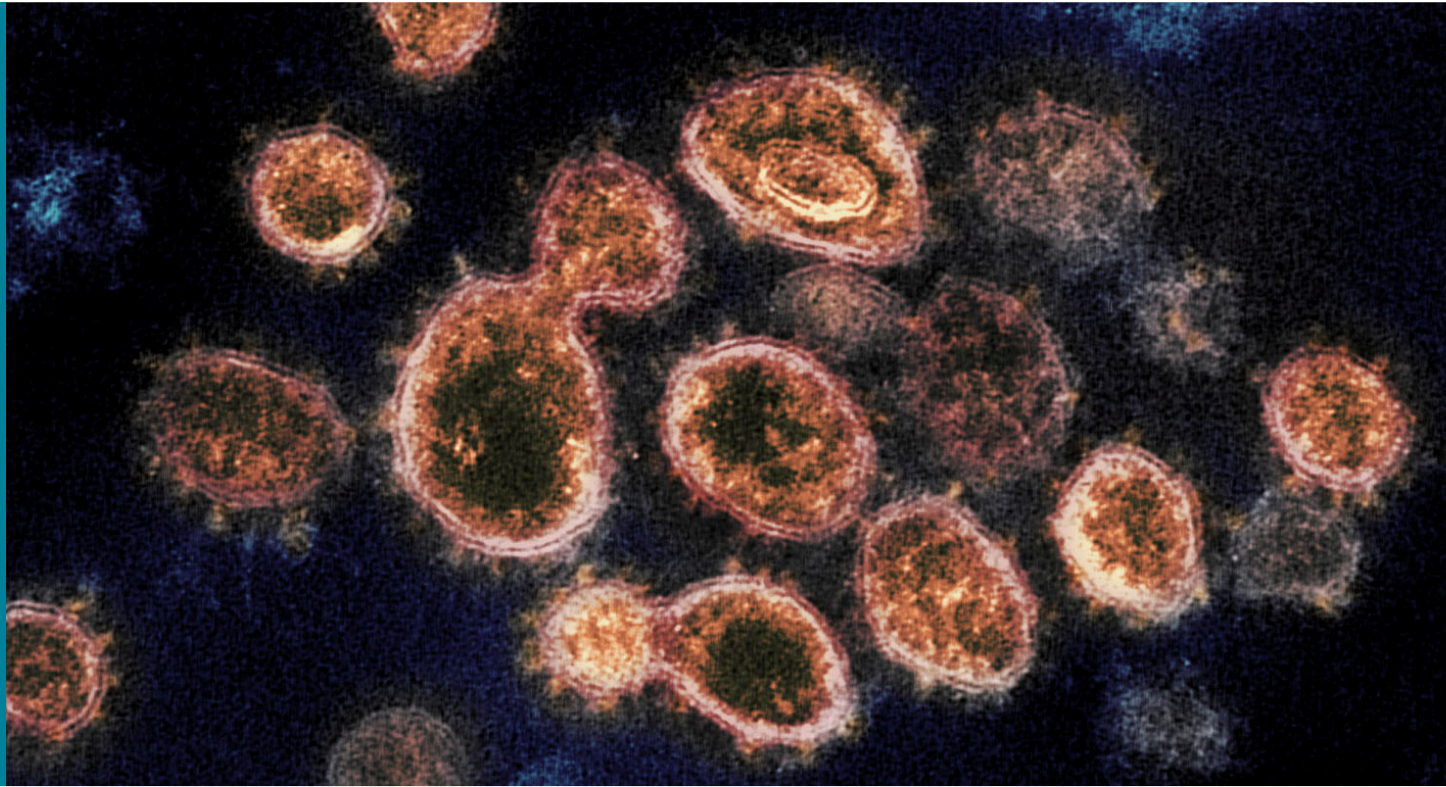


## CHAPTER 26

# Vision and Optical Instruments



**FIGURE 26.1** This transmission electron microscope image shows SARS-CoV-2, the coronavirus that causes COVID-19, isolated from a patient in the U.S. Virus particles are shown emerging from the surface of cells cultured in the lab. The spikes on the outer edge of the virus particles give coronaviruses their name: crown-like. (credit: NIAID-RML, NIH Image Gallery/Flickr)

### CHAPTER OUTLINE

#### 26.1 Physics of the Eye

#### 26.2 Vision Correction

#### 26.3 Color and Color Vision

#### 26.4 Microscopes

#### 26.5 Telescopes

#### 26.6 Aberrations

**INTRODUCTION TO VISION AND OPTICAL INSTRUMENTS** Explore how the image on the computer screen is formed. How is the image formation on the computer screen different from the image formation in your eye as you look down the microscope? How can videos of living cell processes be taken for viewing later on, and by many different people?

Seeing faces and objects we love and cherish is a delight—one's favorite teddy bear, a picture on the wall, or the sun rising over the mountains. Intricate images help us understand nature and are invaluable for developing techniques and technologies in order to improve the quality of life. The image of a red blood cell that almost fills the cross-sectional area of a tiny capillary makes us wonder how blood makes it through and not get stuck. We are able to see bacteria and viruses and understand their structure. It is the knowledge of physics that provides fundamental understanding and models required to develop new techniques and instruments. Therefore, physics is called an *enabling science*—a science that enables development and advancement in other areas. It is through optics and imaging that physics enables advancement in major areas of biosciences. This chapter illustrates the enabling nature of physics through an understanding of how a human eye is able to see, how we are able to use optical

instruments to see beyond what is possible with the naked eye, and how we develop methods of vision correction. It is convenient to categorize these instruments on the basis of geometric optics (see [Geometric Optics](#)) and wave optics (see [Wave Optics](#)).

## 26.1 Physics of the Eye

### LEARNING OBJECTIVES

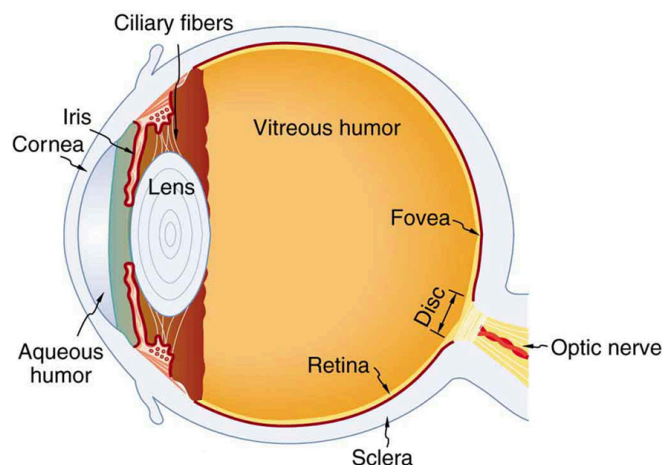
By the end of this section, you will be able to:

- Explain the image formation by the eye.
- Explain why peripheral images lack detail and color.
- Define refractive indices.
- Analyze the accommodation of the eye for distant and near vision.

Early thinkers had a wide array of theories regarding vision. Euclid and Ptolemy believed that the eyes emitted rays of light; others promoted the idea that objects gave off some particle or substance that was discerned by the eye. Ibn al-Haytham (sometimes called Alhazen), who was mentioned earlier as an originator of the scientific method, conducted a number of experiments to illustrate how the anatomical construction of the eye led to its ability to form images. He recognized that light reflected from objects entered the eye through the lens and was passed to the optic nerve. Al-Haytham did not fully understand the mechanisms involved, but many subsequent discoveries in vision, reflection, and magnification built on his discoveries and methods.

The eye is perhaps the most interesting of all optical instruments. The eye is remarkable in how it forms images and in the richness of detail and color it can detect. However, our eyes commonly need some correction, to reach what is called “normal” vision, but should be called ideal rather than normal. Image formation by our eyes and common vision correction are easy to analyze with the optics discussed in [Geometric Optics](#).

[Figure 26.2](#) shows the basic anatomy of the eye. The cornea and lens form a system that, to a good approximation, acts as a single thin lens. For clear vision, a real image must be projected onto the light-sensitive retina, which lies at a fixed distance from the lens. The lens of the eye adjusts its power to produce an image on the retina for objects at different distances. The center of the image falls on the fovea, which has the greatest density of light receptors and the greatest acuity (sharpness) in the visual field. The variable opening (or pupil) of the eye along with chemical adaptation allows the eye to detect light intensities from the lowest observable to  $10^{10}$  times greater (without damage). This is an incredible range of detection. Our eyes perform a vast number of functions, such as sense direction, movement, sophisticated colors, and distance. Processing of visual nerve impulses begins with interconnections in the retina and continues in the brain. The optic nerve conveys signals received by the eye to the brain.



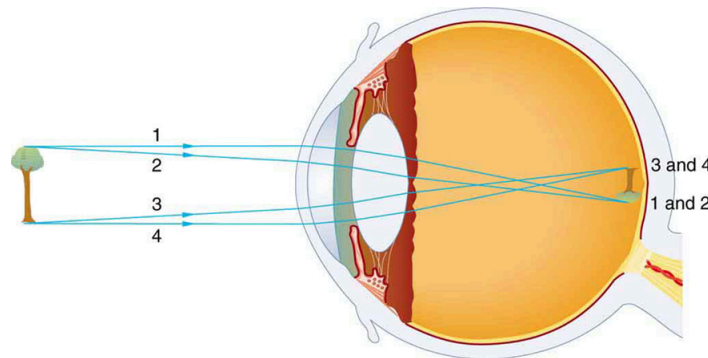
**FIGURE 26.2** The cornea and lens of an eye act together to form a real image on the light-sensing retina, which has its densest concentration of receptors in the fovea and a blind spot over the optic nerve. The power of the lens of an eye is adjustable to provide an image on the retina for varying object distances. Layers of tissues with varying indices of refraction in the lens are shown here. However, they have been omitted from other pictures for clarity.

Refractive indices are crucial to image formation using lenses. [Table 26.1](#) shows refractive indices relevant to the eye. The biggest change in the refractive index, and bending of rays, occurs at the cornea rather than the lens. The

ray diagram in [Figure 26.3](#) shows image formation by the cornea and lens of the eye. The rays bend according to the refractive indices provided in [Table 26.1](#). The cornea provides about two-thirds of the power of the eye, owing to the fact that speed of light changes considerably while traveling from air into cornea. The lens provides the remaining power needed to produce an image on the retina. The cornea and lens can be treated as a single thin lens, even though the light rays pass through several layers of material (such as cornea, aqueous humor, several layers in the lens, and vitreous humor), changing direction at each interface. The image formed is much like the one produced by a single convex lens. This is a case 1 image. Images formed in the eye are inverted but the brain inverts them once more to make them seem upright.

Material	Index of Refraction
Water	1.33
Air	1.0
Cornea	1.38
Aqueous humor	1.34
Lens	1.41 average (varies throughout the lens, greatest in center)
Vitreous humor	1.34

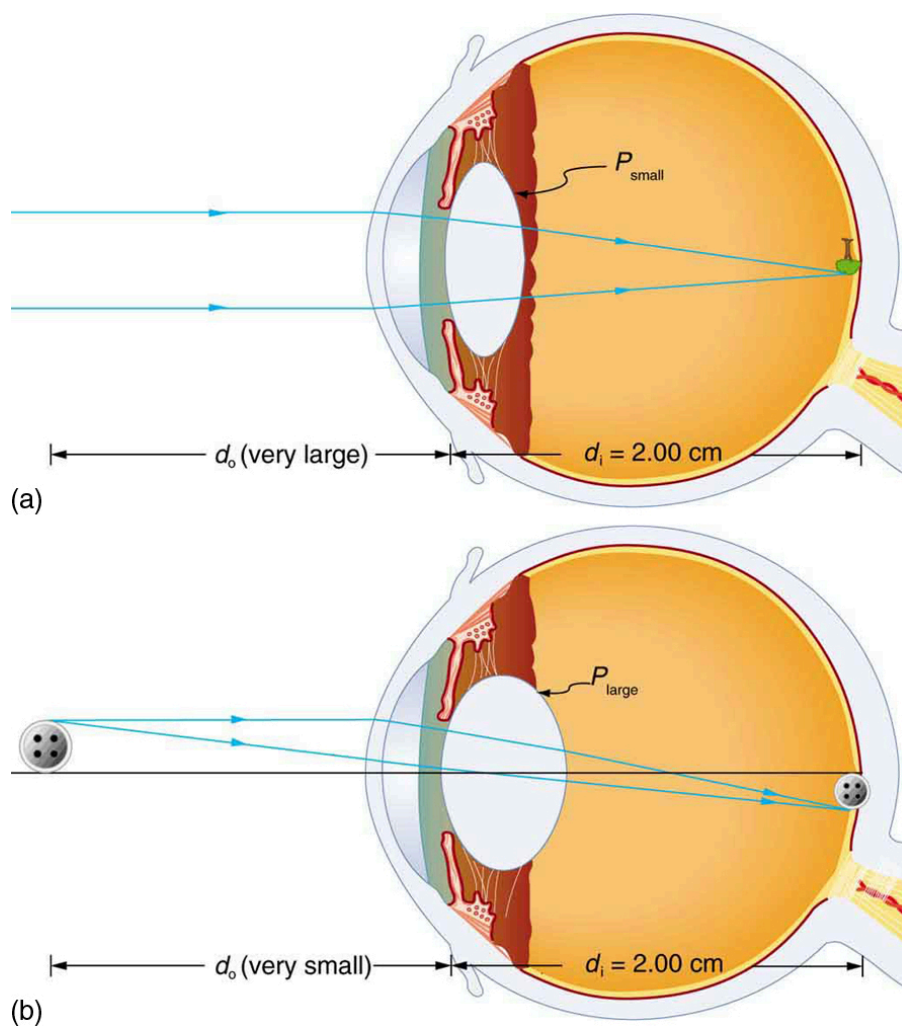
**TABLE 26.1** Refractive Indices Relevant to the Eye



**FIGURE 26.3** An image is formed on the retina with light rays converging most at the cornea and upon entering and exiting the lens. Rays from the top and bottom of the object are traced and produce an inverted real image on the retina. The distance to the object is drawn smaller than scale.

