



Chapter 17

Reflection and Mirrors

What You'll Learn

- You will learn how light reflects off different surfaces.
- You will learn about the different types of mirrors and their uses.
- You will use ray tracing and mathematical models to describe images formed by mirrors.

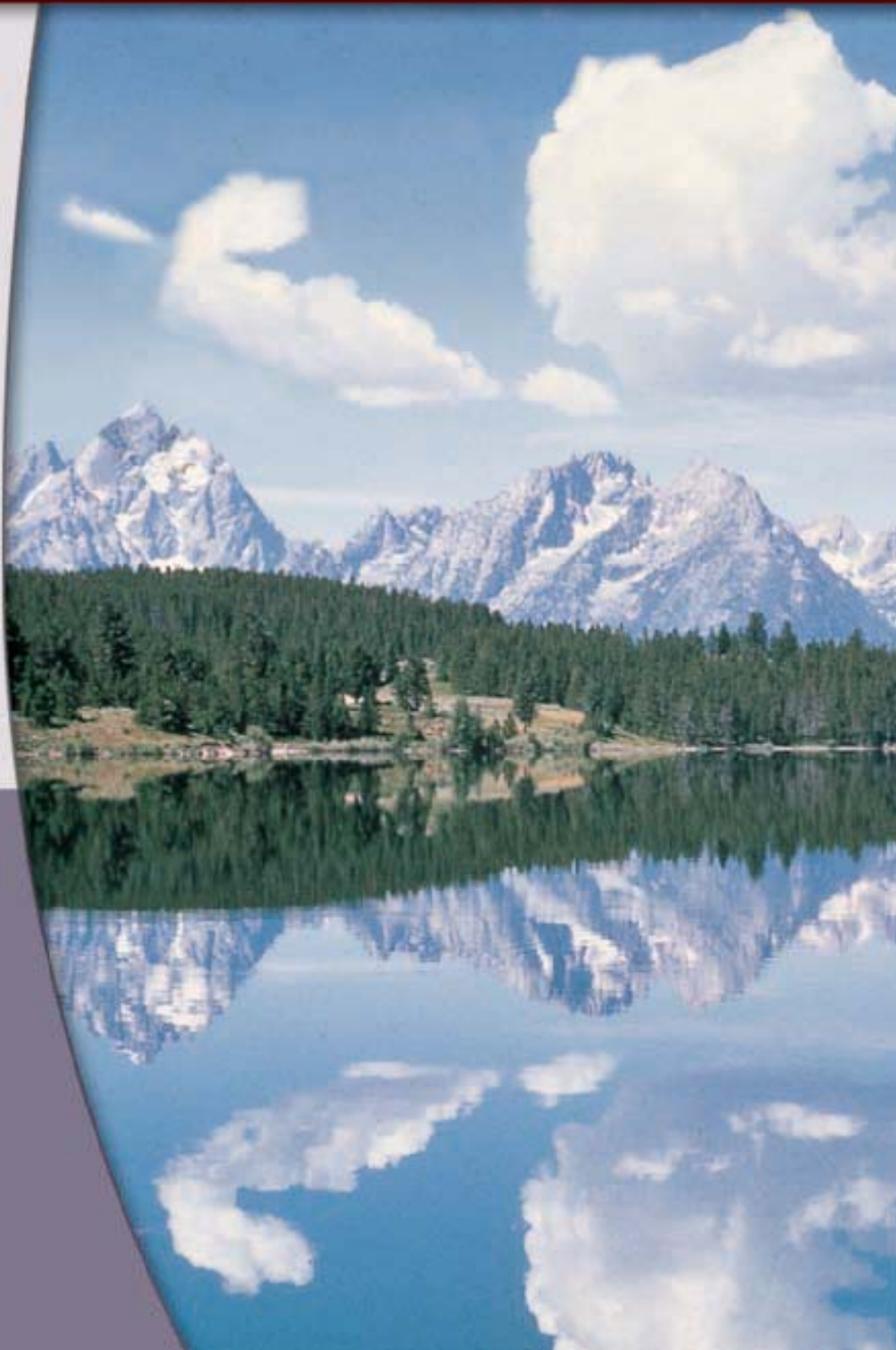
Why It's Important

How light reflects off a surface into your eyes determines the reflection that you see. When you look down at the surface of a lake, you see an upright reflection of yourself.

Mountain Scene When you look across a lake, you might see a scene like the one in this photo. The image of the trees and mountains in the lake appears to you to be upside-down.

Think About This ►

Why would the image you see of yourself in the lake be upright, while the image of the mountain is upside-down?



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LAUNCH Lab



How is an image shown on a screen?

Question

What types of mirrors are able to reflect an image onto a screen?

Procedure



1. Obtain an index card, a plane mirror, a concave mirror, a convex mirror, and a flashlight from your teacher.
2. Turn off the room lights and stand near the window.
3. Hold the index card in one hand. Hold the flat, plane mirror in the other hand.
4. Reflect the light coming through the window onto the index card. **CAUTION: Do not look directly at the Sun or at the reflection of the Sun in a mirror.** Slowly move the index card closer to and then farther away from the mirror and try to make a clear image of objects outside the window.
5. If you can project a clear image, this is called a real image. If you only see a fuzzy light on the index card then no real image is formed. Record your observations.

6. Repeat steps 3–5 with the concave and convex mirror.
7. Perform step 4 for each mirror with a flashlight and observe the reflection on the index card.

Analysis

Which mirror(s) produced a real image?

What are some things you notice about the image(s) you see?

Critical Thinking Based upon your observation of the flashlight images, propose an explanation of how a real image is formed.



17.1 Reflection from Plane Mirrors

Undoubtedly, as long as there have been humans, they have seen their faces reflected in the quiet water of lakes and ponds. When you look at the surface of a body of water, however, you don't always see a clear reflection. Sometimes, the wind causes ripples in the water, and passing boats create waves. Disturbances on the surface of the water prevent the light from reflecting in a manner such that a clear reflection is visible.

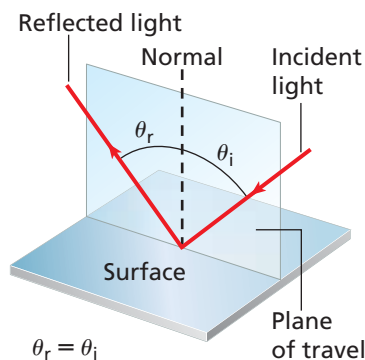
Almost 4000 years ago, Egyptians understood that reflection requires smooth surfaces. They used polished metal mirrors to view their images. Sharp, well-defined, reflected images were not possible until 1857, however, when Jean Foucault, a French scientist, developed a method of coating glass with silver. Modern mirrors are produced using ever-increasing precision. They are made with greater reflecting ability by the evaporation of aluminum or silver onto highly polished glass. The quality of reflecting surfaces is even more important in applications such as lasers and telescopes. More than ever before, clear reflections in modern, optical instruments require smooth surfaces.

► Objectives

- **Explain** the law of reflection.
- **Distinguish** between specular and diffuse reflection.
- **Locate** the images formed by plane mirrors.

► Vocabulary

specular reflection
diffuse reflection
plane mirror
object
image
virtual image



■ **Figure 17-1** The incident ray and the reflected ray are in the same plane of travel.

Concepts in Motion

Interactive Figure To see an animation on the law of reflection, visit physicspp.com.

The Law of Reflection

What happens to the light that is striking this book? When you hold the book up to the light, you will see that no light passes through it. Recall from Chapter 16 that an object like this is called opaque. Part of the light is absorbed, and part is reflected. The absorbed light spreads out as thermal energy. The behavior of the reflected light depends on the type of surface and the angle at which the light strikes the surface.

Recall from Chapter 14 that when a wave traveling in two dimensions encounters a barrier, the angle of incidence is equal to the angle of reflection of the wave. This same two-dimensional reflection relationship applies to light waves. Consider what happens when you bounce-pass a basketball. The ball bounces in a straight line, as viewed from above, to the other player. Light reflects in the same way as a basketball. **Figure 17-1** shows a ray of light striking a reflecting surface. The normal is an imaginary line that is perpendicular to a surface at the location where light strikes the surface. The reflected ray, the incident ray, and the normal to the surface always will be in the same plane. Although the light is traveling in three dimensions, the reflection of the light is planar (two-dimensional). The planar and angle relationships are known together as the law of reflection.

Law of Reflection $\theta_r = \theta_i$

The angle that a reflected ray makes as measured from the normal to a reflective surface equals the angle that the incident ray makes as measured from the same normal.

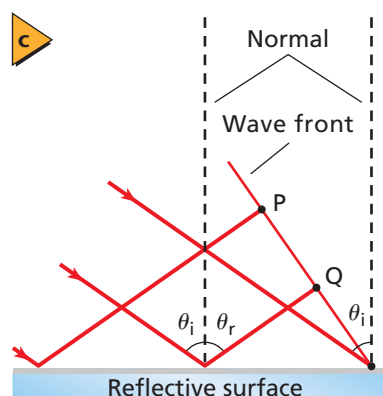
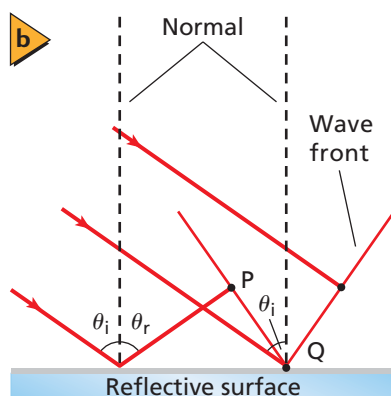
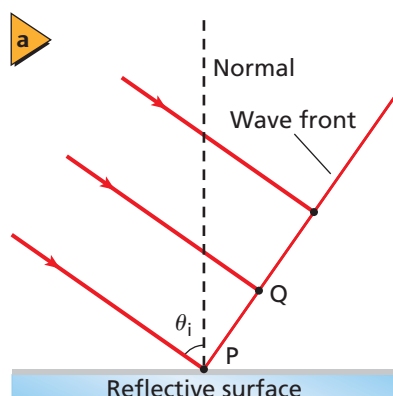
Color Convention

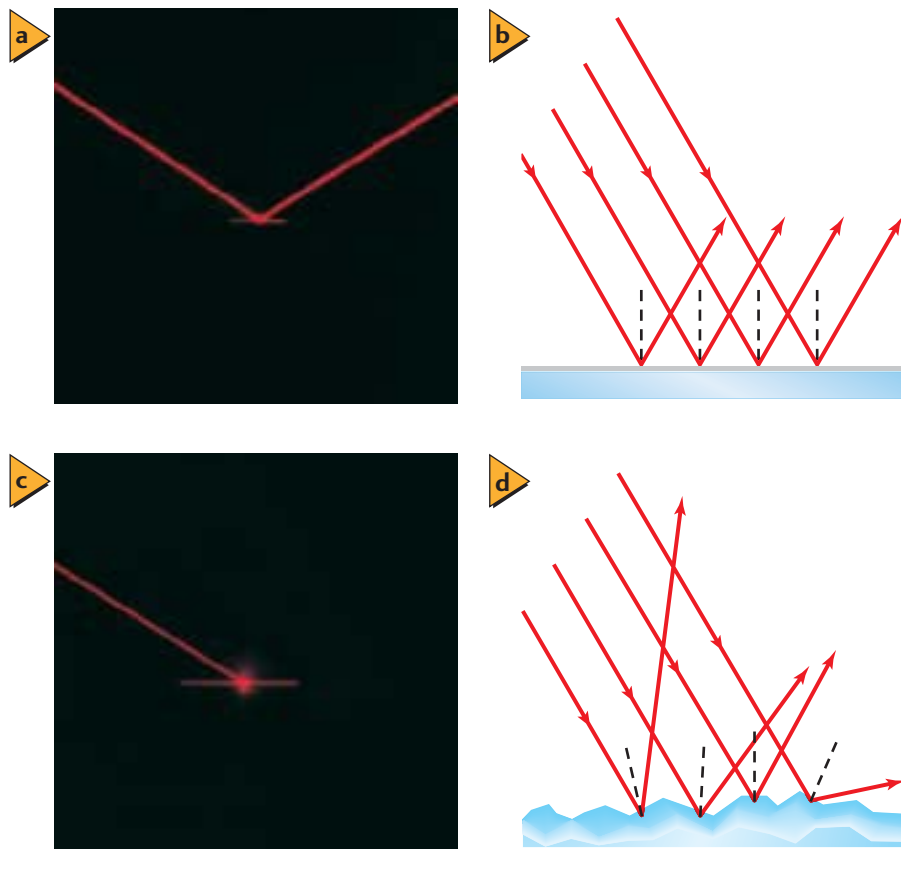
- Light rays and wave fronts are **red**.
- Mirrors are **light blue**.



