

Four butterflies, but only one is real!

The others—small, large, upright, and turned upside down—are images that result from reflection and refraction in a single piece of glass. What must be the shape of the glass? How does the glass produce all those butterflies?

➡ Look at the text on page 426 for the answer.

magnification

converging

refraction



diverging

CHAPTER

18 Mirrors and Lenses



It's an illusion any magician would be proud to claim: Presto! Four butterflies from one! What could be more amazing? Only one of the butterflies is real!

Mirrors are part of everyday life. You use a flat mirror to check your hair in the morning. When you drive, you use a different-shaped mirror to check if there is another car in the lane next to you. In all, mirrors are useful in everyday life. Lenses, however, are essential to our lives. We are able to see because each of our eyes has a lens. That lens produces an image of the world around us. In fact, all the optical devices that are part of your everyday life—eyeglasses, contact lenses, magnifying glasses, microscopes, cameras, camcorders—produce images following the same laws of reflection and refraction.

Light rays follow a complex route as they encounter mirrors or pass through a variety of lenses. As you work through this chapter, you will learn how to determine the paths taken by the rays of light that reflect from an object such as the real butterfly and then bend as they pass through lenses of different shapes. This means not just the lens shown in the photograph, but also the lens of the camera that caught the image. As complex as a light ray's route may be, you can use the laws of optics to trace its journey and discover where it joins other rays to form an image. You will learn about these laws as you study this chapter.

WHAT YOU'LL LEARN

- You will locate real and virtual images produced by plane, concave, and convex mirrors.
- You will recognize the causes of aberrations in lenses and mirrors and how these can be minimized.

WHY IT'S IMPORTANT

- The laws of reflection and refraction that produce images on the retinas of your eyes are also the basis for optical instruments that allow scientists to see into outer space and into the world of subatomic particles.

PHYSICS Online



To find out more about mirrors and lenses, visit the Glencoe Science Web site at science.glencoe.com



CONTENTS



18.1

Mirrors



OBJECTIVES

- **Explain** how concave, convex, and plane mirrors form images.
- **Locate** images using ray diagrams, and **calculate** image location and size using equations.
- **Explain** the cause of spherical aberration and how the effect may be overcome.
- **Describe** uses of parabolic mirrors.

Color Conventions

- Light rays are **red**.
- Lenses and mirrors are **light blue**.
- Objects are **indigo**.
- Images are **light violet**.

FIGURE 18-1 The reflected rays that enter the eye appear to originate at a point behind the mirror.

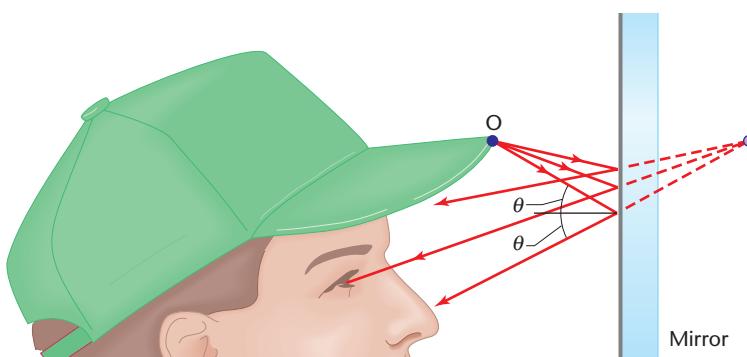
Mirrors are the oldest optical instruments. Undoubtedly, prehistoric humans saw their faces reflected in the quiet water of lakes or ponds. Almost 4000 years ago, Egyptians used polished metal mirrors to view their images. But sharp, well-defined reflected images were not possible until 1857, when Jean Foucault, a French scientist, developed a method of coating glass with silver.

Objects and Images in Plane Mirrors

If you looked at yourself in a bathroom mirror this morning, you saw your image in a plane mirror. A **plane mirror** is a flat, smooth surface from which light is reflected by regular reflection rather than by diffuse reflection. This means that light rays are reflected with equal angles of incidence and reflection.

In describing mirrors and lenses, the word *object* is used in a new way. You were the object when you looked into the bathroom mirror. An **object** is a source of spreading, or diverging, light rays. Every point on an object is a source of diverging light rays. An object may be luminous, such as a candle and a lamp. But more often, an object, such as the moon or the page you are reading is illuminated. An illuminated object usually reflects light diffusely in all directions.

Figure 18-1 shows how some of the rays reflected off point O on the bill of a baseball cap strike a plane mirror. The equal angles of incidence and reflection are shown for three rays. Notice that they diverge when they leave the point of the cap, and they continue to diverge after they are reflected from the mirror. The person sees those rays that enter the pupil of his eye. The dashed lines are sight lines, the backward extensions of the rays leaving the mirror. They converge at point I. The eye and brain interpret the rays as having come from point I. This point is called the **image** of the bill of the cap. Because the rays do not actually converge on that point, this kind of image is called a **virtual image**.



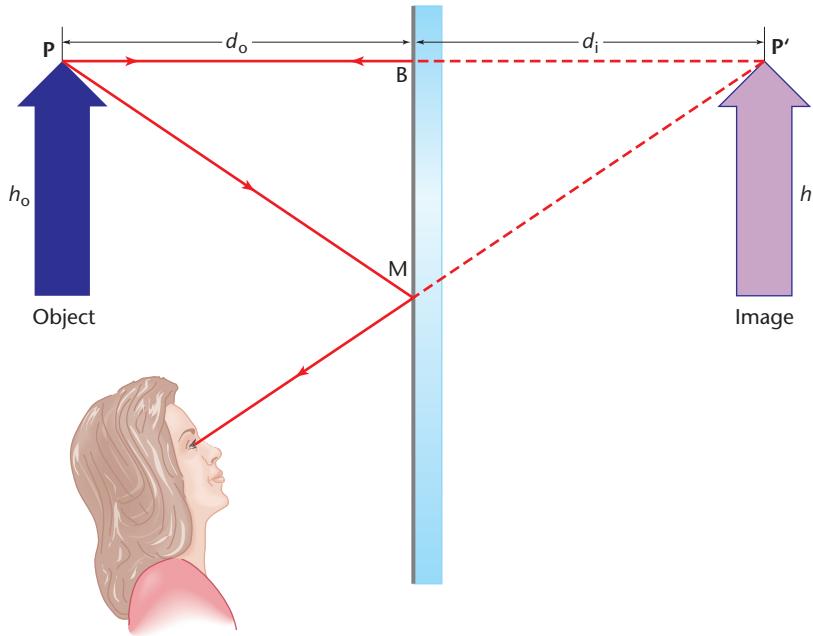


FIGURE 18–2 Light rays (two are shown) leave a point on the object. Some strike the mirror and are reflected into the eye. Sight lines, drawn as dashed lines, extend from the location on the mirror where the reflections occurred back to where they converge. The image is located where the sight lines converge. By geometry, $d_i = d_o$.

Where is the image located? **Figure 18–2** shows two of the rays that leave point P on the object. One ray strikes the mirror at B, the other at M. Both rays are reflected with equal angles of incidence and reflection. Ray PB, which strikes the mirror at an angle of 90° , is reflected back on itself. Ray PM is reflected into the observer's eye. Sight lines, shown in **Figure 18–2** as dashed lines, are extended back from B and M, the positions at which the two rays are reflected from the mirror. The sight lines converge at point P', which is the image of point P. The distance between the object and mirror, the object distance, is line PB, which has a length d_o . Similarly, the distance between the image and the mirror is the length of line P'B and is called the image distance, d_i . The object distance and the image distance, d_o and d_i respectively, are corresponding sides of the two congruent triangles PBM and P'BM. Therefore, $d_o = d_i$.

How large is the image? If you drew the paths and the sight lines of two rays originating from the bottom of the arrow, you would find that they converge at the bottom of the image. Therefore, the object and the image have the same size, or, as **Figure 18–2** shows, $h_o = h_i$. The image and the object are pointing in the same direction, so the image is called an **erect image**.

Is there a difference between you and your image in the mirror? Follow the rays and sight lines in **Figure 18–3a**. The ray that diverges from the right hand of the object converges at what appears to be the left hand of the image. You might ask why the top and bottom are not also reversed. If you look at the figure carefully, you'll see that the direction that is reversed is the one perpendicular to the surface of the mirror. Left and right are reversed, but in the same way that a right-hand glove can be worn on the left hand by turning it inside out. Thus, it is more correct to say that the front and back of an image are reversed.

Pocket Lab

Where's the image?

Suppose that you are standing directly in front of a mirror and see your image. Exactly where is the image? Here is a way to find out. Find a camera with a focusing ring that has distances marked on it. Stand 1.0 m from a mirror and focus on the edge of the mirror. Check the reading on the focusing ring. It should be 1.0 m. Now focus on your image. What is the reading on the ring now?

Analyze and Conclude

Summarize your results and write a brief conclusion.

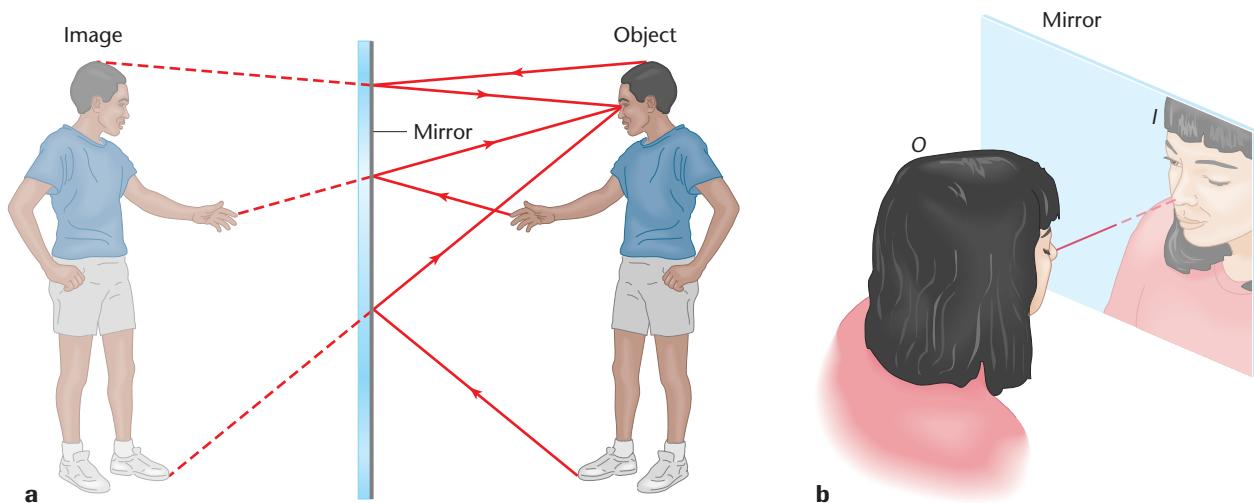


FIGURE 18-3 The image formed in a plane mirror is the same size as the object and is the same distance behind the mirror as the object is in front. If you blink your right eye, it looks as if your left eye blinks.