As noted, the image must fall precisely on the retina to produce clear vision — that is, the image distance  $d_i$  must equal the lens-to-retina distance. Because the lens-to-retina distance does not change, the image distance  $d_i$  must be the same for objects at all distances. The eye manages this by varying the power (and focal length) of the lens to accommodate for objects at various distances. The process of adjusting the eye's focal length is called **accommodation**. A person with normal (ideal) vision can see objects clearly at distances ranging from 25 cm to essentially infinity. However, although the near point (the shortest distance at which a sharp focus can be obtained) increases with age (becoming meters for some older people), we will consider it to be 25 cm in our treatment here.

[Figure 26.4](#) shows the accommodation of the eye for distant and near vision. Since light rays from a nearby object can diverge and still enter the eye, the lens must be more converging (more powerful) for close vision than for distant vision. To be more converging, the lens is made thicker by the action of the ciliary muscle surrounding it. The eye is most relaxed when viewing distant objects, one reason that microscopes and telescopes are designed to produce distant images. Vision of very distant objects is called *totally relaxed*, while close vision is termed *accommodated*, with the closest vision being *fully accommodated*.



**FIGURE 26.4** Relaxed and accommodated vision for distant and close objects. (a) Light rays from the same point on a distant object must be nearly parallel while entering the eye and more easily converge to produce an image on the retina. (b) Light rays from a nearby object can diverge more and still enter the eye. A more powerful lens is needed to converge them on the retina than if they were parallel.

We will use the thin lens equations to examine image formation by the eye quantitatively. First, note the power of a lens is given as  $p = 1/f$ , so we rewrite the thin lens equations as

$$P = \frac{1}{d_o} + \frac{1}{d_i} \quad 26.1$$

and

$$\frac{h_i}{h_o} = -\frac{d_i}{d_o} = m. \quad 26.2$$

We understand that  $d_i$  must equal the lens-to-retina distance to obtain clear vision, and that normal vision is possible for objects at distances  $d_o = 25$  cm to infinity.

### Take-Home Experiment: The Pupil

Look at the central transparent area of someone's eye, the pupil, in normal room light. Estimate the diameter of the pupil. Now turn off the lights and darken the room. After a few minutes turn on the lights and promptly estimate the diameter of the pupil. What happens to the pupil as the eye adjusts to the room light? Explain your observations.

The eye can detect an impressive amount of detail, considering how small the image is on the retina. To get some



idea of how small the image can be, consider the following example.



### EXAMPLE 26.1

#### Size of Image on Retina

What is the size of the image on the retina of a  $1.20 \times 10^{-2}$  cm diameter human hair, held at arm's length (60.0 cm) away? Take the lens-to-retina distance to be 2.00 cm.

#### Strategy

We want to find the height of the image  $h_i$ , given the height of the object is  $h_o = 1.20 \times 10^{-2}$  cm. We also know that the object is 60.0 cm away, so that  $d_o = 60.0$  cm. For clear vision, the image distance must equal the lens-to-retina distance, and so  $d_i = 2.00$  cm. The equation  $\frac{h_i}{h_o} = -\frac{d_i}{d_o} = m$  can be used to find  $h_i$  with the known information.

#### Solution

The only unknown variable in the equation  $\frac{h_i}{h_o} = -\frac{d_i}{d_o} = m$  is  $h_i$ :

$$\frac{h_i}{h_o} = -\frac{d_i}{d_o}. \quad 26.3$$

Rearranging to isolate  $h_i$  yields

$$h_i = -h_o \cdot \frac{d_i}{d_o}. \quad 26.4$$

Substituting the known values gives

$$\begin{aligned} h_i &= -(1.20 \times 10^{-2} \text{ cm}) \frac{2.00 \text{ cm}}{60.0 \text{ cm}} \\ &= -4.00 \times 10^{-4} \text{ cm}. \end{aligned} \quad 26.5$$

#### Discussion

This truly small image is not the smallest discernible—that is, the limit to visual acuity is even smaller than this. Limitations on visual acuity have to do with the wave properties of light and will be discussed in the next chapter. Some limitation is also due to the inherent anatomy of the eye and processing that occurs in our brain.



### EXAMPLE 26.2

#### Power Range of the Eye

Calculate the power of the eye when viewing objects at the greatest and smallest distances possible with normal vision, assuming a lens-to-retina distance of 2.00 cm (a typical value).

#### Strategy

For clear vision, the image must be on the retina, and so  $d_i = 2.00$  cm here. For distant vision,  $d_o \approx \infty$ , and for close vision,  $d_o = 25.0$  cm, as discussed earlier. The equation  $P = \frac{1}{d_o} + \frac{1}{d_i}$  as written just above, can be used directly to solve for  $P$  in both cases, since we know  $d_i$  and  $d_o$ . Power has units of diopters, where  $1 \text{ D} = 1/\text{m}$ , and so we should express all distances in meters.

#### Solution

For distant vision,

$$P = \frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{\infty} + \frac{1}{0.0200 \text{ m}}. \quad 26.6$$

Since  $1/\infty = 0$ , this gives

$$P = 0 + 50.0/\text{m} = 50.0 \text{ D (distant vision).} \quad 26.7$$

Now, for close vision,

$$\begin{aligned} P &= \frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{0.250 \text{ m}} + \frac{1}{0.0200 \text{ m}} \\ &= \frac{4.00}{\text{m}} + \frac{50.0}{\text{m}} = 4.00 \text{ D} + 50.0 \text{ D} \\ &= 54.0 \text{ D (close vision).} \end{aligned} \quad 26.8$$

### Discussion

For an eye with this typical 2.00 cm lens-to-retina distance, the power of the eye ranges from 50.0 D (for distant totally relaxed vision) to 54.0 D (for close fully accommodated vision), which is an 8% increase. This increase in power for close vision is consistent with the preceding discussion and the ray tracing in [Figure 26.4](#). An 8% ability to accommodate is considered normal but is typical for people who are about 40 years old. Younger people have greater accommodation ability, whereas older people gradually lose the ability to accommodate. When an optometrist identifies accommodation as a problem in elder people, it is most likely due to stiffening of the lens. The lens of the eye changes with age in ways that tend to preserve the ability to see distant objects clearly but do not allow the eye to accommodate for close vision, a condition called **presbyopia** (literally, elder eye). To correct this vision defect, we place a converging, positive power lens in front of the eye, such as found in reading glasses. Commonly available reading glasses are rated by their power in diopters, typically ranging from 1.0 to 3.5 D.

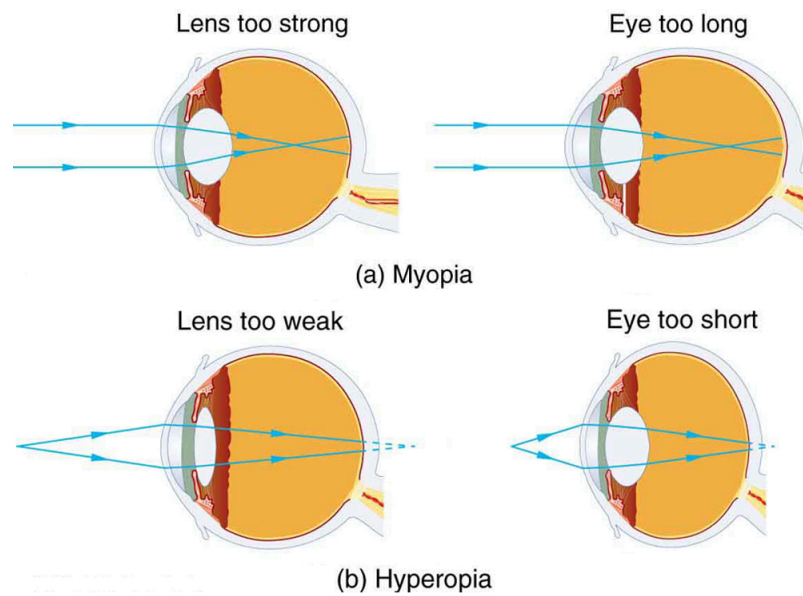
## 26.2 Vision Correction

### LEARNING OBJECTIVES

By the end of this section, you will be able to:

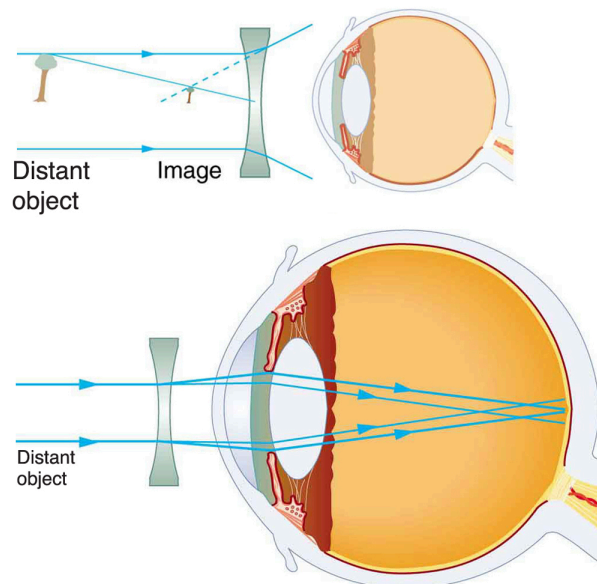
- Identify and discuss common vision defects.
- Explain nearsightedness and farsightedness corrections.
- Explain laser vision correction.

The need for some type of vision correction is very common. Common vision defects are easy to understand, and some are simple to correct. [Figure 26.5](#) illustrates two common vision defects. **Nearsightedness**, or **myopia**, is the inability to see distant objects clearly while close objects are clear. The eye overconverges the nearly parallel rays from a distant object, and the rays cross in front of the retina. More divergent rays from a close object are converged on the retina for a clear image. The distance to the farthest object that can be seen clearly is called the **far point** of the eye (normally infinity). **Farsightedness**, or **hyperopia**, is the inability to see close objects clearly while distant objects may be clear. A farsighted eye does not converge sufficient rays from a close object to make the rays meet on the retina. Less diverging rays from a distant object can be converged for a clear image. The distance to the closest object that can be seen clearly is called the **near point** of the eye (normally 25 cm).



**FIGURE 26.5** (a) The nearsighted (myopic) eye converges rays from a distant object in front of the retina; thus, they are diverging when they strike the retina, producing a blurry image. This can be caused by the lens of the eye being too powerful or the length of the eye being too great. (b) The farsighted (hyperopic) eye is unable to converge the rays from a close object by the time they strike the retina, producing blurry close vision. This can be caused by insufficient power in the lens or by the eye being too short.

Since the nearsighted eye over converges light rays, the correction for nearsightedness is to place a diverging spectacle lens in front of the eye. This reduces the power of an eye that is too powerful. Another way of thinking about this is that a diverging spectacle lens produces a case 3 image, which is closer to the eye than the object (see [Figure 26.6](#)). To determine the spectacle power needed for correction, you must know the person's far point—that is, you must know the greatest distance at which the person can see clearly. Then the image produced by a spectacle lens must be at this distance or closer for the nearsighted person to be able to see it clearly. It is worth noting that wearing glasses does not change the eye in any way. The eyeglass lens is simply used to create an image of the object at a distance where the nearsighted person can see it clearly. Whereas someone not wearing glasses can see clearly *objects* that fall between their near point and their far point, someone wearing glasses can see *images* that fall between their near point and their far point.



**FIGURE 26.6** Correction of nearsightedness requires a diverging lens that compensates for the overconvergence by the eye. The diverging lens produces an image closer to the eye than the object, so that the nearsighted person can see it clearly.

### EXAMPLE 26.3

#### Correcting Nearsightedness

What power of spectacle lens is needed to correct the vision of a nearsighted person whose far point is 30.0 cm? Assume the spectacle (corrective) lens is held 1.50 cm away from the eye by eyeglass frames.

#### Strategy

You want this nearsighted person to be able to see very distant objects clearly. That means the spectacle lens must produce an image 30.0 cm from the eye for an object very far away. An image 30.0 cm from the eye will be 28.5 cm to the left of the spectacle lens (see [Figure 26.6](#)). Therefore, we must get  $d_i = -28.5$  cm when  $d_o \approx \infty$ . The image distance is negative, because it is on the same side of the spectacle as the object.

#### Solution

Since  $d_i$  and  $d_o$  are known, the power of the spectacle lens can be found using  $P = \frac{1}{d_o} + \frac{1}{d_i}$  as written earlier:

$$P = \frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{\infty} + \frac{1}{-0.285 \text{ m}}. \quad 26.9$$

Since  $1/\infty = 0$ , we obtain:

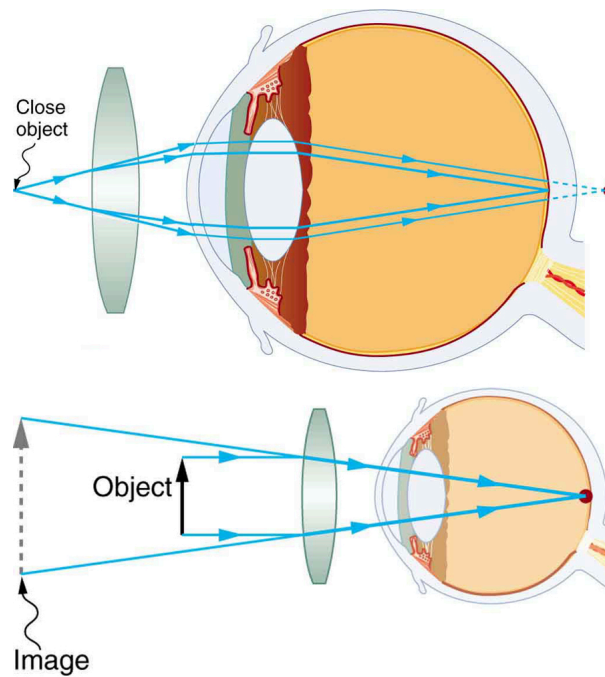
$$P = 0 - 3.51/\text{m} = -3.51 \text{ D}. \quad 26.10$$

#### Discussion

The negative power indicates a diverging (or concave) lens, as expected. The spectacle produces a case 3 image closer to the eye, where the person can see it. If you examine eyeglasses for nearsighted people, you will find the lenses are thinnest in the center. Additionally, if you examine a prescription for eyeglasses for nearsighted people, you will find that the prescribed power is negative and given in units of diopters.

