We use devices made from lenses, mirrors, or other optical components every time we put on a pair of eyeglasses, take a photograph, look at the sky through a telescope, and so on. In this chapter we examine how these and other optical instruments work. For the most part, our analyses will involve the laws of reflection and refraction and the procedures of geometric optics. However, to explain certain phenomena we must use the wave nature of light.

## 25.1 THE CAMERA

The single-lens photographic **camera** is a simple optical instrument whose essential features are shown in Figure 25.1. It consists of a light-tight box, a converging lens that produces a real image, and a film behind the lens to receive the image. Focusing is accomplished by varying the distance between lens and film—with an adjustable bellows in old-style cameras and with other mechanical arrangements in newer models. For proper focusing, which leads to sharp images, the lens-to-film distance will depend on the object distance as well as on the focal length of the lens. The shutter, located behind the lens, is a mechanical device that is opened for selected time intervals. With this arrangement, moving objects can be photographed with the use of short exposure times, and dark scenes (low light levels) with the use of long exposure times. Without this control, it would be impossible to take stop-action photographs. For example, a speeding race car would move far enough while the shutter was open to produce a blurred image. Typical shutter "speeds" are 1/30, 1/60, 1/125, and 1/250 s. Stationary objects are often shot with a shutter speed of 1/60 s. More sophisticated cameras have a second adjustable aperture either behind or in front of the lens, to provide further control of the intensity of light reaching the film.

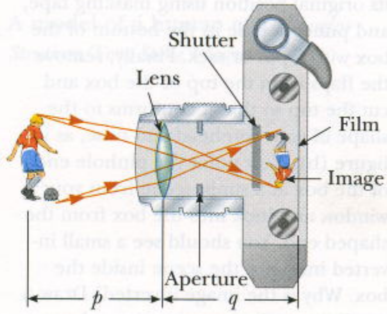



**Figure 25.1** A cross-sectional view of a simple camera.

The brightness of the image focused on the film depends on the diameter and focal length of the lens. The amount of light reaching the film, and hence the brightness of the image formed on the film, increases with the size of the lens. The focal length of the lens also affects the brightness of the image. We can see this by considering the lateral magnification equation for a thin lens:

$$M = \frac{h'}{h} = -\frac{q}{p}$$

$$h' = -h\frac{q}{p}$$

where $h$ and $h'$ are the object and image heights, respectively, and $p$ and $q$ are the object and image distances. When $p$ is large, $q$ is approximately equal to the focal length, $f$. Thus, we have

$$h' \approx -h\frac{f}{p}$$

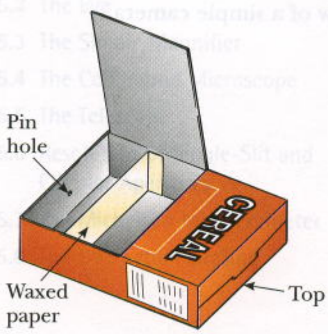
From this result, we see that a lens with a short focal length produces a small image, corresponding to a small value of $h'$.

A small image is brighter than a larger one because all of the incoming light is concentrated in a much smaller area. Because the brightness of the image depends

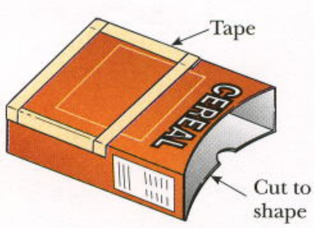
### QUICKLAB

## A Simple Pin-Hole Camera

Find a large cereal box and remove its paper lining. Cut one side of the box across the middle and two sides to form a flap, as in figure (a). Fold back the flap and tape a piece of waxed paper across the width and tape the paper about 2 inches from the bottom of the box. This serves as the viewing screen for your camera. Then tape the flap back to its original position using masking tape, and punch a hole in the bottom of the box with a pin or tack. Finally, remove the flaps from the top of the box and cut the top so that it conforms to the shape of your forehead and nose, as in figure (b). Now point the pinhole end of the box at a sunlit scene from your window and look into the box from the shaped end. You should see a small inverted image of the scene inside the box. Why is the image inverted? Draw a ray diagram that supports your observation.