Pocket Lab

Real or Virtual?



Hold a small concave mirror at arm's length and look at your image. What do you see? Is the image in front or behind the mirror? What happens to the image as you slowly bring the mirror toward your face?

Analyze and Conclude Briefly summarize your observations and conclusions.

Concave Mirrors

Look at your reflection in the inside surface of a spoon. The spoon acts as a concave mirror. A **concave mirror** reflects light from its inner ("caved in") surface. In a spherical concave mirror, the mirror is part of the inner surface of a hollow sphere, as shown in **Figure 18-4**. The sphere of radius r has a geometric center, C. Point A is the center of the mirror, and the line CA is the **principal axis**, that is, the straight line perpendicular to the surface of the mirror at its center.

How does light reflect from a concave mirror? Think of a concave mirror as a large number of small plane mirrors arranged around the surface of a sphere, as shown in **Figure 18-5a**. Each mirror is perpendicular to a radius of the sphere. When a ray strikes a mirror, it is reflected with equal angles of incidence and reflection. **Figure 18-4** shows that a ray parallel to the principal axis is reflected at P and crosses the principal axis at some point, F. A parallel ray an equal distance below the principal axis would, by symmetry, also cross the principal axis at F. These parallel rays meet, or converge, at F, which is called the **focal point** of the mirror. The two sides FC and FP of the triangle CFP are equal in length. Thus, the focal point, F, is half the distance between the mirror and the center of curvature, C.

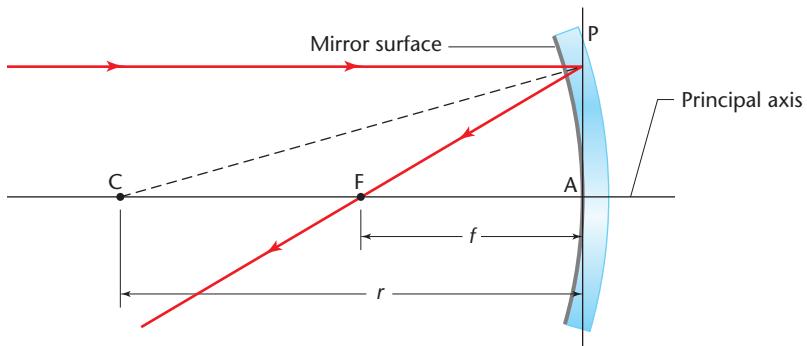
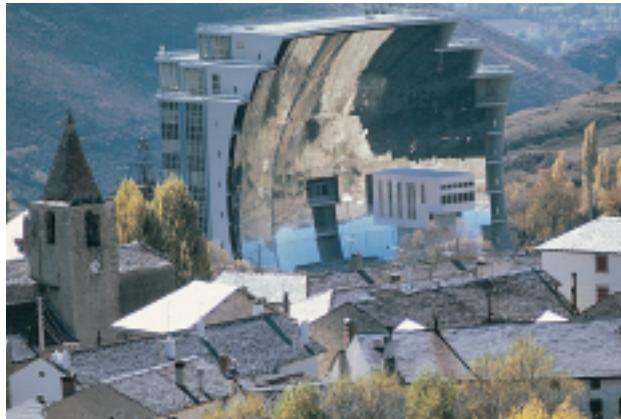
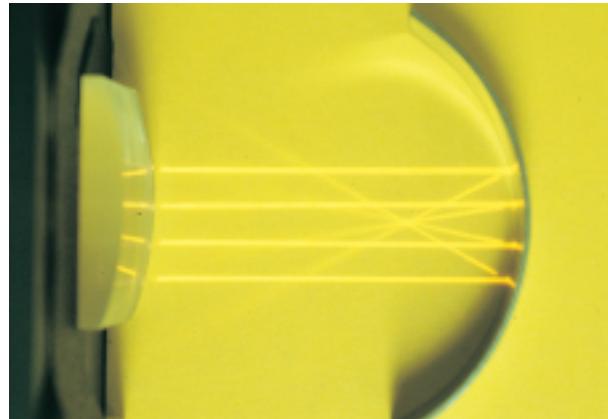


FIGURE 18-4 The focus of a spherical concave mirror is located halfway between the center of curvature and the mirror surface. Rays entering parallel to the principal axis are reflected to converge at the focal point, F.

**a****b**

How can you find the location of the focal point of a concave mirror? First you need parallel light rays, because only parallel rays will converge at the focal point. Because the sun is so far away, you can consider it a source of nearly parallel rays. If you point the principal axis of a concave mirror at the sun, all the rays will be reflected through the focal point. Hold a piece of paper near the mirror and move the paper toward and away from the mirror until the smallest and sharpest spot is formed. The spot must be at the focal point because, as was just discussed, the rays striking the mirror are, for all practical purposes, parallel. The distance from the focal point to the mirror along the principal axis is the **focal length**, f , of the mirror. In **Figure 18–4**, notice that the focal length is half the radius of curvature of the mirror, or $2f = r$.

Real versus virtual images The bright spot that you see when you position a piece of paper at the focal point of a concave mirror as it reflects rays from the sun is an image of the sun. The image is a **real image** because rays actually converge and pass through the image. A real image can be seen on a piece of paper or projected onto a screen. In contrast, the image produced by a plane mirror is behind the mirror. The rays reflected from a plane mirror never actually converge but appear to diverge from a point behind the mirror. A virtual image cannot be projected onto a screen or captured on a piece of paper because light rays do not converge at a virtual image.

Real images formed by concave mirrors To develop a graphical method of finding the image produced by a concave mirror, recall that every point on an object emits or reflects light rays in all possible directions. It's impossible and unnecessary to follow all those rays, but you can select just two rays and, for simplicity, draw them from only one point. You can also use a simplified model of the mirror in which all rays are reflected from a plane rather than from the curved surface of the mirror. That model will be explained shortly. Here is a set of rules to use in finding images.

FIGURE 18–5 The surface of a concave mirror reflects light to a given point, as in **(b)**. A solar furnace in the French Alps, shown in **(a)**, reflects light in a similar way from a group of plane mirrors arranged in a curve.

Pocket Lab

Focal Points



Take a concave mirror into an area of direct sunlight. Use a piece of clay to hold the mirror steady so that the concave mirror directly faces the sun. Move your finger toward or away from the mirror in the area of reflected light to find the brightest spot (focal point). Turn the mirror so that the convex side faces the sun and repeat the experiment.

Analyze and Conclude

Record and explain your results.



Lens/Mirror Equation Conventions Applied to Mirrors

d_o is positive for real objects.

d_o is negative for virtual
objects.

d_i is positive for real images.

d_i is negative for virtual
images.

f is positive for concave
mirrors.

f is negative for convex
mirrors.

PROBLEM SOLVING STRATEGIES

Locating Images in Mirrors by Ray Tracing

1. Choose a scale for your drawing such that the drawing is approximately the width of your paper, about 20 cm.
 - a. If the object is beyond F, as shown in **Figure 18–6**, then the image will be on the object side of the mirror. Therefore, draw the mirror at the right edge of your paper.
 - b. If the object is beyond C, the image distance will be smaller, so draw the object near the left edge of your paper.
 - c. If the object is between C and F, the image will be beyond C. The closer the object is to F, the farther away the image will be, so leave room at the left side of your paper.
 - d. Choose a scale such that the larger distance, that of the image or the object, is 15 to 20 cm on your paper. Let 1 cm on the paper represent 1, 2, 4, 5, or 10 actual centimeters.
2. Draw the principal axis. Draw a vertical line where the principal axis touches the mirror. If the focal point is known, indicate that position on the principal axis. Label it F. Locate and label the center of curvature, C, at twice the focal distance from the mirror.
3. Draw the object and label its top O_1 . Choose a scale for the object that is different from that of the overall drawing because otherwise it may be too small to be seen.
4. Draw ray 1, the parallel ray. Ray 1 is parallel to the principal axis. All rays parallel to the principal axis are reflected through the focal point, F.
5. Draw ray 2, the focus ray. It passes through the focal point, F, on its way to the mirror and is reflected parallel to the principal axis.
6. The image is located where ray 1 and ray 2 cross after reflection. Label the image I_1 . Draw a vertical line from I_1 to the principal axis to represent the image.

Pocket Lab



Makeup

Do you have a makeup mirror in your home? Does this mirror produce images that are larger or smaller than your face?

What does this tell you about the curvature? Feel the surface of the mirror. Does this confirm your prediction about the curvature? Try to discover the focal length of this mirror.

Analyze and Conclude

Record your procedure and briefly explain your observations and results.

How would you describe the image in **Figure 18–6**? It is a real image because the rays actually converge at the point where the image is located. It is inverted. The object O_1 is above the axis, but the image point I_1 is below the axis. The image is reduced in size; it is smaller than the object. Thus, the image is real, inverted, and reduced.

Where is the image? If the object is beyond C, as it is in **Figure 18–6**, the image is between C and F. If the object is moved outward from C, the image moves inward toward F and shrinks in size. If the object is brought closer to C, the image moves outward from the mirror. If the object is at C, the image will be there also, and it will be the same size as the object. If the object is moved even closer to F, but not inside it, the image will move farther away and become larger.