Since the farsighted eye under converges light rays, the correction for farsightedness is to place a converging spectacle lens in front of the eye. This increases the power of an eye that is too weak. Another way of thinking about this is that a converging spectacle lens produces a case 2 image, which is farther from the eye than the object (see [Figure 26.7](#)). To determine the spectacle power needed for correction, you must know the person's near point—that is, you must know the smallest distance at which the person can see clearly. Then the image produced by a spectacle lens must be at this distance or farther for the farsighted person to be able to see it clearly.





**FIGURE 26.7** Correction of farsightedness uses a converging lens that compensates for the under convergence by the eye. The converging lens produces an image farther from the eye than the object, so that the farsighted person can see it clearly.



### EXAMPLE 26.4

#### Correcting Farsightedness

What power of spectacle lens is needed to allow a farsighted person, whose near point is 1.00 m, to see an object clearly that is 25.0 cm away? Assume the spectacle (corrective) lens is held 1.50 cm away from the eye by eyeglass frames.

#### Strategy

When an object is held 25.0 cm from the person's eyes, the spectacle lens must produce an image 1.00 m away (the near point). An image 1.00 m from the eye will be 98.5 cm to the left of the spectacle lens because the spectacle lens is 1.50 cm from the eye (see Figure 26.7). Therefore,  $d_i = -98.5$  cm. The image distance is negative, because it is on the same side of the spectacle as the object. The object is 23.5 cm to the left of the spectacle, so that  $d_o = 23.5$  cm.

#### Solution

Since  $d_i$  and  $d_o$  are known, the power of the spectacle lens can be found using  $P = \frac{1}{d_o} + \frac{1}{d_i}$ :

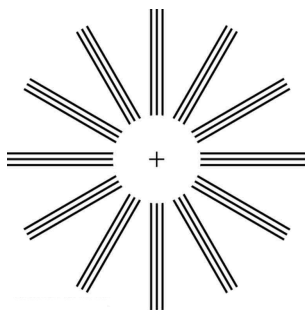
$$\begin{aligned} P &= \frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{0.235 \text{ m}} + \frac{1}{-0.985 \text{ m}} \\ &= 4.26 \text{ D} - 1.02 \text{ D} = 3.24 \text{ D}. \end{aligned} \quad 26.11$$

#### Discussion

The positive power indicates a converging (convex) lens, as expected. The convex spectacle produces a case 2 image farther from the eye, where the person can see it. If you examine eyeglasses of farsighted people, you will find the lenses to be thickest in the center. In addition, a prescription of eyeglasses for farsighted people has a prescribed power that is positive.

Another common vision defect is **astigmatism**, an unevenness or asymmetry in the focus of the eye. For example, rays passing through a vertical region of the eye may focus closer than rays passing through a horizontal region, resulting in the image appearing elongated. This is mostly due to irregularities in the shape of the cornea but can

also be due to lens irregularities or unevenness in the retina. Because of these irregularities, different parts of the lens system produce images at different locations. The eye-brain system can compensate for some of these irregularities, but they generally manifest themselves as less distinct vision or sharper images along certain axes. [Figure 26.8](#) shows a chart used to detect astigmatism. Astigmatism can be at least partially corrected with a spectacle having the opposite irregularity of the eye. If an eyeglass prescription has a cylindrical correction, it is there to correct astigmatism. The normal corrections for short- or farsightedness are spherical corrections, uniform along all axes.



**FIGURE 26.8** This chart can detect astigmatism, unevenness in the focus of the eye. Check each of your eyes separately by looking at the center cross (without spectacles if you wear them). If lines along some axes appear darker or clearer than others, you have an astigmatism.

Contact lenses have advantages over glasses beyond their cosmetic aspects. One problem with glasses is that as the eye moves, it is not at a fixed distance from the spectacle lens. Contacts rest on and move with the eye, eliminating this problem. Because contacts cover a significant portion of the cornea, they provide superior peripheral vision compared with eyeglasses. Contacts also correct some corneal astigmatism caused by surface irregularities. The tear layer between the smooth contact and the cornea fills in the irregularities. Since the index of refraction of the tear layer and the cornea are very similar, you now have a regular optical surface in place of an irregular one. If the curvature of a contact lens is not the same as the cornea (as may be necessary with some individuals to obtain a comfortable fit), the tear layer between the contact and cornea acts as a lens. If the tear layer is thinner in the center than at the edges, it has a negative power, for example. Skilled optometrists will adjust the power of the contact to compensate.

Other advances in vision correction demonstrate the interconnectedness and value of scientific research. In the 1980s, Donna Strickland and Gérard Mourou worked on ways to make small but powerful lasers. Up until that time, powerful lasers had to be quite large in order to function properly. Essentially, the intensity of the beam itself would modify the instrument's ability to function and create too much heat to be practical. Strickland and Mourou used ultrashort laser pulses passed over a grating that modified the beam but retained its power. Chirped pulse amplification, as it became known, has been used to develop most of the highest-powered lasers in the world, but also some of the smallest and most common. Decades after their initial discovery, Strickland and Mourou were awarded the Nobel Prize for Physics (with Strickland becoming the third woman to receive the award) partly due to CPA's pivotal role in the increasingly common practice of laser vision correction—an application neither planned during their initial research.

**Laser vision correction** has progressed rapidly in the last few years. It is the latest and by far the most successful in a series of procedures that correct vision by reshaping the cornea. As noted at the beginning of this section, the cornea accounts for about two-thirds of the power of the eye. Thus, small adjustments of its curvature have the same effect as putting a lens in front of the eye. To a reasonable approximation, the power of multiple lenses placed close together equals the sum of their powers. For example, a concave spectacle lens (for nearsightedness) having  $P = -3.00$  D has the same effect on vision as reducing the power of the eye itself by 3.00 D. So to correct the eye for nearsightedness, the cornea is flattened to reduce its power. Similarly, to correct for farsightedness, the curvature of the cornea is enhanced to increase the power of the eye—the same effect as the positive power spectacle lens used for farsightedness. Laser vision correction uses high intensity electromagnetic radiation to ablate (to remove material from the surface) and reshape the corneal surfaces.

Today, the most commonly used laser vision correction procedure is *Laser in situ Keratomileusis (LASIK)*. The top layer of the cornea is surgically peeled back and the underlying tissue ablated by multiple bursts of finely controlled ultraviolet radiation produced by an excimer laser. Lasers are used because they not only produce well-focused

intense light, but they also emit very pure wavelength electromagnetic radiation that can be controlled more accurately than mixed wavelength light. The 193 nm wavelength UV commonly used is extremely and strongly absorbed by corneal tissue, allowing precise evaporation of very thin layers. A computer controlled program applies more bursts, usually at a rate of 10 per second, to the areas that require deeper removal. Typically a spot less than 1 mm in diameter and about  $0.3\ \mu\text{m}$  in thickness is removed by each burst. Nearsightedness, farsightedness, and astigmatism can be corrected with an accuracy that produces normal distant vision in more than 90% of the patients, in many cases right away. The corneal flap is replaced; healing takes place rapidly and is nearly painless. More than 1 million Americans per year undergo LASIK (see [Figure 26.9](#)).



**FIGURE 26.9** Laser vision correction is being performed using the LASIK procedure. Reshaping of the cornea by laser ablation is based on a careful assessment of the patient's vision and is computer controlled. The upper corneal layer is temporarily peeled back and minimally disturbed in LASIK, providing for more rapid and less painful healing of the less sensitive tissues below. (credit: U.S. Navy photo by Mass Communication Specialist 1st Class Brien Aho)

## 26.3 Color and Color Vision

### LEARNING OBJECTIVES

By the end of this section, you will be able to:

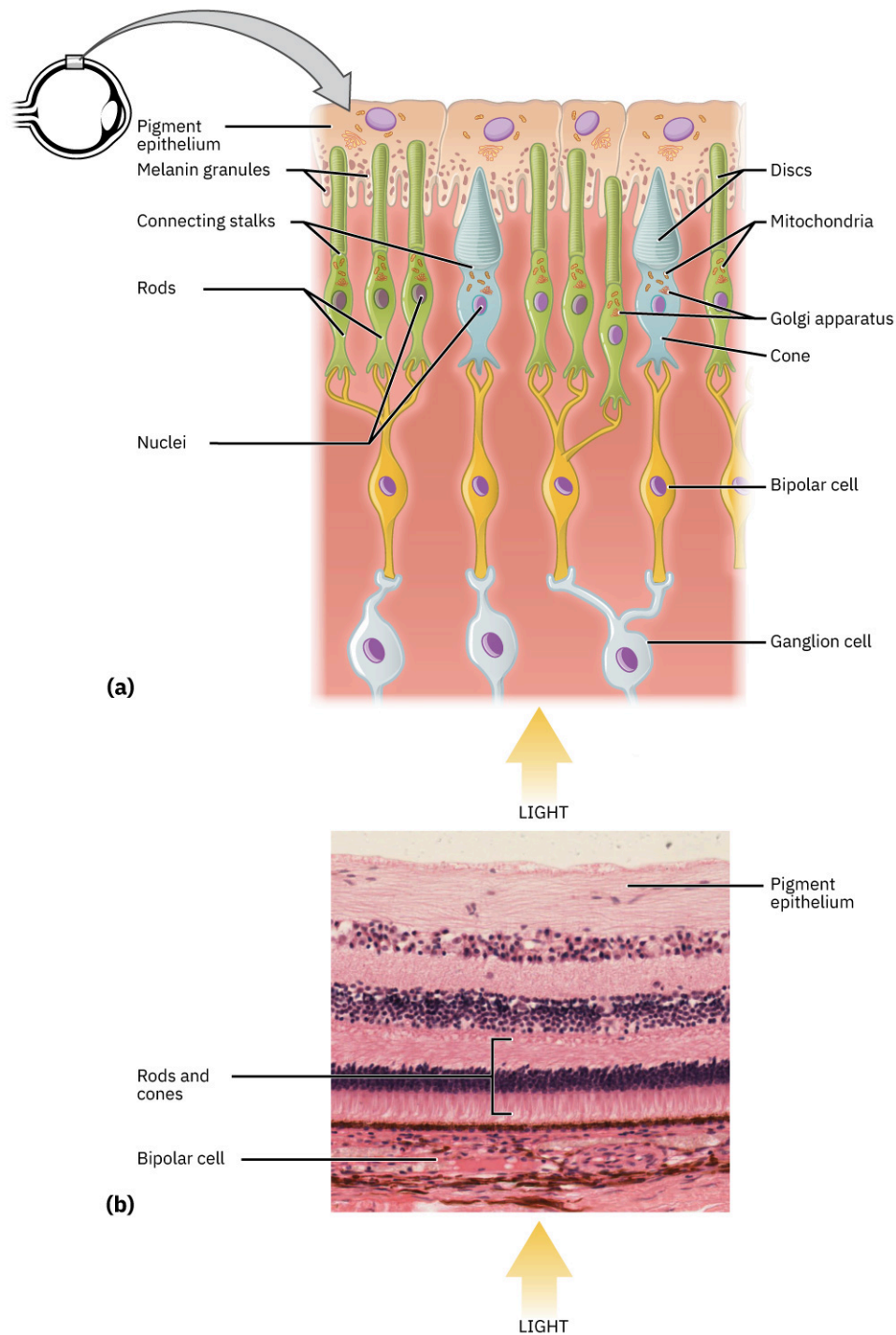
- Explain the simple theory of color vision.
- Outline the coloring properties of light sources.
- Describe the retinex theory of color vision.

The gift of vision is made richer by the existence of color. Objects and lights abound with thousands of hues that stimulate our eyes, brains, and emotions. Two basic questions are addressed in this brief treatment—what does color mean in scientific terms, and how do we, as humans, perceive it?

### Simple Theory of Color Vision

We have already noted that color is associated with the wavelength of visible electromagnetic radiation. When our eyes receive pure-wavelength light, we tend to see only a few colors. Six of these (most often listed) are red, orange, yellow, green, blue, and violet. These are the rainbow of colors produced when white light is dispersed according to different wavelengths. There are thousands of other **hues** that we can perceive. These include brown, teal, gold, pink, and white. One simple theory of color vision implies that all these hues are our eye's response to different combinations of wavelengths. This is true to an extent, but we find that color perception is even subtler than our eye's response for various wavelengths of light.

The two major types of light-sensing cells (photoreceptors) in the retina are **rods and cones**. Rods are more sensitive than cones by a factor of about 1000 and are solely responsible for peripheral vision as well as vision in very dark environments. They are also important for motion detection. There are about 120 million rods in the human retina. Rods do not yield color information. You may notice that you lose color vision when it is very dark, but you retain the ability to discern grey scales.



**FIGURE 26.10** (a) All photoreceptors have inner segments containing the nucleus and other important organelles and outer segments with membrane arrays containing the photosensitive opsin molecules. Rod outer segments are long columnar shapes with stacks of membrane-bound discs that contain the rhodopsin pigment. Cone outer segments are short, tapered shapes with folds of membrane in place of the discs in the rods. (b) Tissue of the retina shows a dense layer of nuclei of the rods and cones. LM  $\times 800$ . (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

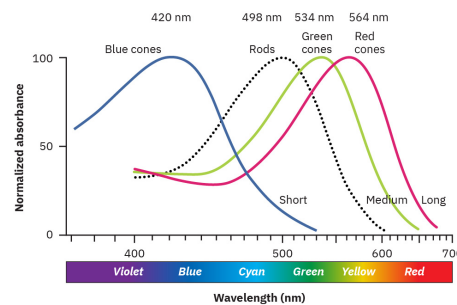
### Take-Home Experiment: Rods and Cones

1. Go into a darkened room from a brightly lit room, or from outside in the Sun. How long did it take to start seeing shapes more clearly? What about color? Return to the bright room. Did it take a few minutes before

you could see things clearly?

