationary mirror, the speed of light could be calculated. In the 1920s, Michelson set up the rotating mirror on the top of Mt. Wilson in southern California and the stationary mirror on Mt. Baldy (Mt. San Antonio) 35 km away. He later measured the speed of light in vacuum using a long evacuated tube.

The accepted value today for the speed of light, c, in vacuum is[†]

$$c = 2.99792458 \times 10^8 \text{ m/s}.$$

We usually round this off to

$$c = 3.00 \times 10^8 \text{ m/s}$$

when extremely precise results are not required. In air, the speed is only slightly less. In other transparent materials such as glass and water, the speed is always less than that in vacuum. For example, in water light travels at about $\frac{3}{4}c$. The ratio of the speed of light in vacuum to the speed v in a given material is called the **index of refraction**, n, of that material:

$$n = \frac{c}{v} \tag{23-1}$$

The index of refraction is never less than 1 (that is, $n \geq 1$), and its value for various materials is given in Table 23-1. (As we shall see later, n varies somewhat with the wavelength of the light- -except in vacuum—so a partic-

TABLE 23-1
Indices of Refraction[†]

Medium	$n = c/v$
	1.46
	1.52
	1.58
	1.51
	1.53
	2.42

[†] $\lambda = 589$ nm

Speed of light in vacuum

Index of refraction

[†] As discussed in Chapter 1 (p. 9), the speed of light is now *defined* to have this value, and the length of the standard meter is defined as the distance light travels in vacuum in a time of exactly $1/299,792,458$ of a second.

must be very small, because its size determines the amount of blurring in the image. A small square hole is quite satisfactory. A piece of household aluminum foil is folded twice and the corner fold cut off with a razor blade, leaving good clean edges. After several such trials, and examination with a magnifying glass, a good square hole can be selected. The photograph reproduced in Fig. 1B was taken with such a pinhole camera. Note the undistorted perspective lines as well as the depth of focus in the picture.

1.2   THE SPEED OF LIGHT

The ancient astronomers believed that light traveled with an infinite speed. Any major event that occurred among the distant stars was believed to be observable instantly at all other points in the universe.

It is said that around 1600 Galileo tried to measure the speed of light but was not successful. He stationed himself on a hilltop with a lamp and his assistant on a distant hilltop with another lamp. The plan was for Galileo to uncover his lamp at an agreed signal, thereby sending a flash of light toward his assistant. Upon seeing the light the assistant was to uncover his lamp, sending a flash of light back to Galileo, who observed the total elapsed time. Many repetitions of this experiment, performed at greater and greater distances between the two observers, convinced Galileo that light must travel at an infinite speed.

We now know that the speed of light is *finite* and that it has an approximate value of

$$v = 300,000 \text{ km/s} = 186,400 \text{ mi/s}$$

In 1849 the French physicist Fizeau* became the first man to measure the speed of light here on earth. His apparatus is believed to have looked like Fig. 1C. His account of this experiment is quite detailed, but no diagram of his apparatus is given in his notes.

An intense beam of light from a source S is first reflected from a half-silvered mirror G and then brought to a focus at the point O by means of lens L_1. The diverging beam from O is made into a parallel beam by lens L_2. After traveling a distance of 8.67 km to a distant lens L_3 and mirror M, the light is reflected back toward the source. This returning beam retraces its path through L_2, O, and L_1, half of it passing through G and entering the observer's eye at E.

The function of the toothed wheel is to cut the light beam into short pulses and to measure the time required for these pulses to travel to the distant mirror and back. When the wheel is at rest, light is permitted to pass through one of the openings at O.

* Armand H. L. Fizeau (1819–1896), French physicist, was born of a wealthy French family that enabled him to be financially independent. Instead of shunning work, however, he devoted his life to diligent scientific experiment. His most important achievement was the measurement of the speed of light in 1849, carried on in Paris between Montmartre and Suresnes. He also gave the correct explanation of the Doppler principle as applied to light coming from the stars and showed how the effect could be used to measure stellar velocities. He carried out his experiments on the velocity of light in a moving medium in 1851 and showed that light is dragged along by a moving stream of water.
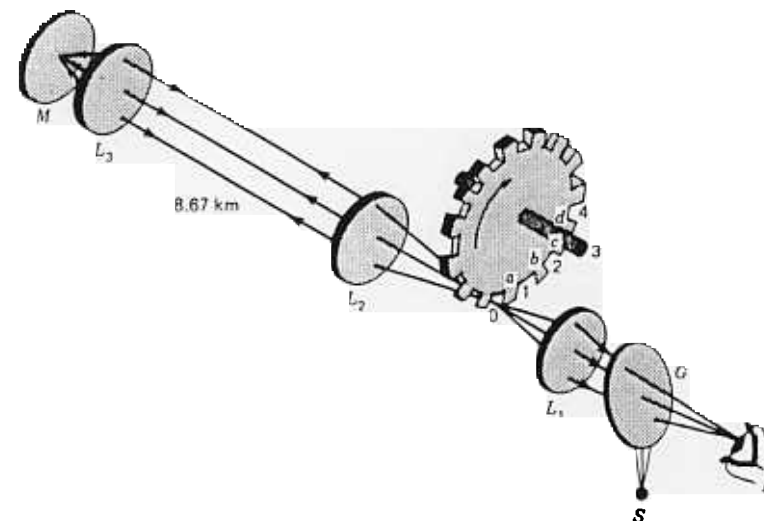
FIGURE 1C
Experimental arrangement described by the French physicist Fizeau, with which he determined the speed of light in air in 1849.