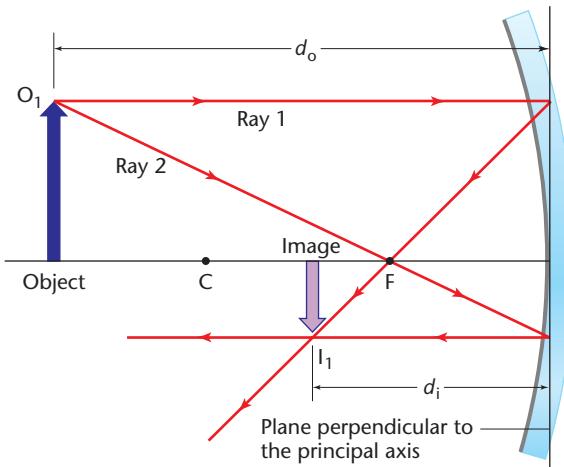


FIGURE 18–6 Note that both rays pass through the focal point, ray 1 after it is reflected from the mirror and ray 2 on its way to the mirror. The image is real, inverted, and reduced in size.

Math Handbook

To review **solving equations**, see the Math Handbook, Appendix A, page 740.

All features of the image can be found mathematically. You can use geometry to relate the focal length of the mirror, f , to the distance from the object to the mirror, d_o , and to the distance from the image to the mirror, d_i . The equation for this is called the **lens/mirror equation**:

$$\text{Lens/Mirror Equation} \quad \frac{1}{f} = \frac{1}{d_i} + \frac{1}{d_o}$$

This is the first equation you have seen that contains the inverses of all quantities. You should first solve this equation for the quantity you are seeking. For example, if you are given the object and image distances and asked to find the focal length, you would first add the fractions on the right side of the equation using the least common denominator, $d_i d_o$.

$$\frac{1}{f} = \frac{d_o + d_i}{d_i d_o}$$

Then take the reciprocal of both sides.

$$f = \frac{d_i d_o}{d_o + d_i}$$

Another useful equation is the definition of magnification. **Magnification**, m , is the ratio of the size of the image, h_i , to the size of the object, h_o .

$$\text{Magnification} \quad m = \frac{h_i}{h_o}$$

By using similar triangles in a ray diagram, you obtain the following.

$$\text{Magnification} \quad m = \frac{-d_i}{d_o}$$

You can write a single equation for the image height in terms of the object height and the image and object distances by equating the two

HELP WANTED OPTICIAN

Eye-care professionals are needed for customer assistance and behind-the-scenes positions. Interpersonal skills and skills in precision lab work are a must. Vocational/technical school preparation, including an associate's degree, is desired but extensive apprenticeship experience may be substituted. Excellent finger dexterity, flexibility to work irregular shifts, and appropriate certification are required. For information contact:
Opticians Association of America
7023 Little River Turnpike
Suite 207
Annandale, VA 22003

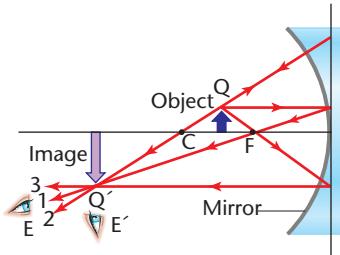


FIGURE 18-7 To the eye at E, it appears that there is an object at Q' blocking the view of the mirror. However, if the eye moves to E' and looks toward Q', the object disappears because there is no light reflected from Q' to E'.

preceding expressions. The right side of each equation equals the magnification, m , and therefore, they are equal to each other.

$$\frac{h_i}{h_o} = \frac{-d_i}{d_o}, \text{ or } h_i = -h_o \left(\frac{d_i}{d_o} \right)$$

Describing a real image In the case of real images, d_i and d_o are both positive, so h_i will be negative. This means that the magnification is also negative. When the magnification is negative, the image is inverted. What is the magnification of a plane mirror? Recall that in that case, d_i and d_o have the same magnitude, but the image is behind the mirror. Therefore, d_i is negative and the magnification is +1, which means that the image and the object are the same size.

How can you tell if an image is real? If an image is real, the rays will converge on it in a ray diagram. In the lens/mirror equation, d_i will be positive. If you use an actual mirror, you can put a piece of paper at the location of the image and you'll see the image. You also can see the image floating in space if you place your eye so that the rays that form the image fall on your eye. But as **Figure 18-7** shows, you must stare at the location of the image and not at the mirror or object.

When solving problems involving mirrors, you may be asked to locate the image by means of a scale drawing using the methods of the problem solving strategy. At other times, when you are asked to find the image mathematically, you should also make a careful sketch to enable you to visualize the situation and check the reasonableness of your results.

Example Problem

Calculating a Real Image Formed by a Concave Mirror

A concave mirror has a radius of curvature of 20.0 cm. An object, 2.0 cm high, is placed 30.0 cm from the mirror.

- a. Where is the image located?
- b. How high is the image?

Sketch the Problem

- Sketch the situation; locate the object and mirror.
- Draw two principal rays.

Calculate Your Answer

Known:

$$h_o = 2.0 \text{ cm}$$

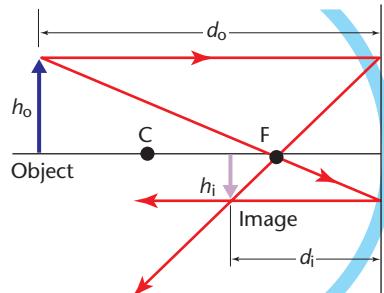
$$d_o = 30.0 \text{ cm}$$

$$r = 20.0 \text{ cm}$$

Unknown:

$$d_i = ?$$

$$h_i = ?$$



Strategy:

Focal length is half the radius of curvature. Use lens/mirror equation to find image location.

Calculations:

$$f = r/2 = 10.0 \text{ cm}$$

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}, \text{ so } d_i = \frac{fd_o}{(d_o - f)}$$

$$d_i = \frac{(10.0 \text{ cm})(30.0 \text{ cm})}{30.0 \text{ cm} - 10.0 \text{ cm}} = 15.0 \text{ cm}$$

Use magnification relations to find height of image.

$$m = \frac{h_i}{h_o} = \frac{-d_i}{d_o}, \text{ so } h_i = \frac{-d_i h_o}{d_o}$$

$$h_i = \frac{(-15.0 \text{ cm})(2.0 \text{ cm})}{30.0 \text{ cm}} = -1.0 \text{ cm}$$

Check Your Answer

- Are your units correct? All distances are in cm.
- Do the signs make sense? Positive location and negative height agree with the drawing.
- Are the magnitudes realistic? The magnitudes agree with the drawing.

Virtual images formed by concave mirrors You have seen that as the object approaches the focal point, F, of a concave mirror, the image moves farther away from the mirror. If the object is at the focal point, all reflected rays are parallel. They never meet, and so the image is said to be at infinity. What happens if the object is moved even closer to the mirror, that is, between the focal point and the mirror? The ray diagram is shown in **Figure 18–8**. Again, two rays are drawn to locate the image of a point on an object. As before, ray 1 is drawn parallel to the principal axis and reflected through the focal point. To draw ray 2, first draw a dashed line from the focal point to the point on the object. Then draw ray 2 as an extension of the dashed line to the mirror where it is reflected parallel to the principal axis. Note that ray 1 and ray 2 diverge

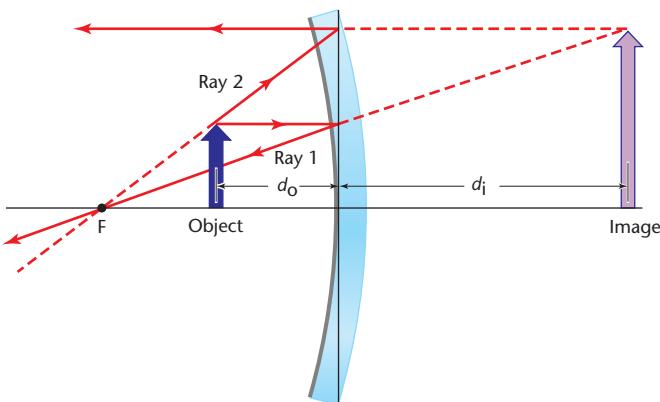


FIGURE 18–8 When an object is located between the focal point and a spherical concave mirror, an enlarged, upright, virtual image is formed behind the mirror.



FIGURE 18–9 Objects placed between the focal point and the surface of a concave mirror form enlarged, virtual images.

as they leave the mirror, so there can be no real image. However, the dashed lines behind the mirror are sight lines coming from an apparent origin behind the mirror. These sight lines converge to form a virtual image located behind the mirror. When you use the lens/mirror equation in solving problems involving concave mirrors, you will find that d_i is negative. The image is upright and enlarged like the statuette in **Figure 18–9**.

An upright, enlarged image is a feature of shaving and makeup mirrors, which are concave mirrors. When you use a shaving or makeup mirror, you must hold the mirror close to your face and in doing so, you are placing your face within the focal length of the mirror.

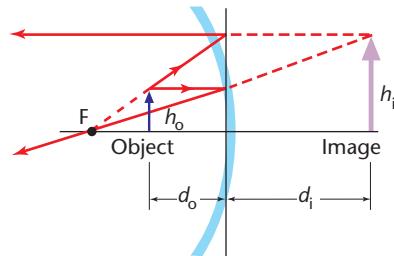
Example Problem

A Concave Mirror as a Magnifier

An object, 2.0 cm high, is placed 5.0 cm in front of a concave mirror with a focal length of 10.0 cm. How large is the image, and where is it located?

Sketch the Problem

- Sketch the situation; locate the object and mirror.
- Draw two principal rays.
- Extend the rays behind the mirror to locate the image.



Calculate Your Answer

Known:

$$h_o = 2.0 \text{ cm}$$

$$d_o = 5.0 \text{ cm}$$

$$f = 10.0 \text{ cm}$$

Unknown:

$$d_i = ?$$

$$h_i = ?$$

Strategy:

Use lens/mirror equation to find image location.