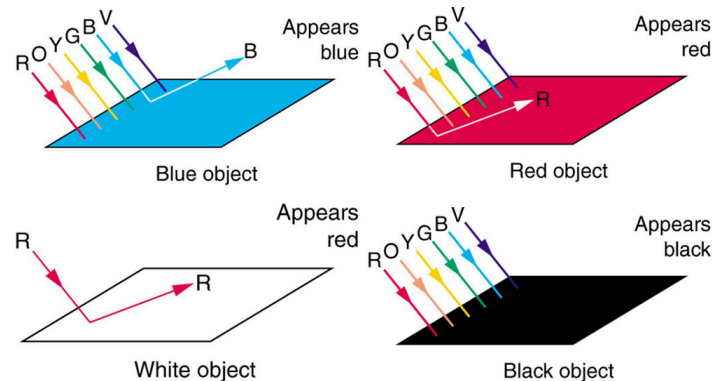
2. Demonstrate the sensitivity of foveal vision. Look at the letter G in the word ROGERS. What about the clarity of the letters on either side of G?

Cones are most concentrated in the fovea, the central region of the retina. There are no rods here. The fovea is at the center of the macula, a 5 mm diameter region responsible for our central vision. The cones work best in bright light and are responsible for high resolution vision. There are about 6 million cones in the human retina. There are three types of cones, and each type is sensitive to different ranges of wavelengths, as illustrated in [Figure 26.11](#). A **simplified theory of color vision** is that there are three *primary colors* corresponding to the three types of cones. The thousands of other hues that we can distinguish among are created by various combinations of stimulations of the three types of cones. Color television uses a three-color system in which the screen is covered with equal numbers of red, green, and blue phosphor dots. The broad range of hues a viewer sees is produced by various combinations of these three colors. For example, you will perceive yellow when red and green are illuminated with the correct ratio of intensities. White may be sensed when all three are illuminated. Then, it would seem that all hues can be produced by adding three primary colors in various proportions. But there is an indication that color vision is more sophisticated. There is no unique set of three primary colors. Another set that works is yellow, green, and blue. A further indication of the need for a more complex theory of color vision is that various different combinations can produce the same hue. Yellow can be sensed with yellow light, or with a combination of red and green, and also with white light from which violet has been removed. The three-primary-colors aspect of color vision is well established; more sophisticated theories expand on it rather than deny it.



**FIGURE 26.11** The image shows the relative sensitivity of the three types of cones, which are named according to wavelengths of greatest sensitivity. Rods are about 1000 times more sensitive, and their curve peaks at about 500 nm. Evidence for the three types of cones comes from direct measurements in animal and human eyes and testing of people with color blindness.

Consider why various objects display color—that is, why are feathers blue and red in a crimson rosella? The *true color of an object* is defined by its absorptive or reflective characteristics. [Figure 26.12](#) shows white light falling on three different objects, one pure blue, one pure red, and one black, as well as pure red light falling on a white object. Other hues are created by more complex absorption characteristics. Pink, for example on a galah cockatoo, can be due to weak absorption of all colors except red. An object can appear a different color under non-white illumination. For example, a pure blue object illuminated with pure red light will *appear* black, because it absorbs all the red light falling on it. But, the true color of the object is blue, which is independent of illumination.



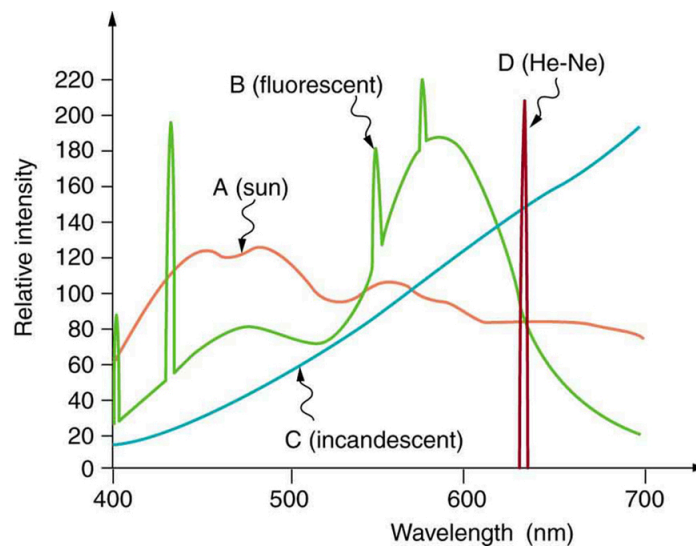
**FIGURE 26.12** Absorption characteristics determine the true color of an object. Here, three objects are illuminated by white light, and one by pure red light. White is the equal mixture of all visible wavelengths; black is the absence of light.



Similarly, *light sources have colors* that are defined by the wavelengths they produce. A helium-neon laser emits pure red light. In fact, the phrase “pure red light” is defined by having a sharp constrained spectrum, a characteristic of laser light. The Sun produces a broad yellowish spectrum, fluorescent lights emit bluish-white light, and incandescent lights emit reddish-white hues as seen in [Figure 26.13](#). As you would expect, you sense these colors when viewing the light source directly or when illuminating a white object with them. All of this fits neatly into the simplified theory that a combination of wavelengths produces various hues.

### Take-Home Experiment: Exploring Color Addition

This activity is best done with plastic sheets of different colors as they allow more light to pass through to our eyes. However, thin sheets of paper and fabric can also be used. Overlay different colors of the material and hold them up to a white light. Using the theory described above, explain the colors you observe. You could also try mixing different crayon colors.

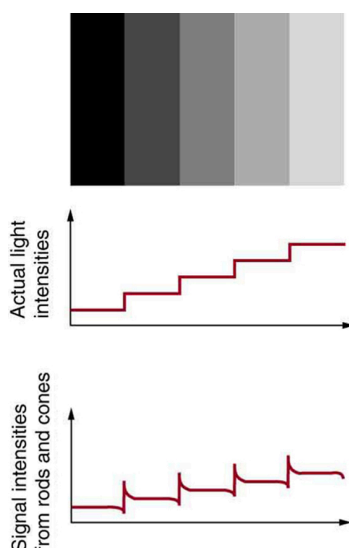


**FIGURE 26.13** Emission spectra for various light sources are shown. Curve A is average sunlight at Earth’s surface, curve B is light from a fluorescent lamp, and curve C is the output of an incandescent light. The spike for a helium-neon laser (curve D) is due to its pure wavelength emission. The spikes in the fluorescent output are due to atomic spectra—a topic that will be explored later.

### Color Constancy and a Modified Theory of Color Vision

The eye-brain color-sensing system can, by comparing various objects in its view, perceive the true color of an object under varying lighting conditions—an ability that is called **color constancy**. We can sense that a white tablecloth, for example, is white whether it is illuminated by sunlight, fluorescent light, or candlelight. The wavelengths entering the eye are quite different in each case, as the graphs in [Figure 26.13](#) imply, but our color vision can detect the true color by comparing the tablecloth with its surroundings.

Theories that take color constancy into account are based on a large body of anatomical evidence as well as perceptual studies. There are nerve connections among the light receptors on the retina, and there are far fewer nerve connections to the brain than there are rods and cones. This means that there is signal processing in the eye before information is sent to the brain. For example, the eye makes comparisons between adjacent light receptors and is very sensitive to edges as seen in [Figure 26.14](#). Rather than responding simply to the light entering the eye, which is uniform in the various rectangles in this figure, the eye responds to the edges and senses false darkness variations.



**FIGURE 26.14** The importance of edges is shown. Although the grey strips are uniformly shaded, as indicated by the graph immediately below them, they do not appear uniform at all. Instead, they are perceived darker on the dark side and lighter on the light side of the edge, as shown in the bottom graph. This is due to nerve impulse processing in the eye.

One theory that takes various factors into account was advanced by Edwin Land (1909 – 1991), the creative founder of the Polaroid Corporation. Land proposed, based partly on his many elegant experiments, that the three types of cones are organized into systems called **retinexes**. Each retinex forms an image that is compared with the others, and the eye-brain system thus can compare a candle-illuminated white table cloth with its generally reddish surroundings and determine that it is actually white. This **retinex theory of color vision** is an example of modified theories of color vision that attempt to account for its subtleties. One striking experiment performed by Land demonstrates that some type of image comparison may produce color vision. Two pictures are taken of a scene on black-and-white film, one using a red filter, the other a blue filter. Resulting black-and-white slides are then projected and superimposed on a screen, producing a black-and-white image, as expected. Then a red filter is placed in front of the slide taken with a red filter, and the images are again superimposed on a screen. You would expect an image in various shades of pink, but instead, the image appears to humans in full color with all the hues of the original scene. This implies that color vision can be induced by comparison of the black-and-white and red images. Color vision is not completely understood or explained, and the retinex theory is not totally accepted. It is apparent that color vision is much subtler than what a first look might imply.



## PHET EXPLORATIONS

### Color Vision

Make a whole rainbow by mixing red, green, and blue light. Change the wavelength of a monochromatic beam or filter white light. View the light as a solid beam, or see the individual photons.

[Click to view content \(https://openstax.org/books/college-physics-2e/pages/26-3-color-and-color-vision\)](https://openstax.org/books/college-physics-2e/pages/26-3-color-and-color-vision)



## 26.4 Microscopes

### LEARNING OBJECTIVES

By the end of this section, you will be able to:

- Investigate different types of microscopes.
- Learn how image is formed in a compound microscope.

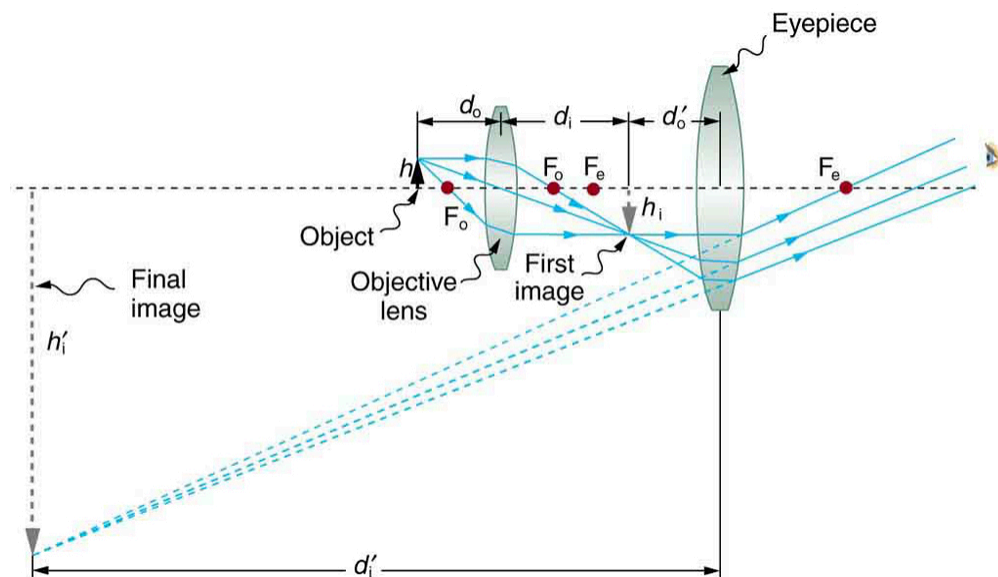
Although the eye is marvelous in its ability to see objects large and small, it obviously has limitations to the smallest details it can detect. Human desire to see beyond what is possible with the naked eye led to the use of optical instruments. In this section we will examine microscopes, instruments for enlarging the detail that we cannot see with the unaided eye. The microscope is a multiple-element system having more than a single lens or mirror. (See

**Figure 26.15** A microscope can be made from two convex lenses. The image formed by the first element becomes the object for the second element. The second element forms its own image, which is the object for the third element, and so on. Ray tracing helps to visualize the image formed. If the device is composed of thin lenses and mirrors that obey the thin lens equations, then it is not difficult to describe their behavior numerically.



**FIGURE 26.15** Multiple lenses and mirrors are used in this microscope. (credit: U.S. Navy photo by Tom Watanabe)

Microscopes were first developed in the early 1600s by eyeglass makers in The Netherlands and Denmark. The simplest **compound microscope** is constructed from two convex lenses as shown schematically in **Figure 26.16**. The first lens is called the **objective lens**, and has typical magnification values from  $5\times$  to  $100\times$ . In standard microscopes, the objectives are mounted such that when you switch between objectives, the sample remains in focus. Objectives arranged in this way are described as parfocal. The second, the **eyepiece**, also referred to as the ocular, has several lenses which slide inside a cylindrical barrel. The focusing ability is provided by the movement of both the objective lens and the eyepiece. The purpose of a microscope is to magnify small objects, and both lenses contribute to the final magnification. Additionally, the final enlarged image is produced in a location far enough from the observer to be easily viewed, since the eye cannot focus on objects or images that are too close.



**FIGURE 26.16** A compound microscope composed of two lenses, an objective and an eyepiece. The objective forms a case 1 image that is larger than the object. This first image is the object for the eyepiece. The eyepiece forms a case 2 final image that is further magnified.