This law can be explained in terms of the wave model of light. **Figure 17-2** shows a wave front of light approaching a reflective surface. As each point along the wave front reaches the surface, it reflects off at the same angle as the preceding point. Because all points are traveling at the same speed, they all travel the same total distance in the same time. Thus, the wave front as a whole leaves the surface at an angle equal to its incident angle. Note that the wavelength of the light does not affect this process. Red, green, and blue light all follow this law.

■ **Figure 17-2** A wave front of light approaches a reflective surface. Point P on the wave front strikes the surface first **(a)**. Point Q strikes the surface after point P reflects at an angle equal to the incident angle **(b)**. The process continues with all points reflecting off at angles equal to their incident angles, resulting in a reflected wave front **(c)**.





■ **Figure 17-3** When a beam of light strikes a mirrored surface **(a)**, the parallel rays in the beam reflect in parallel and maintain the light as a beam **(b)**. When the light beam strikes a rough surface **(c)**, the parallel rays that make up the beam are reflected from different microscopic surfaces, thereby diffusing the beam **(d)**.



Smooth and rough surfaces Consider the beam of light shown in **Figure 17-3a**. All of the rays in this beam of light reflect off the surface parallel to one another, as shown in **Figure 17-3b**. This occurs only if the reflecting surface is not rough on the scale of the wavelength of light. Such a surface is considered to be smooth relative to the light. A smooth surface, such as a mirror, causes **specular reflection**, in which parallel light rays are reflected in parallel.

What happens when light strikes a surface that appears to be smooth, but actually is rough on the scale of the wavelength of light, such as the page of this textbook or a white wall? Is light reflected? How could you demonstrate this? **Figure 17-3c** shows a beam of light reflecting off a sheet of paper, which has a rough surface. All of the light rays that make up the beam are parallel before striking the surface, but the reflected rays are not parallel, as shown in **Figure 17-3d**. This is **diffuse reflection**, the scattering of light off a rough surface.

The law of reflection applies to both smooth and rough surfaces. For a rough surface, the angle that each incident ray makes with the normal equals the angle that its reflected ray makes with the normal. However, on a microscopic scale, the normals to the surface locations where the rays strike are not parallel. Thus, the reflected rays cannot be parallel. The rough surface prevents them from being parallel. In this case, a reflected beam cannot be seen because the reflected rays are scattered in different directions. With specular reflection, as with a mirror, you can see your face. But no matter how much light is reflected off a wall or a sheet of paper, you will never be able to use them as mirrors.

► EXAMPLE Problem 1

Changing the Angle of Incidence A light ray strikes a plane mirror at an angle of 52.0° to the normal. The mirror then rotates 35.0° around the point where the beam strikes the mirror so that the angle of incidence of the light ray decreases. The axis of rotation is perpendicular to the plane of the incident and the reflected rays. What is the angle of rotation of the reflected ray?

1 Analyze and Sketch the Problem

- Sketch the situation before the rotation of the mirror.
- Draw another sketch with the angle of rotation applied to the mirror.

Known:

$$\theta_{i, \text{initial}} = 52.0^\circ$$

$$\Delta\theta_{\text{mirror}} = 35.0^\circ$$

Unknown:

$$\Delta\theta_r = ?$$

2 Solve for the Unknown

For the angle of incidence to reduce, rotate clockwise.

$$\begin{aligned}\theta_{i, \text{final}} &= \theta_{i, \text{initial}} - \Delta\theta_{\text{mirror}} \\ &= 52.0^\circ - 35.0^\circ \\ &= 17.0^\circ \text{ clockwise from the new normal}\end{aligned}$$

Substitute $\theta_{i, \text{initial}} = 52.0^\circ$, $\Delta\theta_{\text{mirror}} = 35.0^\circ$

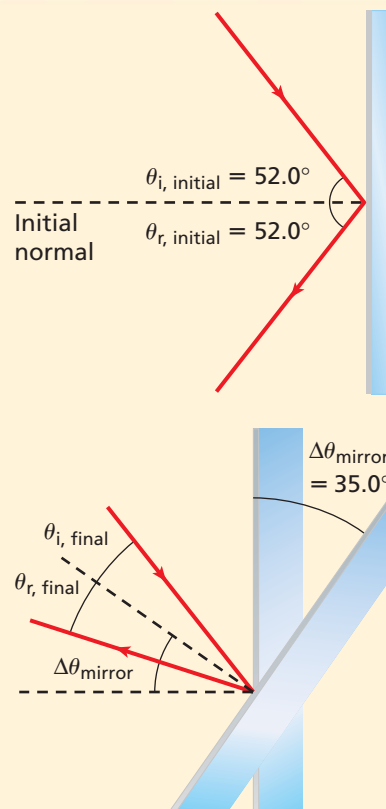
Apply the law of reflection.

$$\begin{aligned}\theta_{r, \text{final}} &= \theta_{i, \text{final}} \\ &= 17.0^\circ \text{ counterclockwise from the new normal}\end{aligned}$$

Substitute $\theta_{i, \text{final}} = 17.0^\circ$

Using the two sketches, determine the angle through which the reflected ray has rotated.

$$\begin{aligned}\Delta\theta_r &= 52.0^\circ + 35.0^\circ - 17.0^\circ \\ &= 70.0^\circ \text{ clockwise from the original angle}\end{aligned}$$



Math Handbook

Operations with
Significant Digits
pages 835–836

3 Evaluate the Answer

- **Is the magnitude realistic?** Comparing the final sketch with the initial sketch shows that the angle the light ray makes with the normal decreases as the mirror rotates clockwise toward the light ray. It makes sense, then, that the reflected ray also rotates clockwise.

► PRACTICE Problems

• Additional Problems, Appendix B
• Solutions to Selected Problems, Appendix C

1. Explain why the reflection of light off ground glass changes from diffuse to specular if you spill water on it.
2. If the angle of incidence of a ray of light is 42° , what is each of the following?
 - a. the angle of reflection
 - b. the angle the incident ray makes with the mirror
 - c. the angle between the incident ray and the reflected ray
3. If a light ray reflects off a plane mirror at an angle of 35° to the normal, what was the angle of incidence of the ray?
4. Light from a laser strikes a plane mirror at an angle of 38° to the normal. If the laser is moved so that the angle of incidence increases by 13° , what is the new angle of reflection?
5. Two plane mirrors are positioned at right angles to one another. A ray of light strikes one mirror at an angle of 30° to the normal. It then reflects toward the second mirror. What is the angle of reflection of the light ray off the second mirror?



Objects and Plane-Mirror Images

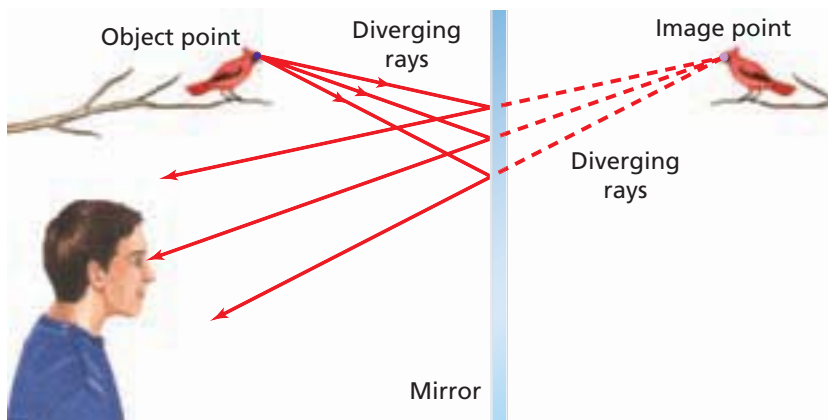
If you looked at yourself in a mirror this morning you saw your reflection in a plane mirror. A **plane mirror** is a flat, smooth surface from which light is reflected by specular reflection. To understand reflection from a mirror, you must consider the object of the reflection and the type of image that is formed. In Chapter 16, the word *object* was used to refer to sources of light. In describing mirrors, the word *object* is used in the same way, but with a more specific application. An **object** is a source of light rays that are to be reflected by a mirrored surface. An object can be a luminous source, such as a lightbulb, or an illuminated source, such as a girl, as shown in **Figure 17-4**. Most objects that you will work with in this chapter are a source of light that diverges, or spreads out from the source.

Consider a single point on the bird in **Figure 17-5**. Light reflects diffusely from the crest of the bird, the object point. What happens to the light? Some of the light travels from the bird to the mirror and reflects. What does the boy see? Some of the reflected light from the bird hits his eyes. Because his brain processes this information as if the light has traveled a straight path, it seems to the boy as if the light had followed the dashed lines. The light seems to have come from a point behind the mirror, the image point.

The boy in Figure 17-5 sees rays of light that come from many points on the bird. The combination of the image points produced by reflected light rays forms the **image** of the bird. It is a **virtual image**, which is a type of image formed by diverging light rays. A virtual image is always on the opposite side of the mirror from the object. Images of real objects produced by plane mirrors are always virtual images.

Properties of Plane-Mirror Images

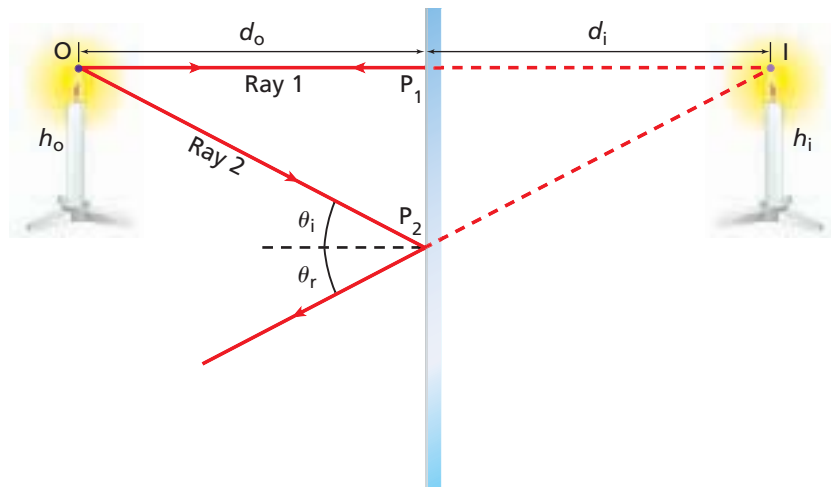
Looking at yourself in a mirror, you can see that your image appears to be the same distance behind the mirror as you are in front of the mirror. How could you test this? Place a ruler between you and the mirror. Where does the image touch the ruler? You also see that your image is oriented as you are, and it matches your size. This is where the expression *mirror image* originates. If you move toward the mirror, your image moves toward the mirror. If you move away, your image also moves away.



■ **Figure 17-4** The lightbulb is a luminous source that produces diverging light by shining in all directions. The girl is an illuminated source that produces diverging light by the diffused reflection from her body of light that comes from the lightbulb.