In this position all lenses and the distant mirror are aligned so that an image of the light source S can be seen by the observer at E.

The wheel is then set rotating with slowly increasing speed. At some point the light passing through O will return just in time to be stopped by tooth a. At this same speed light passing through opening 1 will return in time to be stopped by the next tooth b. Under these circumstances the light S is completely eclipsed from the observer. At twice this speed the light will reappear and reach a maximum intensity. This condition occurs when the light pulses getting through openings 1, 2, 3, 4, ... return just in time to get through openings 2, 3, 4, 5, ..., respectively.

Since the wheel contained 720 teeth, Fizeau found the maximum intensity to occur when its speed was 25 rev/s. The time required for each light pulse to travel over and back could be calculated by $(\frac{1}{720})(\frac{1}{25}) = 1/18,000$ s. From the measured distance over and back of 17.34 km, this gave a speed of

$$v = \frac{d}{t} = \frac{17.34 \text{ km}}{1/18,000 \text{ s}} = 312,000 \text{ km/s}$$

In the years that followed Fizeau's first experiments on the speed of light, a number of experimenters improved on his apparatus and obtained more and more accurate values for this universal constant. About three-quarters of a century passed, however, before A. A. Michelson, and others following him, applied new and improved

methods to visible light, radio waves, and microwaves and obtained the speed of light accurate to approximately six significant figures.

Electromagnetic waves of all wavelengths, from X rays at one end of the spectrum to the longest radio waves, are believed to travel with exactly the same speed in a vacuum. These more recent experiments will be treated in detail in Chap. 19, but we give here the most generally accepted value of this universal constant,

$$c = 299{,}792.5 \text{ km/s} = 2.997925 \times 10^8 \text{ m/s} \qquad (1a)$$

For practical purposes where calculations are to be made to four significant figures, the speed of light in air or in a vacuum may be taken to be

$$c = 3.0 \times 10^8 \text{ m/s} \qquad (1b)$$

One is often justified in using this rounded value since it differs from the more accurate value in Eq. (1a) by less than 0.1 percent.

1.3 THE SPEED OF LIGHT IN STATIONARY MATTER

In 1850, the French physicist Foucault* completed and published the results of an experiment in which he had measured the speed of light in water. Foucault's experiment was of great importance for it settled a long controversy over the nature of light. Newton and his followers in England and on the Continent believed light to be made up of small particles emitted by every light source. The Dutch physicist Huygens, on the other hand, believed light to be composed of waves, similar to water or sound waves.

According to Newton's corpuscular theory, light should travel faster in an optically dense medium like water than in a less dense medium like air. Huygens' wave theory required light to travel slower in the more optically dense medium. Upon sending a beam of light back and forth through a long tube containing water, Foucault found the speed of light to be less than in air. This result was considered by many to be a strong confirmation of the wave theory.

Foucault's apparatus for this experiment is shown in Fig. 1D. Light coming through a slit S is reflected from a plane rotating mirror R to the equidistant concave mirrors M_1 and M_2. When R is in the position 1, the light travels to M_1, back along the same path to R, through the lens L, and by reflection to the eye at E. When R is in position 2, the light travels the lower path through an auxiliary lens L' and tube