To see how the microscope in **Figure 26.16** forms an image, we consider its two lenses in succession. The object is slightly farther away from the objective lens than its focal length  $f_o$ , producing a case 1 image that is larger than the object. This first image is the object for the second lens, or eyepiece. The eyepiece is intentionally located so it can further magnify the image. The eyepiece is placed so that the first image is closer to it than its focal length  $f_e$ . Thus the eyepiece acts as a magnifying glass, and the final image is made even larger. The final image remains inverted, but it is farther from the observer, making it easy to view (the eye is most relaxed when viewing distant objects and

normally cannot focus closer than 25 cm). Since each lens produces a magnification that multiplies the height of the image, it is apparent that the overall magnification  $m$  is the product of the individual magnifications:

$$m = m_o m_e, \quad 26.12$$

where  $m_o$  is the magnification of the objective and  $m_e$  is the magnification of the eyepiece. This equation can be generalized for any combination of thin lenses and mirrors that obey the thin lens equations.

### Overall Magnification

The overall magnification of a multiple-element system is the product of the individual magnifications of its elements.



### EXAMPLE 26.5

#### Microscope Magnification

Calculate the magnification of an object placed 6.20 mm from a compound microscope that has a 6.00 mm focal length objective and a 50.0 mm focal length eyepiece. The objective and eyepiece are separated by 23.0 cm.

#### Strategy and Concept

This situation is similar to that shown in [Figure 26.16](#). To find the overall magnification, we must find the magnification of the objective, then the magnification of the eyepiece. This involves using the thin lens equation.

#### Solution

The magnification of the objective lens is given as

$$m_o = -\frac{d_i}{d_o}, \quad 26.13$$

where  $d_o$  and  $d_i$  are the object and image distances, respectively, for the objective lens as labeled in [Figure 26.16](#). The object distance is given to be  $d_o = 6.20$  mm, but the image distance  $d_i$  is not known. Isolating  $d_i$ , we have

$$\frac{1}{d_i} = \frac{1}{f_o} - \frac{1}{d_o}, \quad 26.14$$

where  $f_o$  is the focal length of the objective lens. Substituting known values gives

$$\frac{1}{d_i} = \frac{1}{6.00 \text{ mm}} - \frac{1}{6.20 \text{ mm}} = \frac{0.00538}{\text{mm}}. \quad 26.15$$

We invert this to find  $d_i$ :

$$d_i = 186 \text{ mm}. \quad 26.16$$

Substituting this into the expression for  $m_o$  gives

$$m_o = -\frac{d_i}{d_o} = -\frac{186 \text{ mm}}{6.20 \text{ mm}} = -30.0. \quad 26.17$$

Now we must find the magnification of the eyepiece, which is given by

$$m_e = -\frac{d_i'}{d_o'}, \quad 26.18$$

where  $d_i'$  and  $d_o'$  are the image and object distances for the eyepiece (see [Figure 26.16](#)). The object distance is the distance of the first image from the eyepiece. Since the first image is 186 mm to the right of the objective and the eyepiece is 230 mm to the right of the objective, the object distance is  $d_o' = 230 \text{ mm} - 186 \text{ mm} = 44.0 \text{ mm}$ . This places the first image closer to the eyepiece than its focal length, so that the eyepiece will form a case 2 image as shown in the figure. We still need to find the location of the final image  $d_i'$  in order to find the magnification. This is

done as before to obtain a value for  $1/d_i'$ :

$$\frac{1}{d_i'} = \frac{1}{f_e} - \frac{1}{d_o'} = \frac{1}{50.0 \text{ mm}} - \frac{1}{44.0 \text{ mm}} = -\frac{0.00273}{\text{mm}}. \quad 26.19$$

Inverting gives

$$d_i' = -\frac{\text{mm}}{0.00273} = -367 \text{ mm}. \quad 26.20$$

The eyepiece's magnification is thus

$$m_e = -\frac{d_i'}{d_o'} = -\frac{-367 \text{ mm}}{44.0 \text{ mm}} = 8.33. \quad 26.21$$

So the overall magnification is

$$m = m_o m_e = (-30.0)(8.33) = -250. \quad 26.22$$

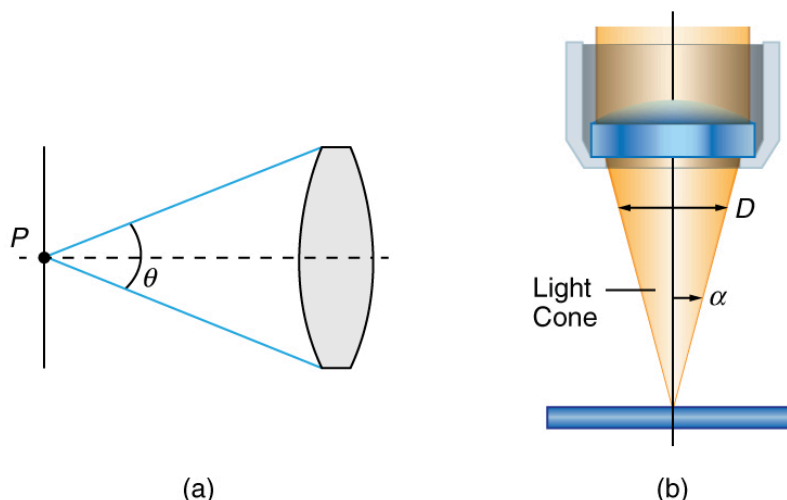
### Discussion

Both the objective and the eyepiece contribute to the overall magnification, which is large and negative, consistent with [Figure 26.16](#), where the image is seen to be large and inverted. In this case, the image is virtual and inverted, which cannot happen for a single element (case 2 and case 3 images for single elements are virtual and upright). The final image is 367 mm (0.367 m) to the left of the eyepiece. Had the eyepiece been placed farther from the objective, it could have formed a case 1 image to the right. Such an image could be projected on a screen, but it would be behind the head of the person in the figure and not appropriate for direct viewing. The procedure used to solve this example is applicable in any multiple-element system. Each element is treated in turn, with each forming an image that becomes the object for the next element. The process is not more difficult than for single lenses or mirrors, only lengthier.

Normal optical microscopes can magnify up to  $1500\times$  with a theoretical resolution of  $\sim 0.2 \mu\text{m}$ . The lenses can be quite complicated and are composed of multiple elements to reduce aberrations. Microscope objective lenses are particularly important as they primarily gather light from the specimen. Three parameters describe microscope objectives: the **numerical aperture** ( $NA$ ), the magnification ( $m$ ), and the working distance. The  $NA$  is related to the light gathering ability of a lens and is obtained using the angle of acceptance  $\theta$  formed by the maximum cone of rays focusing on the specimen (see [Figure 26.17\(a\)](#)) and is given by

$$NA = n \sin \alpha, \quad 26.23$$

where  $n$  is the refractive index of the medium between the lens and the specimen and  $\alpha = \theta/2$ . As the angle of acceptance given by  $\theta$  increases,  $NA$  becomes larger and more light is gathered from a smaller focal region giving higher resolution. A  $0.75 NA$  objective gives more detail than a  $0.10 NA$  objective.



**FIGURE 26.17** (a) The numerical aperture ( $NA$ ) of a microscope objective lens refers to the light-gathering ability of the lens and is



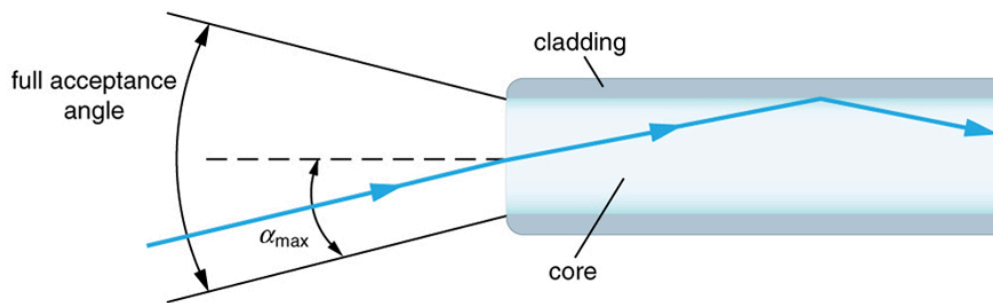
calculated using half the angle of acceptance  $\theta$ . (b) Here,  $\alpha$  is half the acceptance angle for light rays from a specimen entering a camera lens, and  $D$  is the diameter of the aperture that controls the light entering the lens.

While the numerical aperture can be used to compare resolutions of various objectives, it does not indicate how far the lens could be from the specimen. This is specified by the “working distance,” which is the distance (in mm usually) from the front lens element of the objective to the specimen, or cover glass. The higher the  $NA$  the closer the lens will be to the specimen and the more chances there are of breaking the cover slip and damaging both the specimen and the lens. The focal length of an objective lens is different than the working distance. This is because objective lenses are made of a combination of lenses and the focal length is measured from inside the barrel. The working distance is a parameter that microscopists can use more readily as it is measured from the outermost lens. The working distance decreases as the  $NA$  and magnification both increase.

The term  $f/\#$  in general is called the  $f$ -number and is used to denote the light per unit area reaching the image plane. In photography, an image of an object at infinity is formed at the focal point and the  $f$ -number is given by the ratio of the focal length  $f$  of the lens and the diameter  $D$  of the aperture controlling the light into the lens (see [Figure 26.17\(b\)](#)). If the acceptance angle is small the  $NA$  of the lens can also be used as given below.

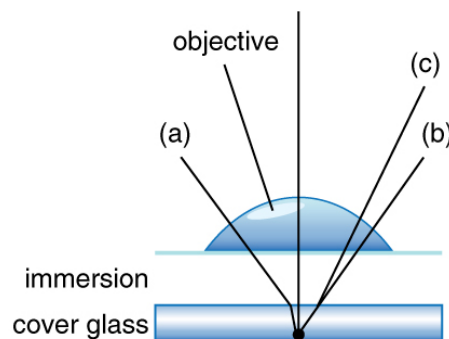
$$f/\# = \frac{f}{D} \approx \frac{1}{2NA}. \quad 26.24$$

As the  $f$ -number decreases, the camera is able to gather light from a larger angle, giving wide-angle photography. As usual there is a trade-off. A greater  $f/\#$  means less light reaches the image plane. A setting of  $f/16$  usually allows one to take pictures in bright sunlight as the aperture diameter is small. In optical fibers, light needs to be focused into the fiber. [Figure 26.18](#) shows the angle used in calculating the  $NA$  of an optical fiber.



**FIGURE 26.18** Light rays enter an optical fiber. The numerical aperture of the optical fiber can be determined by using the angle  $\alpha_{\max}$ .

Can the  $NA$  be larger than 1.00? The answer is ‘yes’ if we use immersion lenses in which a medium such as oil, glycerine or water is placed between the objective and the microscope cover slip. This minimizes the mismatch in refractive indices as light rays go through different media, generally providing a greater light-gathering ability and an increase in resolution. [Figure 26.19](#) shows light rays when using air and immersion lenses.

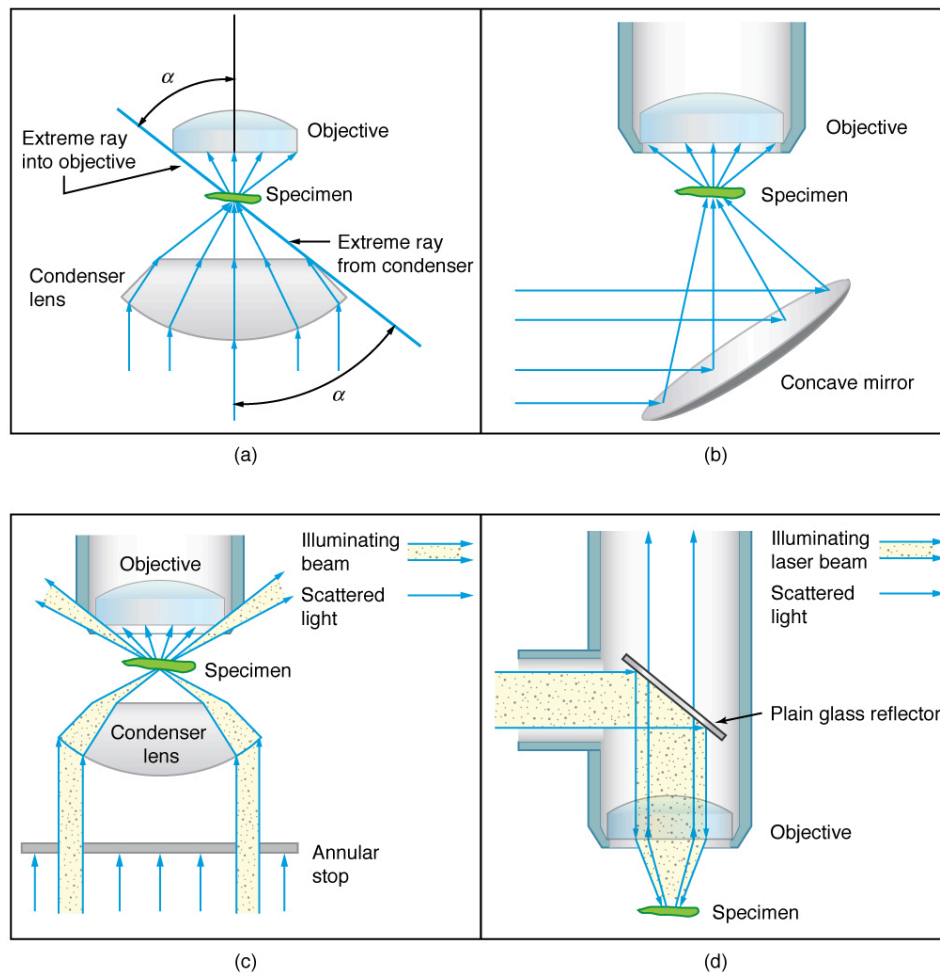


**FIGURE 26.19** Light rays from a specimen entering the objective. Paths for immersion medium of air (a), water (b) ( $n = 1.33$ ), and oil (c) ( $n = 1.51$ ) are shown. The water and oil immersions allow more rays to enter the objective, increasing the resolution.