■ **Figure 17-5** The reflected rays that enter the eye appear to originate at a point behind the mirror.



■ **Figure 17-6** 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 rays are reflected back to where they converge. The image is located where the sight lines converge: $d_i = -d_o$.

MINI LAB

Virtual Image Position



Suppose you are looking at your image in a plane mirror. Can you measure the location of the image?

1. Obtain a camera from your teacher with a focusing ring that has distances marked on it.
2. 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.
3. **Measure** the position of the image by focusing the camera on your image. Check the reading on the focusing ring.

Analyze and Conclude

4. How far is the image behind the mirror?
5. Why is the camera able to focus on a virtual image that is behind the mirror even though there is no real object behind the mirror?

Image position and height The geometric model of **Figure 17-6** demonstrates why the distances are the same. Two rays from point O at the tip of the candle strike the mirror at point P_1 and point P_2 , respectively. Both rays are reflected according to the law of reflection. The reflected rays are extended behind the mirror as sight lines, converging at point I, which is the image of point O. Ray 1, which strikes the mirror at an angle of incidence of 0° , is reflected back on itself, so the sight line is at 90° to the mirror, just as ray 1. Ray 2 is also reflected at an angle equal to the angle of incidence, so the sight line is at the same angle to the mirror as ray 2.

This geometric model reveals that line segments $\overline{OP_1}$ and $\overline{IP_1}$ are corresponding sides of two congruent triangles, $\triangle OP_1P_2$ and $\triangle IP_1P_2$. The position of the object with respect to the mirror, or the object position, d_o , has a length equal to the length of $\overline{OP_1}$. The apparent position of the image with respect to the mirror, or the image position, d_i , has a length equal to the length of $\overline{IP_1}$. Using the convention that image position is negative to indicate that the image is virtual, the following is true.

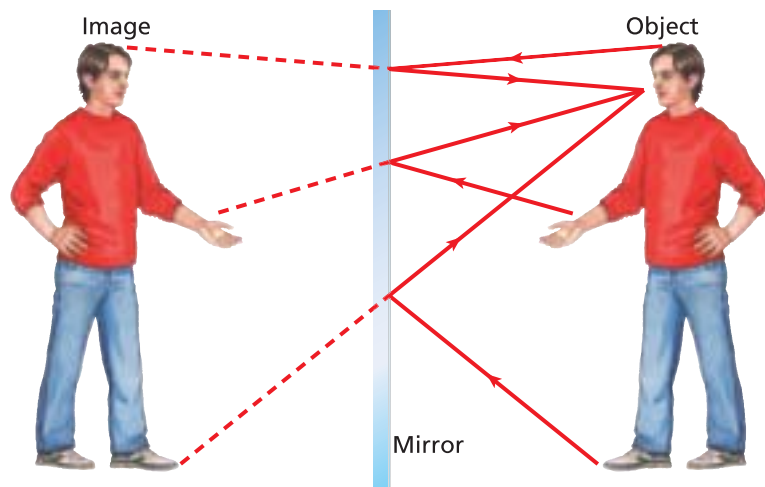
Plane-Mirror Image Position $d_i = -d_o$

With a plane mirror, the image position is equal to the negative of the object position. The negative sign indicates that the image is virtual.

You can draw rays from the object to the mirror to determine the size of the image. The sight lines of two rays originating from the bottom of the candle in Figure 17-6 will converge at the bottom of the image. Using the law of reflection and congruent-triangle geometry, the following is true of the object height, h_o , and image height, h_i , and any other dimension of the object and image.

Plane-Mirror Image Height $h_i = h_o$

With a plane mirror, image height is equal to object height.



■ **Figure 17-7** 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. However, when the boy blinks his right eye, the left eye of his image blinks.

Image orientation A plane mirror produces an image with the same orientation as the object. If you are standing on your feet, a plane mirror produces an image of you standing on your feet. If you are doing a headstand, the mirror shows you doing a headstand. However, there is a difference between you and the appearance of your image in a mirror. Follow the sight lines in **Figure 17-7**. The ray that diverges from the right hand of the boy converges at what appears to be the left hand of his image. Left and right appear to be reversed by a plane mirror. Why, then, are top and bottom not also reversed? This does not happen because a plane mirror does not really reverse left and right. The mirror in Figure 17-7 only reverses the boy's image such that it is facing in the opposite direction as the boy, or, in other words, it produces a front-to-back reversal.

Consider the image of the mountain in the photo at the beginning of the chapter. In this case, the image of the mountain can be described as upside down, but the image is actually a front-to-back reversal of your view of the actual mountain. Because the mirror (the lake surface) is horizontal, rather than vertical, your perspective, or angle of view, makes the image look upside down. Turn your book 90° counterclockwise and look at Figure 17-7 again. The actual boy is now facing down, and his image is facing up, upside down relative to the actual boy, just like the image of the mountain. The only thing that has changed is your perspective.

17.1 Section Review

6. **Reflection** A light ray strikes a flat, smooth, reflecting surface at an angle of 80° to the normal. What is the angle that the reflected ray makes with the surface of the mirror?
7. **Law of Reflection** Explain how the law of reflection applies to diffuse reflection.
8. **Reflecting Surfaces** Categorize each of the following as a specular or a diffuse reflecting surface: paper, polished metal, window glass, rough metal, plastic milk jug, smooth water surface, and ground glass.
9. **Image Properties** A 50-cm-tall dog stands 3 m from a plane mirror and looks at its image. What is the image position, height, and type?
10. **Image Diagram** A car is following another car down a straight road. The first car has a rear window tilted 45° . Draw a ray diagram showing the position of the Sun that would cause sunlight to reflect into the eyes of the driver of the second car.
11. **Critical Thinking** Explain how diffuse reflection of light off an object enables you to see an object from any angle.



17.2 Curved Mirrors

► Objectives

- **Explain** how concave and convex mirrors form images.
- **Describe** properties and uses of spherical mirrors.
- **Determine** the locations and sizes of spherical mirror images.

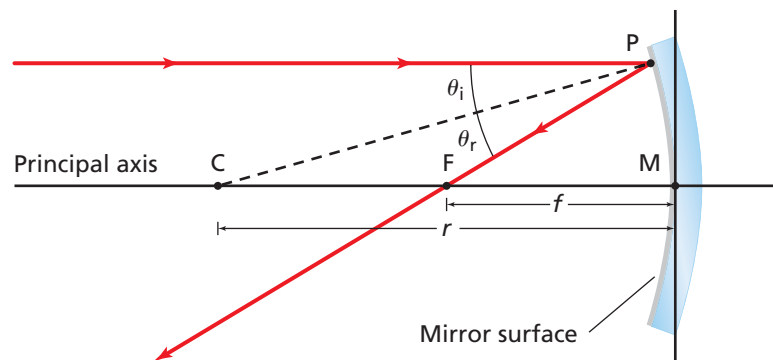
► Vocabulary

concave mirror
principal axis
focal point
focal length
real image
spherical aberration
magnification
convex mirror

If you look at the surface of a shiny spoon, you will notice that your reflection is different from what you see in a plane mirror. The spoon acts as a curved mirror, with one side curved inward and the other curved outward. The properties of curved mirrors and the images that they form depend on the shape of the mirror and the object's position.

Concave Mirrors

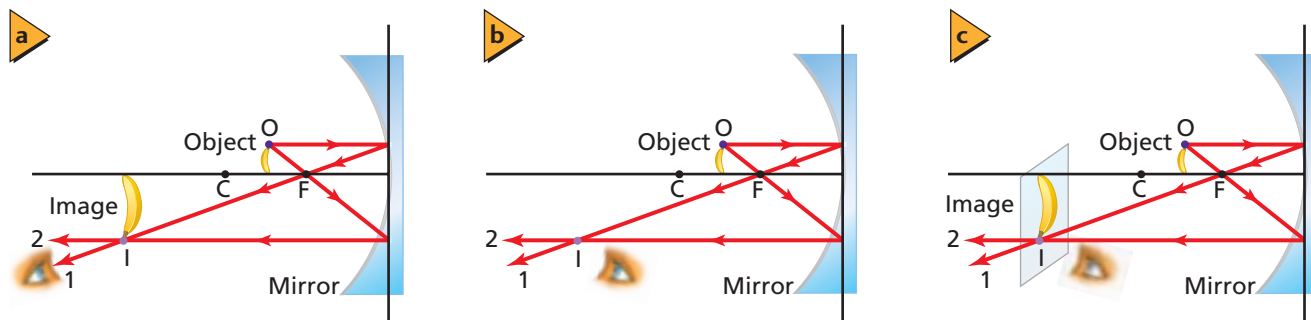
The inside surface of a shiny spoon, the side that holds food, acts as a concave mirror. A **concave mirror** has a reflective surface, the edges of which curve toward the observer. Properties of a concave mirror depend on how much it is curved. **Figure 17-8** shows how a spherical concave mirror works. In a spherical concave mirror, the mirror is shaped as if it were a section of a hollow sphere with an inner reflective surface. The mirror has the same geometric center, C , and radius of curvature, r , as a sphere of radius, r . The line that includes line segment CM is the **principal axis**, which is the straight line perpendicular to the surface of the mirror that divides the mirror in half. Point M is the center of the mirror where the principal axis intersects the mirror.



■ **Figure 17-8** The focal point 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 .

When you point the principal axis of a concave mirror toward the Sun, all the rays are reflected through a single point. You can locate this point by moving a sheet of paper toward and away from the mirror until the smallest and sharpest spot of sunlight is focused on the paper. This spot is called the **focal point** of the mirror, the point where incident light rays that are parallel to the principal axis converge after reflecting from the mirror. The Sun is a source of parallel light rays because it is very far away. All of the light that comes directly from the Sun must follow almost parallel paths to Earth, just as all of the arrows shot by an archer must follow almost parallel paths to hit within the circle of a bull's-eye.

When a ray strikes a mirror, it is reflected according to the law of reflection. Figure 17-8 shows that a ray parallel to the principal axis is reflected and crosses the principal axis at point F , the focal point. F is at the halfway point between M and C . The **focal length**, f , is the position of the focal point with respect to the mirror along the principal axis and can be expressed as $f = r/2$. The focal length is positive for a concave mirror.



Graphical Method of Finding the Image

You have already drawn rays to follow the path of light that reflects off plane mirrors. This method is even more useful when applied to curved mirrors. Not only can the location of the image vary, but so can the orientation and size of the image. You can use a ray diagram to determine properties of an image formed by a curved mirror. **Figure 17-9** shows the formation of a **real image**, an image that is formed by the converging of light rays. The image is inverted and larger than the object. The rays actually converge at the point where the image is located. The point of intersection, I' , of the two reflected rays determines the position of the image. You can see the image floating in space if you place your eye so that the rays that form the image fall on your eye, as in **Figure 17-9a**. As **Figure 17-9b** shows, however, your eye must be oriented so as to see the rays coming from the image location. You cannot look at the image from behind. If you were to place a movie screen at this point, the image would appear on the screen, as shown in **Figure 17-9c**. You cannot do this with virtual images.

To more easily understand how ray tracing works with curved mirrors, you can use simple, one-dimensional objects, such as the arrow shown in **Figure 17-10a**. A spherical concave mirror produces an inverted real image if the object position, d_o , is greater than twice the focal length, f . The object is then beyond the center of curvature, C . If the object is placed between the center of curvature and the focal point, F , as shown in **Figure 17-10b**, the image is again real and inverted. However, the size of the image is now greater than the size of the object.