Calculations:

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}, \text{ so } d_i = \frac{fd_o}{d_o - f}$$

$$d_i = \frac{(10.0 \text{ cm})(5.0 \text{ cm})}{5.0 \text{ cm} - 10.0 \text{ cm}} = -1.0 \times 10^1 \text{ cm, virtual}$$

$$m = \frac{h_i}{h_o} = \frac{-d_i}{d_o}, \text{ so } h_i = \frac{-d_i h_o}{d_o}$$

$$h_i = \frac{-(-1.0 \times 10^1 \text{ cm})(2.0 \text{ cm})}{5.0 \text{ cm}} = 4.0 \text{ cm, upright}$$

Check Your Answer

- Are your units correct? All are cm.
- Do your signs make sense? Negative location means virtual image; positive height means upright image. These agree with the ray diagram.
- Are the magnitudes realistic? Magnitudes agree with the diagram.

Practice Problems

Calculate a real image formed by a concave mirror.

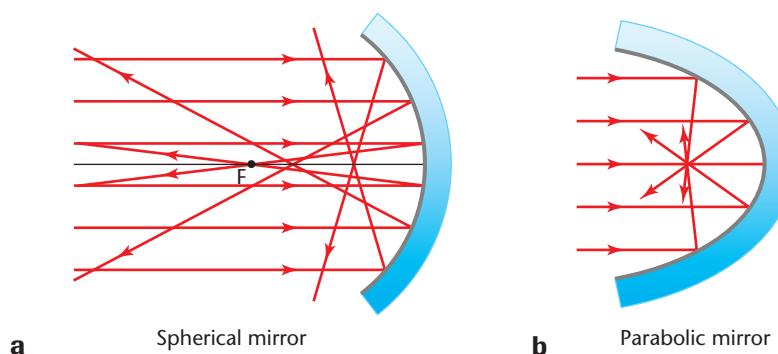
1. Use a ray diagram drawn to scale to solve the Example Problem.
2. An object 3.0 mm high is 10.0 cm in front of a concave mirror having a 6.0-cm focal length. Find the image and its height by means of
 - a. a ray diagram drawn to scale.
 - b. the lens/mirror and magnification equations.
3. An object is 4.0 cm in front of a concave mirror having a 12.0-cm radius. Locate the image using the lens/mirror equation and a scale ray diagram.
4. A 4.0-cm-high candle is placed 10.0 cm from a concave mirror having a focal length of 16.0 cm. Find the location and height of the image.
5. What is the radius of curvature of a concave mirror that magnifies by a factor of +3.0 an object placed 25 cm from the mirror?

F.Y.I.

Sunlight can be concentrated at the focal point of a large concave mirror. If a cooking pot is placed at that point, the temperatures produced are high enough to cook the food.

Image defects in concave mirrors In tracing rays, you have reflected the rays from a vertical line rather than the curved surface of the mirror. The mirror/lens equation also assumes that all reflections occur from a plane perpendicular to the principal axis that passes through the mirror. Real rays, however, are reflected off the mirror itself, so they will look like the drawing in **Figure 18–10a**. Notice that only parallel rays close to the principal axis are reflected through the focal point. Other rays converge at points closer to the mirror. The image formed by parallel rays in a large spherical mirror is a disk, not a point. This effect is called **spherical aberration**.

A mirror ground to the shape of a parabola, **Figure 18–10b**, suffers no spherical aberration; all parallel rays are reflected to a single spot. For that reason, parabolic mirrors have been used in telescopes. But many of the newest telescopes use spherical mirrors and specially shaped secondary mirrors or lenses to eliminate the aberration.



Pocket Lab

Burned Up

Convex (converging) lenses can be used as magnifying glasses. Use someone's eyeglasses to see if they magnify. Are the glasses converging? Can the lenses be used in sunlight to start a fire?

Analyze and Conclude

Use your answers to describe the lens.

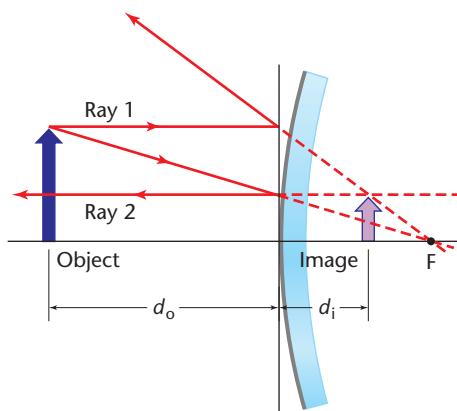
FIGURE 18–10 Some rays reflected from a concave spherical mirror converge at points other than the focus, as shown in (a). A parabolic mirror, such as the one shown in (b), focuses all parallel rays at a point.



FIGURE 18–11 No real image is formed by a convex mirror. An erect, virtual image, reduced in size, is formed at the apparent intersection of the extended rays. Convex mirrors are often used as wide-angle mirrors for safety and security.

Convex Mirrors

A **convex mirror** is a spherical mirror that reflects light from its outer surface. Rays reflected from a convex mirror always diverge. Thus, convex mirrors do not form real images. When drawing ray diagrams, the focal point, F , is placed behind the mirror, at a distance halfway between the mirror and the center of curvature. When using the lens/mirror equation, the focal length, f , of a convex mirror is a negative number, and d_i is negative because the image is behind the mirror.

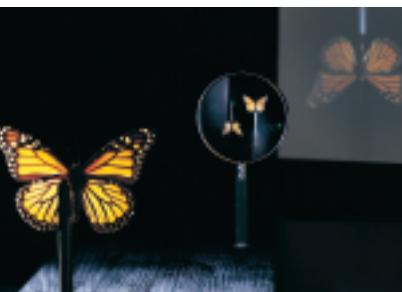


The ray diagram in **Figure 18–11** shows how an image is formed in a convex mirror. Ray 1 approaches the mirror parallel to the principal axis. To draw the reflected ray, draw a dashed line from the focal point, F , to the point where ray 1 strikes the mirror. The reflected ray is in the same direction as the dashed line. Ray 2 approaches the mirror on a path that, if extended behind the mirror, would pass through F . The reflected part of ray 2 is parallel to the principal axis. The two reflected rays diverge, as if coming from a point behind the mirror. The image, located at the apparent intersection of the extended rays behind the mirror, is virtual, erect, and reduced in size.

Convex mirrors form images reduced in size, and therefore, the images seem farther away. But convex mirrors also reflect an enlarged field of view. Rearview mirrors used in cars are often convex mirrors, as are mirrors used in stores to observe shoppers.

Ordinary glass also reflects some light. If the glass is curved outward, it will act as a convex mirror. You can frequently see reduced images of yourself if you look into someone's eyeglasses. The photo at the beginning of this chapter shows a glass lens that reflects some light off both its front (convex) and rear (concave) surfaces. What must be the shape of the glass? How does the glass produce all those butterflies?

Both reflected images are reduced in size; one is upright and the other is inverted. The upright image comes from the convex surface, the inverted one from the concave surface.



Example Problem

Image in a Security Mirror

A convex security mirror in a warehouse has a radius of curvature of 1.0 m. A 2.0-m-high forklift is 5.0 m from the mirror. What is the location and size of the image?

Sketch the Problem

- Sketch the situation; locate the mirror and the object.
- Draw two principal rays.

Calculate Your Answer

Known:

$$h_o = 2.0 \text{ m}$$

$$r = 1.0 \text{ m}$$

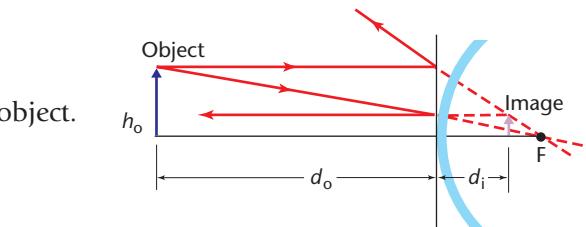
$$d_o = 5.0 \text{ m}$$

Strategy:

The focal length is negative for convex mirrors.

Use the lens/mirror equation to find the location.

Combine the magnification equations to determine height.



Unknown:

$$d_i = ?$$

$$h_i = ?$$

Calculations:

$$f = (-1/2)r = -1.0 \text{ m}/2 = -0.50 \text{ m}$$

$$d_i = fd_o/(d_o - f)$$

$$d_i = (-0.5 \text{ m})(5.0 \text{ m})/(5.0 \text{ m} - (-0.50 \text{ m})) \\ = -0.45 \text{ m, virtual}$$

$$h_i = -d_i h_o/d_o$$

$$h_i = -(-0.45 \text{ m})(2.0 \text{ m})/(5.0 \text{ m}) \\ = 0.18 \text{ m, upright, reduced}$$

Check Your Answer

- Are your units correct? All distances are in meters.
- Do the signs make sense? Negative location means virtual image; positive height means upright image. These agree with the diagram.
- Are the magnitudes realistic? They agree with the diagram.

Practice Problems

6. An object is 20.0 cm in front of a convex mirror with a -15.0-cm focal length. Find the location of the image using
 - a scale ray diagram.
 - the lens/mirror equation.
7. A convex mirror has a focal length of -12 cm . A lightbulb with a diameter of 6.0 cm is placed 60.0 cm in front of the mirror. Locate the image of the lightbulb. What is its diameter?
8. A convex mirror is needed to produce an image three-fourths the size of the object and located 24 cm behind the mirror. What focal length should be specified?

F.Y.I.

In 1857, Jean Foucault developed a technique for silvering glass to make mirrors for telescopes. Silvered glass mirrors are lighter and less likely to tarnish than metal mirrors previously used.

Physics & Technology

The Hubble Space Telescope

Astronomers have known for decades that to see farther into space and time, telescopes must collect more light and this requires larger mirrors. But massive mirrors bend under their own weight, distorting the images being observed. Atmospheric distortions, temperature effects, and light pollution also limit the performance of Earth-based telescopes.