When using a microscope we do not see the entire extent of the sample. Depending on the eyepiece and objective lens we see a restricted region which we say is the field of view. The objective is then manipulated in two-dimensions above the sample to view other regions of the sample. Electronic scanning of either the objective or the sample is used in scanning microscopy. The image formed at each point during the scanning is combined using a

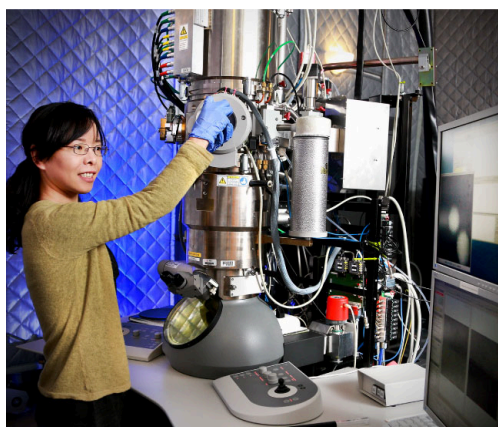
computer to generate an image of a larger region of the sample at a selected magnification.

When using a microscope, we rely on gathering light to form an image. Hence most specimens need to be illuminated, particularly at higher magnifications, when observing details that are so small that they reflect only small amounts of light. To make such objects easily visible, the intensity of light falling on them needs to be increased. Special illuminating systems called condensers are used for this purpose. The type of condenser that is suitable for an application depends on how the specimen is examined, whether by transmission, scattering or reflecting. See [Figure 26.20](#) for an example of each. White light sources are common and lasers are often used. Laser light illumination tends to be quite intense and it is important to ensure that the light does not result in the degradation of the specimen.

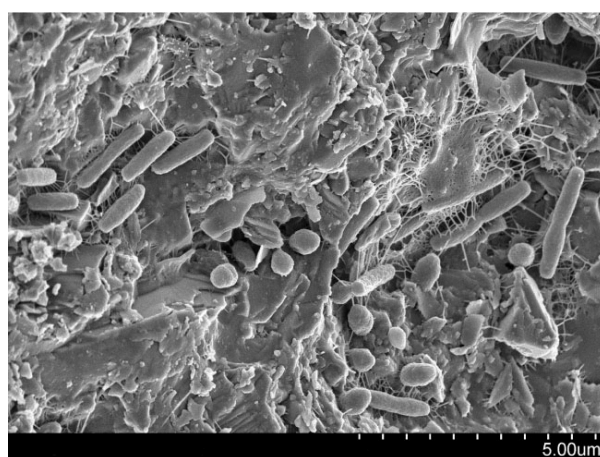


**FIGURE 26.20** Illumination of a specimen in a microscope. (a) Transmitted light from a condenser lens. (b) Transmitted light from a mirror condenser. (c) Dark field illumination by scattering (the illuminating beam misses the objective lens). (d) High magnification illumination with reflected light – normally laser light.

We normally associate microscopes with visible light, but x ray and electron microscopes provide greater resolution. The focusing and basic physics is the same as that just described, even though the lenses require different technology. The electron microscope requires vacuum chambers so that the electrons can proceed unheeded. Magnifications of 50 million times provide the ability to determine positions of individual atoms within materials. An electron microscope is shown in [Figure 26.21](#). We do not use our eyes to form images; rather images are recorded electronically and displayed on computers. In fact observing and saving images formed by optical microscopes on computers is now done routinely. Video recordings of what occurs in a microscope can be made for viewing by many people at later dates. Advances in this powerful technology continue. In the 1990s, Pratibha L. Gai invented the environmental transmission electron microscope (ETEM), which was the first device capable of observing individual atoms in chemical reactions.



**FIGURE 26.21** An electron microscope has the capability to image individual atoms on a material. The microscope uses vacuum technology, sophisticated detectors and state of the art image processing software. Researchers use the devices in their work on biological and, in the case of Miaofang Chi (pictured), lithium ion battery materials and fuel cell catalysts. (credit: Oak Ridge National Laboratory)



**FIGURE 26.22** A natural community of bacteria growing on a single grain of sand, which was imaged using a Scanning Electron Microscope. (credit: The Lewis Lab at Northeastern University. Image created by Anthony D'Onofrio, William H. Fowle, Eric J. Stewart, and Kim Lewis.)

### Take-Home Experiment: Make a Lens

Look through a clear glass or plastic bottle and describe what you see. Now fill the bottle with water and describe what you see. Use the water bottle as a lens to produce the image of a bright object and estimate the focal length of the water bottle lens. How is the focal length a function of the depth of water in the bottle?

## 26.5 Telescopes

### LEARNING OBJECTIVES

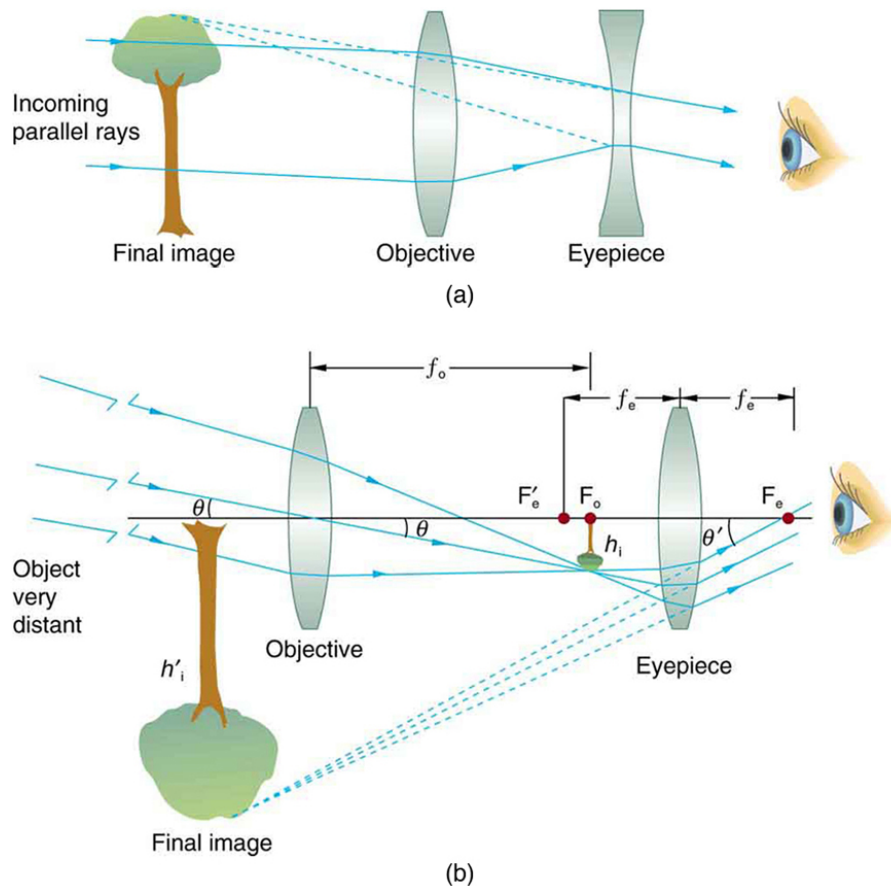
By the end of this section, you will be able to:

- Outline the invention of a telescope.
- Describe the working of a telescope.

Telescopes are meant for viewing distant objects, producing an image that is larger than the image that can be seen with the unaided eye. Telescopes gather far more light than the eye, allowing dim objects to be observed with greater magnification and better resolution. Although Galileo is often credited with inventing the telescope, he actually did not. What he did was more important. He constructed several early telescopes, was the first to study the heavens with them, and made monumental discoveries using them. Among these are the moons of Jupiter, the craters and mountains on the Moon, the details of sunspots, and the fact that the Milky Way is composed of vast numbers of individual stars.

[Figure 26.23\(a\)](#) shows a telescope made of two lenses, the convex objective and the concave eyepiece, the same construction used by Galileo. Such an arrangement produces an upright image and is used in spyglasses and opera

glasses.



**FIGURE 26.23** (a) Galilei made telescopes with a convex objective and a concave eyepiece. These produce an upright image and are used in spyglasses. (b) Most simple telescopes have two convex lenses. The objective forms a case 1 image that is the object for the eyepiece. The eyepiece forms a case 2 final image that is magnified.

The most common two-lens telescope, like the simple microscope, uses two convex lenses and is shown in [Figure 26.23\(b\)](#). The object is so far away from the telescope that it is essentially at infinity compared with the focal lengths of the lenses ( $d_o \approx \infty$ ). The first image is thus produced at  $d_i = f_o$ , as shown in the figure. To prove this, note that

$$\frac{1}{d_i} = \frac{1}{f_o} - \frac{1}{d_o} = \frac{1}{f_o} - \frac{1}{\infty}. \quad 26.25$$

Because  $1/\infty = 0$ , this simplifies to

$$\frac{1}{d_i} = \frac{1}{f_o}, \quad 26.26$$

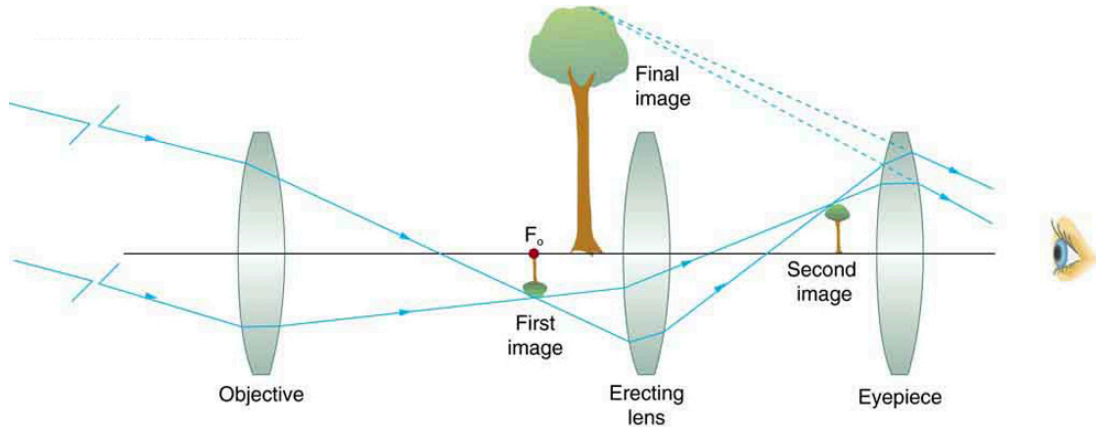
which implies that  $d_i = f_o$ , as claimed. It is true that for any distant object and any lens or mirror, the image is at the focal length.

The first image formed by a telescope objective as seen in [Figure 26.23\(b\)](#) will not be large compared with what you might see by looking at the object directly. For example, the spot formed by sunlight focused on a piece of paper by a magnifying glass is the image of the Sun, and it is small. The telescope eyepiece (like the microscope eyepiece) magnifies this first image. The distance between the eyepiece and the objective lens is made slightly less than the sum of their focal lengths so that the first image is closer to the eyepiece than its focal length. That is,  $d_o'$  is less than  $f_e$ , and so the eyepiece forms a case 2 image that is large and to the left for easy viewing. If the angle subtended by an object as viewed by the unaided eye is  $\theta$ , and the angle subtended by the telescope image is  $\theta'$ , then the **angular magnification**  $M$  is defined to be their ratio. That is,  $M = \theta'/\theta$ . It can be shown that the angular magnification of a telescope is related to the focal lengths of the objective and eyepiece; and is given by

$$M = \frac{\theta'}{\theta} = -\frac{f_o}{f_e}. \quad 26.27$$

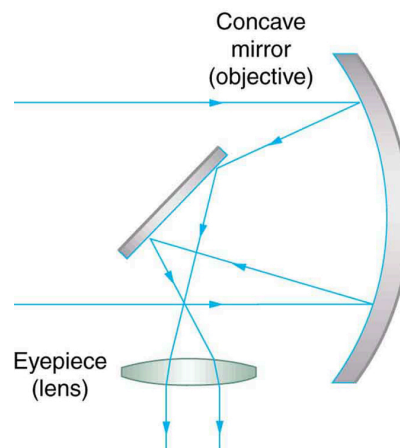
The minus sign indicates the image is inverted. To obtain the greatest angular magnification, it is best to have a long focal length objective and a short focal length eyepiece. The greater the angular magnification  $M$ , the larger an object will appear when viewed through a telescope, making more details visible. Limits to observable details are imposed by many factors, including lens quality and atmospheric disturbance.

The image in most telescopes is inverted, which is unimportant for observing the stars but a real problem for other applications, such as telescopes on ships or telescopic gun sights. If an upright image is needed, Galileo's arrangement in [Figure 26.23\(a\)](#) can be used. But a more common arrangement is to use a third convex lens as an eyepiece, increasing the distance between the first two and inverting the image once again as seen in [Figure 26.24](#).



**FIGURE 26.24** This arrangement of three lenses in a telescope produces an upright final image. The first two lenses are far enough apart that the second lens inverts the image of the first one more time. The third lens acts as a magnifier and keeps the image upright and in a location that is easy to view.

A telescope can also be made with a concave mirror as its first element or objective, since a concave mirror acts like a convex lens as seen in [Figure 26.25](#). Flat mirrors are often employed in optical instruments to make them more compact or to send light to cameras and other sensing devices. There are many advantages to using mirrors rather than lenses for telescope objectives. Mirrors can be constructed much larger than lenses and can, thus, gather large amounts of light, as needed to view distant galaxies, for example. Large and relatively flat mirrors have very long focal lengths, so that great angular magnification is possible.