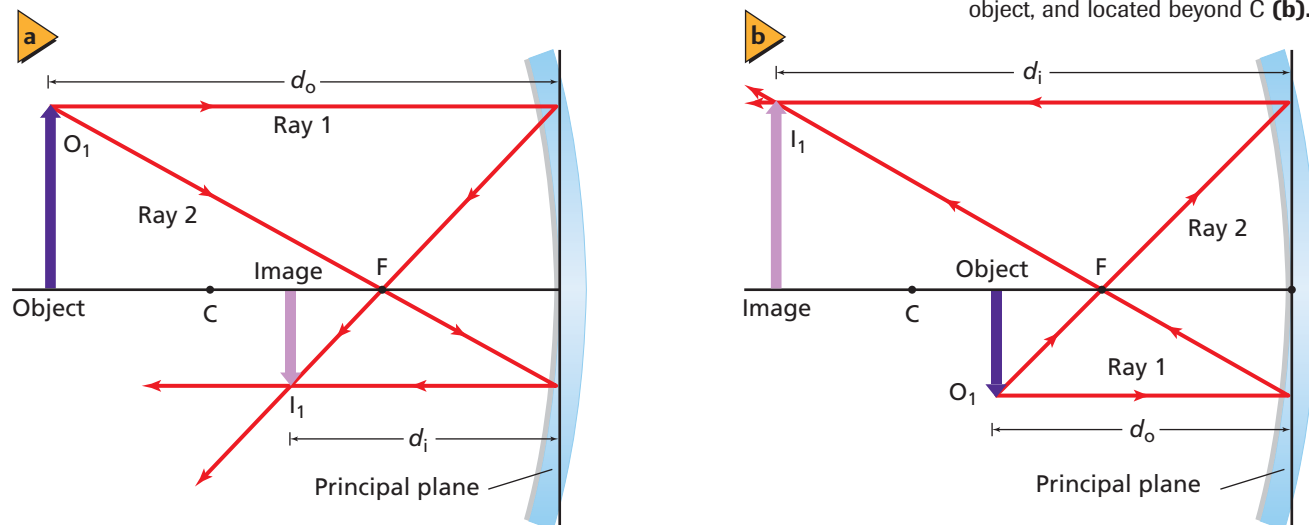


Figure 17-9 The real image, as seen by the unaided eye (**a**). The unaided eye cannot see the real image if it is not in a location to catch the rays that form the image (**b**). The real image as seen on a white screen (**c**).

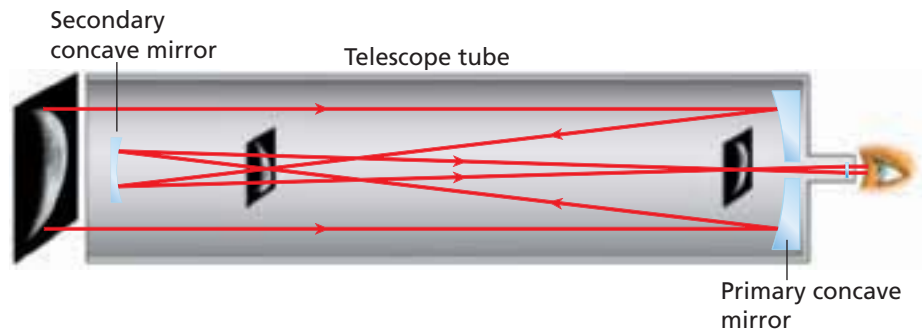


Interactive Figure To see an animation on the graphical method of finding the image, visit physicspp.com.

Figure 17-10 When the object is farther from the mirror than C , the image is a real image that is inverted and smaller compared to the object (**a**). When the object is located between C and F , the real image is inverted, larger than the object, and located beyond C (**b**).



■ **Figure 17-11** A Gregorian telescope produces a real image that is upright.



Astronomy Connection

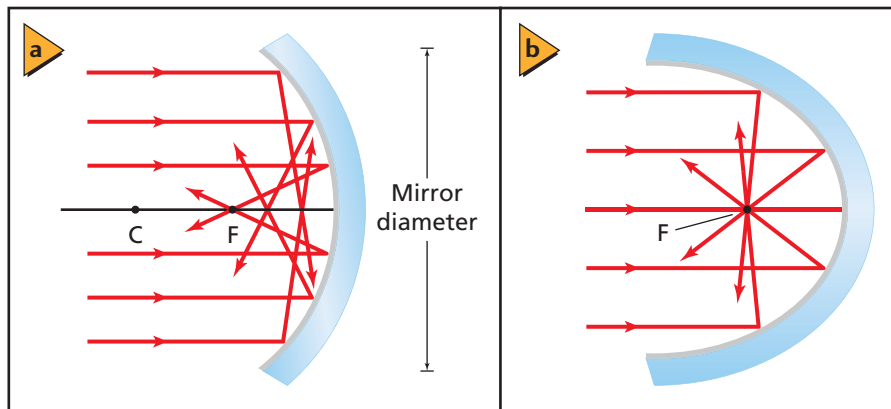
How can the inverted real image created by a concave mirror be turned right-side up? In 1663, Scottish astronomer James Gregory developed the Gregorian telescope, shown in **Figure 17-11**, to resolve this problem. It is composed of a large concave mirror and a small concave mirror arranged such that the smaller mirror is outside of the focal point of the larger mirror. Parallel rays of light from distant objects strike the larger mirror and reflect toward the smaller mirror. The rays then reflect off the smaller mirror and form a real image that is oriented exactly as the object is.

► PROBLEM-SOLVING Strategies

Using Ray Tracing to Locate Images Formed by Spherical Mirrors

Use the following strategies for spherical-mirror problems. Refer to Figure 17-10.

1. Using lined or graph paper, draw the principal axis of the mirror as a horizontal line from the left side to the right side of your paper, leaving six blank lines above and six blank lines below.
2. Place a point and a label on the principal axis the object, C, and F, as follows.
 - a. If the mirror is a concave mirror and the object is beyond C, away from the mirror, place the mirror at the right side of the page, place the object at the left side of the page, and place C and F to scale.
 - b. If the mirror is a concave mirror and the object is between C and F, place the mirror at the right side of the page, place C at the center of the paper, F halfway between the mirror and C, and the object to scale.
 - c. For any other situation, place the mirror in the center of the page. Place the object or F (whichever is the greatest distance from the mirror) at the left side of the page, and place the other to scale.
3. To represent the mirror, draw a vertical line at the mirror point that extends the full 12 lines of space. This is the principal plane.
4. Draw the object as an arrow and label its top O_1 . For concave mirrors, objects inside of C should not be higher than three lines high. For all other situations, the objects should be six lines high. The scale for the height of the object will be different from the scale along the principal axis.
5. Draw ray 1, the parallel ray. It is parallel to the principal axis and reflects off the principal plane and passes through F.
6. Draw ray 2, the focus ray. It passes through F, reflects off the principal plane, and is reflected parallel to the principal axis.
7. The image is located where rays 1 and 2 (or their sight lines) cross after reflection. Label the point I_1 . The image is an arrow perpendicular from the principal axis to I_1 .



■ **Figure 17-12** A concave spherical mirror reflects some rays, such that they converge at points other than the focus **(a)**. A parabolic mirror focuses all parallel rays at a point **(b)**.

Real image defects in concave mirrors In tracing rays, you have reflected the rays from the principal plane, which is a vertical line representing the mirror. In reality, rays are reflected off the mirror itself, as shown in **Figure 17-12a**. Notice that only parallel rays that are close to the principal axis, or paraxial rays, are reflected through the focal point. Other rays converge at points closer to the mirror. The image formed by parallel rays reflecting off a spherical mirror with a large mirror diameter and a small radius of curvature is a disk, not a point. This effect, called **spherical aberration**, makes an image look fuzzy, not sharp.

A mirror ground to the shape of a parabola, as in **Figure 17-12b**, suffers no spherical aberration. Because of the cost of manufacturing large, perfectly parabolic mirrors, many of the newest telescopes use spherical mirrors and smaller, specially-designed secondary mirrors or lenses to correct for spherical aberration. Also, spherical aberration is reduced as the ratio of the mirror's diameter, shown in Figure 17-12a, to its radius of curvature is reduced. Thus, lower-cost spherical mirrors can be used in lower-precision applications.

Mathematical Method of Locating the Image

The spherical mirror model can be used to develop a simple equation for spherical mirrors. You must use the paraxial ray approximation, which states that only rays that are close to and almost parallel with the principal axis are used to form an image. Using this, in combination with the law of reflection, leads to the mirror equation, relating the focal length, f , object position, d_o , and image position, d_i , of a spherical mirror.

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

The reciprocal of the focal length of a spherical mirror is equal to the sum of the reciprocals of the image position and the object position.

When using this equation to solve problems, it is important to remember that it is only approximately correct. It does not predict spherical aberration, because it uses the paraxial ray approximation. In reality, light coming from an object toward a mirror is diverging, so not all of the light is close to or parallel to the axis. When the mirror diameter is small relative to the radius of curvature to minimize spherical aberration, this equation predicts image properties more precisely.

APPLYING PHYSICS

► **Hubble Trouble** In 1990, NASA launched the *Hubble Space Telescope* into orbit around Earth. *Hubble* was expected to provide clear images without atmospheric distortions. However, soon after it was deployed, *Hubble* was found to have a spherical aberration. In 1993, corrective optics, called COSTAR, were installed on *Hubble* to enable it to produce clear images. ◀



▶ Connecting Math to Physics

Adding and Subtracting Fractions When using the mirror equation, you first use math to move the fraction that contains the quantity you are seeking to the left-hand side of the equation and everything else to the right. Then you combine the two fractions on the right-hand side using a common denominator that results from multiplying the denominators.

Math	Physics
$\frac{1}{x} = \frac{1}{y} + \frac{1}{z}$	$\frac{1}{f} = \frac{1}{d_i} + \frac{1}{d_o}$
$\frac{1}{y} = \frac{1}{x} - \frac{1}{z}$	$\frac{1}{d_i} = \frac{1}{f} - \frac{1}{d_o}$
$\frac{1}{y} = \left(\frac{1}{x}\right)\left(\frac{z}{z}\right) - \left(\frac{1}{z}\right)\left(\frac{x}{x}\right)$	$\frac{1}{d_i} = \left(\frac{1}{f}\right)\left(\frac{d_o}{d_o}\right) - \left(\frac{1}{d_o}\right)\left(\frac{f}{f}\right)$
$\frac{1}{y} = \frac{z-x}{xz}$	$\frac{1}{d_i} = \frac{d_o - f}{fd_o}$
$y = \frac{xz}{z-x}$	$d_i = \frac{fd_o}{d_o - f}$

Using this approach, the following relationships can be derived for image position, object position, and focal length:

$$d_i = \frac{fd_o}{d_o - f} \quad d_o = \frac{fd_i}{d_i - f} \quad f = \frac{d_i d_o}{d_o + d_i}$$

Magnification Another property of a spherical mirror is **magnification**, m , which is how much larger or smaller the image is relative to the object. In practice, this is a simple ratio of the image height to the object height. Using similar-triangle geometry, this ratio can be written in terms of image position and object position.

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

The magnification of an object by a spherical mirror, defined as the image height divided by the object height, is equal to the negative of the image position, divided by the object position.

Image position is positive for a real image when using the preceding equations. Thus, the magnification is negative, which means that the image is inverted compared to the object. If the object is beyond point C, the absolute value of the magnification for the real image is less than 1. This means that the image is smaller than the object. If the object is placed between point C and point F, the absolute value of the magnification for the real image is greater than 1. Thus, the image is larger than the object.

EXAMPLE Problem 2

Real Image Formation by a Concave Mirror A concave mirror has a radius of 20.0 cm. A 2.0-cm-tall object is 30.0 cm from the mirror. What is the image position and image height?

1 Analyze and Sketch the Problem

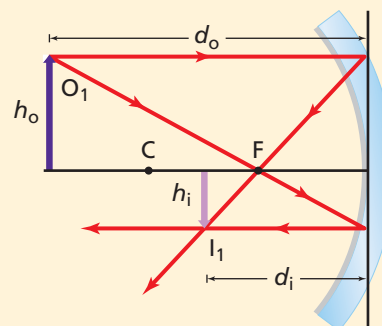
- Draw a diagram with the object and the mirror.
- Draw two principal rays to locate the image in the diagram.