---

* Jean Bernard Leon Foucault (1819–1868), French physicist. After studying medicine he became interested in experimental physics and with A. H. L. Fizeau carried out experiments on the speed of light. After working together for some time, they quarreled over the best method to use for "chopping" up a light beam, and thereafter went their respective ways. Fizeau (using a toothed wheel) and Foucault (using a rotating mirror) did admirable work, each supplementing the work of the other. With a rotating mirror Foucault in 1850 was able to measure the speed of light in a number of different media. In 1851 he demonstrated the earth's rotation by the rotation of the plane of oscillation of a long, freely suspended, heavy pendulum. For the development of this device, known today as a *Foucault pendulum*, and his invention of the gyroscope, he received the Copley medal of the Royal Society of London, in 1855. He also discovered the eddy currents induced in a copper disk moving in a strong magnetic field and invented the optical polarizer which bears his name.
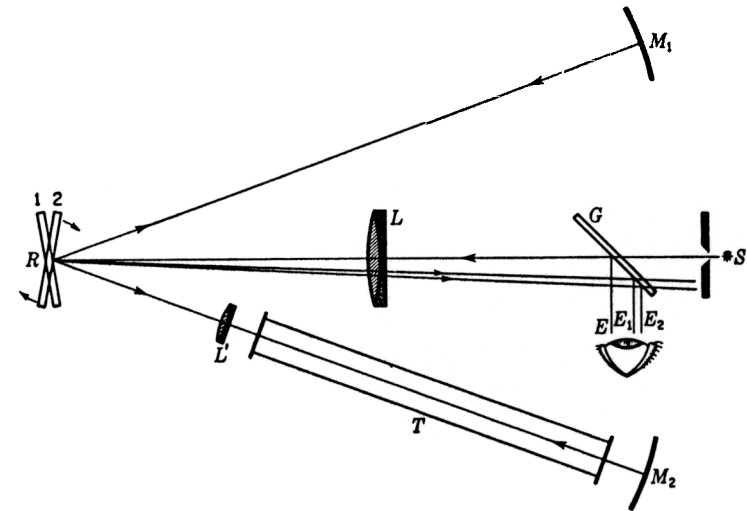

FIGURE 1D
Foucault's apparatus for determining the speed of light in water.

T to M_2, back to R, through L to G, and then to the eye E. If now the tube T is filled with water and the mirror is set into rotation, there will be a displacement of the images from E to E_1 and E_2. Foucault observed that the light ray through the tube was more displaced than the other. This means that it takes the light longer to travel the lower path through water than it does the upper path through the air.

The image observed was due to a fine wire parallel to, and stretched across, the slit. Since sharp images were desired at E_1 and E_2, the auxiliary lens L' was necessary to avoid bending the light rays at the ends of the tube T.

Over 40 years later the American physicist Michelson (first American Nobel laureate 1907) measured the speed of light in air and water. For water he found the value of 225,000 km/s, which is just three-fourths the speed in a vacuum. In ordinary optical glass, the speed was still lower, about two-thirds the speed in a vacuum.

The speed of light in air at normal temperature and pressure is about 87 km/s less than in a vacuum, or $v = 299{,}706$ km/s. For many practical purposes this difference may be neglected and the speed of light in air taken to be the same as in a vacuum, $v = 3.0 \times 10^8$ m/s.

1.4 THE REFRACTIVE INDEX

The index of refraction, or refractive index, of any optical medium is defined as the ratio between the speed of light in a vacuum and the speed of light in the medium:

$$\text{Refractive index} = \frac{\text{speed in vacuum}}{\text{speed in medium}} \qquad (1c)$$

College Physics

Serway & Faughn

be sure. However, the question, "Is light a wave or a particle?" is an inappropriate one. Sometimes it acts like a wave, sometimes like a particle. Fortunately, it never acts like both in the same experiment.

24.2 Measurements of the Speed of Light

Light travels at such a high speed ($c \approx 3 \times 10^8$ m/s) that early attempts to measure its speed were unsuccessful. Galileo attempted to measure the speed of light by positioning two observers in towers separated by about 5 miles. 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. The velocity could then be obtained, in principle, knowing the transit time of the light beams between lanterns. However, at a speed of 186,000 mi/s, light would travel the ten-mile roundtrip in a time of approximately 54 μs. Thus, it is impossible to measure the speed of light in this manner because the transit time is very small compared with the reaction time of the observers.