One approach scientists are using to overcome these difficulties is to place telescopes in Earth orbit. The Hubble Space Telescope, the first orbiting telescope, was launched in 1990. Among the revelations provided by the Hubble telescope are views of galaxies so distant that they show us what some parts of the universe looked like just a few hundred million years after its birth. Detailed images of the comet Hale-Bopp, which visited our

region of the solar system in 1997, enabled astronomers to estimate the size of the comet's nucleus and observe violent eruptions that took place as different parts of the nucleus turned to face the sun. Hubble also has captured images of giant plumes of gas and dust produced by a volcanic eruption on Io, one of Jupiter's moons.

In 1997, Hubble produced spectacular images of jets of gas and dust blown into space by a massive black hole at the center of the Egg Nebula, about 3000 light-years from Earth.

Thinking Critically What are some of the advantages and disadvantages of placing a telescope in orbit?

18.1 Section Review

1. Draw a ray diagram showing your eye placed 12 cm from a plane mirror. Two rays leave a point on an eyelash and enter opposite sides of the pupil of your eye, 1 cm apart. Locate the image of the eyelash.
2. If a beam of parallel light rays is sent into a spherical concave mirror, do all the rays converge at the focal point?
3. If a mirror produces an erect, virtual image, can you immediately conclude that it is a plane mirror? Explain.
4. **Critical Thinking** A concave mirror is used to produce a real image of a distant object. A small plane mirror is put between the mirror and the image. The mirror is put at a 45° angle to the principal axis of the concave mirror.
 - a. Make a ray diagram. Is the image of the plane mirror real or virtual? Explain.
 - b. If the small mirror were a convex mirror, would the image be real or virtual? Explain.



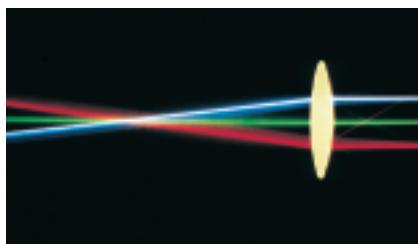
Lenses

18.2

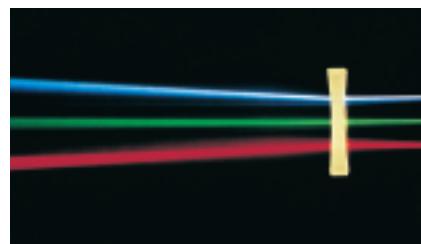
Eyeglasses were made from lenses as early as the thirteenth century. Around 1610, Galileo used two lenses as a telescope. With this instrument, he discovered the moons of Jupiter. Since Galileo's time, lenses have been used in many optical instruments such as microscopes and cameras. Lenses are probably the most useful and important of all optical devices.

Types of Lenses

A **lens** is made of transparent material, such as glass or plastic, with a refractive index larger than that of air. Each of the lens's two faces is part of a sphere and can be convex, concave, or flat. A lens is called a **convex lens** if it is thicker at the center than at the edges. Convex lenses are converging lenses because they refract parallel light rays so that the light rays meet. A **concave lens** is thinner in the middle than at the edges and is called a diverging lens because rays passing through it spread out. Use **Figure 18–12** to compare the shapes of the two types of lenses and the paths of light rays as they pass through each lens.



a



b

OBJECTIVES

- **Describe** how real and virtual images are formed by convex and concave lenses.
- **Locate** the image with a ray diagram and find the image location and size using a mathematical model.
- **Define** chromatic aberration and **explain** how it can be reduced.
- **Explain** how optical instruments such as microscopes and telescopes work.

FIGURE 18–12 In (a), the refracted rays converge, while in (b) they diverge.

Convex Lenses

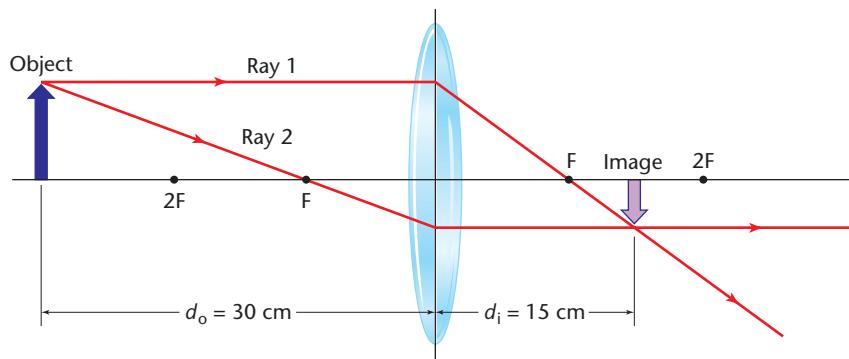
When light passes through a lens, refraction occurs at the two lens surfaces. In Chapter 17, you learned that Snell's law and geometry can be used to predict the paths of rays passing through a lens. To simplify your drawings and calculations, you will use the same approximation you used with mirrors, that is, that all refraction occurs on a plane, called the principal plane, that passes through the center of the lens. This approximation, called the thin lens model, applies to all the lenses you will learn about in this book.

Real images from convex lenses Have you ever used a lens for the purpose shown in **Figure 18–13**? By positioning the lens so that the rays of the sun converge on the leaf, the camper produces the image of the sun on the leaf's surface. The image is real. Because the rays are converging on a small spot, enough energy is being concentrated there that it could set the leaf ablaze. The rays of the sun are examples of light rays



FIGURE 18–13 A converging lens can be used to start a fire in a pile of leaves.

FIGURE 18–14 When an object is placed well beyond the principal focus of a convex lens, the image is real, inverted, and reduced in size. If the object were placed at the position of the image, you could locate the new image by tracing the same rays in the opposite direction.



that are almost exactly parallel to the principal axis because they have come from such a distant source. After being refracted in the lens, the rays converge at a point called the focal point, F , of the lens. **Figure 18–14** shows two focal points, one on each side of the lens. This is because the lens is symmetrical and light can pass through it in both directions. The two focal points are important in drawing rays, as you will see. The distance from the lens to a focal point is the focal length, f . The focal length depends upon the shape of the lens and the refractive index of the lens material.

In **Figure 18–14**, you can trace rays from an object located far from a convex lens. Ray 1 is parallel to the principal axis. It refracts and passes through F on the other side of the lens. Ray 2 passes through F on its way to the lens. After refraction, its path is parallel to the principal axis. The two rays intersect at a point beyond F and locate the image. Rays selected from other points on the object would converge at corresponding points on the image. Note that the image is real, inverted, and smaller than the object.

Where is the image of an object that is closer to the lens than the object in **Figure 18–14** is? You can find the location of the image without drawing another ray diagram. If you imagine the object in the position of the image in **Figure 18–14**, you can easily locate the new object by using a basic principle of optics that states that if a reflected or refracted ray is reversed in direction, it will follow its original path in the reverse direction. This means that the image and object may be interchanged by changing the direction of the rays. Imagine that the path of light through the lens in **Figure 18–14** is reversed and the object is at a distance of 15 cm from the right side of the lens. The new image, located at 30 cm from the left side of the lens, is again real and inverted, but it is now larger than the object.

If the object were placed at a distance twice the focal length from the lens, that is, at the point $2F$ on **Figure 18–14**, the image also would be found at $2F$. Because of symmetry, the image and object would have the same size. Thus, you can conclude that if an object is more than twice the focal length from the lens, the image is reduced in size. If the object is between F and $2F$, then the image is enlarged.

Lens/Mirror Equation Conventions Applied to Lenses

- f is positive for convex lenses.
- f is negative for concave lenses.
- d_o is positive on the object side of the lens.
- d_i is positive on the other side (image side) of the lens, where images are real.
- d_i is negative on the object side of the lens where images are virtual.

The lens/mirror equation can be used to find the location of an image, and the magnification equation can be used to find its size.

$$\frac{1}{f} = \frac{1}{d_i} + \frac{1}{d_o}$$

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

Recall that you used the lens/mirror equation, as well as the equation for magnification, in solving problems involving mirrors. The following Example Problem will show you how to apply these equations to problems involving lenses.

Example Problem

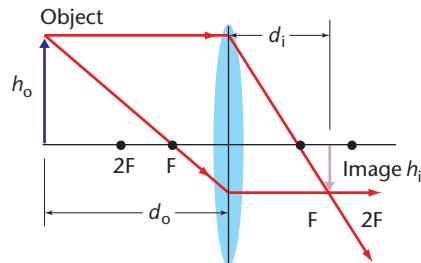
An Image Formed by a Convex Lens

An object is placed 32.0 cm from a convex lens that has a focal length of 8.0 cm.

- a. Where is the image?
- b. If the object is 3.0 cm high, how high is the image?
- c. Is the image inverted or upright?

Sketch the Problem

- Sketch the situation, locating the object and lens.
- Draw two principal rays.



Calculate Your Answer

Known:

$$d_o = 32.0 \text{ cm}$$

$$h_o = 3.0 \text{ cm}$$

$$f = 8.0 \text{ cm}$$

Unknown:

$$d_i = ?$$

$$h_i = ?$$

Strategy:

Use lens/mirror equation

to determine d_i .

Calculations:

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}, \text{ so } d_i = \frac{fd_o}{d_o - f}$$

$$d_i = \frac{(8.0 \text{ cm})(32.0 \text{ cm})}{32.0 \text{ cm} - 8.0 \text{ cm}}$$

= 11 cm, real

Solve magnification relations to find image height.

$$m = \frac{h_i}{h_o} = \frac{-d_i}{d_o}, \text{ so } h_i = \frac{-d_i h_o}{d_o}$$

$$h_i = \frac{-(11 \text{ cm})(3.0 \text{ cm})}{32.0 \text{ cm}} = -1.0 \text{ cm, inverted}$$

Check Your Answer

- Are the units correct? All are in cm.
- Do the signs make sense? Location is positive (real); height is negative (inverted). These are in agreement with the diagram.
- Are the magnitudes realistic? Location and height agree with the drawing.

Practice Problems

9. Use a ray diagram to find the image position of an object 30 cm to the left of a convex lens with a 10-cm focal length. (Let 1 cm on the drawing represent 20 cm.)
10. An object, 2.25 mm high, is 8.5 cm to the left of a convex lens of 5.5-cm focal length. Find the image location and height.
11. An object is placed to the left of a 25-mm focal length convex lens so that its image is the same size as the object. What are the image and object locations?