Known:

$$\begin{aligned} h_o &= 2.0 \text{ cm} \\ d_o &= 30.0 \text{ cm} \\ r &= 20.0 \text{ cm} \end{aligned}$$

Unknown:

$$\begin{aligned} d_i &= ? \\ h_i &= ? \end{aligned}$$



2 Solve for the Unknown

Focal length is half the radius of curvature.

$$\begin{aligned} f &= \frac{r}{2} \\ &= \frac{20.0 \text{ cm}}{2} \\ &= 10.0 \text{ cm} \end{aligned} \quad \text{Substitute } r = 20.0 \text{ cm}$$

Use the mirror equation and solve for image position.

$$\begin{aligned} \frac{1}{f} &= \frac{1}{d_i} + \frac{1}{d_o} \\ d_i &= \frac{fd_o}{d_o - f} \\ &= \frac{(10.0 \text{ cm})(30.0 \text{ cm})}{30.0 \text{ cm} - 10.0 \text{ cm}} \\ &= 15.0 \text{ cm (real image, in front of the mirror)} \end{aligned} \quad \text{Substitute } f = 10.0 \text{ cm, } d_o = 30.0 \text{ cm}$$

Use the magnification equation and solve for image height.

$$\begin{aligned} m &= \frac{h_i}{h_o} = \frac{-d_i}{d_o} \\ h_i &= \frac{-d_i h_o}{d_o} \\ &= \frac{-(15.0 \text{ cm})(2.0 \text{ cm})}{30.0 \text{ cm}} \\ &= -1.0 \text{ cm (inverted, smaller image)} \end{aligned} \quad \text{Substitute } d_i = 15.0 \text{ cm, } h_o = 2.0 \text{ cm, } d_o = 30.0 \text{ cm}$$

Physics online

Personal Tutor For an online tutorial on image position and image height, visit physicspp.com.

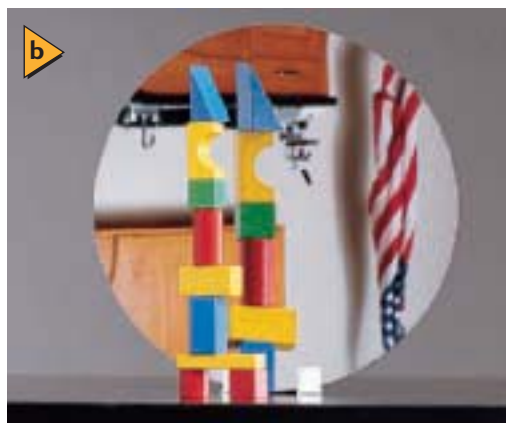
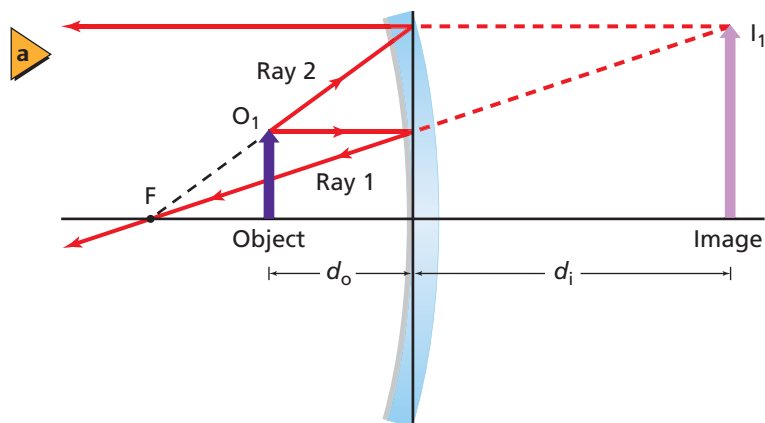
3 Evaluate the Answer

- **Are the units correct?** All positions are in centimeters.
- **Do the signs make sense?** Positive position and negative height agree with the drawing.

PRACTICE Problems

• Additional Problems, Appendix B
• Solutions to Selected Problems, Appendix C

- Use a ray diagram, drawn to scale, to solve Example Problem 2.
- An object is 36.0 cm in front of a concave mirror with a 16.0-cm focal length. Determine the image position.
- A 3.0-cm-tall object is 20.0 cm from a 16.0-cm-radius concave mirror. Determine the image position and image height.
- A concave mirror has a 7.0-cm focal length. A 2.4-cm-tall object is 16.0 cm from the mirror. Determine the image height.
- An object is near a concave mirror of 10.0-cm focal length. The image is 3.0 cm tall, inverted, and 16.0 cm from the mirror. What are the object position and object height?



■ **Figure 17-13** When an object is located between the focal point and a spherical concave mirror, a virtual image that is upright and larger compared to the object is formed behind the mirror **(a)**, as shown with the stack of blocks **(b)**. What else do you see in this picture?

Virtual Images with Concave Mirrors

You have seen that as an 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, therefore, and the image is said to be at infinity, so the object could never be seen. What happens if the object is moved even closer to the mirror?

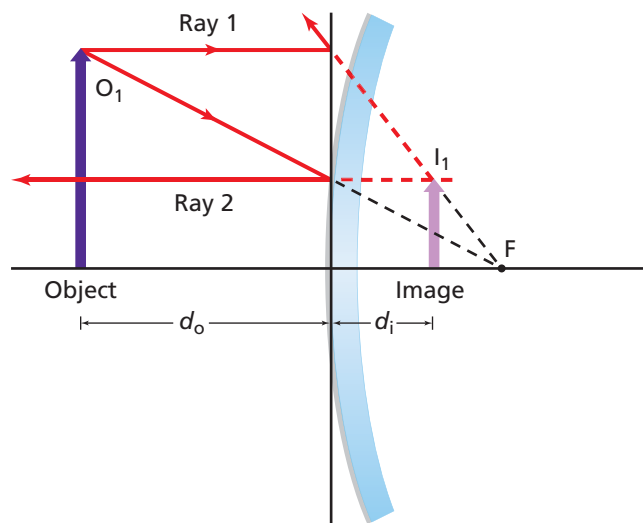
What do you see when you move your face close to a concave mirror? The image of your face is right-side up and behind the mirror. A concave mirror produces a virtual image if the object is located between the mirror and the focal point, as shown in the ray diagram in **Figure 17-13a**. Again, two rays 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. Ray 2 is drawn as a line from the point on the object to the mirror, along a line defined by the focal point and the point on the object. At the mirror, ray 2 is reflected parallel to the principal axis. Note that ray 1 and ray 2 diverge as they leave the mirror, so there cannot be a real image. However, sight lines extended behind the mirror converge, showing that the virtual image forms behind the mirror.

When you use the mirror equation to solve problems involving concave mirrors for which an object is between the mirror and the focal point, you will find that the image position is negative. The magnification equation gives a positive magnification greater than 1, which means that the image is upright and larger compared to the object, like the image in **Figure 17-13b**.

CHALLENGE PROBLEM

An object of height h_o is located at d_o relative to a concave mirror with focal length f .

1. Draw and label a ray diagram showing the focal length and location of the object if the image is located twice as far from the mirror as the object. Prove your answer mathematically. Calculate the focal length as a function of object position for this placement.
2. Draw and label a ray diagram showing the location of the object if the image is located twice as far from the mirror as the focal point. Prove your answer mathematically. Calculate the image height as a function of the object height for this placement.
3. Where should the object be located so that no image is formed?



■ **Figure 17-14** A convex mirror always produces virtual images that are upright and smaller compared to the object.

Convex Mirrors

In the first part of this chapter, you learned that the inner surface of a shiny spoon acts as a concave mirror. If you turn the spoon around, the outer surface acts as a **convex mirror**, a reflective surface with edges that curve away from the observer. What do you see when you look at the back of a spoon? You see an upright, but smaller image of yourself.

Properties of a spherical convex mirror are shown in **Figure 17-14**. Rays reflected from a convex mirror always diverge. Thus, convex mirrors form virtual images. Points F and C are behind the mirror. In the mirror equation, f and d_i are negative numbers because they are both behind the mirror.

The ray diagram in Figure 17-14 represents how an image is formed by a spherical convex mirror. The figure uses two rays, but remember that there are an infinite number of rays. Ray 1 approaches the mirror parallel to the principal axis. The reflected ray is drawn along a sight line from F through the point where ray 1 strikes the mirror. Ray 2 approaches the mirror on a path that, if extended behind the mirror, would pass through F. The reflected part of ray 2 and its sight line are parallel to the principal axis. The two reflected rays diverge, and the sight lines intersect behind the mirror at the location of the image. An image produced by a single convex mirror is a virtual image that is upright and smaller compared to the object.

The magnification equation is useful for determining the apparent dimensions of an object as seen in a spherical convex mirror. If you know the diameter of an object, you can multiply by the magnification fraction to see how the diameter changes. You will find that the diameter is smaller, as are all other dimensions. This is why the objects appear to be farther away than they actually are for convex mirrors.

Field of view It may seem that convex mirrors would have little use because the images that they form are smaller than the objects. However, this property of convex mirrors does have practical uses. By forming smaller images, convex mirrors enlarge the area, or field of view, that an observer sees, as shown in **Figure 17-15**. Also, the center of this field of view is visible from any angle of an observer off the principal axis of the mirror; thus, the field of view is visible from a wide perspective. For this reason, convex mirrors often are used in cars as passenger-side rearview mirrors.



■ **Figure 17-15** Convex mirrors produce images that are smaller than the objects. This increases the field of view for observers.

EXAMPLE Problem 3

Image in a Security Mirror A convex security mirror in a warehouse has a -0.50-m focal length. A 2.0-m -tall forklift is 5.0 m from the mirror. What are the image position and image height?

1 Analyze and Sketch the Problem

- Draw a diagram with the mirror and the object.
- Draw two principal rays to locate the image in the diagram.

Known:

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

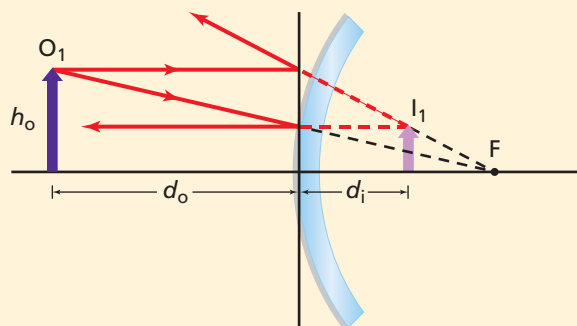
$$d_o = 5.0\text{ m}$$

$$f = -0.50\text{ m}$$

Unknown:

$$d_i = ?$$

$$h_i = ?$$



2 Solve for the Unknown

Use the mirror equation and solve for image position.

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

$$d_i = \frac{fd_o}{d_o - f}$$

$$= \frac{(-0.50\text{ m})(5.0\text{ m})}{5.0\text{ m} - 0.50\text{ m}} \quad \text{Substitute } f = -0.50\text{ m}, d_o = 5.0\text{ m}$$

$$= -0.45\text{ m (virtual image, behind the mirror)}$$

Use the magnification equation and solve for image height.

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

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

$$= \frac{-(-0.45\text{ m})(2.0\text{ m})}{(5.0\text{ m})} \quad \text{Substitute } d_i = -0.45\text{ m}, h_o = 2.0\text{ m}, d_o = 5.0\text{ m}$$

$$= 0.18\text{ m (upright, smaller image)}$$

Math Handbook

Isolating a Variable
page 845

3 Evaluate the Answer

- **Are the units correct?** All positions are in meters.
- **Do the signs make sense?** A negative position indicates a virtual image; a positive height indicates an image that is upright. These agree with the diagram.