Roemer's Method

The first successful estimate of the speed of light was made in 1675 by the Danish astronomer Ole Roemer (1644–1710). His technique involved astronomical observations of one of the moons of Jupiter, called Io. At that time only four of Jupiter's moons had been discovered, and the periods of their orbits were known. Io, the innermost moon, has a period of 42.5 h, and its orbit, the orbit of Jupiter, and the orbit of the Earth all lie in approximately the same plane. As a result, Io goes into eclipse behind Jupiter every 42.5 h as seen from Earth. Using the orbital motion of Io as a clock, Roemer expected to find a constant period over long time intervals. Instead, Roemer observed a systematic variation in Io's period. He found that the periods were larger than average when Earth receded from Jupiter and smaller than average when Earth approached Jupiter. If Io had a constant period, Roemer should have been able to observe a particular eclipse and be able to predict when the next eclipse would occur. However, when Roemer checked to see if the second eclipse did occur at the predicted time, he often found that his predictions did not agree with the actual time of the eclipse. For example, consider the situation shown in Figure 24.1. Suppose an eclipse had occurred when the Earth was at position E_1. Knowing the period of Io, Roemer was able to predict when an eclipse should occur three months later when the Earth was at position E_2. However, the eclipse at E_2 actually occurred at a time approximately 600 s later than the predicted time. Roemer attributed this discrepancy to the fact that the distance between the Earth and Jupiter was changing between these observations. In three months (one quarter of the Earth's period), the Earth has moved through one fourth of its orbit from E_1 to E_2 as shown in Figure 24.1. In the same time interval, Jupiter, whose period is about 12 years, has moved a much shorter distance from J_1 to J_2. Therefore as the Earth moves from E_1 to E_2 light from Jupiter has to travel an additional distance equal to the radius of the Earth's orbit.
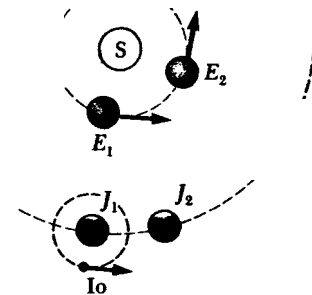
Figure 24.1
As the Earth moves from E_1 to E_2, Jupiter moves only from J_1 to J_2.

Using data available at that time, Roemer would have estimated the speed of light to be about 2.1×10^8 m/s. The large discrepancy between this value and the currently accepted value of 3×10^8 m/s is due to a large error in the assumed radius of the Earth's orbit. This experiment is important historically because it demonstrated that light does have a finite speed and established a rough estimate of the magnitude of this speed.

Fizeau's Technique
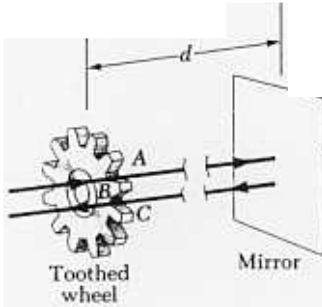
Figure 24.2

Fizeau's method for measuring the speed of light using a rotating, toothed wheel.

The first successful method of measuring the speed of light using purely terrestrial techniques was developed in 1849 by Armand H. L. Fizeau (1819 – 1896). Figure 24.2 represents a simplified diagram of his apparatus. The basic idea is to measure the total time it takes light to travel from some point to a distant mirror and back. If d is the distance between the light source and the mirror and if the transit time for one round trip is t, then the speed of light is $c = 2d/t$. To measure the transit time, Fizeau used a rotating toothed wheel, which converts an otherwise continuous beam of light into a series of light pulses. Additionally, the rotation of the wheel controls what an observer at the light source sees. For example, if the light passing the opening at point A in Figure 24.2 should return at the instant that tooth B had rotated into position to cover the return path, the light would not reach the observer. At a faster rate of rotation, the opening at point C could move into position to allow the reflected beam to pass and reach the observer. Knowing the distance, d, the number of teeth in the wheel, and the angular velocity of the wheel, Fizeau arrived at a value of $c = 3.1 \times 10^8$ m/s. Similar measurements made by subsequent investigators yielded more accurate values for c, approximately 2.9977×10^8 m/s.

A variety of other, more accurate measurements have been reported for the value of c. A recent value obtained using laser techniques is

$$c = 2.997924574(12) \times 10^8 \text{ m/s}$$

where the (12) indicates the uncertainty in the last two digits. The number of significant figures here is certainly impressive. In fact, the speed of light has been determined with such high accuracy that it is now used to define the SI unit of length, the meter. As noted in Chapter 1, the meter is defined as the distance traveled by light in a vacuum during a time of 1/299,792,458 s.

Example 24.1   Measuring the Speed of Light with Fizeau's Toothed Wheel

Assume the toothed wheel of the Fizeau experiment has 360 teeth and is rotating with a speed of 27.5 rev/s when the light from the source is extinguished, that is, when a burst of light passing through opening A in Figure 24.2 is blocked by tooth B on return. If the distance to the mirror is 7500 m, find the speed of light.

Solution
If the wheel has 360 teeth, it will turn through an angle of 1/720 rev in the time that passes while the light makes its round trip. From the definition of angular velocity, we see that the time is

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