(a)




(b)

on $f$ and on $D$, the diameter of the lens, a quantity called the ***f*-number** is defined as

$$f\text{-number} \equiv \frac{f}{D} \qquad [25.1]$$

For example, if a camera has a lens of focal length 52 mm and is set with $f$-number 4, the aperture diameter is $D = f/4 = (52 \text{ mm})/4 = 13$ mm.

The $f$-number is a measure of the light-concentrating power of a lens and determines what is called the speed of the lens. A fast lens has a small $f$-number and usually a small focal length and large diameter. Camera lenses are often marked with a range of $f$-numbers such as 2.8, 4, 5.6, 8, 11, 16. They are selected by adjusting the aperture, which effectively changes $D$. When the $f$-number is increased by one position, or one "stop," the light admitted decreases by a factor of 2. Likewise, the shutter speed is changed in steps by a factor of 2. The smallest $f$-number corresponds to the case in which the aperture is wide open and as much of the lens area is in use as possible. Fast lenses, with $f$-numbers as low as 1.2, are relatively expensive because it is more difficult to keep aberrations acceptably small. A simple camera for routine snapshots usually has a fixed focal length and fixed aperture size, with an $f$-number of about 11.

### EXAMPLE 25.1 Choosing the $f$-Number

Suppose you are using a single-lens 35-mm camera (35 mm is the width of the film strip) with only two $f$-stops, $f/2.8$ and $f/22$. Which $f$-number would you use on a cloudy day? Why?

**Solution** Substituting the given $f$-numbers into Equation 25.1, we have

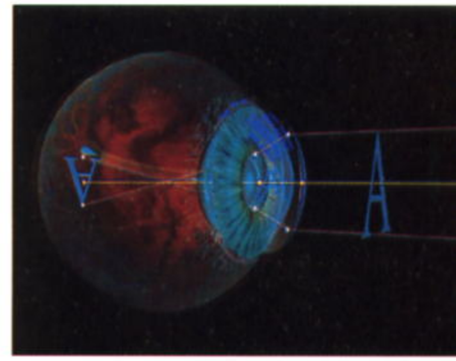
$$2.8 = \frac{f_1}{D_1} \qquad \text{and} \qquad 22 = \frac{f_2}{D_2}$$

The focal length of the camera is fixed ($f_1 = f_2$ in the two equations), but the diameter of the aperture is not. On a cloudy day, you should make the shutter opening as large as possible. As these equations indicate, the largest value of $D$ produces the smallest $f$-number. Thus, you should use the 2.8 setting.

## 25.2 THE EYE

The eye is a remarkable and extremely complex organ. Because of this complexity, defects sometimes arise that impair vision. To compensate for the defects, external aids, such as eyeglasses, are often used. In this section we describe the parts of the eye, their purposes, and some of the corrections that can be made when the eye does not function properly. You will find that the eye has much in common with the camera. Like the camera, the eye gathers light and produces a sharp image. However, the mechanisms by which the eye controls the amount of light admitted and adjusts itself to produce correctly focused images are far more complex, intricate, and effective than those in even the most sophisticated camera. In all respects, the eye is a wonder of design.

Figure 25.2 shows the essential parts of the eye. The front is covered by a transparent membrane called the *cornea.* Inward from the cornea are a clear liquid region (the *aqueous humor*), a variable aperture (the *iris* surrounding the *pupil*), and the *crystalline lens.* Most of the refraction occurs in the cornea, because the liquid medium surrounding the lens has an average index of refraction close to that of the lens. The iris, the colored portion of the eye, is a muscular diaphragm that regulates the amount of light entering the eye by dilating the pupil (increasing its diameter) in light of low intensity and contracting the pupil in high-intensity light. The pupil diameter can vary from about $f/2.8$ to $f/16$.



A model of a human eye. *(Douglas Struthers/Tony Stone Images)*

Light entering the eye is focused by the cornea-lens system onto the back surface of the eye, called the *retina.* The surface of the retina consists of millions of sensitive receptors called *rods* and *cones.* When stimulated by light, these structures send impulses via the optic nerve to the brain, where a distinct image of an object is perceived.