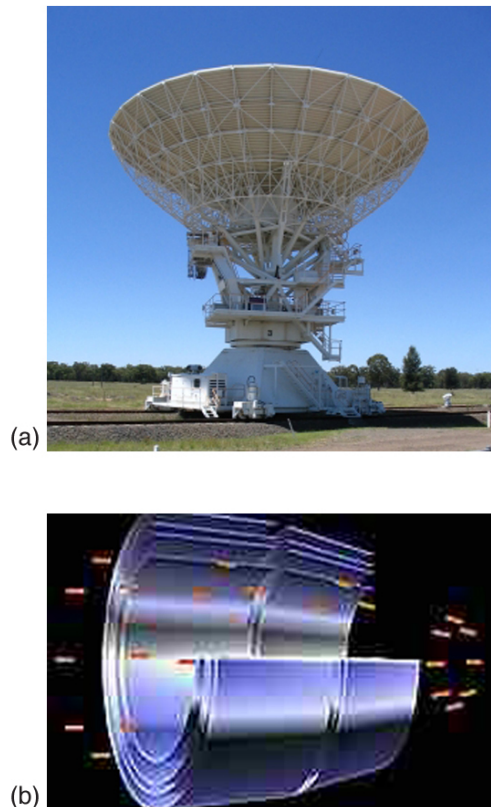


**FIGURE 26.25** A two-element telescope composed of a mirror as the objective and a lens for the eyepiece is shown. This telescope forms an image in the same manner as the two-convex-lens telescope already discussed, but it does not suffer from chromatic aberrations. Such telescopes can gather more light, since larger mirrors than lenses can be constructed.

Telescopes, like microscopes, can utilize a range of frequencies from the electromagnetic spectrum. [Figure 26.26\(a\)](#) shows the Australia Telescope Compact Array, which uses six 22-m antennas for mapping the southern skies using radio waves. [Figure 26.26\(b\)](#) shows the focusing of x rays on the Chandra X-ray Observatory—a satellite orbiting earth since 1999 and looking at high temperature events as exploding stars, quasars, and black holes. X rays, with

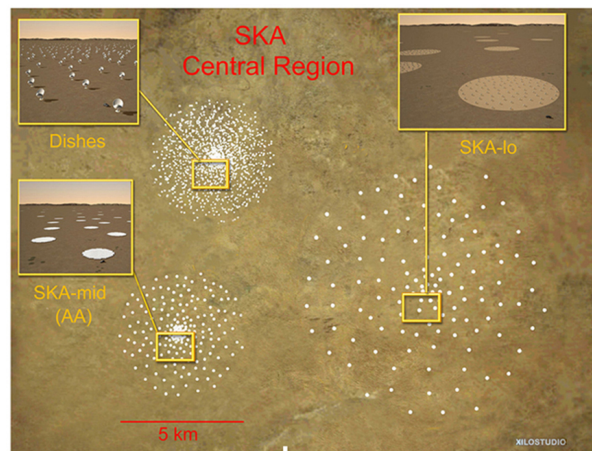


much more energy and shorter wavelengths than RF and light, are mainly absorbed and not reflected when incident perpendicular to the medium. But they can be reflected when incident at small glancing angles, much like a rock will skip on a lake if thrown at a small angle. The mirrors for the Chandra consist of a long barrelled pathway and 4 pairs of mirrors to focus the rays at a point 10 meters away from the entrance. The mirrors are extremely smooth and consist of a glass ceramic base with a thin coating of metal (iridium). Four pairs of precision manufactured mirrors are exquisitely shaped and aligned so that x rays ricochet off the mirrors like bullets off a wall, focusing on a spot.



**FIGURE 26.26** (a) The Australia Telescope Compact Array at Narrabri (500 km NW of Sydney). (credit: Ian Bailey) (b) The focusing of x rays on the Chandra Observatory, a satellite orbiting earth. X rays ricochet off 4 pairs of mirrors forming a barrelled pathway leading to the focus point. (credit: NASA)

A current exciting development is a collaborative effort involving 17 countries to construct a Square Kilometre Array (SKA) of telescopes capable of covering from 80 MHz to 2 GHz. The initial stage of the project is the construction of the Australian Square Kilometre Array Pathfinder in Western Australia (see [Figure 26.27](#)). The project will use cutting-edge technologies such as **adaptive optics** in which the lens or mirror is constructed from lots of carefully aligned tiny lenses and mirrors that can be manipulated using computers. A range of rapidly changing distortions can be minimized by deforming or tilting the tiny lenses and mirrors. The use of adaptive optics in vision correction is a current area of research.



**FIGURE 26.27** An artist's impression of the Australian Square Kilometre Array Pathfinder in Western Australia is displayed. (credit: SPDO, XILOSTUDIOS)

## 26.6 Aberrations

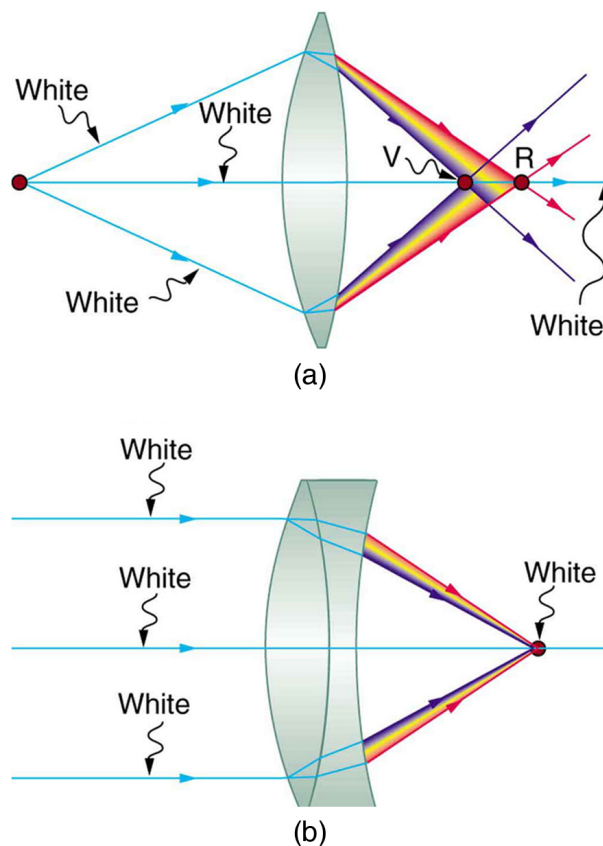
### LEARNING OBJECTIVES

By the end of this section, you will be able to:

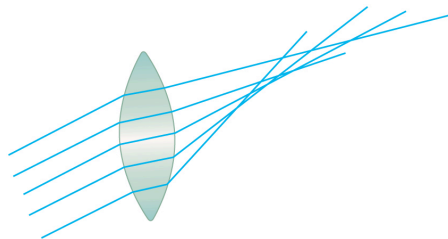
- Describe optical aberration.

Real lenses behave somewhat differently from how they are modeled using the thin lens equations, producing **aberrations**. An aberration is a distortion in an image. There are a variety of aberrations due to a lens size, material, thickness, and position of the object. One common type of aberration is chromatic aberration, which is related to color. Since the index of refraction of lenses depends on color or wavelength, images are produced at different places and with different magnifications for different colors. (The law of reflection is independent of wavelength, and so mirrors do not have this problem. This is another advantage for mirrors in optical systems such as telescopes.) [Figure 26.28\(a\)](#) shows chromatic aberration for a single convex lens and its partial correction with a two-lens system. Violet rays are bent more than red, since they have a higher index of refraction and are thus focused closer to the lens. The diverging lens partially corrects this, although it is usually not possible to do so completely. Lenses of different materials and having different dispersions may be used. For example an achromatic doublet consisting of a converging lens made of crown glass and a diverging lens made of flint glass in contact can dramatically reduce chromatic aberration (see [Figure 26.28\(b\)](#)).

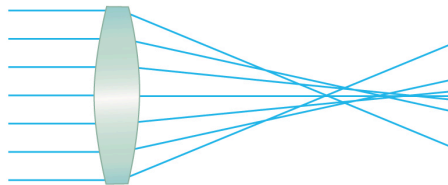
Quite often in an imaging system the object is off-center. Consequently, different parts of a lens or mirror do not refract or reflect the image to the same point. This type of aberration is called a coma and is shown in [Figure 26.29](#). The image in this case often appears pear-shaped. Another common aberration is spherical aberration where rays converging from the outer edges of a lens converge to a focus closer to the lens and rays closer to the axis focus further (see [Figure 26.30](#)). Aberrations due to astigmatism in the lenses of the eyes are discussed in [Vision Correction](#), and a chart used to detect astigmatism is shown in [Figure 26.8](#). Such aberrations can also be an issue with manufactured lenses.



**FIGURE 26.28** (a) Chromatic aberration is caused by the dependence of a lens's index of refraction on color (wavelength). The lens is more powerful for violet (V) than for red (R), producing images with different locations and magnifications. (b) Multiple-lens systems can partially correct chromatic aberrations, but they may require lenses of different materials and add to the expense of optical systems such as cameras.



**FIGURE 26.29** A coma is an aberration caused by an object that is off-center, often resulting in a pear-shaped image. The rays originate from points that are not on the optical axis and they do not converge at one common focal point.



**FIGURE 26.30** Spherical aberration is caused by rays focusing at different distances from the lens.

The image produced by an optical system needs to be bright enough to be discerned. It is often a challenge to obtain a sufficiently bright image. The brightness is determined by the amount of light passing through the optical system. The optical components determining the brightness are the diameter of the lens and the diameter of pupils, diaphragms or aperture stops placed in front of lenses. Optical systems often have entrance and exit pupils to specifically reduce aberrations but they inevitably reduce brightness as well. Consequently, optical systems need to strike a balance between the various components used. The iris in the eye dilates and constricts, acting as an entrance pupil. You can see objects more clearly by looking through a small hole made with your hand in the shape of a fist. Squinting, or using a small hole in a piece of paper, also will make the object sharper.

So how are aberrations corrected? The lenses may also have specially shaped surfaces, as opposed to the simple spherical shape that is relatively easy to produce. Expensive camera lenses are large in diameter, so that they can gather more light, and need several elements to correct for various aberrations. Further, advances in materials science have resulted in lenses with a range of refractive indices—technically referred to as graded index (GRIN) lenses. Spectacles often have the ability to provide a range of focusing ability using similar techniques. GRIN lenses are particularly important at the end of optical fibers in endoscopes. Advanced computing techniques allow for a range of corrections on images after the image has been collected and certain characteristics of the optical system are known. Some of these techniques are sophisticated versions of what are available on commercial packages like Adobe Photoshop.

## Glossary

**aberration** failure of rays to converge at one focus because of limitations or defects in a lens or mirror

**accommodation** the ability of the eye to adjust its focal length is known as accommodation

**adaptive optics** optical technology in which computers adjust the lenses and mirrors in a device to correct for image distortions

**angular magnification** a ratio related to the focal lengths of the objective and eyepiece and given as

$$M = -\frac{f_o}{f_e}$$

**astigmatism** the result of an inability of the cornea to properly focus an image onto the retina

**color constancy** a part of the visual perception system that allows people to perceive color in a variety of conditions and to see some consistency in the color

**compound microscope** a microscope constructed from two convex lenses, the first serving as the ocular lens(close to the eye) and the second serving as the objective lens

**eyepiece** the lens or combination of lenses in an optical instrument nearest to the eye of the observer

**far point** the object point imaged by the eye onto the retina in an unaccommodated eye

**farsightedness** another term for hyperopia, the condition of an eye where incoming rays of light reach the retina before they converge into a focused image

**hues** identity of a color as it relates specifically to the spectrum

**hyperopia** the condition of an eye where incoming rays of light reach the retina before they converge into a focused image

**laser vision correction** a medical procedure used to correct astigmatism and eyesight deficiencies such as myopia and hyperopia

**myopia** a visual defect in which distant objects appear blurred because their images are focused in front of the retina rather than being focused on the retina

**near point** the point nearest the eye at which an object is accurately focused on the retina at full accommodation

**nearsightedness** another term for myopia, a visual defect in which distant objects appear blurred because their images are focused in front of the retina rather than being focused on the retina

**numerical aperture** a number or measure that expresses the ability of a lens to resolve fine detail in an object being observed. Derived by mathematical formula  $NA = n \sin \alpha$ , where  $n$  is the refractive index of the medium between the lens and the specimen and  $\alpha = \theta/2$

**objective lens** the lens nearest to the object being examined

**presbyopia** a condition in which the lens of the eye becomes progressively unable to focus on objects close to the viewer

**retinex** a theory proposed to explain color and brightness perception and constancies; is a combination of the words retina and cortex, which are the two areas responsible for the processing of visual information

**retinex theory of color vision** the ability to perceive color in an ambient-colored environment

**rods and cones** two types of photoreceptors in the human retina; rods are responsible for vision at low light levels, while cones are active at higher light levels

**simplified theory of color vision** a theory that states that there are three primary colors, which correspond to the three types of cones

## Section Summary

### 26.1 Physics of the Eye

- Image formation by the eye is adequately described by the thin lens equations:  

$$P = \frac{1}{d_o} + \frac{1}{d_i} \text{ and } \frac{h_i}{h_o} = -\frac{d_i}{d_o} = m.$$
- The eye produces a real image on the retina by adjusting its focal length and power in a process called accommodation.
- For close vision, the eye is fully accommodated and has its greatest power, whereas for distant vision, it is totally relaxed and has its smallest power.

- The loss of the ability to accommodate with age is called presbyopia, which is corrected by the use of a converging lens to add power for close vision.

### 26.2 Vision Correction

- Nearsightedness, or myopia, is the inability to see distant objects and is corrected with a diverging lens to reduce power.
- Farsightedness, or hyperopia, is the inability to see close objects and is corrected with a converging lens to increase power.
- In myopia and hyperopia, the corrective lenses



produce images at a distance that the person can see clearly—the far point and near point, respectively.

### 26.3 Color and Color Vision

- The eye has four types of light receptors—rods and three types of color-sensitive cones.
- The rods are good for night vision, peripheral vision, and motion changes, while the cones are responsible for central vision and color.
- We perceive many hues, from light having mixtures of wavelengths.
- A simplified theory of color vision states that there are three primary colors, which correspond to the three types of cones, and that various combinations of the primary colors produce all the hues.
- The true color of an object is related to its relative absorption of various wavelengths of light. The color of a light source is related to the wavelengths it produces.
- Color constancy is the ability of the eye-brain system to discern the true color of an object illuminated by various light sources.
- The retinex theory of color vision explains color constancy by postulating the existence of three retinexes or image systems, associated with the three types of cones that are compared to obtain sophisticated information.