Pocket Lab

Fish-Eye Lens



How can fish focus light with their eyes? The light from an object in the water goes from the water into the fish eye, which is also mostly water. Obtain a converging lens and observe that it can be used as a magnifying glass. Now hold the lens under water in an aquarium. Does the lens still magnify?

Analyze and Conclude

Compare the magnifying ability of the glass lens when used under water and in air. Would a more curved lens bend the light more? Would you predict that the index of refraction of the material in a fish eye is the same as water? Defend your prediction.

Why use a large lens? For simplicity, you have drawn ray diagrams as if only two rays formed the image. But, in reality, all the rays that leave a point on the object and pass through the lens converge and form an image at the same spot. **Figure 18–15a** shows more of the rays involved. Notice that only the rays that hit the lens are imaged at the same spot. If you put a piece of paper at the image location, the size of the spot will be smallest at that point. If you move the paper in either direction along the principal axis, the size of the spot gets bigger but fuzzier. You would say that the image is out of focus.

What would happen if you used a lens of larger diameter? More of the rays that miss the lens would now go through it, as you can see in **Figure 18–15b**. With more rays converging on the image, it would be brighter. Would the reverse be true if you used a smaller lens? Fewer rays would pass through the smaller lens and focus on the image, so the image would be dimmer. Cameras use this principle to allow the aperture to be adjusted for dimmer or brighter days.

Virtual images If an object is placed at the focal point of a convex lens, the refracted rays will emerge in a parallel beam. If the object is brought closer to the lens, the rays do not converge on the opposite side of the lens. Instead, the image appears on the same side of the lens as the object. This image is virtual, erect, and enlarged.

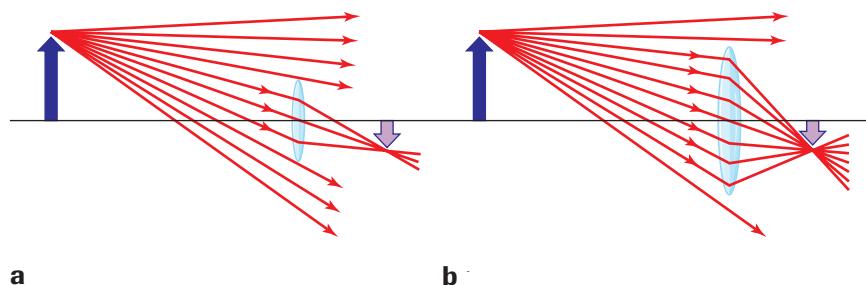


FIGURE 18–15 All the rays that pass through the lens focus at the same point. A larger lens allows more rays to pass through and thus produces a brighter image.

Physics Lab



Seeing Is Believing

Problem

How can you locate the image of a lens?

Materials



large-diameter convex lens

large-diameter concave lens

2 small balls of clay

2 rulers

2- or 3-cm-long nail

2 pieces of paper



Procedure

1. Assemble the equipment as shown in the photo using the concave lens.
2. Look through the lens to make sure that you can see both ends of the nail. Move the nail closer or farther from the lens until both ends are visible.

Data and Observations

1. Mark the paper to show the tip of the nail, the head of the nail, and also the lens line.
2. Line up your straight edge to point to the head of the nail. Have your lab partner verify that the edge is accurate.
3. Draw the line of sight.
4. Move to another position and draw a second line of sight to the head of the nail.
5. Repeat steps 2–4, this time drawing two lines of sight to the tip of the nail.
6. Use a new sheet of paper and repeat steps 1–5 using the convex lens.
7. When you are finished, put away any materials that can be reused.

Analyze and Conclude

1. **Analyzing Data** The image can be located by extending the lines of sight until they intersect. Extend the two lines of sight that point to the image head. Extend the two lines of sight that point to the image tip. Describe the results.
2. **Analyzing Data** Repeat the analysis for the convex lens, and describe the results.
3. **Comparing Data** Record your observations and image descriptions in a table.

Data and Observations			
Lens	Image Size (with respect to object)	Image Type (upright or upside down)	Image Location (with respect to object and lens)
concave			
convex			

4. **Extending Results** How would the image size and location change if you moved the object closer to the lens? Do the answers depend on whether the lens is concave or convex?

Apply

1. Describe an application of a similar arrangement for a convex lens.

Figure 18–16 shows how a convex lens forms a virtual image. The object is between F and the lens. Ray 1, as usual, approaches the lens parallel to the principal axis and is refracted through the focal point, F. Ray 2 travels from the tip of the object, in the direction it would have if it had started at F on the object side of the lens. The dashed line from F to the object shows you how to draw ray 2. Ray 2 leaves the lens parallel to the principal axis. Rays 1 and 2 diverge as they leave the lens. Thus, no real image is possible. Drawing sight lines for the two rays back to their apparent intersection locates the virtual image. It is on the same side of the lens as the object, erect, and larger than the object.

Example Problem

A Magnifying Glass

A convex lens with a focal length of 6.0 cm is held 4.0 cm from an insect that is 0.50 cm long.

- Where is the image located?
- How large does the insect appear to be?

Sketch the Problem

- Sketch the situation, locating the lens and the object.
- Draw two principal rays.

Calculate Your Answer

Known:

$$d_o = 4.0 \text{ cm}$$

$$h_o = 0.50 \text{ cm}$$

$$f = 6.0 \text{ cm}$$

Unknown:

$$d_i = ?$$

$$h_i = ?$$

Strategy:

Use lens/mirror equation to determine d_i .

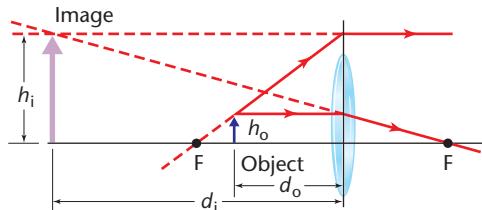
Calculations:

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}, \text{ so } d_i = \frac{fd_o}{d_o - f}$$

$$d_i = \frac{(6.0 \text{ cm})(4.0 \text{ cm})}{4.0 \text{ cm} - 6.0 \text{ cm}} = -12 \text{ cm, virtual}$$

$$m = \frac{h_i}{h_o} = \frac{-d_i}{d_o}, \text{ so } h_i = \frac{-d_i h_o}{d_o}$$

$$h_i = \frac{-(-12 \text{ cm})(0.50 \text{ cm})}{4.0 \text{ cm}} = 1.5 \text{ cm, upright}$$



Solve magnification relations to find image height.

Check Your Answer

- Are your units correct? All are in cm.
- Do the signs make sense? Negative d_i means virtual image; positive h_i means upright image, as the diagram shows.
- Are the magnitudes realistic? They agree with the diagram.

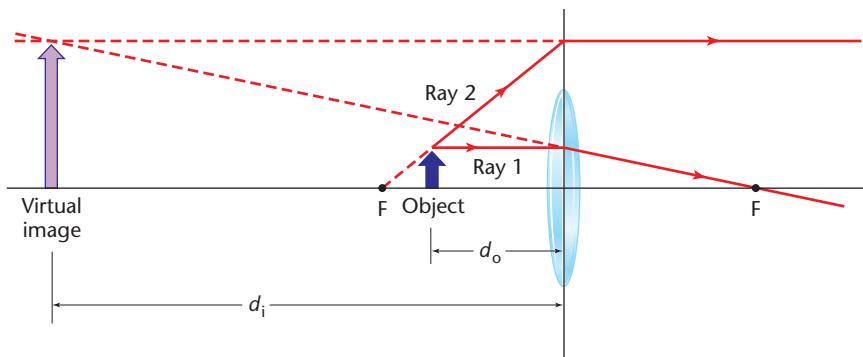


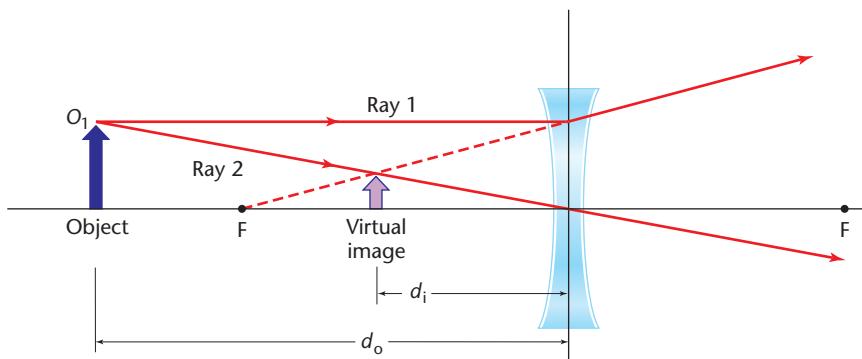
FIGURE 18–16 The two principal rays show that an upright, enlarged, virtual image, formed by a convex lens when the object is located between the lens and the principal focus. Drawing principal rays allows you to locate and construct the image of an object. These rays do not necessarily pass through the lens itself.

Practice Problems

12. A newspaper is held 6.0 cm from a convex lens of 20.0-cm focal length. Find the image distance of the newsprint image.
13. A magnifying glass has a focal length of 12.0 cm. A coin, 2.0 cm in diameter, is placed 3.4 cm from the lens. Locate the image of the coin. What is the diameter of the image?
14. A stamp collector wants to magnify an image by 4.0 when the stamp is 3.5 cm from the lens. What focal length is needed for the lens?

Concave Lenses

In **Figure 18–17**, you can see how an image is formed by a concave lens. A concave lens causes all rays to diverge. Ray 1 leaves O_1 and approaches the lens parallel to the principal axis. It leaves the lens in the direction it would have if it had passed through the focal point F . Ray 2 passes directly through the center of the lens without bending. Rays 1 and 2 diverge after passing through the lens. Their apparent intersection is i , on the same side of the lens as the object. The image is virtual, erect, and reduced in size. This is true no matter how far from the lens the object is located. The focal length of a concave lens is negative.