The eye focuses on a given object by varying the shape of the pliable crystalline lens through an amazing process called **accommodation.** An important component in accommodation is the *ciliary muscle,* which is attached to the lens. When the eye is focused on distant objects, the ciliary muscle is relaxed. For an object distance of infinity, the focal length of the eye (the distance between the lens and the retina) is about 1.7 cm. The eye focuses on nearby objects by tensing the ciliary muscle. This action effectively reduces the focal length by slightly decreasing the radius of curvature of the lens, which allows the image to be focused on the retina. This lens adjustment takes place so swiftly that we are not aware of the change. In this respect, as in others, even the finest electronic camera is a toy compared with the eye. It is evident that there is a limit to accommodation, because objects that are very close to the eye produce blurred images. **The near point is the smallest distance for which the lens will produce a sharp image on the retina.** This

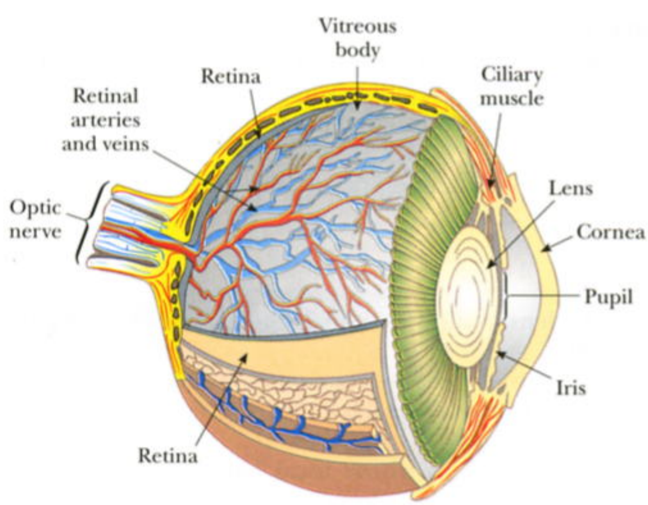



**Figure 25.2** Essential parts of the eye. Can you correlate the essential parts of the eye with those of the simple camera in Figure 25.1?

distance usually increases with age. Typically, the near point of the eye is about 18 cm at age 10, about 25 cm at age 20, 50 cm at age 40, and 500 cm or greater at age 60.

## Defects of the Eye

An eye can have several abnormalities that keep it from functioning properly. These can often be corrected with eyeglasses, contact lenses, or surgery.

When the relaxed eye produces an image of a nearby object *behind* the retina, as in Figure 25.3a, the abnormality is known as **hyperopia,** and the person is said to be *farsighted.* With this defect, distant objects are seen clearly but near objects are blurred. Either the hyperopic eye is too short or the ciliary muscle cannot change the shape of the lens enough to focus the image properly. The condition can be corrected with a converging lens, as shown in Figure 25.3b.

APPLICATION

Correcting Eye Defects with Optical Lenses.

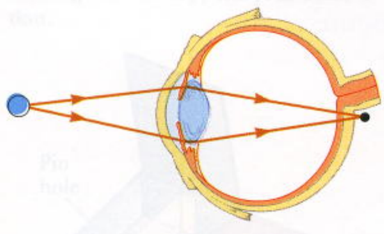
Another condition, known as **myopia,** or *nearsightedness,* occurs either when the eye is longer than normal or when the maximum focal length of the lens is insufficient to produce a clearly formed image on the retina. In this case, light from a distant object is focused in front of the retina (Fig. 25.4a). The distinguishing feature of this imperfection is that distant objects are not seen clearly. Nearsightedness can be corrected with a diverging lens, as in Figure 25.4b.

Beginning in middle age (around age 40) most people lose some of their accommodation power, usually as a result of hardening of the crystalline lens. This causes farsightedness, which can be corrected with converging lenses.