PRACTICE Problems

• Additional Problems, Appendix B
• Solutions to Selected Problems, Appendix C

- An object is located 20.0 cm in front of a convex mirror with a -15.0-cm focal length. Find the image position using both a scale diagram and the mirror equation.
- A convex mirror has a focal length of -13.0 cm . A lightbulb with a diameter of 6.0 cm is placed 60.0 cm from the mirror. What is the lightbulb's image position and diameter?
- A convex mirror is needed to produce an image that is three-fourths the size of an object and located 24 cm behind the mirror. What focal length should be specified?
- A 7.6-cm -diameter ball is located 22.0 cm from a convex mirror with a radius of curvature of 60.0 cm . What are the ball's image position and diameter?
- A 1.8-m -tall girl stands 2.4 m from a store's security mirror. Her image appears to be 0.36 m tall. What is the focal length of the mirror?



Table 17-1					
Single-Mirror System Properties					
Mirror Type	f	d_o	d_i	m	Image
Plane	N/A	$d_o > 0$	$ d_i = d_o$ (negative)	Same size	Virtual
Concave	+	$d_o > r$	$r > d_i > f$	Reduced, inverted	Real
		$r > d_o > f$	$d_i > r$	Enlarged, inverted	Real
		$f > d_o > 0$	$ d_i > d_o$ (negative)	Enlarged	Virtual
Convex	–	$d_o > 0$	$ f > d_i > 0$ (negative)	Reduced	Virtual

Mirror Comparison

How do the various types of mirrors compare? **Table 17-1** compares the properties of single-mirror systems with objects that are located on the principal axis of the mirror. Virtual images are always behind the mirror, which means that the image position is negative. When the absolute value of a magnification is between zero and one, the image is smaller than the object. A negative magnification means the image is inverted relative to the object. Notice that the single plane mirror and convex mirror produce only virtual images, whereas the concave mirror can produce real images or virtual images. Plane mirrors give simple reflections, and convex mirrors expand the field of view. A concave mirror acts as a magnifier when an object is within the focal length of the mirror.

17.2 Section Review

- 22. Image Properties** If you know the focal length of a concave mirror, where should you place an object so that its image is upright and larger compared to the object? Will this produce a real or virtual image?
- 23. Magnification** An object is placed 20.0 cm in front of a concave mirror with a focal length of 9.0 cm. What is the magnification of the image?
- 24. Object Position** The placement of an object in front of a concave mirror with a focal length of 12.0 cm forms a real image that is 22.3 cm from the mirror. What is the object position?
- 25. Image Position and Height** A 3.0-cm-tall object is placed 22.0 cm in front of a concave mirror having a focal length of 12.0 cm. Find the image position and height by drawing a ray diagram to scale. Verify your answer using the mirror and magnification equations.
- 26. Ray Diagram** A 4.0-cm-tall object is located 14.0 cm from a convex mirror with a focal length of -12.0 cm. Draw a scale ray diagram showing the image position and height. Verify your answer using the mirror and magnification equations.
- 27. Radius of Curvature** A 6.0-cm-tall object is placed 16.4 cm from a convex mirror. If the image of the object is 2.8 cm tall, what is the radius of curvature of the mirror?
- 28. Focal Length** A convex mirror is used to produce an image that is two-thirds the size of an object and located 12 cm behind the mirror. What is the focal length of the mirror?
- 29. Critical Thinking** Would spherical aberration be less for a mirror whose height, compared to its radius of curvature, is small or large? Explain.

Concave Mirror Images

Alternate CBL instructions can be found on the Web site.

physicspp.com

A concave mirror reflects light rays that arrive parallel to the principal axis through the focal point. Depending on the object position, different types of images can be formed. Real images can be projected onto a screen while virtual images cannot. In this experiment you will investigate how changing the object position affects the image location and type.

QUESTION

What are the conditions needed to produce real and virtual images using a concave mirror?

Objectives

- **Collect and organize data** of object and image positions.
- **Observe** real and virtual images.
- **Summarize** conditions for production of real and virtual images with a concave mirror.

Safety Precautions



- **Do not look at the reflection of the Sun in a mirror or use a concave mirror to focus sunlight.**

Materials

concave mirror	two metersticks
flashlight	four meterstick supports
screen support	screen
mirror holder	lamp with a 15-W lightbulb

Procedure

1. Determine the focal length of your concave mirror by using the following procedure.
CAUTION: Do not use the Sun to perform this procedure. Reflect light from a flashlight onto a screen and slowly move the screen closer or farther away from the mirror until a sharp, bright image is visible. Measure the distance between the screen and the mirror along the principal axis. Record this value as the actual focal length of the mirror, f .
2. On the lab table, set up two metersticks on supports in a V orientation. Place the zero measurement ends at the apex of the two metersticks.
3. Place the mirror in a mirror holder and place it at the apex of the two metersticks.
4. Using the lamp as the object of the reflection, place it on one meterstick at the opposite end from the apex. Place the screen, supported by a screen support, on the other meterstick at the opposite end from the apex.
5. Turn the room lights off.
6. Turn on the lamp. **CAUTION: Do not touch the hot lightbulb.** Measure object position, d_o , and record this as Trial 1. Measure the object height, h_o , and record it as Trial 1. This is measured as the actual height of the lightbulb, or glowing filament if the bulb is clear.
7. Adjust the mirror or metersticks, as necessary, such that the reflected light shines on the screen. Slowly move the screen back and forth along the meterstick until a sharp image is seen. Measure image position, d_i , and the image height, h_i , and record these as Trial 1.



Data Table

Trial	d_o (cm)	d_i (cm)	h_o (cm)	h_i (cm)
1				
2				
3				
4				
5				

Calculation Table

Trial	$\frac{1}{d_o}$ (cm ⁻¹)	$\frac{1}{d_i}$ (cm ⁻¹)	$\frac{1}{d_o} + \frac{1}{d_i}$ (cm ⁻¹)	f_{calc} (cm)	% error
1					
2					
3					
4					
5					

- Move the lamp closer to the mirror so that d_o is twice the focal length, f . Record this as Trial 2. Move the screen until an image is obtained on the screen. Measure d_i and h_i , and record these as Trial 2.
- Move the lamp closer to the mirror so that d_o is a few centimeters larger than f . Record this as Trial 3. Move the screen until an image is obtained on the screen. Measure d_i and h_i , and record these as Trial 3.
- Move the lamp so that d_o is equal to f . Record this as Trial 4 data. Move the screen back and forth and try to obtain an image. What do you observe?
- Move the lamp so that d_o is less than f by a few centimeters. Record this as Trial 5. Move the screen back and forth and try to obtain an image. What do you observe?

Analyze

- Use Numbers** Calculate $1/d_o$ and $1/d_i$ and enter the values in the calculation table.
- Use Numbers** Calculate the sum of $1/d_o$ and $1/d_i$ and enter the values in the calculation table. Calculate the reciprocal of this number and enter it in the calculation table as f_{calc} .
- Error Analysis** Compare the experimental focal length, f_{calc} , with f , the accepted focal length, by finding the percent error.

$$\text{percent error} = \frac{|f - f_{\text{calc}}|}{f} \times 100$$

Conclude and Apply

- Classify** What type of image was observed in each of the trials?
- Analyze** What conditions cause real images to be formed?
- Analyze** What conditions cause virtual images to be formed?

Going Further

- What are the conditions needed for the image to be larger than the object?
- Review the methods used for data collection. Identify sources of error and what might be done to improve accuracy.

Real-World Physics

What advantage would there be in using a telescope with a concave mirror?



To find out more about reflection, visit the Web site: physicspp.com

Adaptive Optical Systems

Objects in space are difficult to observe from Earth because they twinkle. Our moving, unevenly-heated atmosphere refracts their light in a chaotic manner. It's like trying to look at a small object through the bottom of an empty, clear, glass jar while rotating the jar.

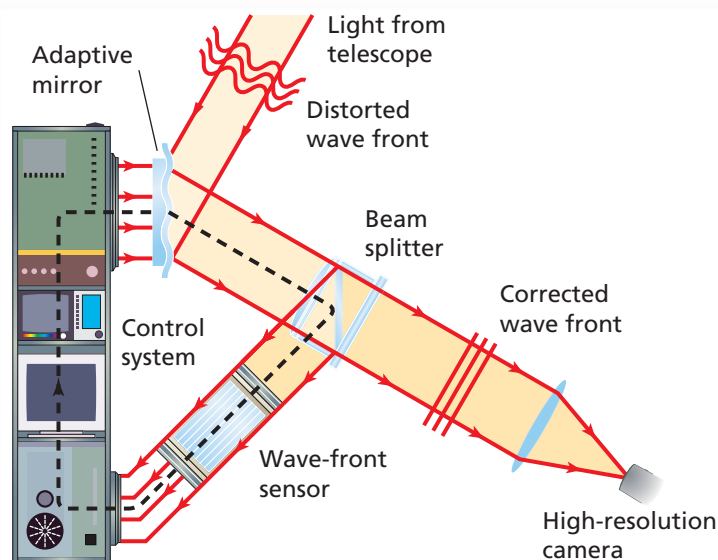
Flexible Adaptive Mirror

An adaptive optical system (AOS) continuously compensates for the distortion of the atmosphere, removing the twinkle from star images to allow astronomers to view and photograph steady images of the most distant objects in the visible universe.

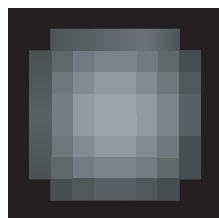
An AOS directs the magnified image of the stars from the telescope onto a flexible adaptive mirror made of thin glass. This mirror is stretched across 20–30 movable pistons that can poke or pull the surface of the mirror into many complicated shapes. Each piston is driven by a fast, computer-controlled motor. When the mirror surface is shaped into just the right pattern at just the right time, it will compensate for the convective movement of the atmosphere between the telescope and the star, and reflect a clear image to the observer or camera.

Wave-Front Sensor To detect the atmospheric distortion at each instant of time, a wave-front sensor looks at a single star through the telescope. This device has an array of tiny lenses (lenslets) in several rows. Each lenslet forms an image of the star on a sensitive screen behind it. The position of each image can be read by the computer.

If each image is not directly behind its lenslet, then the computer knows that the star's light waves are being distorted by the atmosphere. A star is a distant point source of light, so it should produce plane waves. Distorted images of a star are non-planar light waves, and these uneven waves cause the images of the star behind some of the lenslets to be displaced.



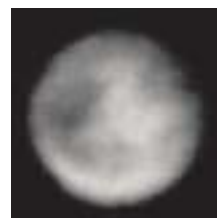
AOS compensates for distortion when viewing Titan, Saturn's largest moon.



Conventional telescope



Hubble Space Telescope



Keck telescope with AOS

The computer looks at this error and calculates how the adaptive mirror should be wrinkled to bring each of the lenslet images back into place. The star image reflected to the observer then will be correct, and a clear image of all other objects (like galaxies and planets) in the vicinity also will be seen clearly. The adaptive mirror is re-shaped about 1000 times per second.

Going Further

1. **Research** What is done if there is not a suitable star for the wave-front sensor to analyze in a region of space under observation?
2. **Apply** Research how adaptive optics will be used in the future to correct vision.