Pocket Lab

Bright Ideas



Stick the edge of a converging lens into a ball of clay and place the lens on a tabletop. Use a small lightbulb on one side and a screen on the other side to get a sharp image of the bulb. Predict what will happen to the image if you place your hand over the top half of the lens. Try it.

Analyze and Conclude What happened? How much of the lens is needed for a complete image?

FIGURE 18–17 Concave lenses are used in eyeglasses to correct nearsightedness and in combination with convex lenses in cameras and telescopes.

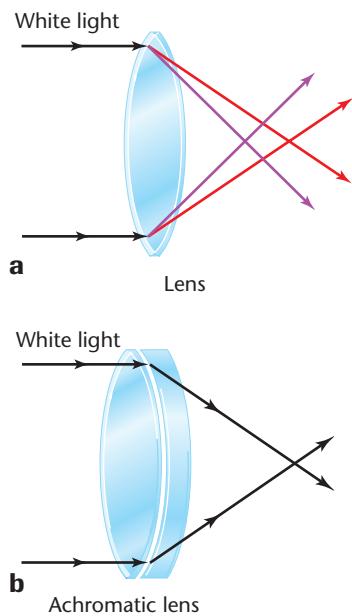


FIGURE 18-18 Chromatic aberration is depicted in **a**, which shows light of different wavelengths focused at different points. The achromatic lens in **b** is a combination of a convex and a concave lens, which minimizes the chromatic defect.

Defects of lenses The model you have used for drawing rays through lenses suggests that all rays that pass through all parts of a lens focus at the same location. However, this is only an approximation. In real lenses, rays that pass through the extreme edges of the lens are focused at a location different from rays that pass through the center. This inability of the lens to focus all parallel rays to a single point is called spherical aberration. Lenses as well as mirrors have spherical aberration. Spherical aberration is eliminated in inexpensive cameras by using only the centers of lenses. In more expensive instruments, many lenses, often five or more, are used to form a sharp, well-defined image.

Lenses have a second defect that mirrors do not. The edges of a lens resemble a prism, and different wavelengths of light are bent at slightly different angles, as you can see in **Figure 18-18a**. Thus, the light that passes through a lens, especially near the edges, is slightly dispersed. An object viewed through a lens appears ringed with color. This effect is called **chromatic aberration**. The term *chromatic* comes from the Greek *chromo*, which means “related to color.”

Chromatic aberration is always present when a single lens is used, but this defect can be greatly reduced by joining a convex lens with a concave lens that has a different index of refraction. Such a combination of lenses is shown in **Figure 18-18b**. Both lenses disperse light, but the dispersion caused by the converging lens is almost canceled by that caused by the diverging lens. The index of refraction of the diverging lens is chosen so that the combination lens still converges the light. A lens constructed in this way is called an **achromatic lens**. All precision optical instruments use achromatic lenses.

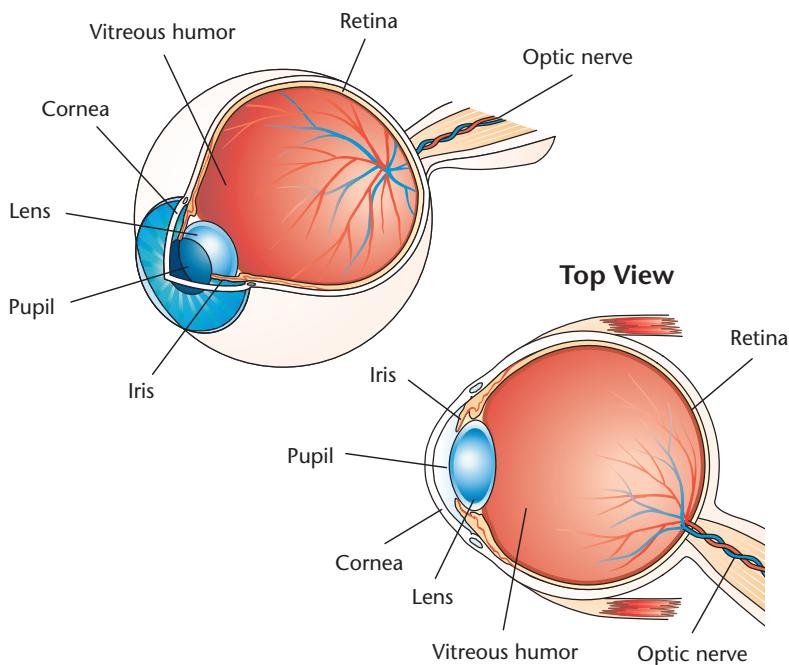
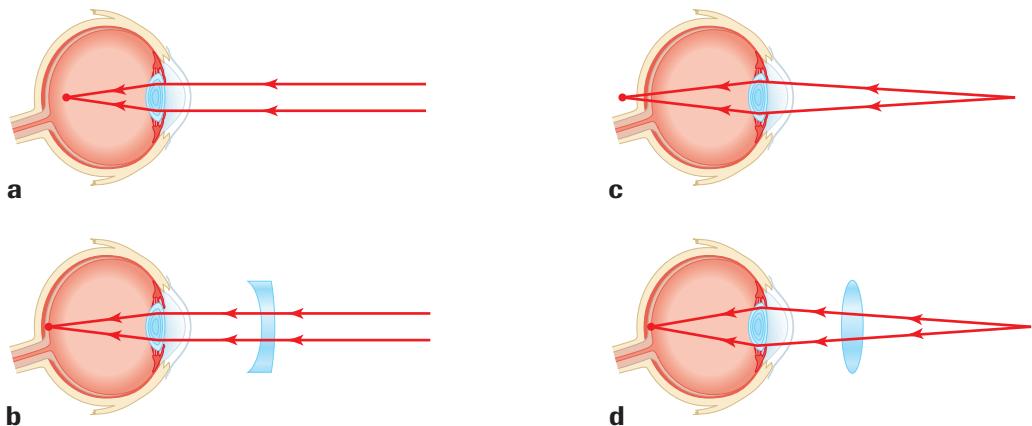


FIGURE 18-19 The curved surfaces of the cornea and lens refract light rays that enter the eye through the pupil to form an image on the retina.



Optical Instruments that Use Lenses

Although the eye itself is a remarkable optical device, its abilities can be greatly extended by a wide variety of instruments composed of lenses and mirrors. The eye is a fluid-filled, almost spherical vessel that forms the image of an object on the retina, as shown in **Figure 18-19**. Most of the refraction occurs at the curved surface of the cornea. The eye lens is made of flexible material with a refractive index different from that of the fluid. Muscles can change the shape of the lens, thereby changing its focal length. When the muscles are relaxed, the image of distant objects is focused on the retina. When the muscles contract, the focal length is shortened, permitting images of objects 25 cm or closer to be focused on the retina.

The eyes of many people do not focus sharp images on the retina. Instead, images are found either in front of the retina or behind it. External lenses, in the form of eyeglasses or contact lenses, are needed to adjust the focal length and move the image to the retina. **Figure 18-20** shows that the nearsighted, or myopic, eye has too short a focal length. Images of distant objects are formed in front of the retina. Concave lenses correct this defect by diverging the light rays, thus increasing the image distance, and placing the image on the retina. You also can see in **Figure 18-20** that farsightedness, or hyperopia, is the result of too long a focal length, which results in the image falling behind the retina. A similar result is caused by the increasing rigidity of the lenses in the eyes of people more than about 45 years old. Their muscles cannot shorten the focal length enough to focus images of close objects on the retina. For either defect, convex lenses produce a virtual image farther from the eye than the object. This image then becomes the object for the eye lens and can be focused on the retina, thereby correcting the defect. Some people have lenses or eye shapes that are not spherical. This defect is called astigmatism, and the result is that vertical lines of images can be in focus while horizontal lines are not. Eyeglasses having a nonspherical shape can correct astigmatism.

FIGURE 18-20 A nearsighted person cannot see distant objects because the image is focused in front of the retina as shown in **a**. The concave lens in **b** corrects this defect. A farsighted person cannot see close objects because the image is focused behind the retina as shown in **c**. The convex lens in **d** corrects this defect.

BIOLOGY CONNECTION

F.Y.I.

The earliest eyeglasses were made of thick, convex lenses. These lenses reminded their makers of lentils. Hence the term *lens*, from the Latin for “lentil beans.”

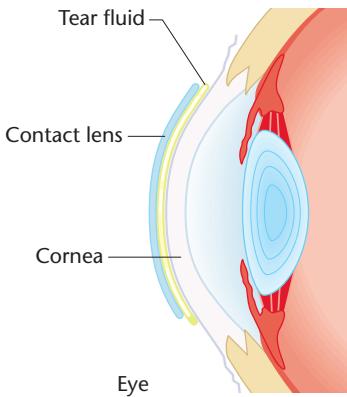


FIGURE 18-21 A contact lens rests on a layer of tears between it and the surface of the cornea.

Contact lenses produce the same results as eyeglasses. These very thin lenses are placed directly on the cornea, as shown in **Figure 18-21**. A thin layer of tears between the cornea and lens keeps the lens in place. Most of the refraction occurs at the air-lens surface, where the change in refractive index is greatest.

Microscopes and telescopes Microscopes allow the eye to see extremely small objects. Most microscopes use at least two convex lenses. An object is placed very close to a lens with a very short focal length, the objective lens. This lens produces a real image located between the second lens, the ocular or eyepiece lens, and its focal point. The ocular produces a greatly magnified virtual image of the image formed by the objective lens.

An astronomical refracting telescope uses two convex lenses. The objective lens of a telescope has a long focal length. The parallel rays from a star or other distant object focus in a plane at the focal point of this lens. The eyepiece lens, with a short focal length, then refracts the rays into another parallel beam. The viewer sees a virtual, enlarged, inverted image. The primary purpose of a telescope is not to magnify the image. It is to increase the angle between the rays from two different stars and to collect more light than would strike the unaided eye.

18.2 Section Review

- What wave behavior allows lenses to work? Describe how a lens focuses light.
- Which of the lenses whose cross sections are shown in **Figure 18-22** are convex or converging lenses? Which are concave or diverging lenses?