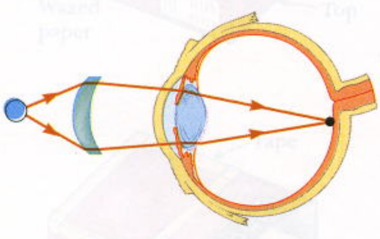
A common eye defect is **astigmatism,** in which light from a point source produces a line image on the retina. This occurs when the cornea or the crystalline lens or both are not perfectly spherical. Astigmatism can be corrected by lenses with different curvatures in two mutually perpendicular directions. A cylindrical lens (a segment of a cylinder) is typically used for this purpose.

The eye is also subject to several diseases. One, which usually occurs later in life, is the formation of **cataracts,** which make the lens partially or totally opaque. The common remedy for cataracts is surgical removal of the lens. Another disease, called **glaucoma,** arises from an abnormal increase in fluid pressure inside the eyeball. This pressure increase can cause a reduction in blood supply to the retina, which can eventually lead to blindness when the nerve fibers of the retina die. If the disease is discovered early enough, it can be treated with medicine or surgery.

Optometrists and ophthalmologists usually prescribe corrective lenses measured in diopters.



(a)



(b)

**Figure 25.3** (a) A farsighted eye is slightly shorter than normal; hence, the image of a nearby object focuses *behind* the retina. (b) The condition can be corrected with a converging lens. (The object is assumed to be very small in these figures.)

The power, $P$, of a lens in diopters equals the inverse of the focal length in meters—that is, $P = 1/f$.

For example, a converging lens whose focal length is $+20$ cm has a power of $+5$ diopters, and a diverging lens whose focal length is $-40$ cm has a power of $-2.5$ diopters.

## Thinking Physics 1

A classic science fiction story, *The Invisible Man,* tells of a person who becomes invisible by changing the index of refraction of his body to that of air. This story has been criticized by students who know how the eye works; they claim the invisible man would be unable to see. On the basis of your knowledge of the eye, could he see or not?

**Explanation** He would not be able to see. In order for the eye to "see" an object, incoming light must be refracted at the cornea and lens to form an image on the retina. If the cornea and lens have the same index of refraction as air, refraction cannot occur, and an image would not be formed.

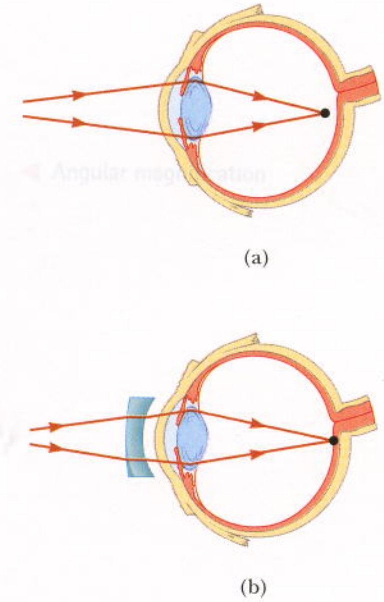



**Figure 25.4** (a) A nearsighted eye is slightly longer than normal; hence, the image of a distant object focuses *in front* of the retina. (b) The condition can be corrected with a diverging lens. (The object is assumed to be very small in these figures.)

## EXAMPLE 25.2 Prescribing a Lens

The near point of an eye is 50.0 cm. (a) What focal length must a corrective lens have to enable the eye to see clearly an object 25.0 cm away?

**Reasoning** The thin-lens equation (Eq. 23.11) enables us to solve this problem. We have placed an object at 25.0 cm, and we want the lens to form an image at the closest point that the eye can see clearly. This corresponds to the near point, 50.0 cm.

**Solution** Applying the thin-lens equation, we have

$$\frac{1}{25.0 \text{ cm}} + \frac{1}{(-50.0 \text{ cm})} = \frac{1}{f}$$

$$f = 50.0 \text{ cm}$$

Why did we use a negative sign for the image distance? Notice that the focal length is positive, indicating the need for a converging lens to correct farsightedness such as this.

(b) What is the power of this lens?