17.1 Reflection from Plane Mirrors

Vocabulary

- specular reflection (p. 459)
- diffuse reflection (p. 459)
- plane mirror (p. 461)
- object (p. 461)
- image (p. 461)
- virtual image (p. 461)

Key Concepts

- According to the law of reflection, the angle that an incident ray makes with the normal equals the angle that the reflected ray makes with the normal.

$$\theta_r = \theta_i$$

- The law of reflection applies to both smooth and rough surfaces. A rough surface, however, has normals that go in lots of different directions, which means that parallel incident rays will not be reflected in parallel.
- A smooth surface produces specular reflection. A rough surface produces diffuse reflection.
- Specular reflection results in the formation of images that appear to be behind plane mirrors.
- An image produced by a plane mirror is always virtual, is the same size as the object, has the same orientation, and is the same distance from the mirror as the object.

$$d_i = -d_o \quad h_i = h_o$$

17.2 Curved Mirrors

Vocabulary

- concave mirror (p. 464)
- principal axis (p. 464)
- focal point (p. 464)
- focal length (p. 464)
- real image (p. 465)
- spherical aberration (p. 467)
- magnification (p. 468)
- convex mirror (p. 471)

Key Concepts

- You can locate the image created by a spherical mirror by drawing two rays from a point on the object to the mirror. The intersection of the two reflected rays is the image of the object point.
- The mirror equation gives the relationship among image position, object position, and focal length of a spherical mirror.

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

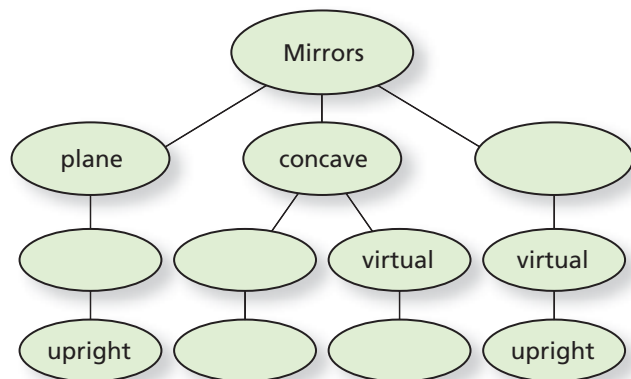
- The magnification of a mirror image is given by equations relating either the positions or the heights of the image and the object.

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

- A single concave mirror produces a real image that is inverted when the object position is greater than the focal length.
- A single concave mirror produces a virtual image that is upright when the object position is less than the focal length.
- A single convex mirror always produces a virtual image that is upright and smaller compared to the object.
- By forming smaller images, convex mirrors make images seem farther away and produce a wide field of view.
- Mirrors can be used in combinations to produce images of any size, orientation, and location desired. The most common use of combinations of mirrors is as telescopes.

Concept Mapping

30. Complete the following concept map using the following terms: *convex*, *upright*, *inverted*, *real*, *virtual*.

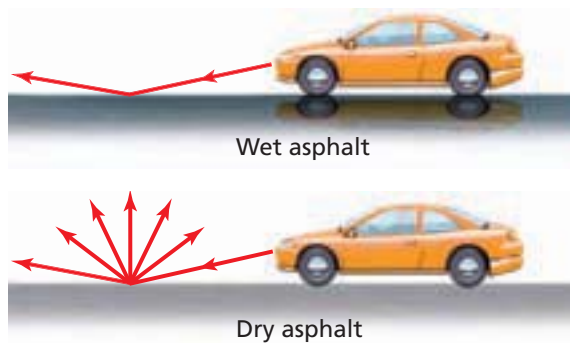


Mastering Concepts

31. How does specular reflection differ from diffuse reflection? (17.1)
32. What is meant by the phrase “normal to the surface”? (17.1)
33. Where is the image produced by a plane mirror located? (17.1)
34. Describe the properties of a plane mirror. (17.1)
35. A student believes that very sensitive photographic film can detect a virtual image. The student puts photographic film at the location of a virtual image. Does this attempt succeed? Explain. (17.1)
36. How can you prove to someone that an image is a real image? (17.1)
37. An object produces a virtual image in a concave mirror. Where is the object located? (17.2)
38. What is the defect that all concave spherical mirrors have and what causes it? (17.2)
39. What is the equation relating the focal point, object position, and image position? (17.2)
40. What is the relationship between the center of curvature and the focal length of a concave mirror? (17.2)
41. If you know the image position and object position relative to a curved mirror, how can you determine the mirror’s magnification? (17.2)
42. Why are convex mirrors used as rearview mirrors? (17.2)
43. Why is it impossible for a convex mirror to form a real image? (17.2)

Applying Concepts

44. **Wet Road** A dry road is more of a diffuse reflector than a wet road. Based on **Figure 17-16**, explain why a wet road appears blacker to a driver than a dry road does.



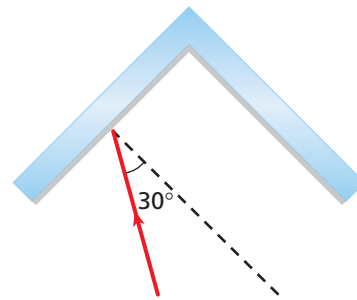
■ Figure 17-16

45. **Book Pages** Why is it desirable that the pages of a book be rough rather than smooth and glossy?
46. Locate and describe the physical properties of the image produced by a concave mirror when the object is located at the center of curvature.
47. An object is located beyond the center of curvature of a spherical concave mirror. Locate and describe the physical properties of the image.
48. **Telescope** You have to order a large concave mirror for a telescope that produces high-quality images. Should you order a spherical mirror or a parabolic mirror? Explain.
49. Describe the properties of the image seen in the single convex mirror in **Figure 17-17**.



■ Figure 17-17

50. List all the possible arrangements in which you could use a spherical mirror, either concave or convex, to form a real image.
51. List all possible arrangements in which you could use a spherical mirror, either concave or convex, to form an image that is smaller compared to the object.
52. **Rearview Mirrors** The outside rearview mirrors of cars often carry the warning "Objects in the mirror are closer than they appear." What kind of mirrors are these and what advantage do they have?
57. Two adjacent plane mirrors form a right angle, as shown in **Figure 17-19**. A light ray is incident upon one of the mirrors at an angle of 30° to the normal.
- What is the angle at which the light ray is reflected from the other mirror?
 - A retroreflector is a device that reflects incoming light rays back in a direction opposite to that of the incident rays. Draw a diagram showing the angle of incidence on the first mirror for which the mirror system acts as a retroreflector.



■ Figure 17-19

Mastering Problems

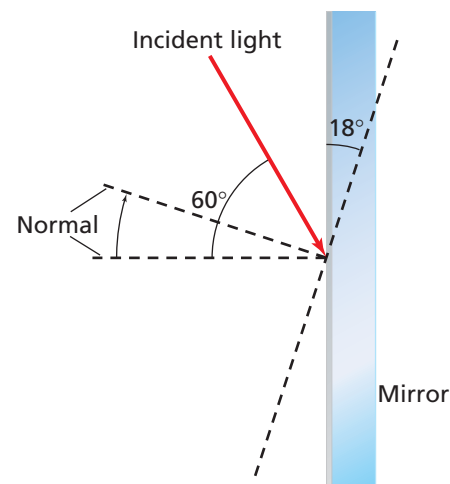
17.1 Reflection from Plane Mirrors

53. A ray of light strikes a mirror at an angle of 38° to the normal. What is the angle that the reflected angle makes with the normal?
54. A ray of light strikes a mirror at an angle of 53° to the normal.
- What is the angle of reflection?
 - What is the angle between the incident ray and the reflected ray?
55. A ray of light incident upon a mirror makes an angle of 36° with the mirror. What is the angle between the incident ray and the reflected ray?
56. **Picture in a Mirror** Penny wishes to take a picture of her image in a plane mirror, as shown in **Figure 17-18**. If the camera is 1.2 m in front of the mirror, at what distance should the camera lens be focused?



■ Figure 17-18

58. 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.
59. Two plane mirrors are connected at their sides so that they form a 45° angle between them. A light ray strikes one mirror at an angle of 30° to the normal and then reflects off the second mirror. Calculate the angle of reflection of the light ray off the second mirror.
60. A ray of light strikes a mirror at an angle of 60° to the normal. The mirror is then rotated 18° clockwise, as shown in **Figure 17-20**. What is the angle that the reflected ray makes with the mirror?

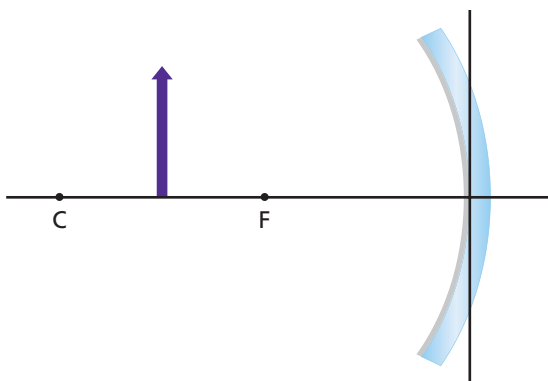


■ Figure 17-20

Chapter 17 Assessment

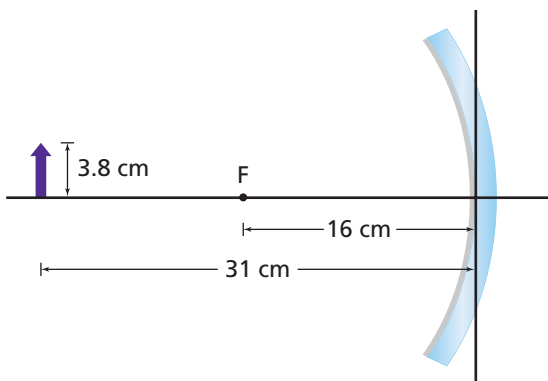
17.2 Curved Mirrors

61. A concave mirror has a focal length of 10.0 cm. What is its radius of curvature?
62. An object located 18 cm from a convex mirror produces a virtual image 9 cm from the mirror. What is the magnification of the image?
63. **Fun House** A boy is standing near a convex mirror in a fun house at a fair. He notices that his image appears to be 0.60 m tall. If the magnification of the mirror is $\frac{1}{3}$, what is the boy's height?
64. Describe the image produced by the object in **Figure 17-21** as real or virtual, inverted or upright, and smaller or larger than the object.



■ Figure 17-21

65. **Star Image** 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?
66. Find the image position and height for the object shown in **Figure 17-22**.



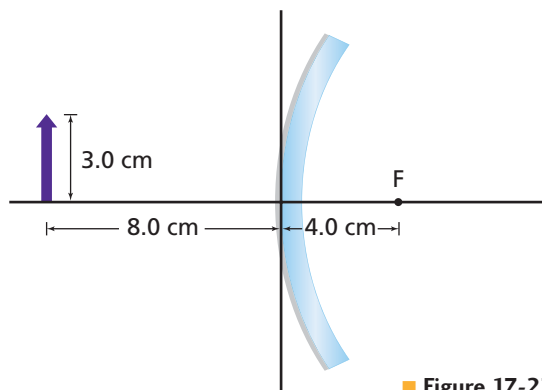
■ Figure 17-22

67. **Rearview Mirror** How far does the image of a car appear behind a convex mirror, with a focal length of -6.0 m, when the car is 10.0 m from the mirror?

68. An object is 30.0 cm from a concave mirror of 15.0 cm focal length. The object is 1.8 cm tall. Use the mirror equation to find the image position. What is the image height?
69. **Dental Mirror** A dentist uses a small mirror with a radius of 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?
70. A 3.0-cm-tall object is 22.4 cm from a concave mirror. If the mirror has a radius of curvature of 34.0 cm, what are the image position and height?
71. **Jeweler's Mirror** 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?
72. Sunlight falls on a concave mirror and forms an image that is 3.0 cm from the mirror. An object that is 24 mm tall is placed 12.0 cm from the mirror.
 - a. Sketch the ray diagram to show the location of the image.
 - b. Use the mirror equation to calculate the image position.
 - c. How tall is the image?
73. Shiny spheres that are placed on pedestals on a lawn are convex mirrors. One such sphere has a diameter of 40.0 cm. A 12-cm-tall robin sits in a tree that is 1.5 m from the sphere. Where is the image of the robin and how tall is the image?