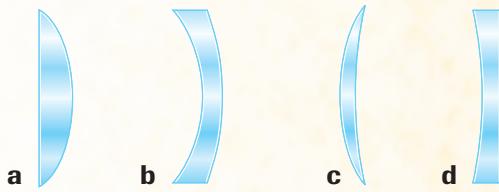


FIGURE 18-22

- Suppose your camera was focused on a person 2 m away. You now want to focus it on a tree that is farther away. Should the lens be moved closer to the film or farther away?

- You first focus white light through a single lens so that red is focused to the smallest point on a sheet of paper. Which direction should you move the paper to best focus blue?

- Critical Thinking** An air lens constructed of two watch glasses is placed in a tank of water. Copy **Figure 18-23** and draw the effect of this lens on parallel light rays incident on the lens.

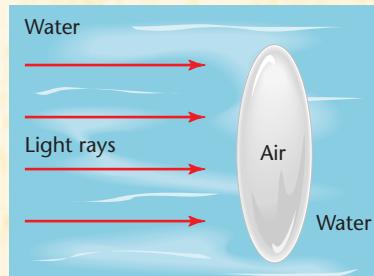


FIGURE 18-23

CHAPTER 18 REVIEW

Summary

Key Terms

18.1

- plane mirror
- object
- image
- virtual image
- erect image
- concave mirror
- principal axis
- focal point
- focal length
- real image
- lens/mirror equation
- magnification
- spherical aberration
- convex mirror

18.2

- lens
- convex lens
- concave lens
- chromatic aberration
- achromatic lens

18.1 Mirrors

- An object is a source of diverging light rays.
- Some mirrors reflect light rays that appear to diverge from a point on the other side of a mirror. The point from which they appear to diverge is called the virtual image.
- The image in a plane mirror is the same size as the object. It is as far behind the mirror as the object is in front of the mirror. The image is virtual and erect.
- The focal point of a convex or concave mirror is halfway between the center of curvature of the mirror and the mirror.
- Parallel rays striking a concave mirror converge at the focal point. Parallel rays striking a convex mirror appear to diverge from the focal point behind the mirror.
- Concave mirrors form real, inverted images if the object is farther from the mirror than the focal point, and virtual, upright images if the object is between the mirror and the focal point.
- Convex mirrors always produce virtual, upright, reduced images.
- Parallel light rays that are far from the principal axis are not reflected by spherical mirrors to converge at the

focal point. This defect is called spherical aberration.



18.2 Lenses

- Convex lenses are thinner at their outer edges than at their centers. Concave lenses are thicker at their outer edges than at their centers.
- Convex lenses produce real, inverted images if the object is farther from the lens than the focal point. If the object is closer than the focal point, a virtual, upright, enlarged image is formed.
- Concave lenses produce virtual, upright, reduced images.
- Lenses have spherical aberrations because parallel rays striking a lens near its edge do not focus at one spot. Lenses also focus light of different wavelength (color) at different locations. This is called chromatic aberration.

Key Equations

18.1

$$\frac{1}{f} = \frac{1}{d_i} + \frac{1}{d_o} \quad m = \frac{h_i}{h_o} \quad m = \frac{-d_i}{d_o}$$

Reviewing Concepts

Section 18.1

1. Describe the physical properties of the image seen in a plane mirror.
2. Where is the image of an object in a plane mirror?
3. Describe the physical properties of a virtual image.
4. A student believes that very sensitive photographic film can detect a virtual image. The student puts photographic

film at the location of the image.

Does this attempt succeed? Explain.

5. How can you prove to someone that an image is a real image?
6. What is the focal length of a plane mirror? Does the lens/mirror equation work for plane mirrors? Explain.
7. An object produces a virtual image in a concave mirror. Where is the object located?



8. Why are convex mirrors used as rearview mirrors?
9. What causes the defect that all concave spherical mirrors have?

Section 18.2

10. Locate and describe the physical properties of the image produced by a convex lens if an object is placed some distance beyond $2F$.
11. What factor, other than the curvature of the surfaces of a lens, determines the location of the focal point of the lens?
12. To project an image from a movie projector onto a screen, the film is placed between F and $2F$ of a converging lens. This arrangement produces an inverted image. Why do the actors appear to be erect when the film is viewed?

Applying Concepts

13. Locate and describe the physical properties of the image produced by a concave mirror when the object is located at the center of curvature.
14. An object is located beyond the center of curvature of a spherical concave mirror. Locate and describe the physical properties of the image.
15. An object is located between the center of curvature and the focus of a concave mirror. Locate and describe the physical properties of the image of the object.
16. You have to order a large concave mirror for a piece of high-quality equipment. Should you order a spherical mirror or a parabolic mirror? Explain.
17. Describe the physical properties of the image seen in a convex mirror.
18. List all the possible arrangements in which you can use a spherical mirror, either concave or convex, to form a real image.
19. List all possible arrangements in which you can use a spherical mirror, either concave or convex, to form an image reduced in size.
20. The outside rearview mirrors of cars often carry the warning "Objects in the mirror are closer than they appear." What kind of mirror is this and what advantage does it have?
21. What physical characteristic of a lens distinguishes a converging lens from a diverging lens?
22. If you try to use a magnifying glass underwater, will its properties change? Explain.

23. Suppose **Figure 18–17** were redrawn with a lens of the same focal length but a larger diameter. How would the location of the image change?

24. Why is there chromatic aberration for light that goes through a lens but there is not chromatic aberration for light that reflects from a mirror?

Problems

Section 18.1

25. Penny wishes to take a picture of her image in a plane mirror. If the camera is 1.2 m in front of the mirror, at what distance should the camera lens be focused?
26. A concave mirror has a focal length of 10.0 cm. What is its radius of curvature?
27. Light from a star is collected by a concave mirror. How far from the mirror is the image of the star if the radius of curvature is 150 cm?
28. An object is 30.0 cm from a concave mirror of 15-cm focal length. The object is 1.8 cm high. Use the lens/mirror equation to find the image. How high is the image?
29. A jeweler inspects a watch with a diameter of 3.0 cm by placing it 8.0 cm in front of a concave mirror of 12.0-cm focal length.
 - a. Where will the image of the watch appear?
 - b. What will be the diameter of the image?
30. A dentist uses a small mirror of radius 40 mm to locate a cavity in a patient's tooth. If the mirror is concave and is held 16 mm from the tooth, what is the magnification of the image?
31. Draw a ray diagram of a plane mirror to show that if you want to see yourself from your feet to the top of your head, the mirror must be at least half your height.
32. Sunlight falls on a concave mirror and forms an image 3.0 cm from the mirror. If an object 24 mm high is placed 12.0 cm from the mirror, where will its image be formed?
 - a. Use a ray diagram.
 - b. Use the lens/mirror equation.
 - c. How high is the image?
33. A production line inspector wants a mirror that produces an upright image with magnification of 7.5 when it is located 14.0 mm from a machine part.
 - a. What kind of mirror would do this job?
 - b. What is its radius of curvature?

- 34.** Shiny lawn spheres placed on pedestals are convex mirrors. One such sphere has a diameter of 40.0 cm. A 12-cm robin sits in a tree 1.5 m from the sphere. Where is the image of the robin and how long is the image?

Section 18.2

- 35.** The focal length of a convex lens is 17 cm. A candle is placed 34 cm in front of the lens. Make a ray diagram to locate the image.
- 36.** The convex lens of a copy machine has a focal length of 25.0 cm. A letter to be copied is placed 40.0 cm from the lens.
- How far from the lens is the copy paper?
 - The machine was adjusted to give an enlarged copy of the letter. How much larger will the copy be?
- 37.** Camera lenses are described in terms of their focal length. A 50.0-mm lens has a focal length of 50.0 mm.
- A camera with a 50.0-mm lens is focused on an object 3.0 m away. Locate the image.
 - A 1000.0-mm lens is focused on an object 125 m away. Locate the image.
- 38.** A convex lens is needed to produce an image that is 0.75 times the size of the object and located 24 cm behind the lens. What focal length should be specified?
- 39.** In order to clearly read a book 25 cm away, a farsighted person needs an image distance of -45 cm from the eye. What focal length is needed for the lens?
- 40.** A slide of an onion cell is placed 12 mm from the objective lens of a microscope. The focal length of the objective lens is 10.0 mm.
- How far from the lens is the image formed?
 - What is the magnification of this image?
 - The real image formed is located 10.0 mm beneath the eyepiece lens. If the focal length of the eyepiece is 20.0 mm, where does the final image appear?
 - What is the final magnification of this compound system?

 **Extra Practice** For more practice solving problems, go to **Extra Practice Problems**, Appendix B.

Critical Thinking Problems

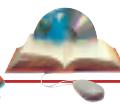
- 41.** Your lab partner used a convex lens to produce an image with $d_i = 25$ cm and $h_i = 4.0$ cm. You are examining a concave lens with a focal length of -15 cm. You place the concave lens between the convex lens and the original image, 10 cm from the image. To your surprise, you see a real, enlarged image on the wall. You are told that the image from the convex lens is now the object for the concave lens, and because it is on the opposite side of the concave lens, it is a virtual object. Use these hints to find the location and size of the new image and to predict whether the concave lens changed the orientation of the original image.
- 42.** What is responsible for the rainbow-colored fringe commonly seen at the edges of a spot of white light from a slide or overhead projector?
- 43.** A lens is used to project the image of an object onto a screen. Suppose you cover the right half of the lens. What will happen to the image?

Going Further

-  **Applying Calculators** You are examining a 5-cm butterfly under a magnifying glass with a focal length of 15 cm. The equation for calculating how large the butterfly appears is $h_i = |(-h_o f)/(d_o - f)|$. Graph this equation on a graphing calculator with h_i on the y -axis (with a range of -50 cm to 50 cm) and d on the x -axis (with a range of 0 cm to 50 cm). How large does the butterfly appear at 5 cm? At 10 cm? 13 cm? 17 cm? 20 cm? 30 cm? 50 cm? For what distances is the image upright?

Team Project Research and interpret the role of refraction and/or reflection in the following industries: contact lenses, cameras, telescopes, sunglasses, and windows.

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