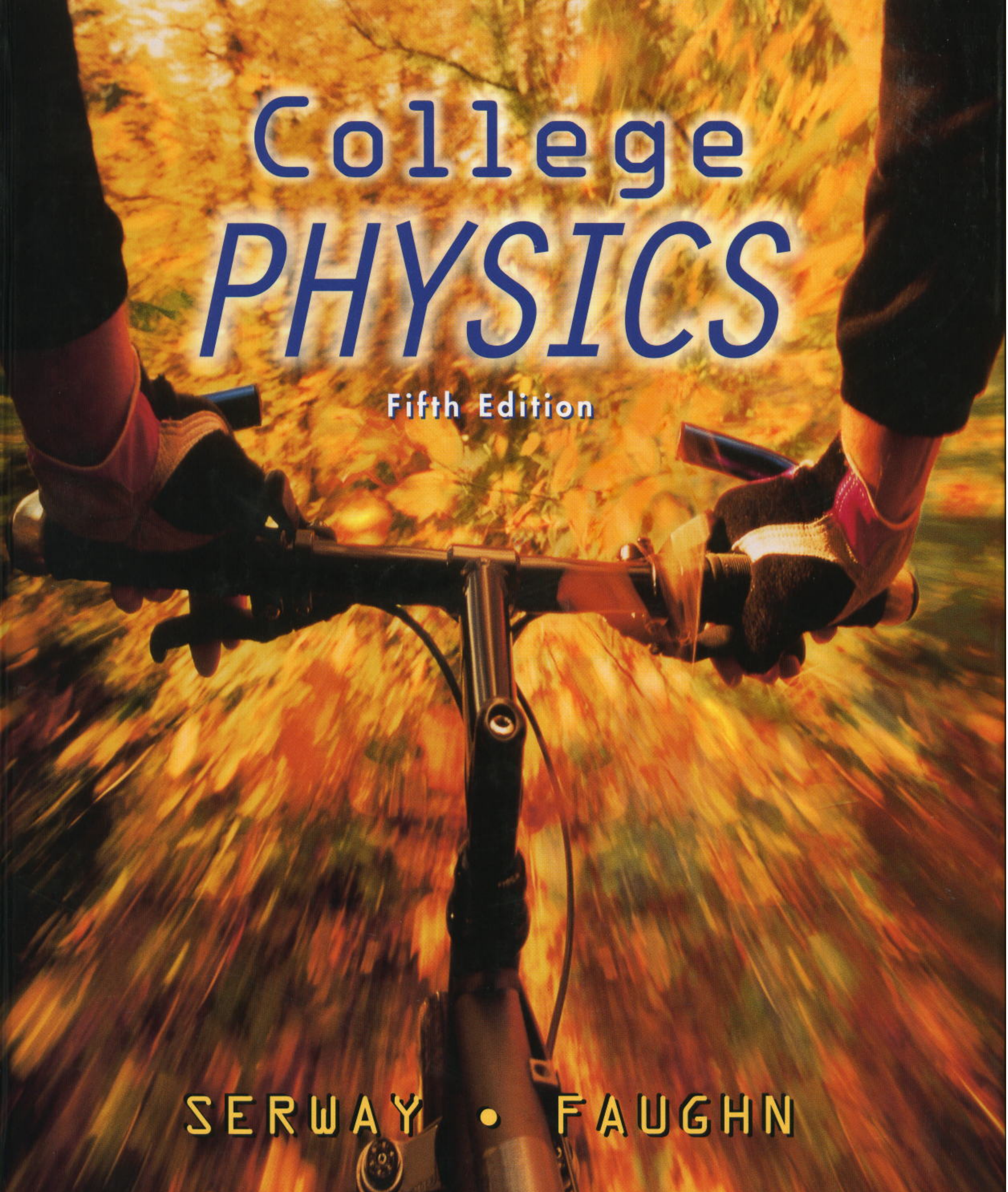
**Solution** The power is the reciprocal of the focal length in meters:

$$P = \frac{1}{f} = \frac{1}{0.500 \text{ m}} = 2.00 \text{ diopters}$$

## EXAMPLE 25.3 A Case of Nearsightedness

A particular nearsighted person cannot see objects clearly when they are beyond [illegible]0.0 cm (the far point of the eye). What focal length should the prescribed lens have to correct this problem?

**Reasoning** For an object at infinity, the purpose of the lens in this instance is to place the image at a distance at which it can be seen clearly.



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