### 26.4 Microscopes

- The microscope is a multiple-element system having more than a single lens or mirror.
  - Many optical devices contain more than a single lens or mirror. These are analysed by considering each element sequentially. The image formed by the first is the object for the second, and so on. The same ray tracing and thin lens techniques apply to each lens element.
  - The overall magnification of a multiple-element system is the product of the magnifications of its individual elements. For a two-element system with an objective and an eyepiece, this is
- $$m = m_o m_e,$$

where  $m_o$  is the magnification of the objective and  $m_e$  is the magnification of the eyepiece, such as for a microscope.

- Microscopes are instruments for allowing us to see detail we would not be able to see with the unaided eye and consist of a range of components.
  - The eyepiece and objective contribute to the magnification. The numerical aperture ( $NA$ ) of an objective is given by
- $$NA = n \sin \alpha$$
- where  $n$  is the refractive index and  $\alpha$  the angle of acceptance.
- Immersion techniques are often used to improve the light gathering ability of microscopes. The specimen is illuminated by transmitted, scattered or reflected light through a condenser.
  - The  $f/\#$  describes the light gathering ability of a lens. It is given by
- $$f/\# = \frac{f}{D} \approx \frac{1}{2 NA}.$$

### 26.5 Telescopes

- Simple telescopes can be made with two lenses. They are used for viewing objects at large distances and utilize the entire range of the electromagnetic spectrum.
  - The angular magnification  $M$  for a telescope is given by
- $$M = \frac{\theta'}{\theta} = -\frac{f_o}{f_e},$$
- where  $\theta$  is the angle subtended by an object viewed by the unaided eye,  $\theta'$  is the angle subtended by a magnified image, and  $f_o$  and  $f_e$  are the focal lengths of the objective and the eyepiece.

### 26.6 Aberrations

- Aberrations or image distortions can arise due to the finite thickness of optical instruments, imperfections in the optical components, and limitations on the ways in which the components are used.
- The means for correcting aberrations range from better components to computational techniques.

## Conceptual Questions

### 26.1 Physics of the Eye

1. If the lens of a person's eye is removed because of cataracts (as has been done since ancient times), why would you expect a spectacle lens of about 16 D to be prescribed?

2. A cataract is cloudiness in the lens of the eye. Is light dispersed or diffused by it?
3. When laser light is shone into a relaxed normal-vision eye to repair a tear by spot-welding the retina to the back of the eye, the rays entering the eye must be parallel. Why?

4. How does the power of a dry contact lens compare with its power when resting on the tear layer of the eye? Explain.
5. Why is your vision so blurry when you open your eyes while swimming under water? How does a face mask enable clear vision?

## 26.2 Vision Correction

6. It has become common to replace the cataract-clouded lens of the eye with an internal lens. This intraocular lens can be chosen so that the person has perfect distant vision. Will the person be able to read without glasses? If the person was nearsighted, is the power of the intraocular lens greater or less than the removed lens?
7. If the cornea is to be reshaped (this can be done surgically or with contact lenses) to correct myopia, should its curvature be made greater or smaller? Explain. Also explain how hyperopia can be corrected.
8. If there is a fixed percent uncertainty in LASIK reshaping of the cornea, why would you expect those people with the greatest correction to have a poorer chance of normal distant vision after the procedure?
9. A person with presbyopia has lost some or all of the ability to accommodate the power of the eye. If such a person's distant vision is corrected with LASIK, will she still need reading glasses? Explain.

## 26.3 Color and Color Vision

10. A pure red object on a black background seems to disappear when illuminated with pure green light. Explain why.
11. What is color constancy, and what are its limitations?

## Problems & Exercises

### 26.1 Physics of the Eye

**Unless otherwise stated, the lens-to-retina distance is 2.00 cm.**

1. What is the power of the eye when viewing an object 50.0 cm away?
2. Calculate the power of the eye when viewing an object 3.00 m away.

12. There are different types of color blindness related to the malfunction of different types of cones. Why would it be particularly useful to study those rare individuals who are color blind only in one eye or who have a different type of color blindness in each eye?
13. Propose a way to study the function of the rods alone, given they can sense light about 1000 times dimmer than the cones.

## 26.4 Microscopes

14. Geometric optics describes the interaction of light with macroscopic objects. Why, then, is it correct to use geometric optics to analyse a microscope's image?
15. The image produced by the microscope in [Figure 26.16](#) cannot be projected. Could extra lenses or mirrors project it? Explain.
16. Why not have the objective of a microscope form a case 2 image with a large magnification? (Hint: Consider the location of that image and the difficulty that would pose for using the eyepiece as a magnifier.)
17. What advantages do oil immersion objectives offer?
18. How does the  $NA$  of a microscope compare with the  $NA$  of an optical fiber?

## 26.5 Telescopes

19. If you want your microscope or telescope to project a real image onto a screen, how would you change the placement of the eyepiece relative to the objective?

## 26.6 Aberrations

20. List the various types of aberrations. What causes them and how can each be reduced?
3. (a) The print in many books averages 3.50 mm in height. How high is the image of the print on the retina when the book is held 30.0 cm from the eye? (b) Compare the size of the print to the sizes of rods and cones in the fovea and discuss the possible details observable in the letters. (The eye-brain system can perform better because of interconnections and higher order image processing.)

4. Suppose a certain person's visual acuity is such that he can see objects clearly that form an image  $4.00\ \mu\text{m}$  high on his retina. What is the maximum distance at which he can read the  $75.0\ \text{cm}$  high letters on the side of an airplane?
5. People who do very detailed work close up, such as jewellers, often can see objects clearly at much closer distance than the normal  $25\ \text{cm}$ .
  - (a) What is the power of the eyes of a woman who can see an object clearly at a distance of only  $8.00\ \text{cm}$ ?
  - (b) What is the size of an image of a  $1.00\ \text{mm}$  object, such as lettering inside a ring, held at this distance?
  - (c) What would the size of the image be if the object were held at the normal  $25.0\ \text{cm}$  distance?
15. The far point of a myopic administrator is  $50.0\ \text{cm}$ .
  - (a) What is the relaxed power of their eyes? (b) If they have the normal  $8.00\%$  ability to accommodate, what is the closest object they can see clearly?
16. A very myopic man has a far point of  $20.0\ \text{cm}$ . What power contact lens (when on the eye) will correct his distant vision?
17. Repeat the previous problem for eyeglasses held  $1.50\ \text{cm}$  from the eyes.
18. A myopic person sees that their contact lens prescription is  $-4.00\ \text{D}$ . What is their far point?
19. Repeat the previous problem for glasses that are  $1.75\ \text{cm}$  from the eyes.
20. The contact lens prescription for a mildly farsighted person is  $0.750\ \text{D}$ , and the person has a near point of  $29.0\ \text{cm}$ . What is the power of the tear layer between the cornea and the lens if the correction is ideal, taking the tear layer into account?

## 26.2 Vision Correction

6. What is the far point of a person whose eyes have a relaxed power of  $50.5\ \text{D}$ ?
7. What is the near point of a person whose eyes have an accommodated power of  $53.5\ \text{D}$ ?
8. (a) A laser vision correction reshaping the cornea of a myopic patient reduces the power of his eye by  $9.00\ \text{D}$ , with a  $\pm 5.0\%$  uncertainty in the final correction. What is the range of diopters for spectacle lenses that this person might need after LASIK procedure? (b) Was the person nearsighted or farsighted before the procedure? How do you know?
9. In a LASIK vision correction, the power of a patient's eye is increased by  $3.00\ \text{D}$ . Assuming this produces normal close vision, what was the patient's near point before the procedure?
10. What was the previous far point of a patient who had laser vision correction that reduced the power of her eye by  $7.00\ \text{D}$ , producing normal distant vision for her?
11. A severely myopic patient has a far point of  $5.00\ \text{cm}$ . By how many diopters should the power of his eye be reduced in laser vision correction to obtain normal distant vision for him?
12. A student's eyes, while reading the blackboard, have a power of  $51.0\ \text{D}$ . How far is the board from his eyes?
13. The power of a physician's eyes is  $53.0\ \text{D}$  while examining a patient. How far from her eyes is the feature being examined?
14. A young woman with normal distant vision has a  $10.0\%$  ability to accommodate (that is, increase) the power of her eyes. What is the closest object she can see clearly?
21. A nearsighted man cannot see objects clearly beyond  $20\ \text{cm}$  from his eyes. How close must he stand to a mirror in order to see what he is doing when he shaves?
22. A teacher sees that a child's contact lens prescription is  $0.750\ \text{D}$ . What is the child's near point?
23. Repeat the previous problem for glasses that are  $2.20\ \text{cm}$  from the eyes.
24. The contact lens prescription for a nearsighted person is  $-4.00\ \text{D}$  and the person has a far point of  $22.5\ \text{cm}$ . What is the power of the tear layer between the cornea and the lens if the correction is ideal, taking the tear layer into account?
25. **Unreasonable Results**  
A boy has a near point of  $50\ \text{cm}$  and a far point of  $500\ \text{cm}$ . Will a  $-4.00\ \text{D}$  lens correct his far point to infinity?

## 26.4 Microscopes

26. A microscope with an overall magnification of  $800$  has an objective that magnifies by  $200$ . (a) What is the magnification of the eyepiece? (b) If there are two other objectives that can be used, having magnifications of  $100$  and  $400$ , what other total magnifications are possible?
27. (a) What magnification is produced by a  $0.150\ \text{cm}$  focal length microscope objective that is  $0.155\ \text{cm}$  from the object being viewed? (b) What is the overall magnification if an  $8\times$  eyepiece (one that produces a magnification of  $8.00$ ) is used?

28. (a) Where does an object need to be placed relative to a microscope for its 0.500 cm focal length objective to produce a magnification of  $-400$ ? (b) Where should the 5.00 cm focal length eyepiece be placed to produce a further fourfold (4.00) magnification?
29. You switch from a  $1.40NA$  60 $\times$  oil immersion objective to a  $1.40NA$  60 $\times$  oil immersion objective. What are the acceptance angles for each? Compare and comment on the values. Which would you use first to locate the target area on your specimen?
30. An amoeba is 0.305 cm away from the 0.300 cm focal length objective lens of a microscope. (a) Where is the image formed by the objective lens? (b) What is this image's magnification? (c) An eyepiece with a 2.00 cm focal length is placed 20.0 cm from the objective. Where is the final image? (d) What magnification is produced by the eyepiece? (e) What is the overall magnification? (See [Figure 26.16](#).)
31. You are using a standard microscope with a  $0.10NA$  4 $\times$  objective and switch to a  $0.65NA$  40 $\times$  objective. What are the acceptance angles for each? Compare and comment on the values. Which would you use first to locate the target area on of your specimen? (See [Figure 26.17](#).)
32. **Unreasonable Results**  
Your friends show you an image through a microscope. They tell you that the microscope has an objective with a 0.500 cm focal length and an eyepiece with a 5.00 cm focal length. The resulting overall magnification is 250,000. Are these viable values for a microscope?

## 26.5 Telescopes

**Unless otherwise stated, the lens-to-retina distance is 2.00 cm.**

33. What is the angular magnification of a telescope that has a 100 cm focal length objective and a 2.50 cm focal length eyepiece?
34. Find the distance between the objective and eyepiece lenses in the telescope in the above problem needed to produce a final image very far from the observer, where vision is most relaxed. Note that a telescope is normally used to view very distant objects.
35. A large reflecting telescope has an objective mirror with a 10.0 m radius of curvature. What angular magnification does it produce when a 3.00 cm focal length eyepiece is used?

36. A small telescope has a concave mirror with a 2.00 m radius of curvature for its objective. Its eyepiece is a 4.00 cm focal length lens. (a) What is the telescope's angular magnification? (b) What angle is subtended by a 25,000 km diameter sunspot? (c) What is the angle of its telescopic image?
37. A 7.5 $\times$  binocular produces an angular magnification of  $-7.50$ , acting like a telescope. (Mirrors are used to make the image upright.) If the binoculars have objective lenses with a 75.0 cm focal length, what is the focal length of the eyepiece lenses?
38. **Construct Your Own Problem**  
Consider a telescope of the type used by Galileo, having a convex objective and a concave eyepiece as illustrated in [Figure 26.23](#)(a). Construct a problem in which you calculate the location and size of the image produced. Among the things to be considered are the focal lengths of the lenses and their relative placements as well as the size and location of the object. Verify that the angular magnification is greater than one. That is, the angle subtended at the eye by the image is greater than the angle subtended by the object.

## 26.6 Aberrations

39. **Integrated Concepts**  
(a) During laser vision correction, a brief burst of 193 nm ultraviolet light is projected onto the cornea of the patient. It makes a spot 1.00 mm in diameter and deposits 0.500 mJ of energy. Calculate the depth of the layer ablated, assuming the corneal tissue has the same properties as water and is initially at 34.0°C. The tissue's temperature is increased to 100°C and evaporated without further temperature increase. (b) Does your answer imply that the shape of the cornea can be finely controlled?

- 40. Critical Thinking** A microscope has the objective lens 6.00 mm from an object. The focal length of the objective lens is 4.00 mm. The eyepiece has a focal length of 50.0 mm and is initially 25.0 mm from the objective lens. (a) The objective lens is moved to 5.00 mm from the objective, effectively lengthening the microscope. How does this affect the magnification of the microscope? (b) Does moving the objective increase closer to the object increase or decrease the magnification, or does it remain the same? (c) Do you think moving the objective from 6 mm to 7 mm from the object will increase or decrease the magnification of the microscope, or will it likely remain the same? (d) What indicates whether the image is upright or inverted?