Mixed Review

74. A light ray strikes a plane mirror at an angle of 28° to the normal. If the light source is moved so that the angle of incidence increases by 34° , what is the new angle of reflection?
75. Copy **Figure 17-23** on a sheet of paper. Draw rays on the diagram to determine the height and location of the image.



■ Figure 17-23

76. An object is located 4.4 cm in front of a concave mirror with a 24.0-cm radius. Locate the image using the mirror equation.
77. A concave mirror has a radius of curvature of 26.0 cm. An object that is 2.4 cm tall is placed 30.0 cm from the mirror.
- Where is the image position?
 - What is the image height?
78. What is the radius of curvature of a concave mirror that magnifies an object by a factor of +3.2 when the object is placed 20.0 cm from the mirror?
79. A convex mirror is needed to produce an image one-half the size of an object and located 36 cm behind the mirror. What focal length should the mirror have?
80. **Surveillance Mirror** A convenience store uses a surveillance mirror to monitor the store's aisles. Each mirror has a radius of curvature of 3.8 m.
- What is the image position of a customer who stands 6.5 m in front of the mirror?
 - What is the image height of a customer who is 1.7 m tall?
81. **Inspection Mirror** A production-line inspector wants a mirror that produces an image that is upright with a magnification of 7.5 when it is located 14.0 mm from a machine part.
- What kind of mirror would do this job?
 - What is its radius of curvature?
82. The object in **Figure 17-24** moves from position 1 to position 2. Copy the diagram onto a sheet of paper. Draw rays showing how the image changes.

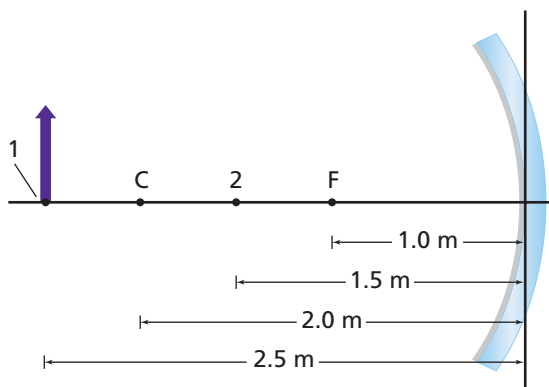


Figure 17-24

83. A ball is positioned 22 cm in front of a spherical mirror and forms a virtual image. If the spherical mirror is replaced with a plane mirror, the image appears 12 cm closer to the mirror. What kind of spherical mirror was used?

84. A 1.6-m-tall girl stands 3.2 m from a convex mirror. What is the focal length of the mirror if her image appears to be 0.28 m tall?
85. **Magic Trick** A magician uses a concave mirror with a focal length of 8.0 m to make a 3.0-m-tall hidden object, located 18.0 m from the mirror, appear as a real image that is seen by his audience. Draw a scale ray diagram to find the height and location of the image.
86. A 4.0-cm-tall object is placed 12.0 cm from a convex mirror. If the image of the object is 2.0 cm tall, and the image is located at -6.0 cm, what is the focal length of the mirror? Draw a ray diagram to answer the question. Use the mirror equation and the magnification equation to verify your answer.

Thinking Critically

87. **Apply Concepts** The ball in **Figure 17-25** slowly rolls toward the concave mirror on the right. Describe how the size of the ball's image changes as it rolls along.

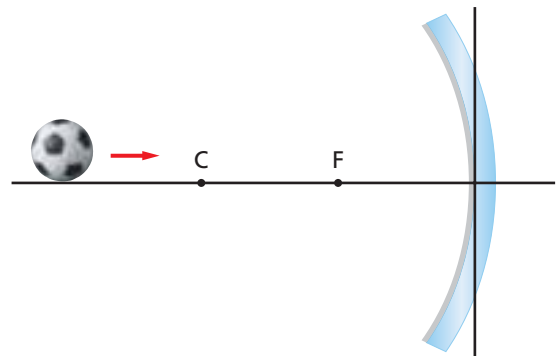


Figure 17-25

88. **Analyze and Conclude** The object in **Figure 17-26** is located 22 cm from a concave mirror. What is the focal length of the mirror?

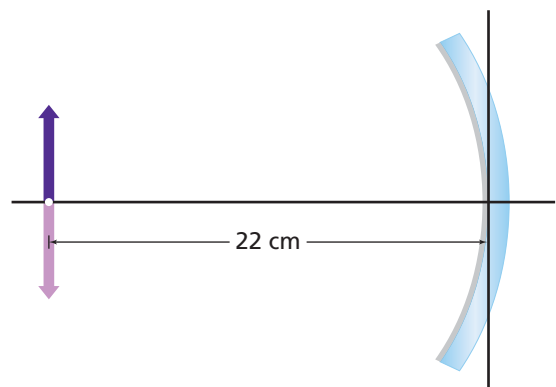
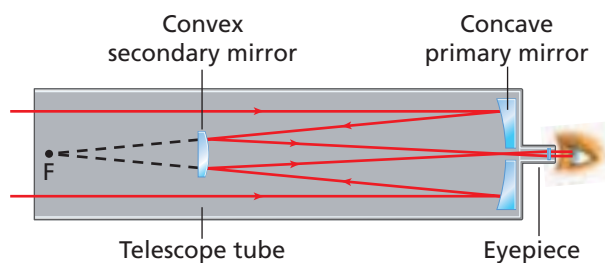


Figure 17-26

Chapter 17 Assessment

89. **Use Equations** Show that as the radius of curvature of a concave mirror increases to infinity, the mirror equation reduces to the relationship between the object position and the image position for a plane mirror.
90. **Analyze and Conclude** An object is located 6.0 cm from a plane mirror. If the plane mirror is replaced with a concave mirror, the resulting image is 8.0 cm farther behind the mirror. Assuming that the object is located between the focal point and the concave mirror, what is the focal length of the concave mirror?
91. **Analyze and Conclude** The layout of the two-mirror system shown in Figure 17-11 is that of a Gregorian telescope. For this question, the larger concave mirror has a radius of curvature of 1.0 m, and the smaller mirror is located 0.75 m away. Why is the secondary mirror concave?
92. **Analyze and Conclude** An optical arrangement used in some telescopes is the Cassegrain focus, shown in **Figure 17-27**. This telescope uses a convex secondary mirror that is positioned between the primary mirror and the focal point of the primary mirror.



■ Figure 17-27

- a. A single convex mirror produces only virtual images. Explain how the convex mirror in this telescope functions within the system of mirrors to produce real images.
- b. Are the images produced by the Cassegrain focus upright or inverted? How does this relate to the number of times that the light crosses?

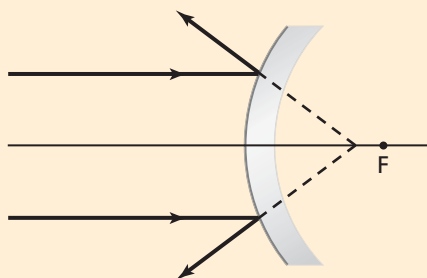
Writing in Physics

93. Research a method used for grinding, polishing, and testing mirrors used in reflecting telescopes. You may report either on methods used by amateur astronomers who make their own telescope optics, or on a method used by a project at a national laboratory. Prepare a one-page report describing the method, and present it to the class.
94. Mirrors reflect light because of their metallic coating. Research and write a summary of one of the following:
- the different types of coatings used and the advantages and disadvantages of each
 - the precision optical polishing of aluminum to such a degree of smoothness that no glass is needed in the process of making a mirror
- ## Cumulative Review
95. A child runs down the school hallway and then slides on the newly waxed floor. He was running at 4.7 m/s before he started sliding and he slid 6.2 m before stopping. What was the coefficient of friction of the waxed floor? (Chapter 11)
96. A 1.0 g piece of copper falls from a height of 1.0×10^3 m from an airplane to the ground. Because of air resistance it reaches the ground moving at a velocity of 70.0 m/s. Assuming that half of the energy lost by the piece was distributed as thermal energy to the copper, how much did it heat during the fall? (Chapter 12)
97. It is possible to lift a person who is sitting on a pillow made from a large sealed plastic garbage bag by blowing air into the bag through a soda straw. Suppose that the cross-sectional area of the person sitting on the bag is 0.25 m^2 and the person's weight is 600 N. The soda straw has a cross-sectional area of $2 \times 10^{-5} \text{ m}^2$. With what pressure must you blow into the straw to lift the person that is sitting on the sealed garbage bag? (Chapter 13)
98. What would be the period of a 2.0-m-long pendulum on the Moon's surface? The Moon's mass is $7.34 \times 10^{22} \text{ kg}$, and its radius is $1.74 \times 10^6 \text{ m}$. What is the period of this pendulum on Earth? (Chapter 14)
99. **Organ pipes** An organ builder must design a pipe organ that will fit into a small space. (Chapter 15)
- Should he design the instrument to have open pipes or closed pipes? Explain.
 - Will an organ constructed with open pipes sound the same as one constructed with closed pipes? Explain.
100. Filters are added to flashlights so that one shines red light and the other shines green light. The beams are crossed. Explain in terms of waves why the light from both flashlights is yellow where the beams cross, but revert back to their original colors beyond the intersection point. (Chapter 16)

Standardized Test Practice

Multiple Choice

- Where is the object located if the image that is produced by a concave mirror is smaller than the object?
☐ (A) at the mirror's focal point
☐ (B) between the mirror and the focal point
☐ (C) between the focal point and center of curvature
☐ (D) past the center of curvature
- What is the focal length of a concave mirror that magnifies, by a factor of +3.2, an object that is placed 30 cm from the mirror?
☐ (A) 23 cm
☐ (B) 32 cm
☐ (C) 44 cm
☐ (D) 46 cm
- An object is placed 21 cm in front of a concave mirror with a focal length of 14 cm. What is the image position?
☐ (A) -42 cm
☐ (B) -8.4 cm
☐ (C) 8.4 cm
☐ (D) 42 cm
- The light rays in the illustration below do not properly focus at the focal point. This problem occurs with _____.
☐ (A) all spherical mirrors
☐ (B) all parabolic mirrors
☐ (C) only defective spherical mirrors
☐ (D) only defective parabolic mirrors
- A ray of light strikes a plane mirror at an angle of 23° to the normal. What is the angle between the reflected ray and the mirror?
☐ (A) 23°
☐ (B) 46°
☐ (C) 67°
☐ (D) 134°
- A concave mirror produces an inverted image that is 8.5 cm tall, located 34.5 cm in front of the mirror. If the focal point of the mirror is 24.0 cm, then what is the height of the object that is reflected?
☐ (A) 2.3 cm
☐ (B) 3.5 cm
☐ (C) 14 cm
☐ (D) 19 cm
- A concave mirror with a focal length of 16.0 cm produces an image located 38.6 cm from the mirror. What is the distance of the object from the front of the mirror?
☐ (A) 2.4 cm
☐ (B) 11.3 cm
☐ (C) 22.6 cm
☐ (D) 27.3 cm
- A convex mirror is used to produce an image that is three-fourths the size of an object and located 8.4 cm behind the mirror. What is the focal length of the mirror?
☐ (A) -34 cm
☐ (B) -11 cm
☐ (C) -6.3 cm
☐ (D) -4.8 cm
- A cup sits 17 cm from a concave mirror. The image of the book appears 34 cm in front of the mirror. What are the magnification and orientation of the cup's image?
☐ (A) 0.5, inverted
☐ (B) 0.5, upright
☐ (C) 2.0, inverted
☐ (D) 2.0, upright



Extended Answer

- A 5.0-cm-tall object is located 20.0 cm from a convex mirror with a focal length of -14.0 cm. Draw a scale-ray diagram showing the image height.

✓ Test-Taking TIP

Your Answers Are Better Than the Test's

When you know how to solve a problem, solve it before looking at the answer choices. Often, more than one answer choice will look good, so do the calculations first, and arm yourself with your answer before looking.